Chapter 2
Microbial-Assisted Phytoremediation: A Convenient Use of Plant and Microbes to Clean Up Soils

A. P. Pinto, A. de Varennes, C. M. B. Dias, and M. E. Lopes

2.1 Introduction

Environmental pollution by metal(loid)s (e.g., heavy metals—HMs) is a severe problem worldwide, as soils and aquatic resources became increasingly contaminated, threatening land ecosystems, surface and groundwater, as well as food safety and human health [1]. The primary sources contributing to this extended pollution are anthropogenic inputs related to the burning of fossil fuels, mining and continued industrial activities, disposal of municipal solid wastes and wastewater discharges or use for irrigation, and excessive utilization of fertilizers and pesticides [1–9]. A consequence of these anthropogenic activities is an increase of contaminated areas, which should be remediated to prevent or mitigate transfer of contaminants into terrestrial, atmospheric, or aquatic environments. Point and diffuse contamination by organic and inorganic pollutants causes wide concerns, and intentional or accidental introduction of these substances in the environment may represent serious impacts on public health.

Soil contamination is an important issue across the European Union (EU). About 3.5 million sites in the EU were estimated to be potentially contaminated

---

A. P. Pinto (✉)
Chemistry Department, University of Évora, CLAV, Évora, Portugal

Institute of Mediterranean Agricultural and Environmental Sciences (ICAAM), University of Évora, Évora, Portugal
e-mail: app@uevora.pt

A. de Varennes
Linking Landscape, Environment, Agriculture and Food, Instituto Superior de Agronomia, University of Lisbon, Lisbon, Portugal

C. M. B. Dias · M. E. Lopes
Chemistry Department, University of Évora, CLAV, Évora, Portugal

HERCULES Laboratory, University of Évora, CLAV, Évora, Portugal

A. A. Ansari et al. (eds.), *Phytoremediation*,
https://doi.org/10.1007/978-3-319-99651-6_2

with 0.5 million sites being highly contaminated and in need of remediation. About 400,000 polluted sites were already identified in Germany, England, Denmark, Spain, Italy, the Netherlands, and Finland. Sweden, France, Hungary, Slovakia, and Austria have at least 200,000 contaminated sites. Greece and Poland reported 10,000 contaminated land areas, while Ireland and Portugal reported fewer than 10,000 contaminated sites [10, 11]. Soils act as a final acceptor of toxic substances/trace elements (e.g., HMs; nonessential metal(loid)s), and these inorganic pollutants can limit development and growth of plants and pose a health hazard to humans and animals because some may be bioaccumulated and bio-magnified along the whole food chain [3, 12–15].

When the concentration of these pollutants is above a defined legal standard value, water, air, and soils are described as polluted, and environmental remediation becomes fundamental to decrease the potential risk of food chain contamination and other associated health risks [13, 16, 17]. Thus, it is necessary to use efficient soil cleanup techniques to restore heavy metal-polluted soils. Over the last decades, several physical, chemical, and biological approaches have been attempted to achieve this goal. Conventional treatments include excavation and transfer of soil to landfills, soil washing with water and solubilizing agents, building a physical cover, solidification through use of stabilizing agents, vitrification at high temperatures, electrochemical separation, etc. which may rapidly remediate soils, but irreversibly damage the ecological environment [18–21].

Between the different approaches for the reclamation of metal(loid)s contaminated soils, special attention is drawn to the technologies of phytoremediation (green and clean technologies) [10]. Phytoremediation is based on efficient, inexpensive, and eco-friendly rehabilitation strategies that use plants and associated soil microorganisms to absorb, accumulate, immobilize, or biodegrade organic and inorganic pollutants, present in different environmental matrices (air, soil, and water), through physical, chemical, and biological processes. Phytoremediation is proposed as a relatively recent technology with sustainable costs [13, 22, 23] that improves the native microflora and the physical, chemical, and biological properties, thus enhancing soil health and fertility [1, 20, 21, 23–27]. Moreover, phytoremediation appears to benefit plant growth and carbon sequestration, because harvested biomass can be used to produce renewable energies like biofuel production [13, 23, 28–30].

Phytoremediation is therefore a suitable option to clean metal(loid)s soil contamination. However, metal(loid)s are immutable, and therefore several of the low-cost phytoremediation options that are available for the remediation of organic contamination, such as phytodegradation and rhizodegradation, are not applicable to metal(loid)s-contaminated soils [31, 32]. Moreover, another phytoremediation technique, phytovolatilization, can only be used for some metals like mercury (Hg) and selenium (Se) which have volatile forms [24, 31]. Remediation options that remain are phytostabilization and phytoextraction [31, 32]. Based on economic implications, the aim of phytoremediation can be (1) plant-based extraction of metals with financial benefit (phytoextraction), (2) risk minimization (phytostabilization), and (3) sustainable soil management in which phytoremediation steadily increases soil fertility allowing growth of crops with added economic value [10, 32].

It can be an effective strategy for in situ or ex situ stabilization, removal, or biodegradation of a great range of pollutants in the different environmental compartments, including trace elements (HMs and nonessential metal(loid)s), radionuclides, excess nutrients, salts, and recalcitrant organic pollutants, like petroleum hydrocarbons (PHC), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), chlorinated solvents, and explosives (e.g., 2,4,6-trinitrotoluene) [1, 33]. Phytoremediation includes a range of plant-based remediation processes, and the most usual are presented in Table 2.1.

Phytoremediation reduces the risks of pollutants dispersion, and it is applicable for the decontamination of soils or wastewaters with mixed pollutants [13, 34]. 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 [13, 35].

The plants considered more efficient for phytoremediation are the metallophytes. These are able to survive and reproduce on metal-polluted soils [31, 36]. However, a great number of known metallophytes have small biomass and slow growth, characteristics that are not advantageous for phytoremediation technologies [31, 37]. Some metallophytes can be further classified as metal hyperaccumulators [31, 36]. Content of specific metal(loid)s in these plants exceeds levels that are usually required for normal growth and development. Hyperaccumulators belong to distantly related families, but share the ability to grow on metalliferous soils and accumulate metals in levels far in excess of those found in the majority of species, without suffering phytotoxic effects [1]. Three basic hallmarks distinguish hyperaccumulators from related non-hyperaccumulating plants: a strongly enhanced rate of metal(loid)s uptake, a faster root-to-shoot translocation, and a greater ability to detoxify and sequester metals in leaves [1].

These plants can be used in phytoextraction applications, but in most cases, hyperaccumulator plants are only able to accumulate one metal, while metal-polluted soils often contain a mixture of metals [31, 32, 36, 38]. This mixed pollution is not only challenging for phytoremediation with hyperaccumulator plants but also for metal-tolerant plants in general as plant metal tolerance mechanisms are

Table 2.1 Overview of most employed phytoremediation techniques (Adapted from [1])

Technique	Description
Phytostabilization	Immobilization of pollutants in the root zone while stabilizing the soil, thus reducing metal leaching and aerial dispersion of contaminated soil particles
Phytoextraction	Uptake of pollutants by plant roots and their translocation and subsequent accumulation in aboveground tissues
Rhizodegradation	Breakdown of organic pollutants through rhizospheric microbes
Phytodegradation	Plant metabolism transforms, breaks down, stabilizes, or volatilizes organic compounds from the soil and groundwater into harmless by-products
Phytovolatilization	Uptake of pollutants by plant roots and their transformation into volatile forms that transfer into the atmosphere

usually metal-specific. Another group of metallophytes, the metal excluders, are also considered appropriate for phytoremediation. These plants accumulate metals from the soil into their roots, but restrict metal(loid)s transport inside the plant. Such plants cannot be used for phytoextraction, rather they can be effective in phytostabilization techniques [31, 39]. Other plants used for phytoextraction of metals are high biomass-producing non-hyperaccumulator plants [32]. In comparison with hyperaccumulators, these plants accumulate a lower concentration of metal(loid)s but produce higher aboveground biomass, removing similar quantities of metals as hyperaccumulators [24, 31]. In conclusion, there are a large number of different plant species and ecotypes referred in the literature with the potential for phytoremediation purposes (phytoextraction or phytostabilization).

The success of phytoremediation is strongly determined by the amount of plant biomass present and the concentration of metal(loid)s in plant tissues. Therefore, high uptake and an efficient root-to-shoot transport system combined with enhanced metal tolerance provide hyperaccumulators with a high potential detoxification potential. However, high levels of metal(loid)s are toxic to most plants and can impair cell metabolism, reduce plant growth, and restrict metal phytoextraction. Physiological mechanisms that may be affected include enzymatic activity, protein structure, water balance, respiration and ATP content, photosynthesis, plant division, and morphogenesis [1, 5]. Phytoremediation has some disadvantages: naturally occurring hyperaccumulators grow slowly, the remediated area is only that close to the root, harvestable aboveground biomass is low, and numerous species cannot be planted in places strongly polluted. So genetic engineering approaches to develop transgenic plants with more favorable characteristics such as high biomass production, more metal accumulation, tolerance against metal toxicity, and well adapted to a variety of climatic conditions might be more beneficial in this respect [40].

Further research is needed in the field of genetic engineering to improve the phytoremediation abilities of transgenic plants and to understand the mechanisms and effectiveness of phytoremediation techniques in order to make these technologies more effective, timesaving, and economically feasible [40].Accordingly, it is necessary to develop other phytoremediation strategies for metal(loid)s-contaminated soils. Strategies to improve phytoremediation efficiency are the use of soil amendments (to increase or decrease metal availability) and the use of the plants' associated microorganisms. The rhizospheric environment is an essential habitat for different microbes including protozoa, algae, fungi, and bacteria. Such microorganisms exhibit a diversity of associations with plants [41, 42]. Microbes have the ability to synthesize and sense signaling molecules that trigger microbial populations to form a biofilm around the root surface and induce a related response. A number of plant-associated microorganisms are favorable because they can enhance the bioavailability of nutrients and mitigate the negative effects of metal(loid)s on plants. Rhizospheric microorganisms possess potential to biodegrade organic pollutants, through rhizodegradation, biotransformation, and volatization [41].

Numerous studies have demonstrated the adverse effect of different metal(loid) s on the soil microbial diversity and their disastrous interaction with plants in polluted soils. Excessive concentrations of metal(loid)s in soils can affect the growth, morphology, and metabolism of microorganisms mainly through destruction of cellular membranes and organelles, enzyme denaturation, and functional or conformational disturbance [41, 43]. To optimize the results of the application of phytoremediation techniques, many researchers have analyzed the dynamics between plants, microorganisms, and metal(loid)s in rhizospheric environments [43–54]. Recently, inoculation of plants with selected and acclimatized microbes (bioaugmentation) has attained salience for phytoremediation of metal(loid)s polluted soils, and assisted phytoremediation techniques are starting to be used to decontaminate polluted soils on large scales [40, 48, 50, 52, 55].

The interface between microbes and plant roots in the rhizosphere is believed to vastly influence the growth and survival of plants. The biotechnological potential of microorganisms to resist and/or remove metals directly from polluted media and their beneficial effects on plant growth may lead to environmental-friendly and cost-effective strategies toward reclamation of polluted soils. Rhizosphere microbes can determine metal availability and change speciation of HMs by producing biosurfactants, organic ligands via microbial degradation of soil organic matter, and exudates (e.g., metabolites, microbial siderophores), which can modify HMs bioavailability and uptake by plants [25, 44, 56–58]. Thus, microbial activities strongly influence metal speciation and transport in the environment. Different organisms exhibit diverse responses to toxic ions, which confer upon them a certain range of metal tolerance.

In conclusion, microbe-assisted phytoremediation has emerged as a sustainable soil cleanup technology with reduced soil disturbance, low maintenance, and overall low costs [25]. Recent studies have demonstrated that microorganisms play an important role in phytoremediation technology. Some species of microorganisms, including biodegradative bacteria, plant growth-promoting bacteria (PGPB), and filamentous fungi, appear to be beneficial in phytoremediation by changing rhizospheric environment, increasing biomass production and bioavailability or stabilization of HMs, and reducing the respective toxicity [23, 59]. Therefore, they can be used in soil amelioration. Microorganisms can produce organic compounds that solubilize and/or stabilize HMs by changing pH and oxidation-reduction potential of their soil environment.

Some polysaccharides secreted by microorganisms can easily bind soil particles, thereby improving the formation of soil aggregates. For example, glomalin and other glycoproteins released by arbuscular mycorrhizal fungi (AMF) may improve soil structure by increasing particle aggregation and aggregating stabilization against wind and water erosion. In addition, some soil bacteria are able to biodegrade toxic organic compounds, including solvents, produced in mineral processing [23].

Microorganisms further play an important role in removing or detoxifying HMs during the phytoremediation process [23]. Although phytoremediation is a sustainable and inexpensive technology for the removal of pollutants from the environment by plants, it is nevertheless a slow process.

Thus, it is important to improve the efficiency and increase the level of the stabilization or removal of toxic metal(loid)s from soils by plants. For this reason, greater attention has been paid to the role that fungi play in plants grown on metal-contaminated soils that have poor nutrients, low water-holding capacity, and adverse physical conditions [60].

2.2 Phytoremediation of Metals Assisted by Fungi

The microbiota can contribute to plant growth, productivity, carbon sequestration, and phytoremediation. Fungi are generally more tolerant to metals than bacteria [44, 61]. Fungi can efficiently explore soil microsites that are not accessible for plant roots due to the small diameter of the mycelia and can compete with other microorganisms for water and metal uptake, protect the roots from direct interaction with the metals, and hinder metal transport through increased soil hydrophobicity [44, 58]. Fungi have been defined as eukaryotic, heterotrophic, and absorptive organisms, which typically develop a branched, tubular body called a mycelium and reproduce by means of sporulation. Furthermore, the ability of fungi to form extended mycelial networks makes them well suitable for bioremediation processes. The application of filamentous fungi can be a promising alternative or a valuable complement in situations of bacterial malfunction [46, 47, 62]. Indeed, they play an important role in organic and inorganic transformation, element cycling, rock and mineral transformations, bio-weathering, mycogenic mineral formation, fungal-clay interactions, and metal-fungal interactions. The extensive hyphal networks in the soil can also significantly contribute to stabilization of soil aggregates; they modify the chemical composition of root exudates and soil pH and control metal(loid)s bioavailability in the soil [60].

Many fungi, such as *Trichoderma*, *Aspergillus*, and the arbuscular mycorrhizal fungi (AM), have shown the potential to improve phytoremediation processes in metal-contaminated soils [45, 63], because they have high ability to immobilize toxic metals by either the formation of insoluble oxalate, biosorption, or chelation onto melanin-like polymers. In fact, vascular plants host a great variety of fungi. In addition to being susceptible to soilborne pathogens, plant roots are also colonized by nonpathogenic or mutualistic fungi, such as AM fungi, ectomycorrhizae (EM), and dark septate endophytes (DSE). The AM fungi comprise about 150 species of zygomycetous fungi, and EM fungi include about 6000 species that are primarily basidiomycetes along with a few ascomycetes and zygomycetes [44].

The AM fungi are associated with most of herbaceous plants and with various woody plant families, while the EM fungi are mainly associated with a limited number of woody plant families [44, 64]. The mycorrhizal fungi facilitate the absorption of nutrients from the soil and help their translocation to host plants, sequester potentially deleterious metal(loid)s, and can stimulate soil microbial activity contributing to the overall biodegradation of soil pollutants [3, 40, 44, 65, 66]. Some DSE have been found as fungal symbionts in members of the *Cruciferae* species, although these are known as non-mycorrhizal plants [44]. The DSE are broadly classified as conidial and sterile septate fungal endophytes, which form melanized structures, such as inter- and intracellular hyphae and microsclerotia, in plant roots. The DSE fungi have been found worldwide and coexist often with different mycorrhizal fungi [44]. They have been reported from more than 600 plant species, including plants that are considered non-mycorrhizal [44, 64].

AM fungi of the Glomeromycota are the most common soil microorganisms in natural and agricultural soils [3, 67]. Approximately 160 AM fungal taxa of the order *Glomales* (Glomeromycota) have been described to date. Based on the morphological and molecular identification methods, the AM fungi were divided into 12 genera (*Acaulospora*, *Ambispora*, *Archaeospora*, *Diversispora*, *Entrophospora*, *Kuklospora*, *Geosiphon*, *Gigaspora*, *Glomus*, *Intraspora*, *Paraglomus*, *Scutellospora*) with the *Glomus* species as dominant [60, 68–70]. AM fungi are ubiquitous and form symbiotic associations with the majority of terrestrial plants [71, 72]. Consequently, they represent an important part of the soil microbiome and provide their hosts with benefits including increased access to nutrients through the enlargement of soil volume that can be assessed by roots/mycelia [3, 40], especially phosphorus; they also improve water acquisition and reinforce pathogen resistance [73, 74]. Therefore, mycorrhizal plants invest less energy into the extension of the root system than non-mycorrhizal plants and are more resistant to drought stress and pathogen attacks [31].

Mycorrhizal fungi keep the number of pathogens low through acidification of the rhizosphere and/or increased production of antibiotics [31, 75]. Mycorrhizal fungi can also increase plant's resistance at a physiological level. It has been shown that AMF can lead to greater resistance to herbivores through the action of jasmonic acid [31, 75]. Moreover, mycorrhizal associations could promote a faster closure of the leaf stomata, preventing plant wilting [31, 75], and boost plant osmolyte levels such as proline [31, 76]. Studies carried out by Sarwat et al. [77] showed that AM fungi inoculation in mustard (*Brassica juncea*) raised osmolyte content as proline and mitigate overall symptoms of drought stress caused by sodium chloride.

Mycorrhiza can assist in phytoremediation either by making metal(loid)s more bioavailable for uptake by plants or by reducing metal toxicity in their host plants [12, 31, 37, 78]. However, the phytoremediation efficiency is extremely dependent on fungal species and ecotype [31, 37, 78–80]. The selection of the fungal isolate to use in phytoremediation determines which plant species can be chosen for the application. Obviously, to be able to exert a beneficial effect on phytoremediation effectiveness, mycorrhizal fungi must first establish a mycorrhizal symbiosis. Therefore, the ability of the fungus to survive in metal(loid)s contaminated areas is a prerequisite for its use in phytoremediation applications.

To ensure their survival in metal(loid)s-contaminated soils, mycorrhizal fungi can use different extracellular and intracellular defense mechanisms. Extracellular mechanisms, such as chelation and cell wall binding or biosorption, may be used to prevent metal uptake. Intracellular mechanisms, including binding to nonprotein thiols and transport into intracellular compartments, can reduce the concentration in the cytosol [31, 37]. Intracellular mechanisms depend on transporter proteins and intracellular chelation (e.g., by metallothioneins, glutathione, organic acids, amino acids, and compound-specific chaperones) [31, 81]. Metal transporter proteins can alleviate metal stress by subcellular compartmentation via transporters into the vacuole or other internal cell compartments and/or vacuolar compartmentation of a complex (e.g., the GSH-M complex). Once chelated, these metal complexes can be transported as well. Furthermore, uptake/efflux of metals via specific transporter systems located in the plasma membrane can be downregulated [31, 81].

Additionally, antioxidative defense processes to detoxify reactive oxygen species (ROS) and mechanisms that focus on the repair of metal-damaged biomolecules can be present [31, 37]. Chelation is a first defense mechanism of mycorrhizal fungi against high metal(loid)s concentrations, which is both metal- and species-dependent. In accordance with the literature, a large range of different chelating agents, excreted by fungi, can be able to chelate metals, but there are also a number of studies reporting the opposite, metal solubilization from metal-containing chelates due to the exudation of organic compounds by mycorrhizal fungi [31, 37, 39, 82, 83]. Mutualistic fungi can also play a role in the protection of roots from metal(loid)s toxicity by mediating the interactions between the metals and the plant roots. The ability of mycorrhizal associations to attenuate metal toxicity for higher plants has been demonstrated [60, 71, 72, 78, 84, 85]. Several mechanisms explain why AM fungi can alleviate the stress of metal(loid)s. Mycorrhizal plants have larger biomass that can dilute the metal concentration [3, 86], and the metal(loid)s can be immobilized and compartmentalized in AM hyphal cells [3, 86, 87]. In particular, some native mycorrhizae surviving at contaminated sites may cause precipitation of metal oxalates in the intracellular spaces of the fungi or the host plant and thus restrict apoplastic transport by the Casparian strip [60, 88]. Alternatively, mycorrhizal fungi can directly protect the plant from the buildup of phytotoxic concentrations of certain pollutants by secreting specific detoxifying compounds (e.g., organic acids) or by binding the pollutants into fungal tissues associated with the roots, thus creating a physical barrier against toxic metal translocation [60, 89].

In addition, AM fungi can produce fungal polyphosphates, metallothioneins, and glycoproteins as glomalin, which have high binding capacities for metal(loid)s [3, 90]. Glomalin is a component of spore and hyphal cell wall of AM fungi and has the ability to sequester metal(loid)s. Driver et al. [91] found that glomalin is tightly bound in AM fungi hyphal and spore walls, and small amounts (<20%) of glomalin are released by AM fungi into the soil environment. Glomalin, though still not biochemically defined, is an N-linked glycoprotein composed of 3–5% N, 36–59% C, 4–6% hydrogen, 33–49% oxygen, and 0.03–0.1% P, and it also contains 0.8–8.8% Fe, which may be responsible for the reddish color of glomalin [92]. Apart from the Glomeromycota, no other fungal group produces this glycoprotein in significant amounts [92].

A number of studies have reported the contributions of glomalin to phytoremediation [92]. While examining the roles of glomalin in metal(loid)s sequestration of two polluted soils, González-Chávez et al. [93] stated the potential of glomalin to reduce availability and toxicity of “potentially toxic elements” such as Cu, Cd, and Pb. Furthermore, Cornejo et al. [94] reported that glomalin-related soil proteins (GRSP) bound to about 28% of the Cu and 6% of the Zn present in a soil highly polluted by these metals. From their study, it appears that the higher the concentration of the pollutants, the higher the ability of GRSP to bind them and make the pollutants unavailable.

Although the mechanisms by which metal(loid)s are sequestrated by glomalin are not clear at all, Malekzadeh et al. [92] proposed that mycelium of AM fungi play a major role in the sequestration of metals. As a result, glomalin may be involved in metal(loid)s sequestration due to its presence on the cell wall of the hyphae. González-Chávez et al. [95] showed that the hyphae of AM fungi sequester Cu as previously illustrated by using transmission electron microscopy and scanning electron microscopy linked to an energy dispersive X-ray spectrometer. This sequestration occurs not only in the mucilaginous outer hyphal wall zone and the cell wall but also inside the hyphal cytoplasm. In conclusion glomalin may reduce toxic elements bioavailability via their stabilization and may decrease their toxicity risk to microorganisms and plants in metal(loid)s-polluted sites [92].

AM fungi may often lower metal(loid) mobility and toxicity either by increasing soil pH [20, 21, 96, 97] or by sequestering inside extraradical mycelium [21, 98]. The phytotoxicity of metal(loid)s and level of plant tolerance are closely related to the stored forms of metal(loid)s and their mobility in plant tissues [20, 21, 99, 100]. Therefore, the distribution of chemical forms could be one of the most important metal(loid)s detoxification mechanisms in plants. It has been reported that AM fungi might enhance the tolerance to Cd of *Medicago sativa* L. by altering Cd chemical forms in different plant tissues [20, 21, 96, 101]. AM fungi can also alter the gene expression that relates to metal tolerance of host plants [3]. AM fungi have also been frequently reported in hyperaccumulators growing in metal-polluted soils indicating that these fungi have evolved a heavy metal tolerance and that they may play important roles in the phytoremediation of these sites [14, 80, 86, 102, 103].

Recently, it has been demonstrated that AM fungi can increase the metal(loid) translocation factor, biomass, and trace element concentration of hyperaccumulators [104–106]. Hyperaccumulators combined with AMF have advantages over the independent use of hyperaccumulators and have been proposed as one of the most promising green remediation techniques [36, 104, 105]. However, it is important to note that reductions [104, 105, 107, 108], increases [104, 105, 109, 110], or no changes of metal(loid)s concentrations in plants following mycorrhizal inoculation have all been observed, depending on the fungal-plant association [104, 105, 111–113].

Sheikh-Assadi et al. [114] reported a higher accumulation of Pb and Cd in the roots of inoculated *Limonium sinuatum* in a pot experiment. Plants inoculated with a mixture of *G. mosseae* and *G. intraradices* and exposed to different Cd and Pb concentrations accumulated Cd and Pb in the roots and translocated very little to the shoots. Total Cd and Pb accumulated in the roots was nearly two to three times higher in AM fungi-inoculated plants compared to non-mycorrhized plants. Furthermore, it was observed that mycorrhized plants had a higher metal tolerance. Therefore, it was concluded that mycorrhization alleviated metal toxicity in the plants and that inoculated *L. sinuatum* could be useful as a Cd or Pb controlling agent for phytoremediation. A good understanding of AM fungal communities under natural metal(loid)s stress can contribute greatly to the recognition of interactions between fungi, hosts, and metal(loid)s and further their rational utilization in metal(loid)s-polluted sites. Compared with AM fungi, endophytic fungi are ubiquitous and comprise a diverse group of fungi also showing potential to enhance phytoremediation [46, 47, 115].

Endophytic microorganisms (including bacteria and fungi) are likely to interact closely with their hosts and are more protected from adverse changes in the environment. Exploiting endophytic microorganisms to reduce metal(loid) toxicity to plants has been investigated to improve phytoremediation efficiencies. Therefore, endophyte symbiosis can counteract metal(loid) stress that exerts negative effects on plant growth.

The endophytic fungi could increase resistance of host plants to multimetal contamination. They possess suitable metal sequestration or chelation systems to increase their tolerance to metal(loid)s, and their higher biomass is also suitable for bioremediation [44, 116]. Furthermore, the presence of metal-resistant endophytic microorganisms may be valuable for host plants because they can enhance both nutrient assimilation and metal bioavailability, through the exuded metabolites in the plant rhizosphere, improving the phytoextraction processes [44, 54]. The metabolic processes operated by endophytes make them relevant resources for phyto(bio)remediation, helping on the phyto(bio)remediation of pollutants and biotransformation of recalcitrant organic compounds through their own degradative capabilities (phytostimulation or rhizodegradation) [44, 48, 117, 118].

Endophytic yeasts *Cryptococcus* sp. CBSB78 and *Rhodotorula* sp. CBSB79 have been isolated from canola roots (*B. chinensis*) in multimetal-contaminated soils and show resistance to Cd, Pb, Zn, and Cu [44, 119, 120]. Multiple HMs hyperaccumulating plants of the genus *Portulaca* contain endophytic fungi such as *Trichoderma*, *Fusarium*, *Aspergillus*, *Paecilomyces*, *Penicillium*, *Paecilomyces*, *Cladosporium*, and *Lasiodiplodia* [44, 46, 47]. *Penicillium* spp. and *Trichoderma* spp. were the most frequently isolated fungal taxa that can counteract HMs stress [44, 121–123]. Recent studies highlight the possible role of fungal endophytes harbored inside S. *nigrum*, which are able to promote host plant growth and enhanced metal extraction, improving the efficiency of phytoremediation in the cleanup of Cd-contaminated soils [56, 57]. In fact, the inoculation of Cd-resistant endophytic fungi with *S. nigrum* increased the plant's tolerance to the high concentrations of Cd, and the parameters related to the biosorption of Cd, including translocation factor, bioconcentration factor, and Cd tolerance index, were significantly enhanced.

In addition, some filamentous fungi such as *Aspergillus niger*, *Mucor rouxii*, and *Rhizopus arrhizus* can be used as sorbents because of their capacity to sorb metal ions such as Cu^{2+}, Co^{2+}, Cd^{2+}, Zn^{2+}, and Pb^{2+} [23].

Table 2.2 summarizes the published studies on microbial effects on plants under metal stress.

Table 2.2 Microbial-mediated metal(loid)s stress tolerance

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Glomerales species *Rhizophagus* (25.4%), *Funneliformis* (19.6%), *Claroideoglomus* (10.7%)	Sb	*Lactuca sativa* *Daucus carota*	Significant increase on its accumulation in carrots (all organs) with higher accumulation in roots In lettuce, accumulation appeared to be dependent on the Sb chemical species Moreover, it was observed for the first time that AM fungi changed the human bioaccessible fraction of Sb in edible organs	Pierart et al. [124]
Funneliformis mosseae, *Rhizophagus irregularis*, *Claroideoglomus lamellosum*	Cr(III), Cr(VI)	*Ricinus communis*	Decreased Cr(VI) concentration in soils	Gil-Cardeza et al. [125]
AM fungi	Pb, As, Cd	*S. melongena*	AM fungi application improved growth, biomass, and antioxidative defense response of plants against metal(loid)s stress The biomass and metal(loid)s uptake increased with AM fungi inoculation	Chaturvedi et al. [73]
Funneliformis mosseae, *Rhizophagus intraradices*	Cd	*S. nigrum*	Significantly enhanced shoot biomass and Cd shoot concentration	Li et al. [65]
Rhizophagus intraradices	Cd	*Oryza sativa*	Significant effects on root biomass, straw, and root Cd concentration	Luo et al. [21]
G. intraradices BEG140, *G. mosseae* BEG95, *G. etunicatum* BEG92, *G. claroideum* BEG96, *G. microaggregatum* BEG56, *G. geosporum* BEG199	Hg	*Zea mays* L.	Played an important role in the biogeochemical cycle of Hg in terrestrial ecosystems, indicating that AM fungi can alter Hg ligand environment and Hg soil to root mobility	Kodre et al. [126]
Rhizophagus irregularis	Cd	*Phragmites australis*	AM fungi improved Cd tolerance by promoting growth and changes in the distributions of elements in the treated plants For the first time, this study determined that *P. australis* inoculated by AM fungi could be a Cd-tolerant species	Huang et al. [127]

(continued)

Table 2.2 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Glomerella truncata PDL-1, *Phomopsis fukushii* PDL-10	Cd	*Solanum nigrum*	Significantly improved shoot and root length, chlorophyll content, and dry weight. The results of this study highlight the possible role of fungal endophytes harbored inside *S. nigrum*, which have the potential to improve the efficiency of phytoremediation or phytostabilization in the cleanup of Cd-contaminated soils	Khan et al. [57]
Funneliformis mosseae	Sb	*Cynodon dactylon*	Plant biomass was significantly increased by the symbiosis. Compared to uninoculated controls, mycorrhizal colonization significantly increased shoot and root Sb concentrations under all Sb treatment levels. Bioconcentration and translocation factors were elevated by mycorrhizal colonization. The fungus served an important role in Sb transport and fate in soil-plant systems	Wei et al. [128]
Claroideoglomus claroideum, *Funneliformis mosseae*	Cd, Pb	*Calendula officinalis* L.	Stimulated accumulation of important secondary metabolites (total phenols, flavonoids, carotenoids) in marigold flowers and, therefore, enhanced the antioxidant capacity. The highest b-carotene values and lycopene were found in the marigold-*F. mosseae* association	Hristozkova et al. [129]
Rhizophagus irregularis	Pb	*Trifolium repens* L.	Significant increase in glomalin production at all levels of Pb. Fungal symbiont seems to change the distribution pattern of Pb in organs including extraradical hyphae and roots	Malekzadeh et al. [92]

(continued)

Table 2.2 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Acaulospora, *Glomus*, *Rhizophagus*	Pb	*Vetiveria zizanioides* *Ricinus communis*	Higher tendency for Pb absorbed by the roots to be transported to the shoots	Schneider et al. [63]
Glomus fasciculatum	Cd, Zn	*Helianthus annuus* L.	Increased the dry biomass of the plant and accumulation of Zn and Cd in roots and shoots	Mani et al. [130]
Claroideoglomus claroideum, Funneliformis mosseae	Cd, Pb	*Calendula officinalis* L.	Accumulation of secondary metabolites (phenols, flavonoids, carotenoids) and enhanced antioxidant capacity	Hristozkova et al. [129]
Glomus viscosum, *Glomus constrictum*, *Glomus intraradices*, *Rhizophagus intraradices*	Mn	*Phytolacca americana*	Accumulated much higher concentrations of Mn, but no obvious correlations with AM fungi	Wei et al. [105]
Glomus etunicatum	Pb	*Calopogonium mucunoides*	Promoting plant nutrient (P, S, and Fe) acquisition, attenuating the negative effects of Pb on membranes, and contributing to the reduction of ROS generation	De Souza et al. [131]
Glomus mosseae	Cd, Pb	*Cajanus cajan* (L.) Millsp.	Reduced metal translocation from root to shoot. Exposure to Cd and Pb significantly increased the levels of PCs and GSH. The metal contents were higher in roots and nodules when compared with that in shoots. The results indicated that PCs and GSH might function as potential biomarkers for metal toxicity, and microbial inoculation showed bioremediation potential by helping pigeon pea to grow in multimetal-contaminated soils	Garg and Aggarwal [132]

(continued)

Table 2.2 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Aspergillus niger, *Penicillium bilaiae*, *Penicillium* sp.	Ni, Cu, Zn, Pb	NA	Main organic acids identified were oxalic acid (*A. niger*) and citric acid (*P. bilaiae*). Exudation rates of oxalate decreased in response to Pb exposure, while exudation rates of citrate were less affected The release of metals was related to the production of chelating acids, but also to the pH decrease. This illustrates the potential to use fungi exudates in bioremediation of contaminated soil	Arwidsson et al. [133]
Scleroderma citrinum, *Amanita muscaria*, *Lactarius rufus* L.	Zn, Cd, Pb	*Pinus sylvestris* L.	Reduced translocation of Zn, Cd, or Pb from roots to shoots in pine seedlings	Krupa and Kozdrój [134]
Beauveria caledonica	Pb	NA	Solubilized Pb from pyromorphite and accumulated the highest water-soluble fraction and total Pb concentration in the mycelium	Fomina et al. [135]
Glomus mosseae	Cu, Pb, Cd	*Sorghum*	Immobilized Cu, Pb, and Cd and accumulated metals in a nontoxic form leading to increased plant growth	González-Chávez et al. [136]
Oidiodendron maius	Zn	NA	Mobilized insoluble inorganic zinc compounds (ZnO and $Zn_3(PO)_2$). Induction of organic acids (malate and citrate) by the metal compounds was at least in part responsible for metal solubilization	Martino et al. [137]

M metal(loid)s, *NA* not applicable

2.3 Phytoremediation of Metals Assisted by Bacteria

Between the microorganisms involved in soil metal(loid)s phytoremediation, the rhizosphere bacteria deserve special attention because they can directly improve the phytoremediation process by changing the metal bioavailability via soil pH adjustment, release of chelators, induced redox changes, etc. [50, 54, 58, 61, 102, 138]. It was further demonstrated that some kinds of microorganisms are able to take up metal(loid)s from contaminated soils by reducing them to a lower redox state [23]. For example, some bacteria, such as *Bacillus arsenicoselenatis*, *Chrysiogenes arsenatis*, and *Sulfurospirillum arsenophilum*, have been found to have a large capacity for mobilizing As in mine tailings, wherein they can rapidly achieve microbial reduction of As(V) [23].

Combining increased rhizospheric plant bioavailability and reduced internal bioavailability of metal(oid)s should allow plants to bioaccumulate higher amounts of metal(oid)s, without increases on phytotoxicity [46, 47, 139]. Further, since the bacterial cells (approximately 1.0–1.5 mm^3) have an extremely high ratio of surface area to volume, they could sorb a greater quantity of metal(loid)s than inorganic soil components (e.g., kaolinite, vermiculite, mica) either by an independent passive metabolism or by a metabolism-dependent active process [50]. Several authors have pointed out that bacterial biosorption/bioaccumulation mechanisms, together with other plant growth-promoting features, accounted for improved plant growth in metal(loid)s-contaminated soils [50, 140, 141].

Plant growth-promoting (PGP) bacteria are so named due to their potential to enhance plant growth. These PGP bacteria may develop symbiotic/mutualistic associations with plants and may be found as free living rhizospheric or endophytic bacteria. Genera including *Gluconacetobacterium*, *Flavobacterium*, *Beijerinckia*, *Klebsiella*, *Erwinia*, *Enterobacter*, *Burkholderia*, *Pseudomonas*, *Serratia*, and *Bacillus* are among the beneficial PGP bacteria able to control plant growth [41, 142, 143]. Some studies have found that plant growth-promoting rhizobacteria (PGPR) have the capacity to alleviate metal-induced phytotoxicity and enhance biomass production of plants when grown in metal(loid)s-contaminated soils. Although the role of PGPR on plant growth and metal(loid)s phytoremediation potential in polluted soils has been studied extensively, the dynamics of plant-endophytic bacteria and their potential role in phytoremediation are only beginning to be described in the literature in recent years [25, 52, 144–147].

The metal-resistant bacteria on roots and in the rhizosphere can benefit from root exudates, but some bacteria enter the plant as endophytes that do not cause harm and can establish a mutualistic association [148, 149]. However, endophytic populations, as rhizospheric populations, can be restricted by biotic and abiotic factors [149–151]. The endophytic bacteria may be more protected from the effects caused by biotic and abiotic stresses than rhizospheric bacteria [149]. In accordance with their life strategies, endophytic bacteria can be classified as "obligate" or "facultative." Obligate endophytes are strictly dependent on the host plant for their growth and survival, and their transmission to other plants occurs vertically or via vectors. Facultative endophytes have a stage in their life cycle in which they exist outside host plants. Endophytic bacteria enter plant tissues usually through the root zone; however, aerial parts of plants, such as flowers, stems, and cotyledons, may also be used for this entry [152]. The bacteria penetrate the plant tissues via germinating radicles [153], secondary roots [154], stomates [155], or as a result of foliar damage [156]. Endophytes, once inside the plant, may either become placed near the entrance area or spread throughout plant tissues. These microorganisms can be present within cells, in the intercellular spaces, or in the vascular system.

Although many reports attest the importance of PGPR in microbial-assisted phytoremediation, the bacterial endophytes offer several advantages over PGPR. For instance, colonization of the plant roots with PGPR is often problematic, because application of the inoculant should be at the exact time required for the plant. Moreover, being in natural biocenosis, they lose competitiveness over endemic bacteria [53]. The survival and colonization potential of PGPR depends also on various factors, such as intrinsic physiological characteristics of the organisms and abiotic and biotic soil factors [53]. The endophytic bacteria may derive significant competitive advantage over PGPR from their close contact with plants. In addition, reinoculation of endophytic bacteria does not affect the indigenous endophyte population in plants [53, 157]. Furthermore, localization within the plant may provide endophytic bacteria with the ability to recolonize the plant surface and tolerate some biotic and abiotic stress situations in the soil [53, 149].

Although this field of research is at an early stage, the available literature suggests that metal-resistant endophytic bacteria cannot only protect plants from metal(loid)s toxicity but also enhance the metal bioaccumulation in plant tissues with concurrent stimulation of plant growth. These beneficial effects exhibited by endophytic bacteria, together with the suggested interrelationship between microbial metal(loid)s tolerance and plant growth-promoting efficiency, indicate that inoculation with endophytic isolates might have significant potential to improve phytoremediation efficiency in polluted soils [53]. Endophytic bacteria reside in plant tissues beneath the epidermal cell layers, from where they can colonize the internal tissues and form a range of different lifestyles with their host including symbiotic, mutualistic, commensalistic, and trophobiotic [52, 158]. They are ubiquitous in a large diversity of plant species and can colonize a particular host with highest densities in root and less from stems to leaves [52, 159].

In general, most endophytes originate from the epiphytic bacterial communities in the rhizosphere or phyllosphere or other plant parts; however, some may be transmitted through the seed or damaged foliar tissues ([160, 161]). The long-term coevolution of plants and endophytic bacteria resulted in an intimate ecosystem, which helps plants to adapt/survive in both biotic and abiotic stress conditions (e.g., pathogen infection, drought, salinity, and contaminants) and enhance the ecological balance of the natural system [52, 162]. Although bacterial endophytes exist in plants variably and transiently [50, 163], they are often capable of triggering physiological changes that promote the growth and development of the plant [50, 164]. In general, the beneficial effects of endophytes are more extensive than those of many rhizobacteria [50].

PGP bacteria can also enhance plant development by acting as biofertilizers (increasing the availability of essential nutrients through, e.g., N_2 fixation and phosphate and iron solubilization), as organic contaminant biodegraders, as phytostimulants (producing plant growth regulators and hormones, such as indoleacetic acid—IAA; cytokinins; and other auxins), as stress controllers (by decreasing ethylene production through the synthesis of 1-aminocyclopropane-1-carboxylic acid deaminase—ACCD), and as plant defense inducers against phytopathogens (by producing siderophores, antibiotics, or fungicidal compounds) [25, 148, 165–170].

Moreover, a number of other beneficial effects on plant growth have been attributed to endophytes which include osmotic adjustment, stomatal regulation, modification of root morphology, enhanced uptake of minerals, and change on nitrogen accumulation and metabolism [148]. In recent years, phytoremediation assisted by bacterial endophytes has been highly recommended for cleaning up of metal(loid)s-polluted soils since 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 plants [50, 52].

Endophytic bacteria improve plant growth in metal-polluted soils in two different ways: (1) directly by producing plant growth beneficial substances including solubilization and bioconversion of mineral nutrients (phosphorus, nitrogen, and potassium) and production of phytohormones, siderophores, and specific enzymes and (2) indirectly by controlling plant pathogens or by inducing a systemic resistance of plants against pathogens. Besides, they also change metal bioaccumulation ability in plants by excreting metal immobilizing extracellular polymeric substances (EPS), as well as metal mobilizing organic acids and biosurfactants [52]. Further, the extracellular polymeric substances secreted by endophytic bacteria, consisting mainly of polysaccharides, proteins, nucleic acids, and lipids, also play a significant role in metal complexation, thereby reducing their bioaccessibility and bioavailability [43, 52].

Joshi and Juwarkar [171] assessed the ability of *Azotobacter* spp. to produce EPS able to form complexes with Cd and Cr decreasing metal uptake by *Triticum aestivum*. Further, the biosurfactants produced by endophytic bacteria seemed to increase the bioavailability of poorly soluble metals and to improve phytoremediation rates [52, 160]. Biosurfactants are low-molecular-weight amphiphilic molecules consisting of a hydrophilic and a hydrophobic moiety, comprising a wide range of chemical structures, such as mycolic acid, glycolipids, lipopeptides, polysaccharide-protein complexes, phospholipids, fatty acids, etc. [52, 172]. These molecules are able to decrease the surface tension, critical micelle concentration, and interfacial tension, thus affecting the distribution of the metals among the phases (Ma 2016). Endophytic bacteria produce the biosurfactants and release to the host as root exudates.

The secreted biosurfactants initially interact with complex insoluble metals on the interface of rhizosphere soil particles and then desorb metals from soil matrix, leading to the change of metal mobility and bioavailability in the soil solution [52, 53]. The interactions between endophytic bacteria, metals, and biosurfactants can be explained from a functional perspective, considering that the key role attributed to biosurfactants is their involvement in facilitating metal uptake [52, 160]. With regard to indirect effects on plant growth promotion, several plant growth-promoting endophytic (PGPE) bacteria are known to diminish the stress effects in plants by suppressing phytopathogen damage [52] either via biological control of pathogens or induced systemic resistance (ISR) of plants against pathogens.

The endophytic bacteria as natural biocontrol agents may have numerous competitive advantages over plant growth-promoting rhizobacteria [52, 53]. Some endophytic bacteria can produce substances that may effectively limit phytopathogens, such as antibiotics, siderophores, a variety of hydrolytic enzymes (such as chitinases, proteases, and glucanases), and antimicrobial volatile organic compounds [52, 173]. In many biocontrol systems, one or more antibiotics have been shown to play a role in disease suppression. For instance, the endophytic bacterial strains *Bacillus megaterium* BP 17 and *Curtobacterium luteum* TC 10 effectively suppressed the burrowing nematode (*Radopholus similis* Thorne) by the synthesis of antibiotics [52, 174]. Recently, Bacon et al. [175] also reported that a patented strain of *Bacillus mojavensis* produced the biosurfactant C-15 surfactin, which was able to control the maize mycotoxic fungus *Fusarium verticillioides*. Additionally, endophytic bacteria can also be effective as competitors of pathogens for colonization niches and bioavailable nutrients, indirectly promoting plant productivity ([176]; Ma 2016).

Induced systemic resistance (ISR) refers to the state of systemically enhanced resistance to a broad spectrum of pathogens [52]. The ISR to various diseases caused by chemicals and plant growth-promoting bacteria is highly beneficial in agroecosystem protection. ISR induced by endophytic bacteria has been demonstrated against various fungal, bacterial, and viral pathogens in many plant taxa ([176]; Ma 2016). Priming plants with bacterial endophytes induced a plant defense system, which pathogens must overcome to colonize the host [52]. Once the defense genes are expressed, ISR activates multiple potential defense mechanisms that include the increased activity of chitinases, β-1,3-glucanases, superoxide dismutase, guaiacol, catalase (CAT), and peroxidases (POS) [52, 177]. The activity of these enzymes is responsible for reactive oxygen species production, and protection of cell organelles against oxidative stress may change as a result of the activity of endophytic bacteria ([178]; Ma 2016).

In addition, Wan et al. [178] and Zhang et al. [179] found that endophytic bacteria could modulate the activity of plant antioxidant enzymes (such as POS, CAT, SOD, glutathione peroxidase, ascorbate peroxidase) and lipid peroxidation (malondialdehyde formation).

Recent experiments with hyperaccumulator plants revealed that the inoculation of soils/seeds/seedlings with metal-resistant endophytic bacteria improved plant growth and accelerated the phytoremediation process in naturally and/or artificially metal(loid)s-contaminated soils by enhancing nutrient acquisition, cell elongation, metal bioaccumulation or stabilization, and alleviation of metal stress in plants [52, 104, 105, 108, 145, 147, 180–183]. Similarly, the colonization and propagation of plant growth-promoting endophytic bacteria are also well known for their role in the enhancement of soil fertility and stimulation of host plant development by providing a plethora of growth regulators [52, 184] and essential nutrients [52] or by synthesizing 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase [52, 185], as well as by reducing disease severity by suppressing pathogens [52, 174]. Further, bioaugmentation with such endophytic bacteria possessing multiple plant growth-promoting traits, including metal resistance/detoxification/accumulation/biotransformation/sequestration, can reduce phytotoxicity and change the bioavailability of metal(loid)s in contaminated soils, making them a perfect choice for microbial-assisted phytoremediation studies [50, 52, 53, 168, 169].

Although metal(loid)s negatively influence endophytic bacterial diversity in plants [52, 181], numerous studies have demonstrated that endophytic bacteria isolated from hyperaccumulator plants exhibit greater metal tolerance than those from non-hyperaccumulator plants [186]. This may be due to the adaptation strategy of endophytic bacteria to metal(loid)-containing environments [52, 187]. Numerous studies have demonstrated the effect of different metal(loid)s on endophyte diversity, biomass, and activity. However, it is well known that the bacteria isolated from polluted environments are tolerant to higher concentrations of metals than those isolated from unpolluted areas. Further, after the addition of metals, metal tolerance is increased in bacterial communities by the death of sensitive species and subsequent competition and adaptation of surviving bacteria [188]. Experimental results suggest that bacterial metal(loid) resistance can be a result of horizontal gene transfer (HGT) mediated by plasmids encoding metal resistance genes [52, 189]. For instance, some mercury-resistant endophytic bacteria express the *MerB* gene encoding organomercurial lyase that cleaves organomercurials into mercuric ion (Hg^{2+}) [52, 190] and *MerA* gene encoding mercuric reductase that converts the highly toxic ionic Hg^{2+} into the less toxic and volatile Hg^0 [52, 191], thus alleviating metal toxicity and improving the efficiency of phytovolatilization. The genes specifying the various functions needed for biodegradation of organomercurials and reduction of Hg^{2+} are organized in the mercury resistance (*Me*) operon, which is mostly found in gram-negative bacteria [52, 190].

Idris et al. [186] investigated the endophytic bacteria and rhizobacteria associated with the Ni hyperaccumulator plant *Thlaspi goesingense* using both cultivation-dependent and cultivation-independent techniques. The results showed that most of the endophytes were cultivation-independent and tolerated higher Ni concentrations than rhizobacteria. Furthermore, endophytic bacteria are thought to exhibit different multiple metal resistance through similar mechanisms described for rhizobacteria [50, 144]. Therefore, the beneficial endophytes have been proposed as potential natural resources to enhance phytoremediation of metal(loid)-contaminated soils, due to their biotechnological applications in metal bioremediation. The study of the diversity and structure of bacterial communities living in niches under metal stress is of paramount importance.

Like rhizobacteria, there are several mechanisms by which PGPE directly facilitate growth of their host plants. The mechanisms include nitrogen fixation, solubilization of minerals, and production of phytohormones, specific enzymes, and siderophores [52, 53, 192]. Bacteria that can fix nitrogen, i.e., convert stable atmospheric nitrogen gas into a biologically useful form, are known as diazotrophs. These organisms reduce dinitrogen to ammonia with the help of the enzyme nitrogenase [193]. Endophytic bacteria with strong associative nitrogen-fixing ability allow plants to survive in nitrogen-poor soil environments and play a major role in promoting plant health and growth, compared to other rhizospheric microbes [52, 194, 195]. Phosphorus (P) is one of the major essential plant nutrients as it plays a crucial role in the overall growth of plants by influencing various key metabolic processes such as cell division and development, energy transport, signal transduction, macromolecular biosynthesis, photosynthesis, root development, and respiration of plants [52, 196, 197]. Phosphorus in soil is immobilized or becomes less soluble by absorption and chemical precipitation, so that the amount of readily bioavailable phosphorus is very low, compared with the total amount of phosphorus present. Therefore, P is often regarded as a limiting nutrient in agricultural soils [197, 198]. Under metal(loid)s stress conditions, some metal-resistant endophytic bacteria were found to solubilize precipitated phosphates in soil by acidification, ion exchange, and release of chelating agents [52, 199] or to mineralize organic phosphorus in soil by exuding extracellular acid phosphatase [52], thereby enhancing P availability to plants. It is well known that endophytic bacteria assimilate soluble P and prevent its subsequent sorption [52, 200]. Hence, these endophytic bacteria may serve as a sink for phosphorus by rapid microbial phosphorus mobilization even under phosphate-limiting conditions. Subsequently, these endophytes become a source of phosphorus to the plant hosts upon its release from bacterial cells.

Phosphate solubilizing bacteria are common in the rhizosphere, and secretion of organic acids and phosphatases facilitates the conversion of insoluble forms of P to bioavailable forms. Endophytes such as *Pseudomonas citronellolis*, *Pseudomonas oryzihabitans*, *Enterobacter agglomerans*, *Pantoea* sp., *Enterobacteriaceae*, *Burkholderia*, *Ralstonia pickettii*, *Erwinia* sp., *Klebsiella pneumoniae*, *Klebsiella oxytoca*, *Acinetobacter* sp., *Acinetobacter calcoaceticus*, *Enterobacter sakazakii*, *Agrobacterium* sp., and *Caulobacter/Asticcacaulis* have been defined as efficient P solubilizers [53]. Iron (Fe) is one of the important elements for life, and almost all organisms, with the exception of certain lactobacilli, need iron-containing proteins involved in physiological activities and a series of enzymatic reactions [52]. However, in the aerobic environment of soils, iron exists mainly as Fe(III) and tends to form insoluble hydroxides and oxyhydroxides, making it largely unavailable to microorganisms. To acquire sufficient iron, bacteria had to develop strategies to solubilize this metal before uptake. In addition to rhizosphere bacteria, metal-resistant endophytic bacteria that also produce siderophores have been isolated from many different plant species.

Siderophores are produced by a diverse group of microbes ranging from animal and plant pathogens to free-living and symbiotic nitrogen-fixing microorganisms. However, siderophore production is most common among plant growth-promoting rhizosphere bacteria, which exhibit their optimum growth and siderophore production activity at extreme environmental conditions, including scarcity of nutrients or the presence of elevated concentrations of metal(loid)s and thus may be particularly useful for phytoremediation purposes. Iron deficiencies induced by excess of metal(loid)s have been reported in various plant species as interveinal chlorosis in younger leaves [54]. Their low iron content generally inhibits both chloroplast development and chlorophyll biosynthesis, thus affecting plant growth [54]. Under such conditions, siderophore-producing bacteria (e.g., rhizosperic, endophytic) might offer a biological rescue system that is capable of scavenging Fe^{3+} and making it available to iron-deficient plants.

In short, iron bioavailability to plant roots may be modified by the microbial production of chelating agents (e.g., siderophores), which can solubilize Fe under iron deficiency conditions. Siderophores are low-molecular-weight organic compounds (500–1500 Da) with an affinity for Fe^{3+} ions, which can also bind other metal ions that can be uptaken by plants [52, 53]. Iron acquisition takes place by two basic strategies. The first is by the uptake of Fe in Fe-siderophore complexes after root-mediated biodegradation of the chelate [52, 53]. The second strategy involves the solubilization of unavailable forms of iron by the release of phytosiderophores. Since microbial siderophores typically have higher affinity for iron than phytosiderophores, plants growing in metal-contaminated soils are able to accumulate high amounts of iron with the help of siderophore-producing bacteria. Hence, bacterial siderophores are assumed to serve as major sources of phytoavailable Fe for plants under metal stress conditions [50, 52].

Mechanisms of iron acquisition in higher plants can be grouped into strategy I and strategy II [54]. Although strategy II plants (*Poaceae*), similar to microorganisms, release (phyto)siderophores (e.g., mugineic acid in barley and avenic acid in oat) to enhance their Fe uptake, in metal-contaminated soils, these plants are unable to accumulate sufficient amounts of iron, unless bacterial siderophores are also present due to their higher affinity for iron [54]. Unlike strategy II plants, strategy I plants (dicots and monocots, except *Poaceae*) do not produce phytosiderophores themselves. Rather, their iron acquisition is achieved by other means, such as an enhanced Fe(III)-reductase activity, the release of reducing agents such as phenolics, and acidification of the rhizosphere [54]. However, this strategy is considered to be less efficient than that of strategy II plants [54]. Therefore, inoculation of plants with bacteria that are able to produce siderophores could help to prevent them from becoming chlorotic when they are grown in metal-polluted soils.

Thus, siderophores act as solubilizing agents for iron from minerals or organic compounds under conditions of iron limitation. In addition to iron, siderophores can also form stable complexes with other metals that are of environmental concern, such as Al, Cd, Cu, Ga, In, Pb, and Zn, as well as with radionuclides including U and Np [54, 201]. Currently, almost 500 different siderophores have been identified [54, 202]. Although they differ widely in their overall structure, the functional groups that coordinate the iron atom are not as diverse. In their metal-binding sites, siderophores have either α-hydroxycarboxylic acid, catechol, or hydroxamic acid moieties and thus can be classified as hydroxycarboxylate-, catecholate-, or hydroxamate-type siderophores [54]. The biosynthetic pathways of siderophores are tightly connected to aerobic metabolism involving molecular oxygen activated by mono-, di-, and N-oxygenases and acids originating from the final oxidation of the citric acid cycle, such as citrate, succinate, and acetate. Moreover, many siderophores are polypeptides that are synthesized by members of the non-ribosomal peptide synthetase multienzyme family, which is also responsible for the synthesis of the majority of microbial peptide antibiotics [54]. However, many of the hydroxamate- and α-hydroxy acid-containing siderophores are not polypeptides but are assembled instead from alternating dicarboxylic acid and either diamine or amino alcohol building blocks (which are nevertheless derived from amino acids) that are linked by amide or ester bonds. Such siderophores are assembled by the non-ribosomal peptide synthetase-independent siderophore pathway, which is widely utilized in bacteria. Several recent reviews describe siderophore structure and biosynthesis mechanisms in more detail [54, 203].

Siderophores generally form 1:1 complexes with Fe^{3+}, which are then taken up by the cell membrane of bacteria, where the Fe^{3+} is reduced to Fe^{2+} and released from the siderophore into the cell. In some cases, the siderophore is destroyed during this reduction, but in other cases, it is recycled [54]. This mechanism of iron uptake from siderophores has already been identified in both gram-negative and gram-positive bacteria [54, 204]. Although siderophores are elicited primarily in response to iron deficiency, external pH is also important for the biosynthesis of microbial siderophores, as well as in their chemical stability in the environment [54]. Production of siderophores by different microorganisms appears to contradict the commonly acknowledged pH-dependence of Fe deficiency. Hydroxamate siderophores in general are prevalent in acidic soils and reflect the preference of low pH values for the synthesis of hydroxamate siderophores by microorganisms. In contrast, neutral to alkaline soils support the production of catecholate siderophores. In addition to pH, heavy metal concentrations in the surrounding environment could also influence microbial growth and siderophore biosynthesis.

Bacterial strains isolated from polluted environments were shown to be tolerant to higher concentrations of metals than those isolated from unpolluted areas [53, 54]. These metal-tolerant bacteria have evolved several mechanisms for survival under metal stress. Interestingly, several studies have found a stimulating effect of heavy metals on siderophore biosynthesis in various bacteria. Two different possible explanations have been suggested for the stimulating effect of heavy metals on siderophore production. Firstly, the heavy metal might be directly involved in the siderophore biosynthesis pathways or their regulation [54, 205]. Alternatively, the free siderophore concentration in the medium might be reduced by complex formation with metal ions. This process interferes with the complexation of siderophores with iron and thus decreases the soluble iron concentration. As iron deficiency stimulates siderophore production, more siderophores would then be produced [54, 206, 207].

Plants inoculated with siderophore-producing bacteria could then take up iron from siderophores via various mechanisms, such as chelate degradation and release of iron, the direct uptake of siderophore-Fe complexes, or by a ligand exchange reaction [54, 208, 209]. A variety of plant species were shown to acquire iron from Fe-siderophore complexes, including *Cucurbita pepo*, *B. juncea*, *Helianthus annuus*, *Medicago sativa*, and *Vigna unguiculata*, and, moreover, it was shown that this acquisition was the reason for their stimulated growth in metal-contaminated soils. Experiments with *Phaseolus vulgaris* revealed that the inoculation with the Pb- and Cd-resistant siderophore-producing bacteria strain *Pseudomonas putida* KNP9 significantly increased plant growth without showing any symptoms of lead and cadmium toxicity compared with the controls [54, 210]. This effect was attributed to the increased level of siderophores produced by the KNP9 strain that were able to provide iron to the plant in the presence of high levels of Pb and Cd.

Inoculation with other rhizobacteria, such as *Pseudomonas* sp. Ps29C and *Bacillus megaterium* Bm4C, which had been isolated from Ni-rich serpentine soils, has also been studied in detail [205, 211, 212]. These bacteria significantly reduced the toxicity of Ni in *B. juncea* and promoted plant growth. Although bacterial siderophores have the potential to sparingly mobilize soluble metals, the efficiency of siderophore-producing bacteria (SPB) to either mobilize or immobilize heavy metals from soils is dependent on several factors, such as the form of the heavy metals present, the charge of the siderophores, as well as the pH of the soil and its mineral composition and organic content [54, 205, 211, 212]. Endophytic bacteria are also able to supply essential vitamins and growth regulators (phytohormones) to plants, which can increase plant nutrient uptake through their effects on root growth dynamics [52, 213].

The phytohormone production by endophytes is believed to play an important role in plant-bacterial interactions and plant growth in metal-contaminated soils [214]. Recent studies investigating the role of phytohormones in protecting plants against metal(loid)s have demonstrated that the endophytic colonization often causes increases in nutrient uptake and plant biomass [52, 184, 213, 215]. These may suggest that metal(loid)s stress alleviation by endophytic bacteria results from a combination of nutritional and biochemical benefits. In general, the phytohormones comprise indole-3-acetic acid (IAA), cytokinins, gibberellins, abscisic acid, and ethylene, which may be either growth inhibitors or promoters depending upon the substance concentration [52, 213]. As a major auxin, IAA is involved in different physiological processes in plants, such as adjustment of plant development [52, 215], induction of plant defense systems [52], and as a cell-cell signaling molecule [52, 216]. IAA is transported downward causing a concentration gradient in different plant parts. Depending on its concentration, inhibition, or stimulation of growth, tissue differentiation may result [52, 217]. More recently, the amount of IAA released by endophytes is thought to play a vital role in modulating the plant-endophyte association and plant development in metal(loid)-contaminated soils [183].

Auxins and cytokinins were found to be produced by strains of *Pseudomonas*, *Enterobacter*, *Staphylococcus*, *Azotobacter*, and *Azospirillum*. These substances, together with gibberellins, may alter plant growth and development [53, 218]. For instance, *Azospirillum*-inoculated roots showed a stimulation of root cell membrane activity, as well as an increase in the levels of free IAA, indole-3-butyric acid, and the specific activities of both the tricarboxylic cycle and the glycolysis pathway [53, 219]. According to the IAA level, root elongation may change qualitatively. A low level of the phytohormone produced by bacteria promotes primary root elongation, whereas a high level of IAA stimulates lateral and adventitious root formation but inhibits primary root growth [220]. Thus, endophytes can facilitate plant growth by altering the plant hormonal balance. *P. fluorescens*, for instance, is generally regarded as being a rhizosphere bacterium that colonizes mainly the elongation and root hair zones of roots. Some *P. fluorescens* can also be endophytic, being found within the roots and stems of some hyperaccumulators [53, 221, 222]. The observed plant growth promotion, under Pb stress after inoculation of plant with *P. fluores-*

cens, is thought to be the consequence of bacterial IAA production and excretion [53, 222]. Therefore, any direct influence on phytohormone production by bacteria may in turn affect their phytostimulating efficiency.

Another way in which the endophytic bacteria might influence the host plant growth is the utilization of ACC as a sole N source. Endophytic bacteria that are generally beneficial to plants in situ, such as *Azotobacter*, *Azospirillum*, *Pseudomonas*, *Enterobacter*, *Staphylococcus*, etc., are known to be involved with production of phytohormones [52, 160]. Luo et al. [20] reported that the enhanced growth of the Cd hyperaccumulator S. *nigrum* L. induced by bacterial endophytes under cadmium stress might be the consequence of both bacterial IAA and ACC deaminase. Ethylene, as a ubiquitous plant hormone, plays a vital role in plant response (growth and survival) to abiotic and biotic stresses including root initiation and nodulation, cell elongation, leaf senescence, abscission and fruit ripening, as well as auxin transport [52, 223]. Ethylene is synthesized in higher plants via the following pathway [49, 52]: (1) the enzyme *S*-adenosyl-L-methionine (SAM) synthetase catalyzes the conversion of methionine and adenosine triphosphate (ATP) to SAM; (2) ACC synthase mediates the hydrolysis of SAM to ACC and 5′-methylthioadenosine (MTA); and (3) ACC is finally oxidized by ACC oxidase to form ethylene, carbon dioxide, and hydrogen cyanide. It has been reported that metal(loid) stress in plants induces ethylene production, which causes the inhibition of root elongation, lateral root growth, and root hair formation. Under such conditions, certain endophytic bacteria might alleviate the stress-mediated impact in plants by enzymatic hydrolysis of ACC.

Ethylene is implicated in virtually all aspects of plant growth and development, ranging from seed germination to shoot growth and leaf abscission [53, 224]. Therefore, production of ACC deaminase is likely an important and efficient way for endophytes to manipulate their plant hosts. The enzyme ACC deaminase may hydrolyze ACC into α-ketobutyrate and ammonia, which can readily metabolized by the bacteria as a source of nitrogen. Endophytic bacteria containing ACC deaminase are usually located inside plant roots in the apoplast. In this way, these bacteria act as a sink for ACC. By lowering ethylene levels, the bacteria increase the growth of plant roots and shoots and reduce the inhibitory effects of ethylene synthesis ([53, 225]; Ma 2016). A higher percentage of endophytes than of rhizosphere bacteria were able to utilize ACC as the sole N source. Experiments with *Methylobacterium oryzae* and *Burkholderia* sp. (isolated from rice tissue) showed the ability of these bacteria to reduce the level of ethylene, protecting tomato (*Lycopersicon esculentum*) from the toxicity of high concentrations of Ni and Cd [53].

The success of phytoremediation is widely dependent on the ability to overcome metal phytotoxicity. Therefore, different bacterial-mediated mechanisms are implicated on the endophyte-host coevolution process either by relieving metal toxicity or by enhancing plant metal tolerance [52, 53, 147]. Shin et al. [183] found that the endophytic bacterial strain *Bacillus* sp. MN3-4 evolved a better defined metal-resistant mechanism, e.g., active export via a P-type ATPase efflux pump, which can transport metal ions across biological membranes against the concentration gradient using energy released by ATP hydrolysis. Endophytic bacteria possessing specific and remarkable metal bioaccumulation abilities can be used in plant-endophyte mutualistic systems to facilitate detoxification of metal(loid)s and improve the efficiency of phytoremediation [52, 183, 226]. It is well known that the transfer of metal(loid)s from soils to plants depends primarily on metal bioavailability which can be affected by several factors, such as soil particle size, nutrients, soil pH, redox potential, organic matter content, and the presence of other ions [48, 52, 55]. Numerous studies have suggested that endophytic bacteria possessing a metal resistance/sequestration pathway (e.g., *ncc-nre*) can alleviate the phytotoxicity and enhance the bioavailability of metal(loid)s through the release of metal chelating agents (e.g., siderophores, biosurfactants, and organic acids), acidification of soils, redox activity, and phosphate solubilization [50, 52].

Currently, the interactions between endophytes and hyperaccumulator plants have attracted the attention of several investigators due to the biotechnological applications for bioremediation and to study the composition of bacterial communities living on naturally contaminated environments. In general, hyperaccumulating plants accumulate huge amounts of metal(loid)s and can therefore provide a specific environment for bacterial endophytes adapted to survive in high metal concentrations. For instance, metal-resistant endophytic bacteria have been isolated from various hyperaccumulating plants such as *Alyssum bertolonii*, *Thlaspi caerulescens*, *Thlaspi goesingense*, and *Nicotiana tabacum* [186, 227–230]. Attempts have been made to characterize the endophytic bacterial communities in plant tissues, but comparisons between studies are difficult to make. An interesting finding was that isolates from shoot and root displayed different tolerances, suggesting that different microbial communities exist in different compartments of the plant [53].

The beneficial effects of endophytes on their hyperaccumulators appear to occur through similar mechanisms described for PGPR. This makes sense because most of the bacterial endophytes isolated from various plants can be considered to be facultatively endophytic and are capable of living outside plant tissues as rhizospheric bacteria. Additionally, many endophytic bacterial taxa from hyperaccumulators were reported to be common soil bacteria [186, 222, 231, 232]. Metal biosorption by bacteria comprises two steps:

1. Passive biosorption of metals by living and dead/inactive cells that essentially take place in the cell wall due to a number of metabolism-independent processes [52, 233]. In this process, metal ions are sorbed rapidly to the cell surface by reactions between metals and functional groups on the cell surface, such as hydroxyl, carbonyl, carboxyl, sulfhydryl, thioether, sulfonate, amine, amide, and phosphonate [50, 52]. Various metal-binding mechanisms such as ion exchange, complexation, coordination, sorption, chelation, electrostatic interaction, or microprecipitation may be synergistically or independently involved.
2. Active biosorption (bioaccumulation) referring to the uptake of metals (transport into cells). This only occurs in living cells through a slower active metabolism-dependent transport of metals into bacterial cells [52, 234]. Once the metals are inside living cells, they may be bound, precipitated, accumulated, sequestered

within specific intracellular organelles, or translocated to specific structures, depending upon the organism and element concerned [50, 52].

Particularly, in order to circumvent metal stress, endophytic bacteria have evolved several types of mechanisms, through which they alleviate the toxicity of metal ions, including the efflux of metal ions from cells and subsequent extracellular precipitation [52, 144], intracellular accumulation [52, 183], biotransformation of toxic metal ions into less or nontoxic forms [52, 108], sequestration of metals on the cell surface or in intracellular polymers, and precipitation, adsorption/desorption, or biomethylation [43, 52]. Binding of metals to extracellular material can immobilize the metal and prevent its entry into the cell. For example, different metal(loid)s can bind to anionic functional groups (e.g., sulfhydryl, carboxyl, hydroxyl, sulfonate, amine, and amide groups) present on cell surfaces. Similarly, microbial extracellular polymers, such as polysaccharides, proteins, and humic compounds, can effectively bind heavy metals. These substances thus detoxify metals simply by complex formation or by forming an effective barrier surrounding the cell [54, 235].

In addition, many bacteria mediate reactions or produce metabolites that result in crystallization and precipitation of metals [54, 206, 207, 236]. Furthermore, a great number of bacteria are known to possess transporters to promote metal(loid)s efflux from cells, in case of toxicity or excessive concentration, via ATPase pumps or chemiosmotic ion/proton pumps [54, 237]. These types of transporters are characterized by a high substrate affinity, and they are therefore able to reduce the metal load in the cytosol. Several bacteria have developed a cytosolic sequestration mechanism for protection from metal(loid)s. Once inside the cell, metal ions might also become compartmentalized or being converted into more innocuous forms. This process can constitute an effective detoxification mechanism, and the respective microbes might be able to accumulate higher intracellular concentrations [54, 237].

Examples include the synthesis of metal-binding proteins such as metallothioneins. These are low-molecular mass cysteine-rich proteins with high affinities for cadmium, copper, silver, lead, mercury, etc. Their production is induced by presence of metals, and their primary function is metal detoxification. In addition, certain bacteria use methylation as a metal resistance or detoxification mechanism. However, this process is considered to be metal-dependent as only some metals are methylated. It involves the transfer of methyl groups to metals and metalloids. Selenium is an example of metalloids that has reduced toxicity when methylated [54, 238]. In the last 15 years, several studies focused on the use of actinobacteria for cleaning up the environment [239]. Strategies such as bioaugmentation, biostimulation, cell immobilization, production of biosurfactants, design of defined mixed cultures, and the use of plant-microbe systems were developed to enhance the capabilities of actinobacteria in bioremediation.

Actinobacteria exhibit diverse physiological and metabolic properties, such as the production of extracellular enzymes and the formation of a wide variety of secondary metabolites [239, 240]. This versatility in secondary metabolite production makes them important tools for pharmaceutical, medical, and biotechnological applications such as bioremediation. The quantitative analysis of soil microbial populations through total culturable numbers showed a marked decrease of the different microbial groups for contaminated soil samples, in comparison with uncontaminated samples. However, actinobacteria showed less sensitivity than other culturable heterotrophic bacteria and asymbiotic nitrogen fixers. Culture-dependent methods have allowed the isolation and characterization of over 35 genera of actinobacteria tolerant to heavy metals [239].

Finally, actinobacteria have demonstrated their potential as tools for bioremediation of several contaminants including oil, rubber, plastics, pesticides, and heavy metals, among others, based on their physiological and metabolic versatility. The real worldwide problem is co-contamination. Environments contaminated with inorganic and organic compounds are considered difficult to bioremediate since metal(loid)s would inhibit biodegradation. Nevertheless, recent works highlighted that actinobacteria strains are able to remove HMs and pesticides simultaneously [239]. *Streptomyces*, *Rhodococcus*, and *Amycolatopsis* are among the most studied genera, although their bioremediation skills were never supported by integrated omic approaches. The relevance of the use of omic tools relies on the fact that this information may be used to enhance bioremediation processes of actinobacteria through pathway engineering techniques. On the basis of the existence of co-contaminated environments, engineering bio-tools resistant to organic and inorganic toxic compounds could be necessary.

Plant-bacteria associations in several metal(loid)s phytoremediation studies are presented on Table 2.3.

2.4 Phytoextraction

Phytoextraction, also known as phytoaccumulation, phytoabsorption, or phytosequestration, is the uptake of contaminants from soil, water, wastewater, or sediments by plant roots and their translocation and accumulation in aboveground biomass, i.e., shoots or any other harvestable plant parts [1, 5]. Plants able to accumulate metal(loid)s are grown on contaminated sites, and the metal-rich aboveground biomass is harvested, resulting in the removal of a fraction of the contaminant. Phytoextraction is the main and most useful phytoremediation technique for removal of heavy metals and metalloids from polluted soils [1, 24]. It is also the most widespread and promising alternative of soil reclamation for commercial applications. Metal translocation to shoots is a crucial biochemical process desirable for an effective phytoextraction because the harvest of root biomass is generally not feasible.

Phytoextraction has important advantages:

- It does not damage/change the landscape.

Table 2.3 Recent examples of bacterial-assisted phytoremediation studies

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Rhizobium sp. strains E20-8 and NII-1	Cd	*Pisum sativum* L.	Overcame Cd toxicity by extracellular immobilization, periplasmic allocation, cytoplasmic sequestration, and biotransformation of toxic products Higher glutathione concentrations allowing cytosolic Cd complexation, reducing Cd deleterious effects, and rendering this strain more tolerant to Cd than the sensitive one Promoted plant growth, thus rendering phytoremediation a more efficient technology	Cardoso et al. [241]
F. tricinctum RSF-4L, *A. alternata RSF-6L*	Cd	*Solanum nigrum*	Increased plant growth and chlorophyll content in inoculated RSF-6L plants in comparison to non-inoculated plants. RSF-6L inoculation decreased uptake of Cd in roots and aboveground parts. Inoculation protected the host as shown by low peroxidase and polyphenol peroxidase activities and high catalase activity	Khan et al. [56]
Microbacterium sp. NE1R5, *Curtobacterium* sp. NM1R1, and *Microbacterium* sp. NM3E9	As, Cu, Pb, Zn	*Brassica nigra*	Facilitated root development and seed germination	Román-Ponce et al. [242]

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Micrococcus sp., *Pseudomonas* sp., *Arthrobacter* sp.	Cd	*Glycine max* L.	Cadmium accumulation in roots, stems, and leaves of *G. max* L. was significantly enhanced by *Arthrobacter* sp. with nutrient biostimulation. A combined use of *G. max* L. and *Arthrobacter* sp. with nutrient biostimulation accelerated cadmium phytoremediation. In addition, cadmium was retained in roots more than in stems and leaves, and *G. max* had the lowest translocation factor at all growth stages, suggesting that *G. max* can be a phytostabilizing plant	Rojjanateeranaj et al. [243]
Thiobacillus thiooxidans	Cd, Pb	*Gladiolus grandiflorus* L.	Promoted root length, plant height, dry biomass, and enhanced accumulation of Cd and Pb	Mani et al. [130]
Bradyrhizobium japonicum	Ni, Cu, Pb	*Lettuce*	Increased the shoot and root lengths	Seneviratne et al. [244]
Pseudomonas putida	Cd, Zn	*Helianthus annuus* L.	Promoted biomass of the plant, accumulation of Zn and Cd in roots and shoots	Mani et al. [130]
Pseudomonas brassicacearum, *Rhizobium leguminosarum*	Zn	*Brassica juncea*	Induced metal chelation and toxicity attenuation	Adediran et al. [245]
Pseudomonas spp. *Lk9*	Cd, Zn, Cu	*Solanum nigrum* L.	Improved soil Fe, P, and metal availability, shoot biomass, and uptake of Cd, Zn, and Cu. Production of siderophores and organic acids that induced growth and metal uptake	Chen et al. [145]

(continued)

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Enterobacter sp. *JYX7*, *Klebsiella* sp. *JYX10*	Cd, Pb, and Zn	*Polygonum pubescens*	Production of IAA, siderophores, ACC deaminase, and solubilized inorganic phosphate improved phytoremediation efficiency	Jing et al. [246]
Bacillus thuringiensis GDB-1	Cd, Ni, As, Cu, Pb, Zn	*Alnus firma*	Production of phytohormones, siderophore, ACC deaminase, and solubilization of phosphorus. Increased biomass, chlorophyll content, nodule number, and accumulation of metal(loid)s (As, Cu, Pb, Ni, and Zn)	Babu et al. [180]
Rhodococcus sp. *TS1*, *Delftia* sp. *TS33*, *Comamonas* sp. *TS37*, *Delftia* sp. *TS41*, *Streptomyces lividans* sp. *PSQ22*	As	*Pteris vittata*	Reduced As(VI) to As(III) and enhanced As uptake by *Pteris vittata*	Yang et al. [247]
Serratia sp. *MSMC541*	As, Cd, Cu	*Lupinus luteus*	Reduced translocation of As, Cd, and Cu from roots to shoots	Aafi et al. [248]
Consortium of sulfur-oxidizing bacteria	Cu	*Oryza sativa*	Increased bioavailability of Cu	Shi et al. [249]
Pseudomonas sp., *Sanguibacter* sp.	Cd, Zn	*Nicotiana tabacum*	Improved biomass production, as well as total plant Cd	Mastretta et al. [229]
Arthrobacter sp. *MT16*, *Microbacterium* sp. *JYC17*, *Pseudomonas chlororaphis SZY6*, *Azotobacter vinelandii GZC24*, *Microbacterium lactium YJ7 (EN)*	Cu	*Brassica napus*	Root length promotion, ACCD, siderophore, IAA, P solubilization	He et al. [250]

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Sanguibacter sp., *Enterobacter* sp., *Pseudomonas* sp.	Cd, Fe	*Nicotiana tabacum*	In several cases, inoculation with endophytes resulted in improved biomass production under conditions of Cd stress, as well as in higher plant Cd concentration and total plant Cd content compared to non-inoculated plants	Mastretta et al. [229]
Cellulosimicrobium cellulans KUCr3	Cr	Chilli plants	Reduced the mobile and toxic Cr(VI) to nontoxic and immobile Cr(III) and decreased Cr uptake by chilli plants	Chatterjee et al. [251]
Streptomyces tendae F4	Cd	*Helianthus annuus*	Promoted plant growth, facilitated soil metal solubilization, enhanced Cd, and Fe uptake	Dimkpa et al. [209]
Achromobacter xylosoxidans Ax10	Cu	*Brassica juncea*	Increased root and shoot length and biomass; ACC deaminase, IAA, and phosphate solubilization	Ma et al. [252]
Enterobacter aerogenes, *Rahnella aquatilis*	Ni, Cr	*Brassica juncea*	Stimulated plant biomass and enhanced phytoextraction of metals (Ni and Cr). Concurrent production of siderophores, ACC deaminase, IAA, and phosphate solubilization	Kumar et al. [140]
Acidithiobacillus thiooxidans, *A. ferrooxidans*, *Leptospirillum ferrooxidans*	Cu, Cd, Hg, Zn	NA	Increased the mobility of Cu, Cd, Hg, and Zn	Beolchini et al. [253]
Streptomyces acidiscabies E13	Al, Cu, Fe, Mn, Ni, U	*Vigna unguiculata*	Protected plants from metal toxicity; enhanced uptake of Al, Cu, Fe, Mn, Ni, and U	Dimkpa et al. [208]

(continued)

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Azotobacter spp.	Cd, Cr	*Triticum aestivum*	Immobilized Cd and Cr and decreased their uptake by *Triticum aestivum*	Joshi and Juwarkar [171]
Bacillus edaphicus NBT	Pb	*Brassica juncea* L. Czern	Promoted plant growth (root and shoot biomass) and Pb uptake	Sheng et al. [222]
Bacillus licheniformis, *B. biosubtyl*, *B. thuringiensis*	Se, Cd, Cr	*Brassica juncea*	Increased metal uptake depending on specific metal-bacteria combinations	Hussein [254]
Streptomyces acidiscabies E13	Ni	*Vigna unguiculata*	Simultaneous inhibition of Ni uptake and solubilization and supply of Fe to plants. Hydroxamate siderophores promoted growth under Ni contamination by binding Fe and Ni, thus playing a dual role of supplying Fe and protecting against Ni	Dimkpa et al. [206]
P. putida HS-2	Ni	*Brassica napus*	Increased seed germination and plant biomass, siderophores, IAA, ACC, deaminase	Rodriguez et al. [255]
Pseudomonas sp. *29C*, *Bacillus megaterium 4C*	Ni	*Brassica juncea*	Increased aboveground biomass, protected plants against the inhibitory effects of Ni, probably due to the production of IAA, siderophore, and solubilization of phosphate	Rajkumar and Freitas [211]
Pseudomonas aeruginosa MKRh3	Cd	*Vigna mungo*	Growth increment, ACCD, siderophore, auxin synthesis, P solubilization. Reduced Cd toxicity and uptake	Ganesan [256]
Pseudomonas sp., *Janthinobacterium lividum*, *Serratia marcescens*, *Flavobacterium* sp., *Streptomyces* sp., *Agromyces* sp.	Cd, Zn	*Salix caprea*	Increased plant leaf biomass, siderophore, IAA. Decreased Zn and Cd uptake	Kuffner et al. [257]
Bacillus sp. *J119* Biosurfactant-producing bacterial strain *Bacillus* sp. J119	Cd	*Solanum lycopersicum*, *Zea mays*, *Brassica napus*	Increased Cd content in aboveground tissues of all plants	Sheng et al. [231]

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Gluconacetobacter diazotrophicus PAl5	Zn	NA	Solubilized ZnO 5-Ketogluconic acid, a derivative of gluconic acid was the major organic acid produced. This organic anion may be an important agent that helped in the solubilization of insoluble Zn compounds	Saravanan et al. [258]
Methylobacterium oryzae CBMB20 *Burkholderia* sp. CBMB40	Ni, Cd	*Lycopersicon esculentum*	Reduced Ni and Cd uptake and their translocation to shoots ACCD activity, phytohormone production	Madhaiyan et al. [141]
Rhodococcus erythropolis MtCC	Cr	*Pisum sativum*	Bacterial metal detoxification mechanism. Increased plant growth in the presence of Cr(VI) at low temperature	Trivedi et al. [259]
Rhizobium sp. *RP5*	Ni, Zn	*Pisum sativum*	Increased nitrogen fixation, growth promotion, and the ability to reduce the toxicity of Ni and Zn	Wani et al. [260]
P. putida ARB86	Ni	*Arabidopsis thaliana*	Increased biomass and chlorophyll content. Nickel influx into plants was decreased by bacterial sorption in the rhizosphere	Someya et al. [261]
Pseudomonas aeruginosa BS2	Cd, Pb	NA	Mobilized Cd and Pb	Juwarkar et al. [262]
Pseudomonas sp. *PsA4*, *Bacillus* sp. *Ba32*	Cr	*Brassica juncea*	Protected the plants against the inhibitory effects of Cr, probably due to the production of IAA, siderophores, and solubilization of phosphate	Rajkumar et al. [263]
Pseudomonas fluorescens	As	*Helianthus annuus*	Increased plant growth	Shilev et al. [264]

(continued)

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
P. putida HS-2	Ni	*Brassica napus*	Increased biomass and total Ni per plant	Farwell et al. [265]
Pseudomonas sp. *RJ10*, *Bacillus* sp. *RJ16*	Cd	*Brassica napus*	Increased root and shoot weight and an increase in Cd content varying from 16% to 74%, compared to the non-inoculated control	Sheng and Xia [266]
P. putida 06909	Cd	*Helianthus annuus*	Increased Cd uptake and decreased toxicity; the bacterium expresses a metal-binding peptide	Wu et al. [267]
Brevibacillus sp. *B-I*	Zn	*Trifolium repens*	Decreased the concentration of Zn in shoot tissues	Vivas et al. [268]
P. fluorescens, *P. putida*	Ni	*Brassica napus*	Increased seed germination and plant growth	Ashour et al. [269]
Pseudomonas putida KNP9	Cd, Pb	*Phaseolus vulgaris*	Reduced Cd and Pb accumulation in *Phaseolus vulgaris*	Tripathi et al. [210]
Pseudomonas asplenii AC	Cu	*Brassica napus*	Increased biomass; IAA	Reed and Glick [270]
Variovorax paradoxus, *Rhodococcus* sp., *Flavobacterium* sp.	Cd	*Brassica juncea*	Increased root length, IAA, siderophores, and ACC deaminase	Belimov et al. [271]
Pseudomonas putida KNP9	Pb, Cd	*Vigna radiata*	Increased biomass and siderophore production. Decreased metal uptake	Tripathi et al. [210]
Pseudomonas tolaasii RP23, *Pseudomonas fluorescens* RS9	Cd, Zn, Ni	*Graminaceae*	Have plant growth-promoting characteristics that can potentially support heavy metal uptake and reduce stress symptoms in plants	Dell'Amico et al. [272]
Stenotrophomonas maltophilia	Se	*Astragalus bisulcatus*	Reduced soluble and harmful Se(IV) to insoluble and unavailable Se(0) and thereby decreased plant Se uptake	Di Gregorio et al. [273]

Table 2.3 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress	References
Rhizosphere bacteria colonizing *T. goesingense*	Ni	*Thlaspi goesingense*	Increased siderophore production	Idris et al. [186]
Pseudomonas fluorescens Avm, *Rhizobium leguminosarum* bv. *phaseoli CPMex46*	Cu, Fe	*Medicago sativa*	Improved Cu and Fe translocation from roots to shoots	Carrillo-Castañeda et al. [274]
Microbacterium arabinogalactanolyticum	Ni	*Alyssum murale*	Increased Ni uptake	Abou-Shanab et al. [275]
Brevibacillus sp.	Pb	*Trifolium pratense*	Decreased Pb uptake; IAA	Vivas et al. [276]
Enterobacter cloacae CAL2	As	*Brassica napus*	Increased biomass; ACC deaminase	Nie et al. [277]
Burkholderia cepacia with ncc-nre ncc-nre nickel resistance system Herbaspirillum seropedicae with ncc-nre nickel resistance system	Ni	*Lupinus luteus*	Facilitated bioaccumulation of Ni in roots	Lodewyckx et al. [278]
Microbacterium saperdae, *Pseudomonas monteilii*, *Enterobacter cancerogenus*	Zn	*Thlaspi caerulescens*	Increased Zn uptake	Whiting et al. [279]
Kluyvera ascorbata SUD165, *SUD165/26*	Ni, Pb, Zn	*Brassica napus*, *Lycopersicon esculentum*, *Brassica juncea*	Increased biomass, ACC deaminase, siderophores	Burd et al. [280]
Kluyvera ascorbata SUD165 Enterobacteriaceae	Ni	*Brassica napus*	Increased biomass and ACC deaminase	Burd et al. [281]

M metal(loid)s, *NA* not applicable

- It preserves the ecosystem.
- It is the main technique of phytoremediation for the removal of heavy metals from soil, sediments, and water.
- It is also considered as the most commercially promising technique because it is inexpensive.

However, although it presents several advantages, there are some factors that limit metal phytoextraction [13, 282]:

- A low bioavailability of metals in the rhizosphere
- A low uptake rate
- A low translocation rate confining the metals in the roots

The amount of metal removed depends on concentration in aboveground plant materials and the plant biomass produced [283, 284]. However, the small biomass and slow growth of many (hyper)accumulators, as well as a low soil metal bioavailability, can limit the effectiveness of phytoextraction [53, 284]. A large number of plant species have the ability to hyperaccumulate metal(oid)s in their tissues. Throughout the years a general increase in pollution and the necessity to find reliable methods for the restoration of contaminated sites have led to an increased interest on hyperaccumulation, phytostabilization, or phytoextraction. Pertinent problems arise when trying to define plants as either hyperaccumulators or as suitable for phytostabilization or phytoextraction events. Plant(part)/soil and plant part/plant part ratios have been described, and new terms have been created, i.e., a particular ratio has been defined by several different names and acronyms. So, in the bibliography different terms have been attributed to the same ratio, and this often represents an overlap in terminology. On the other hand, the same term corresponds to several different ratios, and this could create confusion and misinterpretation in data comparison. Recently, Buscaroli [285] reviewed the various factors, coefficients, and indexes developed so far to evaluate terrestrial plant performance in respect to phytoremediation.

Some important hyperaccumulator families are Brassicaceae, Fabaceae, Caryophyllaceae, Flacourtiaceae, Euphorbiaceae, Asteraceae, Lamiaceae, Poaceae, Violaceae, *and* Scrophulariaceae [1, 5, 193]. The hyperaccumulator species (e.g., *Thlaspi caerulescens*, *Alyssum bertolonii*, *Arabidopsis halleri*) are able to accumulate contaminants but produce little biomass, and therefore it is possible to use species that accumulate less but which produce more biomass like *Brassica* spp., *Arundo donax*, and *Typha*s spp. [1, 13, 286–289]. An ideal plant for trace element phytoextraction should possess the following characteristics: (a) tolerance to the trace element accumulated, (b) fast growth and highly effective trace element accumulating biomass, (c) accumulation of trace elements in the aboveground parts, and (d) easy to harvest [230].

A typical trace element phytoextraction protocol consists of the following steps: (a) cultivation of the appropriate plant/crop species on the contaminated soil, (b) removal of harvestable trace element-enriched biomass from the site, and (c) postharvest treatments (i.e., composting, compacting, thermal treatments) to reduce volume and/or weight of biomass for disposal as a hazardous waste or for its recycling to reclaim the elements that may have an economic value. The storage, treatment, and placement of the contaminated plant biomass are of great concern. Compaction and composting of the plant biomass decrease its volume and transport costs, but increase leaching of dissolved metal organic compounds [10, 290]. One of the most economical approaches to deal with the contaminated biomass is its commercial use as a source of energy [10]. Gasification and combustion are important trends in the production of thermal and electric energies. Direct combustion should be accomplished under control with a reduction in the biomass to 3–6% and the correct placement of the ash [10]. Thermal processing or thermos chemical gasification of the plant biomass into biogas (gaseous fuel) is a complex and high-tech process proceeding at 800–1300 °C. The ash obtained can be used as biore, and this process is termed as phytomining [10, 291]. Another effective method is thermochemical processing of the plant biomass (pyrolysis), which is a process of thermal decomposition of organic compounds in an oxic condition at relatively low temperatures (500–800 °C). This process allows the collection of fluid oils (biofuel, pyrofuel, resins), gases, and coke. The coke retains the heavy metals and is useful as a fuel in industry [10, 292]. To apply phytoextraction techniques, metal(loid)s must be bioavailable and ready to be absorbed by roots. The speciation of metal(loid)s in soils can include [13, 293]:

1. Free metal ions
2. Oxides, hydroxides, and carbonates
3. Integration into the structure of silicate/aluminum minerals
4. Soluble metal complexes
5. Associations with soil organic matter

Metal speciation regulates metal uptake by plant roots and consequently phytoextraction efficiency. Indeed, it is known that low bioavailability of soil metal(loid)s may be a rate-limiting factor for metal uptake by plants. The major limitations of most metal phytoextraction processes are (1) the bioavailability of the target metal(loid)s and (2) the ability of various plants to bioaccumulate metals within their aboveground biomass [48, 294]. Metal bioavailability can be defined as the fraction of metal in the soil that can interact with a biological target. In the soil solution, elements are present as free uncomplexed ions, ion pairs, ions complexed with organic anions, and ions complexed with organic macromolecules and inorganic colloids. The most important metal pools in the solid phase include the metals complexed by organic matter, sorbed onto or occluded within oxides, and clay minerals coprecipitated with secondary pedogenic minerals (e.g., Al, Fe, Mn oxides, carbonates and phosphates, sulfides) or as part of the crystal lattices of primary minerals [44, 61].

Current phytoextraction practices employ either hyperaccumulators or fast-growing high biomass plants, and the phytoextraction process may be enhanced by addition of soil amendments that can increase trace element bioavailability in the soil [230]. When bioavailability of metal(loid)s in the soils is insufficient for active root sorption, transport in solution and mobilization can be promoted using chelating agents [295], such as organic and mineral acids, elemental sulfur, and ammonium fertilizers. This chelant-assisted accumulation of heavy metals by plants that do not concentrate them under normal conditions was termed as chelant-induced hyperaccumulation. The application of chelating agents, for instance, synthetic aminopolycarboxylic acids, is efficient. Hydroxyethylene diamine triacetic acids (HEDTA), ethylenediamine dihydroxyphenylacetic acid, and ethylenediaminetetraacetic acid (EDTA) are potential acidifying chelants [295]. These agents can enhance the phytoextraction of Cu, Cd, Pb, Zn, and Ni [296].

There are a few disadvantages when using chelating agents, i.e., adverse effects on soil microorganisms, possible contamination of groundwater, and slow (several weeks or months) decomposition of the synthetic organic acids [296–298]. Following the application of chelate-forming agents, the removal of metals may continue for a long time. There are some rapid decomposing natural organic acids which are considered alternatives to synthetic chelating agents, i.e., ethylenediamine-*N*,*N*′-disuccinic (EDDS) acids and nitrilotriacetic acid (NTA) [296, 297]. In addition, products of plant metabolism and low-molecular organic compounds, i.e., tartaric [299], acetic [297], and malic acids, putrescine (polyamine), and citric and oxalic acids [300], can also be used for the same purpose. In recent years, different biotechnological approaches have also been used to increase biomass and growth rate of hyperaccumulator plants through genetic engineering tools, i.e., synthesis of various metal-binding peptides [10, 301]. Along with engineering, metal(loid)s accumulation by plants can be enhanced using conventional agronomic practices, i.e., fertilization, irrigation, seed control, shorter growth cycle, and liming [12].

2.4.1 Assisted by Fungi

There is increasing evidence that plant-microbe interactions/dynamics can define the efficiency of metal phytoextraction. Inoculation of the plant rhizosphere with microorganisms is an established route to improve phytoextraction efficiency. In general, microorganisms can improve phytoextraction by increasing the bioavailability of metal(loid)s to the plant and by increasing plant biomass [302].

A frequently utilized strategy to improve phytoextraction is the inoculation of beneficial microorganisms into the plant rhizosphere. Microorganisms may increase plant trace element uptake by three specific mechanisms: (1) they may increase root surface area and hair density, (2) increase element bioavailability, and/or (3) increase soluble element transfer from the rhizosphere to the plant [168]. Furthermore, enhanced plant biomass production can boost an increase on the efficiency of trace element phytoextraction [230]. Increased trace element uptake can be attributed to a microbial modification of the absorptive properties of the roots such as increased root length and surface area and numbers of root hairs or by increasing the bioavailability of trace elements in the rhizosphere and the subsequent translocation to shoots via beneficial effects on plant growth, trace element complexation, and alleviation of phytotoxicity [230].

Regardless of whether trace elements are mainly accumulated in roots or in shoots, internal tolerance mechanisms are the basis for efficient detoxification of the trace elements. These internal detoxification mechanisms are extensively described in the previous sections. Among various microbe-assisted strategies that have been proposed to date, AM fungi are known to benefit their host plants by affecting biological regulation of their phytoextraction efficiency [127, 303, 304]. AM fungi are thought to be one of the most important soil microbial groups that affect metal uptake by plants and metal immobilization in soils [74, 305] and are commonly introduced into soil for land reclamation [74, 127, 306]. Previous studies reported that both host plant biomass and metal concentrations could be increased via AM fungi inoculation [127, 307], thus resulting in increased uptake of metal(loid)s [127, 308]. Different host plants and fungal species as well as environmental conditions could potentially affect response strategies of plants ([88, 127]). The functional diversity is significantly reflected on plant growth, element uptake, and enzymatic activity [127, 309, 310]. In some cases, AM fungi contributed to a significant storage of metal(loid)s at the root level, instead of the aboveground tissues of the host plants (phytostabilization). However, in other cases AM fungi contributed to enhanced uptake and translocation to shoots promoting phytoextraction success [86, 127].

An important point about treating polluted soil with mycorrhizal plants is the selection of appropriate AM species [12]. The species selected from areas polluted with metal(loid)s are the most efficient species which have the ability to survive under metal stress conditions and hence may act more efficiently relative to other AM species [12, 14]. These communities are metabolically and taxonomically diverse, containing microorganisms that are preadapted to conditions in situ and are capable of performing metabolic activities that can alter metal(loid)s bioavailability and promote plant growth [252, 302, 311–314]. Generally, species of the genus *Glomus* are predominant in the rhizosphere of plants growing in metal(loid) s-contaminated soils [12, 315, 316]. AM fungi can colonize hyperaccumulator roots extensively in metal(loid)-contaminated soils forming symbiotic/mutualistic relationships with plants. In general, mycorrhizal hyperaccumulators produce considerably more biomass and grow faster than non-mycorrhizal plants, and because of the ability of AM fungi to survive in severely contaminated soils, they are able to play a role on phytoremediation processes enhancing the capacity of plants to withstand soil phytotoxicity [60, 71, 72]. AM fungi promote plant establishment in metal(loid) s-contaminated soils, strengthening plant defense systems, and promoting its growth [73, 127].

Several biological and physical mechanisms have been proposed to explain metal tolerance of AM fungi and their contribution to metal tolerance of host plants. These tolerance mechanisms are numerous, e.g., extracellular metal sequestration and precipitation, metal binding to the fungal cell walls, intracellular sequestration and complexation, compartmentation, and volatilization, and are broadly described in previous sections. Many fungi can survive and grow with high concentrations of toxic metals [44, 317]. The ability of mycorrhizal associations to decrease metal toxicity to higher plants has been shown for ericoid mycorrhizas, ectomycorrhizas, and arbuscular mycorrhizas, while some ectomycorrhizal fungi accelerate mineral weathering. The mycorrhizal mycelia provide an efficient system for the uptake and direct transport of mobilized essential nutrients to their host plants, which are large sinks [44, 318]. Mineral weathering can also increase the concentrations of phytotoxic aluminum in the soil solution. Some ectomycorrhizal fungi increase Al tolerance through an enhanced exudation of oxalate [44, 319]. Furthermore, AM fungi inoculation can improve plant performance under metal(oid)s stress due to a number of mechanisms involving antioxidant enzymes, lipid peroxidation, and soluble amino acid profile changes caused by the intimate relationship between fungi and the host plant [73, 320, 321]. In fact, when exposed to metal(loid)s such as Cu, Fe, Pb, Cd, Cr, As, Hg, Cr, and Zn, plants enhance their level of reactive oxygen species (ROS) [73, 322, 323].

The contribution of AM fungi, such as *Funneliformis mosseae*, to enhanced Cd and Zn uptake and translocation by *S. nigrum* in heavy metal-contaminated sites has been noted without deleterious effects on plant growth [65, 324–326]. Fiorentino et al. [287] observed increases on Cd phytoextraction by *Arundo donax* assisted by the fungal microorganism *Trichoderma harzianum* in both, leaves (+20%) and rhizomes (+30%), while Chen et al. [327], observed an increase on Pb uptake and consequent accumulation in *Kummerowia striata*, lxeris denticulate and Echinochloa crusgalli.

It has been discovered recently that adding indigenous AM fungi can boost the uptake and accumulation of As and the biomass of *P. vittata* [60]. It was also shown that plants from an As mine site, colonized by AM fungi, accumulated more As than the non-colonized plants. An increase on growth, promoted by the activation of the phosphate transport system in colonized plants, may justify these results.

The process of translocation may be assumed to vary with metal(loid)s concentrations in the substrate, even if they grow with the same AM inoculation. Consequently, whether AM fungi enhance the transport to shoots (phytoextraction) or immobilize in the roots (phytostabilization) depends on metal(loid)s stress in the substrate [127]. AM fungi play different roles to cope with Cd toxicity in *P. australis*. With a low Cd stress, AM enhanced plant growth, and this acted as an accumulator due to the growth dilution effect. However, with high Cd stress, the AM symbiosis leads the plant to act as an excluder [127]. Consequently, in the presence of AM fungi, phytoextraction played the predominant role at low Cd stress, while phytostabilization occurred with high Cd stress [127]. The AM *Glomus intraradices* was shown to enhance growth of *Helianthus annuus*, and as a result, the total Ni is extracted. It also increased the activity of glutamine synthetase, indicating an enhanced Ni tolerance [230, 328].

A stimulation on the biomass of *B. coddii* in mycorrhizal plants led to a higher total Ni content (and hence phytoextraction) [80]. The diverse endophytic fungi isolated from *S. nigrum* showed the symbiotic association of these microbes with the host plant and improved our understanding regarding plant fitness under extreme conditions [56, 57]. The inoculation of *S. nigrum* with both *Glomerella truncata* PDL-1 and *Phomopsis fukushii* PDL-10 increased its tolerance to high concentrations of Cd. As a result, the parameters related to the biosorption of Cd, including translocation, bioconcentration factors, and tolerance index, were significantly enhanced. The strongest evidence for the presence of endophytes was the apparent promotion of plant growth and enhanced biochemical content of chlorophyll as compared to those of non-inoculated control plants [56, 57]. Endophytic fungi may increase host fitness and competitive abilities by increasing successful germination and growth rate or enhancing the uptake nutritional elements by the host [44, 116]. Furthermore, due to possessing suitable degradation pathways, metal sequestration, or chelation systems, fungal endophytes are able to increase host plant tolerance to metal(loid)s and assist the host survival in contaminated soils [44, 116].

2.4.2 Assisted by Bacteria

Plant-associated bacteria can potentially improve phytoremediation by altering the solubility, bioavailability, and transport of metal(loid)s and nutrients by altering soil pH, release of chelators (e.g., siderophores, organic acids, biosurfactants, glycoproteins), methylation, P solubilization, or redox changes [50, 54, 61, 138, 193, 284, 329]. Therefore, plant-associated bacteria can be exploited to improve the efficiency of the phytoextraction processes [48, 168, 169, 222, 230, 232, 257, 330–332]. Bacterial populations associated with plants growing in metalliferous soils have a high diversity. These communities might also have important functions in relation to plant growth under these adverse conditions as well as in improving uptake of trace elements [230]. Plant growth promotion plays a major role in the extraction and removal of trace elements since a simple improvement in biomass results in an increase in the overall trace element yield (phytoextracted trace elements) [230]. The Ni-resistant PGPB strain *Psychrobacter* sp. SRS8 originally isolated from the rhizosphere of the Ni hyperaccumulator *A. serpyllifolium* was found to effectively promote the growth and phytoextraction potential of the energy crops *Ricinus communis* and *Helianthus annuus* in artificially Ni-contaminated soils [50, 230].

The Ni hyperaccumulator *A. serpyllifolium* subsp. *lusitanicum* grown in an ultramafic soil showed a significantly higher translocation and shoot Ni concentration after inoculation with a Ni-resistant rhizosphere bacteria *Arthrobacter nitroguajacolicus* [333]. In both hydroponically and soil-grown plants, inoculating the Cd/Zn hyperaccumulator *S. alfredii* with the metal(loid)-tolerant rhizobacterial strains belonging to the genera *Burkholderia* improved plant tolerance, biomass production, and Cd (and Zn) uptake and extraction [334, 335]. Bacteria can acidify their environment by pumping protons to maintain the electrochemical gradient of membranes. These replace trace element cations at sorption sites and dissolve minerals such as phosphates. Acid-producing rhizosphere bacteria have been intensely studied due to their capacity to release phosphorus from insoluble phosphates. For the purpose, bacteria can produce and secrete an array of organic acids, such as gluconic, 2-ketogluconic, lactic, and acetic acids [302]. The associated decrease in soil pH can also increase the solubility of some metal(loid)s [336].

Recent studies investigating the role of endophytes in metal(loid)s uptake by plants have demonstrated that the production of specific bacterial organic acids (e.g., citric, oxalic, acetic acids, etc.) may result in increased nutrient and metal(loid)s uptake, probably as a result of the decrease in soil pH and their solubilizing power, improving the efficiency of phytoextraction processes [52, 145]. The different metabolites released by PGPB (e.g., siderophores, osmolytes, nitric oxide, antibiotics, biosurfactants, organic acids, and plant growth regulators) can change metal(loid)s uptake either directly through their effects on plant growth or indirectly through acidification, chelation, precipitation, immobilization, and oxidation-reduction reactions in the rhizosphere [50]. Organic chelators scavenge trace element ions from sorption sites and mineral lattices and protect them from resorption [138, 230]. To date two groups of bacterially produced natural chelators are known. These are carboxylic acid anions and siderophores. Among a large variety of carbon compounds, oxalic, malic, and citric acids are some of the most important organic acids identified in roots and in microbial exudates [230, 337].

As the first p*K*a values of most carboxylates are below 3.5 and the cytosolic pH of root cells typically ranges from 7.1 to 7.5, carboxylic acids are typically present in soil solution as fully or partially dissociated forms [162, 230]. In plant cells, complexation with carboxylic acids, particularly malate, citrate, but also with the basic amino acid histidine, is a powerful mechanism for trace element detoxification [230, 338]. In addition to plant growth promotion, bacteria were reported to have a beneficial effect on plant stress tolerance. This may be achieved by the enzyme ACC deaminase leading to a reduction of stress-induced ethylene levels in the plant [230, 280, 339].

For instance, experiments assessed by Sheng et al. [232] have shown the solubilizing potential of the Pb-resistant endophytic bacteria *Pseudomonas fluorescens* G10 and *Microbacterium* sp. G16 on Pb uptake by *Brassica napus*. The results showed that both endophytes enhanced Pb bioavailability, thus increasing Pb accumulation in plant shoots from 76% to 131% (*P. fluorescens*) and from 59% to 80% (*Microbacterium* sp.), compared to the respective control. A possible explanation might be the production of siderophores or organic acids that induce solubilization of Pb.

These effects of inoculation were reported also by Mastretta et al. [229], who reported that the inoculation of *N. tabacum* with the Cd-resistant endophyte *Sanguibacter* sp. increased the concentration of Cd in shoot tissues and consequently the phytoextraction capacity of *N. tabacum*, by approximately threefold compared with the respective uninoculated control. These studies suggest that it should be possible to improve the metal phytoextraction potential of accumulating or hyperaccumulating plants, through the inoculation of seeds or rhizosphere soil with beneficial metal-resistant endophytic bacteria. Although several conditions, such as soil properties, environmental conditions, and microbial activity, must be optimized for any phytoextraction event to become effective, the bioavailability of metals in the rhizosphere is considered to be a critical requirement for metal uptake to take place [54]. Braud et al. [340] reported that inoculating soils with *P. aeruginosa* significantly increased the concentrations of bioavailable Cr and Pb compared with uninoculated controls. Furthermore, they also observed that *P. aeruginosa* significantly enhanced Cr and Pb accumulation in maize shoots by a factor of 4.3 and 3.4, respectively. In this case, metal(loid)s uptake could be correlated with the increased production of siderophores, in particular of pyoverdin and pyochelin [54]. These studies highlighted the potential of inoculating soils or plants with metal(loid)s-resistant siderophore-producing bacteria to further improve their phytoextraction potential.

Siderophores play a significant role in metal mobilization and accumulation, and siderophore-producing microbes are believed to play an important role in the phytoextraction of metal(loid)s [54, 209], as these compounds produced by PGPB may solubilize unavailable forms of metals but also form complexes with bivalent metal(loid)s ions that can be assimilated by root-mediated processes [50, 274, 340]. Siderophores are secreted, and Fe(III)-siderophore complexes are recognized and scavenged from the environment by membrane receptor proteins. They are too large to pass membrane porins [230]. All siderophores possess higher affinity for Fe(III) than for Fe(II) or any other trace element. However, complexes of lower stability are also formed with other trace elements [230, 341]. Divalent cations (e.g., Fe^{2+}, Zn^{2+}, Cu^{2+}, Cd^{2+}) form less stable complexes due to their reduced charge density (charge/size ratio). Addition of trace elements to bacterial cultures induces siderophore synthesis and leads to the formation of siderophore-metal complexes [206–208, 230]. Extracellular complexation by siderophores is considered to be a mechanism of bacterial trace element resistance [230, 332]. Siderophore synthesis was shown to simultaneously increase iron uptake and to reduce cadmium uptake in *Streptomycetes* [208, 209, 230]. In contrast, siderophore-mediated uptake of trivalent trace element cations (Al^{3+}) has been demonstrated in iron-depleted cultures [230]. Synthesis of several siderophores varying in trace element affinity, preferences, and inductivity may convey competitive advantage in trace element contaminated environments [208, 209, 230].

The biosurfactants produced by PGPB also enhance metal(loid)s mobilization and improve phytoextraction on contaminated soils [50, 342]. Biosurfactants can desorb metal(loid)s from the soil matrix and hence increase metal solubility and bioavailability [193, 231, 343]. Certain nitrogen-fixing bacteria produce molybdate-binding tetradentate catecholates, which also function as siderophores [230, 341]. The pigment melanin, which is produced by many fungi and *Streptomycetes*, can bind trace elements to its carboxylic groups and was shown to be involved in trace element sorption and trace element tolerance of *S. scabies* [230, 344]. In addition to beneficial effects on growth by improved plant nutrition, microorganisms can also enhance plant growth directly via the production of phytohormones, including IAA, cytokinins, and gibberellins. These compounds can stimulate germination, growth, and reproduction and protect plants against both biotic and abiotic stress [50, 345]. Indeed, the mechanism most often cited to explain the various direct effects of PGP on plants is the production of phytohormones, and most of the attention has focused on the role of the phytohormone auxin [48, 346, 347]. In addition to the well-characterized effects of microbial auxin and ethylene on plant growth, a number of plant growth-promoting bacteria synthesize cytokinins, which can stimulate the growth of different crops under both stressed and non-stressed conditions helping the phytoextraction processes [48, 348].

In the last years, it has been found that a number of PGPB contain the enzyme ACC deaminase, which can cleave the plant ethylene precursor ACC and thereby lower the level of the phytohormone ethylene in a developing or stressed plant [302].

After working on microbe-assisted Cd phytoextraction, Wei et al. [104, 105] reported that the endophytic bacterial strain *Rahnella* sp. JN27, isolated from roots of *Zea mays*, enhanced Cd bioavailability in the soil and solubilized phosphate, producing indole-3-acetic acid, siderophores, and ACC deaminase. Multiple reports showed that foliar application of IAA or other phytohormones can improve the phytoextraction of metals, including Ni, Pb, and Cd [302, 349, 350]. The proliferation of specific microorganism strains, able to aggressively colonize the root surface, can promote growth and healthier plants, improving root development, and/or enhance plant tolerance to different environmental stresses, strengthening the phytoextraction processes [48, 351]. Accordingly, metal phytoextraction (as well as plant growth) can be helped by soil microorganisms associated with plant roots [48, 351]. Finally, a few studies reported that plant growth and/or trace element accumulation has been improved using combinations of plant-associated microorganisms. In a hydroponic study, a combination of seven As-resistant rhizobacteria (identified as *Pseudomonas* sp., *Comamonas* sp., and *Stenotrophomonas* sp.) enhanced As uptake by the As hyperaccumulator *Pteris vittata*. Microbial exudation of pyochelin-type siderophores, together with root exudates, solubilized As from the growth media spiked with insoluble $FeAsO_4$ and $AlAsO_4$ minerals [352].

In soil-grown plants, inoculation of *Salix caprea* with *Streptomyces* sp. in combination with the fungus *Cadophora finlandica* led to an increase in phytoextraction of Cd and Zn (Table 2.4) [230, 365].

2.5 Conclusions and Future Prospects

Phytoremediation techniques, based on interactions between plants and microorganisms, have been proposed as eco-friendly methods to clean polluted soils. Soil microorganisms can improve pollutant mobilization and respective uptake by plants. The success of phytoextraction depends on several factors, including the concentration of soil pollutants, metal bioavailability for root uptake, and the capability of plants to intercept, sorb, and accumulate metal(loid)s in their tissues. Ultimately, the success of phytoextraction depends on interactions among soil, metals, and plants. However, low bioavailability of metals, low biomass of most hyperaccumulators, and restricted metal translocation to the shoots limit the efficiency of phytoextraction. In order to solve these restrictive factors, some strategies such as advanced agricultural practices, genetic engineering, and chelate treatments need to be adopted to improve phytoextraction performance. The use of natural chelators to

Table 2.4 Results of phytoextraction studies assisted by plant-associated microbes

Microorganisms	M	Test plant	Microbial effects on plants under metal stress, phytoextraction	References
Microbacterium, Variovorax, Micrococcus, Pseudomonas	Zn	*Noccaea caerulescens, Rumex acetosa*	Increase in the growth of both plants, as well as higher values of Zn phytoextraction	Burges et al. [284]
Bacillus pumilus E2S2, *Bacillus* sp. E1S2	Cd, Zn, Pb	*Sedum plumbizincicola*	*B. pumilus* E2S2 significantly increased root and shoot length, biomass, and plant Cd uptake, whereas *Bacillus* sp. E1S2 significantly enhanced the accumulation of Zn. Results demonstrated the potential to improve phytoextraction of soils contaminated with multiple heavy metals by inoculating metal hyperaccumulating plants with their own selected functional endophytic bacterial strains	Ma et al. [147]
Streptomyces sp., *Cadophora finlandica*	Cd, Zn	*Salix caprea*	Increased phytoextraction of Cd and Zn	Sessitsch et al. [230]
Firmicutes sp., *Actinobacteria* sp., *Proteobacteria* sp.	Cu	*Brassica napus*	Increased root and aboveground tissues weight and shoot Cu concentration	Sun et al. [353]
Bacillus subtilis, *B. cereus*, *Flavobacterium* sp., *Pseudomonas aeruginosa*	Zn	*Orychophragmus violaceus*	Increased root length, biomass of root, stems, and leaves, and Zn uptake	He et al. [354]
Burkholderia cepacia	Zn, Cd	*Sedum alfredii*	Higher ability to mobilize Cd and Zn and tolerate high concentrations of soluble Zn. Increased the soluble Zn concentration in the medium from insoluble zinc oxide and zinc carbonate. Oxalic, tartaric, formic, and acetic acids had a significant correlation with the concentrations of Cd and Zn being mobilized	Li et al. [355]
Pseudomonas sp. RJ10, *Bacillus* sp. RJ16	Cd, Pb	*Lycopersicon esculentum*	Increased root length, aboveground biomass and aboveground metal content, siderophores, IAA, ACC deaminase production	He et al. [356]

(continued)

Table 2.4 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress, phytoextraction	References
Psychrobacter sp. *SRA1 and SRA2*, *Bacillus cereus SRA10*	Ni	*Brassica juncea*, *Brassica oxyrrhina*	Significantly increased the accumulation of Ni in the root and shoot tissues reinforcing the efficiency of phytoextraction	Ma et al. [313]
Pseudomonas aeruginosa, *Pseudomonas fluorescens*, *Ralstonia metallidurans*	Cr, Pb	*Zea mays*	Enhanced Cr and Pb uptake by plants through their mobilization	Braud et al. [340]
Pseudomonas fluorescens G10, *Microbacterium* sp. *G16*	Pb	*Brassica napus*	Increased plant weight, ACCD activity, IAA production, P accumulation, and Pb translocation to shoots	Sheng et al. [232]
Bacillus edaphicus NBT	Pb	*Brassica juncea* L. Czern	Promoted plant growth (root and shoot biomass) and Pb uptake	Sheng et al. [222]
Pseudomonas tolaasii ACC23, P. fluorescens ACC9, Mycobacterium sp. *ACC14*	Cd	*Brassica napus*	The strains did not influence Cd concentration in the root or shoot, but they increased plant biomass and consequently the total Cd extracted	Dell'Amico et al. [312]
Enterobacter sp. *NBRI K28*	Ni, Zn, Cr	*Brassica juncea*	Stimulated plant biomass and enhanced phytoextraction of Ni, Zn, and Cr Production of siderophores, IAA, and phosphate solubilization. The strain also exhibited ACC deaminase activity	Kumar et al. [357]
Bacillus subtilis, *Bacillus pumilus*, *Pseudomonas pseudoalcaligene*, *Brevibacterium halotolerans*	Cu, Cr, Pb, Zn	*Zea mays*, *Sorghum bicolor*	Increased metal availability in soil, thus enhancing Cr, Pb, Zn, and Cu accumulation by *Z. mays* and *S. bicolor*	Abou-Shanab et al. [358]
Burkholderia sp. *J62*	Pb, Cd	*Brassica juncea*, *Zea mays*, *Lycopersicon esculentum*	Increased biomass and metal uptake	Jiang et al. [359]
B. weihenstephanensis SM3	Cu, Zn	*Helianthus annuus*	Increased the plant biomass and the accumulation of Cu and Zn in the root and shoot systems	Rajkumar et al. [205]

(continued)

Table 2.4 (continued)

Microorganisms	M	Test plant	Microbial effects on plants under metal stress, phytoextraction	References
P. putida ARB86	Ni	*Arabidopsis thaliana*	Increased biomass and chlorophyll content. Nickel influx into plants was decreased by bacterial sorption in the rhizosphere	Someya et al. [261]
Burkholderia cepacia	Cd, Zn	*Sedum alfredii*	Enhanced plant growth, metal uptake, and translocation of metals from root to shoot	Li et al. [335]
P. marginalis Dp1, *Rhodococcus* sp. *Fp2*	Cd	*Pisum sativum*	Increased Cd concentration in shoots	Safronova et al. [360]
Pseudomonas monteilii	Cd	*Sorghum bicolor*	Enhanced plant biomass, Cd uptake, and translocation to shoots	Duponnois et al. [361]
Azotobacter chroococcum HKN-5, *Bacillus megaterium* HKP-1, *Bacillus mucilaginosus* HKK-1	Cd, Cu, Pb, Zn	*Brassica juncea*	Stimulated plant growth and protected the plant from metal toxicity It did not influence metal concentrations in plant tissues, but led to greater aboveground biomass, thus resulting in much higher metal removal. It also influenced speciation of metals in the soil and consequently altered the bioavailability of metals	Wu et al. [362]
Sinorhizobium sp. Pb002	Pb	*Brassica juncea*	Stimulated biomass production and, hence, phytoextraction of Pb	Di Gregorio et al. [363]
B. subtilis SJ-101	Ni	*Brassica juncea*	Exhibited the capability to produce IAA and to solubilize inorganic phosphate. Promoted plant growth and decreased soluble soil Ni by biosorption and bioaccumulation	Zaidi et al. [364]
Brevibacillus sp. *B-I*	Zn	*Trifolium repens*	Decreased the concentration of Zn in shoot tissues	Vivas et al. [268]

enhance metal bioavailability and inoculation of microorganisms, including bacteria and fungi, may facilitate the phytoextraction appliance at a commercial scale.

A number of bacteria and fungi have been studied by researchers which are able to enhance metal accumulation by plants and the metal(loid)s phytoextraction rate. Fungi are generally more tolerant to metal(loid)s than bacteria. Furthermore, AM fungi can efficiently explore the soil microsites that are not accessible for plant roots. In this context, a combination of plant-associated microorganisms could be more effective in enhancing reclamation of polluted soils than a single microorganism. It has been shown that endophytes (bacteria and fungi) can be a more reliable source of natural biocenosis because of their intimate association with plants. However, an understanding of the mechanisms enabling endophytic microbes to interact with host plants growing in metal-contaminated soils is essential to fully accomplish the biotechnological applications of efficient plant-microbe partnerships. Furthermore, there is ample experimental evidence that metal-resistant SPB are able to survive in adverse environmental conditions, where they carry out a variety of beneficial interactions that increase plant growth and metal(loid)s uptake. The beneficial effects exhibited by SPB indicate that the inoculation with metal-resistant strains may contribute to increase phytoextraction potential in metal-contaminated soils.

However, 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. In addition, inoculation of mixtures of ecologically diverse microbes instead of single strains might represent a highly successful strategy. In this way, beneficial functions might be expressed more continually in a soil or rhizosphere system, even under ecologically distinct conditions. Furthermore, application of genetic engineering may enhance phytoextraction efficiency. After the identification of novel genes, transgenic plants may be produced with superior extracting capacity involving metal(loid)s hypertolerance, raised uptake and translocation to shoots, and highly efficient detoxification mechanisms. Genes for metal chelators production, metal homeostasis, transporters, biodegradative enzymes, metal uptake regulators, and biotic and abiotic stresses relievers are important candidates for making recombinant microbes.

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. It is obvious that the complexity of interactions in the plant-microbe-soil-pollutant systems requires substantial further research efforts to improve our understanding of the rhizosphere processes involved.

Fortunately, modern biotechnology has opened up new possibilities concerning the application of beneficial microbes to improve plant growth, biological control, as well as metal(loid)s phytoremediation.

References

1. Pinto AP, de Varennes A, Lopes ME, Teixeira DM (2016) Biological approaches for remediation of metal-contaminated sites. In: Ansari A, Gill S, Gill R, Lanza G, Newman L (eds) Phytoremediation. Management of environmental contaminants, vol 3. Springer, Wien, Austria, pp 65–112

2. Awad YM, Kim SC, Abd El-Azeem SAM, Kim KH, Kim KR, Kim K et al (2014) Veterinary antibiotics contamination in water, sediment, and soil near a swine manure composting facility. Environ Earth Sci 71:1433–1440
3. 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. https://doi.org/10.1016/j.jes.2014.07.013
4. Moreira H, Marques APGC, Rangel AOSS, Castro PML (2011) Heavy metal accumulation in plant species indigenous to a contaminated Portuguese site: prospects for phytoremediation. Water Air Soil Pollut 221:377–389
5. Pinto AP, Varennes A, Fonseca R, Teixeira DM (2015) Phytoremediation of soils contaminated with heavy metals: techniques and strategies. In: Ansari AA, Gill SS, Gill R, Lanza GR, Newman L (eds) Management of environmental contaminants, vol 1. Springer, Wien, Austria, pp 133–155
6. Song B, Zeng G, Gong J, Liang J, Xu P, Liu Z et al (2017) Evaluation methods for assessing effectiveness of in situ remediation of soil and sediment contaminated with organic pollutants and heavy metals. Environ Int 105:43–55
7. Tang Z, Zhang L, Huang Q, Yang Y, Nie Z, Cheng J et al (2015) Contamination and risk of heavy metals in soils and sediments from a typical plastic waste recycling area in North China. Ecotoxicol Environ Saf 122:343–351
8. Teng Y, Wu J, Lu S, Wang Y, Jiao X, Song L (2014) Soil and soil environmental quality monitoring in China: a review. Environ Int 69:177–199
9. Zeng GM, Chen M, Zeng ZT (2013) Risks of neonicotinoid pesticides. Science 340(6139):1403. https://doi.org/10.1126/science.340.6139.1403-a
10. Mahar A, Wang P, Ali A, Awasthi MK, Lahori AH, Wang Q et al (2016) Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. Ecotoxicol Environ Saf 126:111–121
11. Perez J (2012) The soil remediation industry in Europe: the recent past and future perspectives. Ernst and Young, London, pp 2–22
12. Bhargava A, Carmona FF, Bhargava M, Srivastava S (2012) Approaches for enhanced phytoextraction of heavy metals. J Environ Manage 105:103–120
13. Cristaldi A, Conti GO, Jho EH, Zucarello P, Grass A, Copat C, Ferrante M (2017) Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. Environ Technol Innov 8:309–326
14. Miransari M (2011) Hyperaccumulators, arbuscular mycorrhizal fungi and stress of heavy metals. Biotechnol Adv 29:645–653
15. Shayler H, McBride M, Harrison E (2009) Sources and impacts of contaminants in soils. Department of Crop & Soil Sciences, Cornell Waste Management Institute, Ithaca, NY http://cwmi.css.cornell.edu
16. Conceição Gomes MA, Hauser-Davis RA, Nunes de Souza A, Vitória AP (2016) Metal phytoremediation: general strategies, genetically modified plants and applications in metal nanoparticle contamination. Ecotoxicol Environ Saf 134:133–147
17. Horta A, Malone B, Stockmann U, Minasny B, Bishop TFA, McBratney AB et al (2015) Potential of integrated field spectroscopy and spatial analysis for enhanced assessment of soil contamination: a prospective review. Geoderma 241–242:180–209
18. Cameselle C, Chirakkara RA, Reddy KR (2013) Electrokinetic-enhanced phytoremediation of soils: status and opportunities. Chemosphere 93:626–636
19. Heckenroth A, Rabier J, Dutoit T, Torre F, Prudent P, Laffont-Schwob I (2016) Selection of native plants with phytoremediation potential for highly contaminated Mediterranean soil restoration: tools for a non-destructive and integrative approach. J Environ Manage 183:850–863
20. Luo J, Cai L, Qi S, Wu J, Gu XS (2017) A multi-technique phytoremediation approach to purify metals contaminated soil from e-waste recycling site. J Environ Manage 204:17–22

21. Luo N, Li X, Chen AY, Zhang LJ, Zhao HM, Xiang L et al (2017) Does arbuscular mycorrhizal fungus affect cadmium uptake and chemical forms in rice at different growth stages? Sci Total Environ 599–600:1564–1572
22. Hazrat A, Ezzat K, Muhammad AS (2013) Phytoremediation of heavy metal–concepts and applications. Chemosphere 91:869–881
23. Wang L, Ji B, Hu Y, Liu R, Sun W (2017) A review on in situ phytoremediation of mine tailings. Chemosphere 184:594–600
24. Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metals—concepts and applications. Chemosphere 91:869–881
25. Balseiro-Romero M, Gkorezis P, Kidd PS, Van Hamme J, Weyens N, Monterroso C et al (2017) Use of plant growth promoting bacterial strains to improve *Cytisus striatus* and *Lupinus luteus* development for potential application in phytoremediation. Sci Total Environ 581–582:676–688
26. Mojiri A, Lou Z, Tajuddin RM, Farraji H, Alifar N (2016) Co-treatment of landfill leachate and municipal wastewater using the ZELIAC/zeolite constructed wetland system. J Environ Manage 166:124–130
27. Salam JA, Hatha MAA, Das N (2017) Microbial-enhanced lindane removal by sugarcane (*Saccharum officinarum*) in doped soil-applications in phytoremediation and bioaugmentation. J Environ Manage 193:394–399
28. Afzal M, Khan QM, Sessitsch A (2014) Endophytic bacteria: prospects and applications for the phytoremediation of organic pollutants. Chemosphere 117:232–242
29. Jiang Y, Lei M, Duan L, Longhurst P (2015) Integrating phytoremediation with biomass valorisation and critical element recovery: a UK contaminated land perspective. Biomass Bioenergy 83:328–339
30. Tahir U, Yasmin A, Khan UH (2016) Phytoremediation: potential flora for synthetic dyestuff metabolism. J King Saud Univ Sci 28:119–130. https://doi.org/10.1016/j.jksus.2015.05.009
31. Coninx L, Martinova V, Rineau F (2017) Chapter Four - Mycorrhiza-assisted phytoremediation. Adv Bot Res 83:127–188
32. 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
33. Gerhardt K, Gerwing P, Greenberg B (2017) Opinion: Taking phytoremediation from proven technology to accepted practice. Plant Sci 256:170–185
34. 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
35. Sreelal G, Jayanthi R (2017) Review on phytoremediation technology for removal of soil contaminant. Indian J Sci Res 14:127–130
36. Alford ER, Pilon-Smits EAH, Paschke MW (2010) Metallophytes - a view from the rhizosphere. Plant Soil 337:33–50. https://doi.org/10.1007/s11104-010-0482-3
37. 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
38. Krznaric E, Wevers JHL, Cloquet C, Vangronsveld J, Vanhaecke F, Colpaert JV (2010) Zn pollution counteracts Cd toxicity in metal-tolerant ectomycorrhizal fungi and their host plant, *Pinus sylvestris*. Environ Microbiol 12(8):2133–2134
39. Sheoran V, Sheoran A, Poonia P (2011) Role of hyperaccumulators in phytoextraction of metals from contaminated mining sites: a review. Crit Rev Environ Sci Technol 41:168–214
40. Sarwar N, Imran M, Shaheen MR, Ishaque W, Kamran MA, Matloob A et al (2017) Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere 171:710–721

41. Ashraf MA, Hussain I, Rasheed R, Iqbal M, Riaz M, Arif MS (2017) Advances in microbe-assisted reclamation of heavy metal contaminated soils over the last decade: a review. J Environ Manage 198:132–143
42. Zubair M, Shakir M, Ali Q, Rani N, Fatima N, Farooq S et al (2016) Rhizobacteria and phytoremediation of heavy metals. Environ Technol Rev 5:112–119. https://doi.org/10.1080/21622515.2016.1259358
43. Rajkumar M, Prasad MNV, Sandhya S, Freitas H (2013) Climate change driven plant-metal-microbe interactions. Environ Int 53:74–86
44. Deng Z, Cao L (2017) Fungal endophytes and their interactions with plants in phytoremediation: a review. Chemosphere 168:1100–1106
45. Deng Z, Cao L, Huang H, Jiang X, Wang W, Shi Y et al (2011) Characterization of Cd- and Pb-resistant fungal endophyte Mucor sp. CBRF59 isolated from rapes (*Brassica chinensis*) in a metal-contaminated soil. J Hazard Mater 185:717–724
46. Deng Z, Zhang R, Shi Y, Hu L, Tan H, Cao L (2013) Enhancement of phytoremediation of Cd- and Pb-contaminated soils by self-fusion of protoplasts from endophytic fungus Mucor sp. CBRF59. Chemosphere 91:41–47
47. Deng Z, Zhang R, Shi Y, Hu L, Tan H, Cao L (2013) Characterization of Cd-, Pb-, Zn-resistant endophytic *Lasiodiplodia* sp. MXSF31 from metal accumulating *Portulaca oleracea* and its potential in promoting the growth of rape in metal-contaminated soils. Environ Sci Pollut Res 21:2346–2357
48. Glick BR (2010) Using soil bacteria to facilitate phytoremediation. Biotechnol Adv 28(3):367–374
49. Glick BR, Todorovic B, Czarny J, Cheng Z, Duan J, McConkey B (2007) Promotion of plant growth by bacterial ACC deaminase. Crit Rev Plant Sci 26:227–242
50. Ma Y, Prasad M, Rajkumar M, Freitas H (2011) Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils. Biotechnol Adv 29:248–258
51. Ma Y, Rajkumar M, Rocha I, Oliveira RS, Freitas H (2015) Serpentine bacteria influence metal translocation and bioconcentration of *Brassica juncea* and *Ricinus communis* grown in multi-metal polluted soils. Front Plant Sci 5:757
52. Ma Y, Rajkumar M, Zhang C, Freitas H (2016) Beneficial role of bacterial endophytes in heavy metal phytoremediation. J Environ Manage 174:14–25
53. Rajkumar M, Ae N, Freitas H (2009) Endophytic bacteria and their potential to enhance heavy metal phytoextraction. Chemosphere 77:153–160
54. Rajkumar M, Ae N, Prasad MNV, Freitas H (2010) Potential of siderophore-producing bacteria for improving heavy metal phytoextraction. Trends Biotechnol 28:142–149
55. Lebeau T, Braud A, Jequel K (2008) Performance of bioaugmentation-assisted phytoextraction applied to metal contaminated soils: a review. Environ Pollut 153:497–522
56. Khan A, Ullah I, Waqas M, Park G, Khan A, Hong S et al (2017) Host plant growth promotion and cadmium detoxification in *Solanum nigrum*, mediated by endophytic fungi. Ecotoxicol Environ Saf 136:180–188
57. Khan AR, Waqas M, Ullah I, Khan AL, Khan MA, Lee IJ, Shin JH (2017) Culturable endophytic fungal diversity in the cadmium hyperaccumulator *Solanum nigrum* L. and their role in enhancing phytoremediation. Environ Exp Bot 135:126–135. https://doi.org/10.1016/j.envexpbot.2016.03.005
58. Wenzel WW (2009) Rhizosphere processes and management in plant-assisted bioremediation (phytoremediation) of soils. Plant Soil 321:385–408
59. Cao XF, Liu LP (2015) Using microorganisms to facilitate phytoremediation in mine tailings with multi heavy metals. Adv Mater Res 1094:437–440. https://doi.org/10.4028/www.scientific.net/AMR.1094.437
60. Leung HM, Wang ZW, Ye ZH, Yung KL, Peng XL, Cheung KC (2013) Interactions between arbuscular mycorrhizae and plants in phytoremediation of metal-contaminated soils: a review. Pedosphere 23:549–563

61. Kidd P, Barcelo J, Bernal MP, Navari-Izzo F, Poschenrieder C, Shilev S et al (2009) Trace element behaviour at the root–soil interface: implications in phytoremediation. Environ Exp Bot 67:243–259
62. Harms H, Schlosser D, Wick LY (2011) Untapped potential: exploiting fungi in bioremediation of hazardous chemicals. Nat Rev Microbiol 9:177–189
63. Schneider J, Bundschuh J, Nascimento C (2016) Arbuscular mycorrhizal fungi-assisted phytoremediation of a lead-contaminated site. Sci Total Environ 572:86–97. https://doi.org/10.1016/j.scitotenv.2016.07.185
64. Mandyam K, Jumpponen A (2005) Seeking the elusive function of the root-colonising dark septate endophytic fungi. Stud Mycol 53:173–189
65. Li H, Li X, Xiang L, Zhao HM, Li YW, Cai QY et al (2018) Phytoremediation of soil co-contaminated with Cd and BDE-209 using hyperaccumulator enhanced by AM fungi and surfactant. Sci Total Environ 613–614:447–455
66. Lu YF, Lu M (2015) Remediation of PAH-contaminated soil by the combination of tall fescue, arbuscular mycorrhizal fungus and epigeic earthworms. J Hazard Mater 285:535–541
67. Mohammad A, Mittra B (2013) Effects of inoculation with stress-adapted arbuscular mycorrhizal fungus *Glomus deserticola on* growth of *Solanum melongena L.* and *Sorghum sudanense* Staph. seedlings under salinity and heavy metal stress conditions. Arch Agron Soil Sci 59:173–183
68. Morton JB, Redecker D (2001) Two new families of Glomales, Archaeosporaceae and Paraglomaceae, with two new genera Archaeospora and Paraglomus, based on concordant molecular and morphological characters. Mycologia 93:181–195
69. Sieverding E, Oehl F (2006) Revision of Entrophospora and description of Kuklospora and Intraspora, two new genera in the arbuscular mycorrhizal Glomeromycetes. J Appl Bot Food Qual 80:69–81
70. Walker C, Vestberg M, Demircik F, Stockinger H, Saito M, Sawaki H et al (2007) Molecular phylogeny and new taxa in the Archaeosporales (Glomeromycota): *Ambispora fennica* gen. sp. nov., Ambisporaceae fam. nov., and emendation of Archaeospora and Archaeosporaceae. Mycol Res 111:137–153
71. Leung HM, Wu FY, Cheung KC, Ye ZH, Wong MH (2010) The effect of arbuscular mycorrhizal fungi and phosphate amendment on arsenic uptake, accumulation and growth of *Pteris Vittata* in As-contaminated soil. Int J Phytoremediation 12:384–403
72. Leung HM, Wu FY, Cheung KC, Ye ZH, Wong MH (2010) Synergistic effects of arbuscular mycorrhizal fungi and phosphate rock on heavy metal uptake and accumulation by an arsenic hyperaccumulator. J Hazard Mater 181:497–507
73. Chaturvedi R, Favas P, Pratas J, Varun M, Paul MS (2018) Assessment of edibility and effect of arbuscular mycorrhizal fungi on T *Solanum melongena* L. grown under heavy metal(loid) contaminated soil. Ecotoxicol Environ Saf 148:318–326. https://doi.org/10.1016/j.ecoenv.2017.10.048
74. Qiao Y, Crowley D, Wang K, Zhang H, Li H (2015) Effects of biochar and Arbuscular mycorrhizae on bioavailability of potentially toxic elements in an aged contaminated soil. Environ Pollut 206:636–643
75. Fortin JA, Plenchette C, Piché Y (2009) Mycorrhizas: the new green revolution. Québec City, CA, Editions MultiMondes
76. Garg N, Chandel S (2012) Role of arbuscular mycorrhizal (am) fungi on growth, cadmium uptake, osmolyte, and phytochelatin synthesis in *Cajanus cajan* (l.) millsp. under NaCl and Cd stresses. J Plant Growth Regul 31:292–308
77. Sarwat M, Hashem A, Ahanger MA, Abd Allah EF, Alqarawi AA, Alyemeni MN et al (2016) Mitigation of NaCl stress by arbuscular mycorrhizal fungi through the modulation of osmolytes, antioxidants and secondary metabolites in mustard (*Brassica juncea* L.) plants. Front Plant Sci 7:869
78. Colpaert JV, Wevers JHL, Krznaric E, Adriaensen K (2011) How metal-tolerant ecotypes of ectomycorrhizal fungi protect plants from heavy metal pollution. Ann For Sci 68:17–24

79. Krznaric E, Verbruggen N, Vangronsveld J, Colpaert JV (2009) Cd-tolerant Suillus luteus: a fungal insurance for pines exposed to Cd. Environ Pollut 157:1581–1585
80. Orłowska E, Przybyłowicz W, Orlowski D, Turnau K, Mesjasz-Przybyłowicz J (2011) The effect of mycorrhiza on the growth and elemental composition of Ni-hyperaccumulating plant Berkheya coddii Roessler. Environ Pollut 159:3730–3738
81. Bellion M, Courbot M, Jacob C, Blaudez D, Chalot M (2006) Extracellular and cellular mechanisms sustaining metal tolerance in ectomycorrhizal fungi. FEMS Microbiol Lett 254:173–181
82. Meier S, Borie F, Bolan N, Cornejo P (2012) Phytoremediation of metal-polluted soils by arbuscular mycorrhizal fungi. Crit Rev Environ Sci Technol 42:741–777
83. Vamerali T, Bandiera M, Mosca G (2010) Field crops for phytoremediation of metal-contaminated land. A review. Environ Chem Lett 8:1–17
84. Tian W, Zhang CQ, Qiao P, Milne R (2011) Diversity of culturable ericoid mycorrhizal fungi of *Rhododendron decorum* in Yunnan. China Mycol 103:703–709
85. Wu FY, Ye ZH, Wu SC, Wong MH (2007) Metal accumulation and arbuscular mycorrhizal status in metallicolous and nonmetallicolous populations of *Pteris vittata* L. and *Sedum alfredii* Hance. Planta 226:1363–1378
86. Göhre V, Paszkowski U (2006) Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. Planta 223:1115–1122
87. Andrade SAL, Silveira APD, Mazzafera P (2010) Arbuscular mycorrhiza alters metal uptake and the physiological response of *Coffea arabica* seedlings to increasing Zn and Cu concentrations in soil. Sci Total Environ 408:5381–5391
88. Leyval C, Joner E, Del Val C, Haselwandter K (2001) Potential of arbuscular mycorrhiza for bioremediation. Mycorrhiza 7:308–317
89. Vosátka M, Rydlová J, Sudová R, Vohník M (2006) Mycorrhizal fungi as helping agents in phytoremediation of degraded and contaminated soils. In: Mackova M, Dowling D, Macek T (eds) Phytoremediation rhizoremediation. Springer, Heidelberg, pp 237–257
90. Vodnik D, Grčman H, Maček I, van Elteren JT, Kovačevič M (2008) The contribution of glomalin-related soil protein to Pb and Zn sequestration in polluted soil. Sci Total Environ 392:130–136
91. Driver JD, Holben WE, Rillig MC (2005) Characterization of glomalin as a hyphal wall component of arbuscular mycorrhizal fungi, Soil Biol. Biochem. 37:101–106
92. Malekzadeh E, Aliasgharzad N, Majidi J, Abdolalizadeh J, Aghebati-Maleki L (2016) Contribution of glomalin to Pb sequestration by arbuscular mycorrhizal fungus in a sand culture system with clover plant. Eur J Soil Biol 74:45–51. https://doi.org/10.1016/j.ejsobi.2016.03.003
93. González-Chávez C, D'Haen J, Vangronsveld J, Dodd JC (2002) Copper sorption and accumulation by the extraradical mycelium of different Glomus spp. (arbuscular mycorrhizal fungi) isolated from the same polluted soil. Plant Soil 240:287–297
94. 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 406:154–160
95. González-Chávez C, Harris PJ, Dodd J, Meharg AA (2002) Arbuscular mycorrhizal fungi confer enhanced arsenate resistance on *Holcus lanatus*. New Phytol 155:163–171
96. Luo J, Cai L, Qi S, Wu J, Gu XS (2017) Improvement effects of cytokinin on EDTA assisted phytoremediation and the associated environmental risks. Chemosphere 180:386–393
97. Shen H, Christie P, Li X (2006) Uptake of zinc, cadmium and phosphorus by arbuscular mycorrhizal maize (*Zea mays* L.) from a low available phosphorus calcareous soil spiked with zinc and cadmium. Environ Geochem Health 28:111–119
98. Janoušková M, Pavlíková D (2010) Cadmium immobilization in the rhizosphere of arbuscular mycorrhizal plants by the fungal extraradical mycelium. Plant Soil 332:511–520

99. Yu H, Xiang Z, Zhu Y, Wang J, Yang Z, Yang PZ (2012) Subcellular and molecular distribution of cadmium in two rice genotypes with different levels of cadmium accumulation. J Plant Nutr 35:71–84
100. Zeng F, Zhou W, Qiu B, Ali S, Wu F, Zhang G (2011) Subcellular distribution and chemical forms of chromium in rice plants suffering from different levels of chromium toxicity. J Plant Nutr Soil Sci 174:249–256
101. Wang Y, Jing H, Gao Y (2012) Arbuscular mycorrhizal colonization alters subcellular distribution and chemical forms of cadmium in *Medicago sativa* L. and resists cadmium toxicity. PLoS One 7:3161–3164
102. Rajkumar M, Sandhya S, Prasad M, Freitas H (2012) Perspectives of plant-associated microbes in heavy metal phytoremediation. Biotechnol Adv 30(6):1562–1574
103. Zarei M, Wubet T, Schäfer SH, Savaghebi GR, Jouzani GS, Nekouei MK et al (2010) Molecular diversity of arbuscular mycorrhizal fungi in relation to soil chemical properties and heavy metal contamination. Environ Pollut 158:2757–2765
104. Wei Y, Hou H, Xian Y, Guan S, Li JN, Li FS (2014) Genetic diversity of endophytic bacteria of the manganese-hyperaccumulating plant *Phytolacca americana* growing at a manganese mine. Eur J Soil Biol 62:15–21
105. Wei Y, Hou H, Li JN, ShangGuan YX, Xu YF, Zhang J et al (2014) Molecular diversity of arbuscular mycorrhizal fungi associated with an Mn hyperaccumulator—*Phytolacca americana*, in Mn mining area. Appl Soil Ecol 82:11–17. https://doi.org/10.1016/j.apsoil.2014.05.005
106. Wu FY, Ye ZH, Wong MH (2009) Intraspecific differences of arbuscular mycorrhizal fungi in their impacts on arsenic accumulation by *Pteris vittata* L. Chemosphere 76:1258–1264
107. Lin AJ, Zhang XH, Wong MH, Ye ZH, Lou LQ, Wang YS et al (2007) Increase of multi-metal tolerance of three leguminous plants by arbuscular mycorrhizal fungi colonization. Environ Geochem Health 29:473–481
108. Zhu LJ, Guan DX, Luo J, Rathinasabapathi B, Ma LQ (2014) Characterization of arsenic-resistant endophytic bacteria from hyperaccumuators *Pteris vittata* and *Pteris multifida*. Chemosphere 113:9–16
109. Jamal A, Ayub N, Usman M, Khan AG (2002) Arbuscular mycorrhizal fungi enhance zinc and nickel uptake from contaminated soil by soybean and lentil. Int J Phytoremediation 4:205–221
110. Lingua G, Franchin C, Todeschini V, Castiglione S, Biondi S, Burlando B et al (2008) Arbuscular mycorrhizal fungi differentially affect the response to high zinc concentrations of two registered poplar clones. Environ Pollut 153:137–147
111. Gamalero E, Lingua G, Berta G, Glick BR (2009) Beneficial role of plant growth promoting bacteria and arbuscular mycorrhizal fungi on plant responses to heavy metal stress. Can J Microbiol 55:501–514
112. Liao JP, Lin XG, Cao ZH, Shi YQ, Wong MH (2003) Interactions between arbuscular mycorrhizae and heavy metals under sand culture experiment. Chemosphere 50:847–853
113. Wang F, Lin X, Yin R (2005) Heavy metal uptake by arbuscular mycorrhizas of *Elsholtzia splendens* and the potential for phytoremediation of contaminated soil. Plant Soil 269:225–232
114. Sheikh-Assadi M, Khandam-Mirkohi A, Alemardan A, Moreno-Jiménez E (2015) Mycorrhizal *Limonium sinuatum* (l.) Mill. enhances accumulation of lead and cadmium. Int J Phytoremediation 17:556–562
115. Aly AH, Debbab A, Kjer J, Proksch P (2010) Fungal endophytes from higher plants: a prolific source of phytochemicals and other bioactive natural products. Fungal Divers 41:1–16
116. Aly A, Debbab A, Proksch P (2011) Fungal endophytes: unique plant inhabitants with great promises. Appl Microbiol Biotechnol 90:1829–1845
117. Kuiper I, Lagendijk EL, Bloemberg GV, Lugtenberg BJJ (2004) Rhizoremediation: a beneficial plant microbe interaction. Mol Plant Microbe Interact 17:6–15
118. Stepniewska Z, Kuzniar A (2013) Endophytic microorganisms—promising applications in bioremediation of greenhouse gases. Appl Microbiol Biotechnol 97:9589–9596

119. Deng Z, Wang W, Tan H, Cao L (2012) Characterization of heavy metal-resistant endophytic yeast Cryptococcus sp. CBSB78 from rapes (*Brassica chinensis*) and its potential in promoting the growth of Brassica spp. in metal-contaminated soils. Water Air Soil Pollut 223:5321–5329
120. Wang W, Deng Z, Tan H, Cao L (2013) Effects of Cd, Pb, Zn, Cu-resistant endophytic *Enterobacter sp.* CBSB1 and *Rhodotorula sp.* CBSB79 on the growth and phytoextraction of Brassica plants in multimetal contaminated soils. Int J Phytoremediation 15:488–497
121. Babu AG, Shim J, Shea PJ, Oh BT (2014) *Penicillium aculeatum* PDR-4 and *Tri-choderma* sp. PDR-16 promote phytoremediation of mine tailing soil and bio-energy production with Sorghum sudan grass. Ecol Eng 69:186–191
122. Babu AG, Shim J, Bang KS, Shea PJ, Oh BT (2014) *Trichoderma virens* PDR-28: a heavy metal-tolerant and plant growth-promoting fungus for remediation and bioenergy crop production on mine tailing soil. J Environ Manage 132:129–134
123. Khan AL, Waqas M, Hussain J, Al-Harrasi A, Lee IJ (2014) Fungal endophyte *Penicillium janthinellum* LK5 can reduce cadmium toxicity in *Solanum lycopersicum* (Sitiens and Rhe). Biol Fertil Soils 50:75–85
124. Pierart A, Dumat C, Maes AQM, Sejalon-Delmas N (2018) Influence of arbuscular mycorrhizal fungi on antimony phyto-uptake and compartmentation in vegetables cultivated in urban gardens. Chemosphere 191:272–279
125. Gil-Cardeza ML, Müller DR, Amaya-Martin SM, Viassolo R, Gómez E (2018) Differential responses to high soil chromium of two arbuscular mycorrhizal fungi communities isolated from Cr-polluted and non-polluted rhizospheres of *Ricinus communis*. Sci Total Environ 625:1113–1121
126. Kodre A, Arcon I, Vogel-Mikuš K, Debeljak M, Potisek M, Likar M (2017) Arbuscular mycorrhizal fungi alter Hg root uptake and ligand environment as studied by X-ray absorption fine structure. Environ Exp Bot 133:12–23
127. Huang X, Ho SH, Zhu S, Ma F, Wu J, Yang J et al (2017) Adaptive response of arbuscular mycorrhizal symbiosis to accumulation of elements and translocation in Phragmites australis affected by cadmium stress. J Environ Manage 197:448–455. https://doi.org/10.1016/j.jenvman.2017.04.014
128. Wei Y, Su Q, Sun ZJ, Shen YQ, Li JN, Zhu XL et al (2016) The role of arbuscular mycorrhizal fungi in plant uptake, fractions, and speciation of antimony. Appl Soil Ecol 107:244–250
129. Hristozkova M, Geneva M, Stancheva I, Boychinova M, Djonovab E (2016) Contribution of arbuscular mycorrhizal fungi in attenuation of heavy metal impact on *Calendula officinalis* development. Appl Soil Ecol 101:57–63
130. Mani D, Kumar C, Patel NK (2016) Integrated micro-biochemical approach for phytoremediation of cadmium and lead contaminated soils using *Gladiolus grandiflorus* L. cut flower. Ecotoxicol Environ Saf 124:435–446
131. De Souza LA, Andrade SAL, De Souza SCR, Schiavinato MA (2012) Arbuscular mycorrhiza confers Pb tolerance in *Calopogonium mucunoides*. Acta Physiol Plant 34:523–531
132. Garg N, Aggarwal N (2011) Effects of interactions between cadmium and lead on growth, nitrogen fixation, phytochelatin, and glutathione production in mycorrhizal *Cajanus cajan* (L.) Millsp. J Plant Growth Regul 30:286–300
133. 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
134. Krupa P, Kozdrój J (2007) Ectomycorrhizal fungi and associated bacteria provide protection against heavy metals in inoculated pine (*Pinus sylvestris* L.) seedlings. Water Air Soil Pollut 182:83–90
135. Fomina MA, Alexander IJ, Hillier S, Gadd GM (2004) Zinc phosphate and pyromorphite solubilization by soil plant-symbiotic fungi. Geomicrobiol J 21:351–366

136. González-Chávez 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 130:317–323
137. 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 35:133–141
138. Gadd GM (2004) Microbial influence on metal mobility and application for bioremediation. Geoderma 122:109–119
139. Weyens N, Croes S, Dupae J, Newman L, van der Lelie D, Carleer R et al (2010) Endophytic bacteria improve phytoremediation of Ni and TCE co-contamination. Environ Pollut 158:2422–2427
140. Kumar KV, Srivastava S, Singh N, Behl HM (2009) Role of metal resistant plant growth promoting bacteria in ameliorating fly ash to the growth of *Brassica juncea*. J Hazard Mater 170:51–57
141. 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 69:220–228
142. Dardanelli MS, Manyani H, Gonzalez-Barroso S, Rodríguez-Carvajal MA, Gil-Serrano AM, Espuny MR et al (2010) Effect of the presence of the plant growth promoting rhizobacterium (PGPR) *Chryseobacterium balustinum* Aur9 and salt stress in the pattern of flavonoids exuded by soybean roots. Plant Soil 328:483–493. https://doi.org/10.1007/s11104-009-0127-6
143. Nadeem SM, Zahir ZA, Naveed M, Asghar HN, Arshad M (2010) Rhizobacteria capable of producing ACC-deaminase may mitigate salt stress in wheat. Soil Sci Soc Am J 74:533–542. https://doi.org/10.2136/sssaj2008.0240
144. Babu AG, Shea PJ, Sudhakar D, Jung IB, Oh BT (2015) Potential use of *Pseudomonas koreensis* AGB-1 in association with *Miscanthus sinensis* to remediate heavy metal(loid)-contaminated mining site soil. J Environ Manage 151:160–166
145. Chen L, Luo SL, Li XJ, Wan Y, Chen JL, Liu CB (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
146. He H, Ye Z, Yang D, Yan J, Xiao L, Zhong T et al (2013) Characterization of endophytic Rahnella sp. JN6 from *Polygonum pubescens* and its potential in promoting growth and Cd, Pb, Zn uptake by *Brassica napus*. Chemosphere 90:196–195
147. Ma Y, Oliveira RS, Nai FJ, Rajkumar M, Luo YM, Rocha I et al (2015) The hyperaccumulator *Sedum plumbizincicola* harbors metal-resistant endophytic bacteria that improve its phytoextraction capacity in multi-metal contaminated soil. J Environ Manage 156:62–69
148. Compant S, Clément C, Sessitsch A (2010) Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. Soil Biol Biochem 42:669–678. https://doi.org/10.1016/j.soilbio.2009.11.024
149. Hallmann J, Quadt-Hallmann A, Mahaffee WF, Kloepper JW (1997) Bacterial endophytes in agricultural crops. Can J Microbiol 43:895–914
150. Hallmann J, Rodriguez-Kaban R, Kloepper J (1999) Chitin mediated changes in bacterial communities of the soil, rhizosphere and within roots of cotton in relation to nematode control. Soil Biol Biochem 31:551–560
151. Seghers D, Wittebolle L, Top EM, Verstraete W, Siciliano SD (2004) Impact of agricultural practices on the *Zea mays* L. endophytic community. Appl Environ Microbiol 70:1475–1482
152. Kobayashi DY, Palumbo JD (2000) Bacterial endophytes and their effects on plants and uses in agriculture. In: Bacon CW, White JF (eds) Microbial endophytes. Marcel Dekker, New York, pp 199–236
153. Gagne S, Richard C, Rousseau H, Antoun H (1987) Xylem-residing bacteria in alfalfa roots. Can J Microbiol 33:996–1000
154. Agarwal S, Shende ST (1987) Tetrazolium reducing microorganisms inside the root of Brassica species. Curr Sci 56:187–188

155. Roos IMM, Hattingh MJ (1983) Scanning electron microscopy of Pseudomonas syringae pv. morsprunorum on sweet cherry leaves. Phytopathol Z 108:18–25
156. Leben C, Daft GC, Schmitthenner AF (1968) Bacterial blight of soybeans: population levels of *Pseudomonas glycinea* in relation to symptom development. Phytopathology 58:1143–1146
157. Conn VM, Franco CMM (2004) Effect of microbial inoculants on the indigenous actinobacterial endophyte population in the roots of wheat as determined by terminal restriction fragment length polymorphism. Appl Environ Microbiol 70:6407–6413
158. Schulz B, Boyle C (2006) What are endophytes? In: Schulz BJE, Boyle CJC, Sieber TN (eds) Microbial root endophytes. Springer, Viena, pp 1–15
159. Porteous-Moore F, Barac T, Borremans B, Oeyen L, Vangronsveld J, van der Lelie D et al (2006) Endophytic bacterial diversity in poplar trees growing on a BTEX-contaminated site: the characterisation of isolates with potential to enhance phytoremediation. Syst Appl Microbiol 29:539–556
160. Bacon CW, Hinton DM (2011) In planta reduction of maize seedling stalk lesions by the bacterial endophyte *Bacillus mojavensis*. Can J Microbiol 57:1–8
161. Ma Y, Rajkumar M, Zhang C, Freitas H (2016) Beneficial role of bacterial endophytes in heavy metal phytoremediation. JEnviron Manage. 174:14–25
162. Ryan PR, Delhaize E, Jones DL (2001) Function and mechanism of organic anion exudation from plant roots. Annu Rev Plant Physiol Plant Mol Biol 52:527–560
163. van Overbeek L, van Elsas JD (2008) Effects of plant genotype and growth stage on the structure of bacterial communities associated with potato (*Solanum tuberosum* L.). FEMS Microbiol Ecol 64:283–296
164. Conrath U, Beckers GJM, Flors V, García-Agustín P, Jakab G, Mauch F et al (2006) Priming: getting ready for battle. Mol Plant Microbe Interact 19:1062–1071
165. Becerra-Castro C, Kidd PS, Rodríguez-Garrido B, Monterroso C, Santos-Ucha P, Prieto-Fernández Á (2013) Phytoremediation of hexachlorocyclohexane (HCH)-contaminated soils using bacterial inoculants in soils with distinct organic matter content. Environ Pollut 178:202–210. https://doi.org/10.1016/j..2013.03.027
166. Becerra-Castro C, Prieto-Fernández Á, Kidd PS, Weyens N, Rodríguez-Garrido B, Touceda-González M et al (2013) Improving performance of *Cytisus striatus* on substrates contaminated with hexachlorocyclohexane (HCH) isomers using bacterial inoculants: developing a phytoremediation strategy. Plant Soil 362:247–260. https://doi.org/10.1007/s11104-012-1276-6
167. Lugtenberg B, Kamilova F (2009) Plant-growth-promoting rhizobacteria. Annu Rev Microbiol 63:541–556. https://doi.org/10.1146/annurev.micro.62.081307.162918
168. Weyens N, van der Lelie D, Taghavi S, Newman L, Vangronsveld J (2009) Exploiting plant–microbe partnerships to improve biomass production and remediation. Trends Biotechnol 27:591–598. https://doi.org/10.1016/j.tibtech.2009.07.006
169. Weyens N, van der Lelie D, Taghavi S, Vangronsveld J (2009) Phytoremediation: plant–endophyte partnerships take the challenge. Curr Opin Biotechnol 20:248–254. https://doi.org/10.1016/j.copbio.2009.02.012
170. Zafar M, Abbasi MK, Khan MA, Khaliq A, Sultan T, Aslam M (2012) Effect of plant growth-promoting rhizobacteria on growth, nodulation and nutrient accumulation of lentil under controlled conditions. Pedosphere 22:848–859. https://doi.org/10.1016/S1002-0160(12)60071-X
171. Joshi P, Juwarkar A (2009) In vivo studies to elucidate the role of extracellular polymeric substances from Azotobacter in immobilization of heavy metals. Environ Sci Technol 43:5884–5889
172. Banat IM, Franzetti A, Gandolfi I, Bestetti G, Martinotti MG, Fracchia L et al (2010) Microbial biosurfactants production, applications and future potential. Appl Microbiol Biotechnol 87:427–444
173. Sheoran N, Valiya Nadakkakath A, Munjal V, Kundu A, Subaharan K, Venugopal V et al (2015) Genetic analysis of plant endophytic Pseudomonas putida BP25 and chemo-profiling of its antimicrobial volatile organic compounds. Microbiol Res 173:66–78

174. Aravind R, Eapen SJ, Kumar A, Ramana KV (2010) Screening of endophytic bacteria and evaluation of selected isolates for suppression of burrowing nematode *Radopholus similis Thorne* using three varieties of black pepper (*Piper nigrum* L.). Crop Prot 29:318–324
175. Bacon CW, Hinton DM, Mitchell TR, Snook ME, Olubajo B (2012) Characterization of endophytic strains of *Bacillus mojavensis* and their production of surfactin isomers. Biol Control 62:1–9
176. Alvin A, Miller KI, Neilan BA (2014) Exploring the potential of endophytes from medicinal plants as sources of antimycobacterial compounds. Microbiol Res 169:483–495
177. Gechev TS, van Breusegem F, Stone JM, Denev I, Laloi C (2006) Reactive oxygen species as signals that modulate plant stress responses and programmed cell death. Bioessays 28:1091–1101
178. Wan Y, Luo S, Chen J, Xiao X, Chen L, 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 89:743–750
179. Zhang XX, Li CJ, Nan ZB (2010) Effects of cadmium stress on growth and antioxidative systems in *Achnatherum inebrians* symbiotic with *Neotyphodium gansuense*. J Hazard Mater 175:703–709
180. Babu AG, Kim JD, Oh BT (2013) Enhancement of heavy metal phytoremediation by *Alnus firma* with endophytic *Bacillus thuringiensis* GDB-1. J Hazard Mater 250–251:477–483
181. Luo SL, Chen L, Chen JL, Xiao X, Xu TY, Wan Y et al (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
182. Luo SL, Wan Y, Xiao X, Guo H, Chen L, Xi Q et al (2011) Isolation and characterization of endophytic bacterium LRE07 from cadmium hyperaccumulator *Solanum nigrum L.* and its potential for remediation. Appl Microbiol Biotechnol 89:1637–1644
183. Shin M, Shim J, You Y, Myung H, Bang KS, Cho M et al (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
184. Phetcharat P, Duangpaeng A (2012) Screening of endophytic bacteria from organic rice tissue for indole acetic acid production. Proc Eng 32:177–183
185. Zhang YF, He LY, Chen ZJ, Zhang WH, Wang QY, Qian M et al (2011) Genetic diversity and characterization of heavy metal-resistant-endophytic bacteria and their potential in promoting lead accumulation of rape. J Hazard Mater 186:1720–1725
186. Idris R, Trifonova R, Puschenreiter M, Wenzel WW, Sessitsch A (2004) Bacterial communities associated with flowering plants of the Ni hyperaccumulator *Thlaspi goesingense*. Appl Environ Microbiol 70:2667–2677
187. Idris R, Kuffner M, Bodrossy L, Puschenreiter M, Monchy S, Wenzel WW et al (2006) Characterization of Ni-tolerant methylobacteria associated with the hyperaccumulating plant *Thlaspi goesingense* and description of *Methylobacterium goesingense sp.* nov. Syst Appl Microbiol 29:634–644
188. Diaz-Ravina M, Baath E (1996) Development of metal tolerance in soil bacterial communities exposed to experimentally increased metal levels. Appl Environ Microbiol 62:2970–2977
189. Shoeb E, Badar U, Akhter J, Shams H, Sultana M, Ansari MA (2012) Horizontal gene transfer of stress resistance genes through plasmid transport. World J Microbiol Biotechnol 28:1021–1025
190. Brown NL, Stoyanov JV, Kidd SP, Hobman JL (2003) The MerR family of transcriptional regulators. FEMS Microbiol Rev 27:145–163
191. Cursino L, Mattos SV, Azevedo V, Galarza F, Bucker DH, Chartone-Souza E et al (2000) Capacity of mercury volatilization by mer (from *Escherichia coli*) and glutathione S-transferase (from *Schistosoma mansoni*) genes cloned in *Escherichia coli*. Sci Total Environ 261:109–113

192. Pereira SIA, Castro PML (2014) Diversity and characterization of culturable bacterial endophytes from *Zea mays* and their potential as plant growth-promoting agents in metal-degraded soils. Environ Sci Pollut Res 21:14110–14123
193. Ullah A, Mushtaq H, Ali H, Munis MFH, Javed MT, Chaudhary HJ (2015) Diazotrophs-assisted phytoremediation of heavy metals: a novel approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-014-3699-5
194. Gupta G, Panwar J, Jha PN (2013) Natural occurrence of *Pseudomonas aeruginosa*, a dominant cultivable diazotrophic endophytic bacterium colonizing *Pennisetum glaucum* (L.). R. Br. Appl Soil Ecol 64:252–261
195. Hurek T, Reinhold-Hurek B (2003) *Azoarcus sp*. strain BH72 as a model for nitrogen-fixing grass endophytes. J Biotechnol 106:169–178
196. Ahemad M (2015) Phosphate-solubilizing bacteria-assisted phytoremediation of metalliferous soils: a review. 3 Biotech 5:111–121. https://doi.org/10.1007/s13205-014-0206-0
197. Kumar S (2016) Characterization of phosphate solubilising and mineralizing bacteria from grain legumes. Dissertation, Final thesis, Punjab Agricultural University, Ludhiana, India
198. Guiñazú LB, Andrés JA, Del MFP, Pistorio M, Rosas SB (2010) Response of alfalfa (*Medicago sativa* L.) to single and mixed inoculation with phosphate-solubilizing bacteria and *Sinorhizobium meliloti*. Biol Fertil Soil 46:185–190
199. 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 182:291–296
200. Khan KS, Joergensen RG (2009) Changes in microbial biomass and P fractions in biogenic household waste compost amended with inorganic P fertilizers. Bioresour Technol 100:303–309
201. Neubauer U, Furrer G, Kayser A, Schulin R (2000) Siderophores, NTA, and citrate: potential soil amendments to enhance heavy metal mobility in phytoremediation. Int J Phytoremediation 2:353–368. https://doi.org/10.1080/15226510008500044
202. Boukhalfa H, Crumbliss AL (2002) Chemical aspects of siderophore mediated iron transport. Biometals 15:325–339
203. Barry SM, Challis GL (2009) Recent advances in siderophore biosynthesis. Curr Opin Chem Biol 13:1–11
204. Krewulak KD, Vogel HJ (2008) Structural biology of bacterial iron uptake. Biochim Biophys Acta 1778:1781–1804
205. Rajkumar M, Ma Y, Freitas H (2008) Characterization of metal-resistant plant-growth promoting Bacillus weihenstephanensis isolated from serpentine soil in Portugal. J Basic Microbiol 48:1–9
206. Dimkpa C, Svatos A, Merten D, Büchel G, Kothe E (2008) Hydroxamate siderophores produced by *Streptomyces acidiscabies* E13 bind nickel and promote growth in cowpea (*Vigna unguiculata* L.) under nickel stress. Can J Microbiol 54:163–172
207. Dimkpa CO, Svatos A, Dabrowska 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 74:19–25
208. Dimkpa CO, Merten D, Svatoš A, Büchel G, Kothe E (2009) Metal-induced oxidative stress impacting plant growth in contaminated soil is alleviated by microbial siderophores. Soil Biol Biochem 41:154–162
209. Dimkpa CO, Merten D, Svatos A, Büchel G, Kothe E (2009) Siderophores mediate reduced and increased uptake of cadmium by *Streptomyces tendae* F4 and sunflower (*Helianthus annuus*), respectively. J Appl Microbiol 107:1687–1696
210. Tripathi M, Munot H, Shouche Y, Meyer JM, Goel R (2005) Isolation and functional characterization of siderophore-producing lead- and cadmium-resistant *Pseudomonas putida* KNP9. Curr Microbiol 50:233–237
211. Rajkumar M, Freitas H (2008) Effects of inoculation of plant-growth promoting bacteria on Ni uptake by Indian mustard. Bioresour Technol 99:3491–3498

212. Rajkumar M, Freitas H (2008) Influence of metal resistant-plant growth promoting bacteria on the growth of *Ricinus communis* in soil contaminated with heavy metals. Chemosphere 71:834–842
213. Shi YW, Lou K, Li C (2009) Promotion of plant growth by phytohormone-producing endophytic microbes of sugar beet. Biol Fertil Soils 45:645–653
214. Kuklinsky-Sobral J, Araujo WL, Mendes R, Geraldi IO, Pizzirani-Kleiner AA, Azevedo JL (2004) Isolation and characterization of soybean-associated bacteria and their potential for plant growth promotion. Environ Microbiol 6:1244–1245
215. Gravel V, Antoun H, Tweddell RJ (2007) Growth stimulation and fruit yield improvement of greenhouse tomato plants by inoculation with Pseudomonas putida or Trichoderma atroviride: possible role of indole acetic acid (IAA). Soil Biol Biochem 39:1968–1977
216. Spaepen S, Vanderleyden J, Remans R (2007) Indole-3-acetic acid in microbial and microorganism-plant signaling. FEMS Microbiol Rev 31:425–448
217. Persello-Cartieaux F, Nussaumev L, Robaglia C (2003) Tales from the under-ground: molecular plant–rhizobacteria interactions. Plant Cell Environ 26:189–199
218. Bashan Y, Holguin G (1997) Azospirillum–plant relationships: environmental and physiological advances (1990–1996). Can J Microbiol 43:103–121
219. Fallik E, Sarig S, Okon Y (1994) Morphology and physiology of plant roots associated with Azospirillum. In: Okon Y (ed) Azospirillum/plant associations. CRC Press, London, pp 77–86
220. Xie H, Pasternak JJ, Glick BR (1996) Isolation and characterization of mutants of the plant growth-promoting rhizobacterium *Pseudomonas putida* GR 12-2 that over produce indole acetic acid. Curr Microbiol 32:67–71
221. Rosenblueth M, Martinez-Romero E (2006) Bacterial endophytes and their interactions with hosts. Mol Plant Microbe Interact 2006(19):827–837
222. Sheng XF, Jiang CY, He LY (2008) Characterization of plant growth-promoting inoculated *Bacillus edaphicus* NBT and its effect on lead uptake by Indian mustard in a lead-amended soil. Can J Microbiol 54:417–422
223. Sun Q, Rost TL, Matthews MA (2006) Pruning-induced tylose development in stems of current-year shoots of *Vitis vinifera* (Vitaceae). Am J Bot 93:1567–1576
224. Woodward AW, Bartel B (2005) Auxin: regulation, action, and interaction. Ann Bot London 95:707–735
225. 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 305:42–48
226. Guo HJ, Luo SL, Chen L, Xiao X, Xi Q, Wei WZ et al (2010) Bioremediation of heavy metals by growing hyper-accumulator endophytic bacterium *Bacillus sp.* L14. Bioresour Technol 101:8599–8605
227. Barzanti R, Ozino F, Bazzicalupo M, Gabbrielli R, Galardi F, Gonnelli C et al (2007) Isolation and characterization of endophytic bacteria from the nickel hyperaccumulator plant *Alyssum bertolonii*. Microb Ecol 53:306–316
228. Lodewyckx C, Mergeay M, Vangronsveld J, Clijsters H, van der Lelie D (2002) Isolation, characterization, and identification of bacteria associated with the zinc hyperaccumulator *Thlaspi caerulescens* subsp. calaminaria. Int J Phytoremediation 4:101–115
229. Mastretta C, Taghavi S, van der Lelie D, Mengoni A, Galardi F, Gonnelli C et al (2009) Endophytic bacteria from seeds of *Nicotiana tabacum* can reduce cadmium phytotoxicity. Int J Phytoremediation 11:251–267
230. Sessitsch A, Kuffner M, Kidd P, Vangronsveld J, Wenzel WW, Fallmann K et al (2013) The role of plant-associated bacteria in the mobilization and phytoextraction of trace elements in contaminated soils. Soil Biol Biochem 60:182–194. https://doi.org/10.1016/j.soilbio.2013.01.012

231. Sheng XF, He LY, Wang Q, Ye H, Jiang C (2008) Effects of inoculation of biosurfactant-producing *Bacillus sp*. J119 on plant growth and cadmium uptake in a cadmium-amended soil. J Hazard Mater 155:17–22
232. Sheng XF, Xia JJ, Jiang CY, He LY, 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 156:1164–1170
233. Vijayaraghavan K, Yun YS (2008) Bacterial biosorbents and biosorption. Biotechnol Adv 26:266–291
234. Malik A (2004) Metal bioremediation through growing cells. Environ Int 30:261–262
235. Pulsawat W, Leksawasdi N, Rogers PL, Foster LJR (2003) Anions effects on biosorption of Mn(II) by extracellular polymeric substance (EPS) from *Rhizobium etli*. Biotechnol Lett 25:1267–1270
236. Diels L, Spaans PH, Van Roy S, Hooyberghs L, Ryngaert A, Wouters H et al (2003) Heavy metals removal by sand filters inoculated with metal sorbing and precipitating bacteria. Hydrometallurgy 71:235–241
237. Haferburg G, Kothe E (2007) Microbes and metals: interactions in the environment. J Basic Microbiol 47:453–467. https://doi.org/10.1002/jobm.200700275
238. Ranjard L, Nazaret S, Cournoyer B (2003) Freshwater bacteria can methylate selenium through the thiopurine methyltransferase pathway. Appl Environ Microbiol 69:3784–3790
239. Alvarez A, Saez JM, Costa JSD, Colin VL, Fuentes MS, Cuozzo SA et al (2017) Actinobacteria: current research and perspectives for bioremediation of pesticides and heavy metals. Chemosphere 166:41–62
240. Goodfellow M, Kampfer P, Busse HJ, Trujillo ME, Suzuki KI et al (2012) Bergey's manual of systematic bacteriology. Springer, New York
241. Cardoso P, Corticeiro S, Freitas R, Figueira E (2018) Different efficiencies of the same mechanisms result in distinct Cd tolerance T within *Rhizobium*. Ecotoxicol Environ Saf 150:260–269
242. Román-Ponce B, Reza-Vazquez DM, Gutierrez-Paredes S, De Haro-Cruz MJ, Maldonado-Hernandez J, Bahena-Osorio Y et al (2017) Plant growth-promoting traits in rhizobacteria of heavy metal-resistant plants and their effects on *Brassica nigra* seed germination. Pedosphere 27:511–526
243. Rojjanateeranaj P, Sangthong C, Prapagdee B (2017) Enhanced cadmium phytoremediation of *Glycine max* L. through bioaugmentation of cadmium-resistant bacteria assisted by biostimulation. Chemosphere 185:764–771
244. Seneviratne M, Gunaratnea S, Bandara T, Weerasundara L, Rajakaruna N, Seneviratne G et al (2016) Plant growth promotion by *Bradyrhizobium japonicum* under heavy metal stress. South Afr J Bot 105:19–24
245. Adediran GA, Ngwenyaa BT, Mosselmans JFW, Heal KV, Harvie BA (2015) Mechanisms behind bacteria induced plant growth promotion and Zn accumulation in *Brassica juncea*. J Hazard Mater 283:490–499
246. 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
247. Yang Q, Tu S, Wang G, Liao X, Yan X (2012) Effectiveness of applying arsenate reducing bacteria to enhance arsenic removal from polluted soils by *Pteris vittata* L. Int J Phytoremediation 14:89–99
248. Aafi NE, Brhada F, Dary M, Maltouf AF, Pajuelo E (2012) Rhizostabilization of metals in soils using *Lupinus luteus* inoculated with the metal resistant rhizobacterium *Serratia sp.* MSMC 541. Int J Phytoremediation 14:261–274
249. 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

250. He LY, Zhang YF, Ma HY, Su LN, Chen ZJ, Wang QY et al (2010) Characterization of copper resistant bacteria and assessment of bacterial communities in rhizosphere soils of copper-tolerant plants. Appl Soil Ecol 44:49–55
251. Chatterjee S, Sau GB, Mukherjee SK (2009) Plant growth promotion by a hexavalent chromium reducing bacterial strain, *Cellulosimicrobium cellulans* KUCr3. World J Microbiol Biotechnol 25:1829–1836
252. 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 Manage 90:831–837
253. Beolchini F, Dell'Anno A, Propris LD, Ubaldini S, Cerrone F, Danovaro R (2009) Auto- and heterotrophic acidophilic bacteria enhance the bioremediation efficiency of sediments contaminated by heavy metals. Chemosphere 74:1321–1326
254. Hussein HS (2008) Optimization of plant-bacteria complex for phytoremediation of contaminated soils. Int J Bot 4:437–443
255. Rodriguez H, Vessely S, Shah S, Glick BR (2008) Isolation and characterization of nickel resistant Pseudomonas strains and their effect on the growth of non-transformed and transgenic canola plants. Curr Microbiol 57:170–174
256. Ganesan V (2008) Rhizoremediation of cadmium soil using a cadmium-resistant plant growth-promoting rhizopseudomonad. Curr Microbiol 56:403–407
257. Kuffner M, Puschenreiter M, Wieshammer G, Gorfer M, Sessitsch A (2008) Rhizosphere bacteria affect growth and metal uptake of heavy metal accumulating willows. Plant Soil 304:35–44
258. Saravanan VS, Madhaiyan M, Thangaraju M (2007) Solubilization of zinc compounds by the diazotrophic, plant growth promoting bacterium Gluconacetobacter diazotrophicus. Chemosphere 66:1794–1798
259. Trivedi P, Pandey A, Sa T (2007) Chromate reducing and plant growth promoting activities of psychrotrophic *Rhodococcus erythropolis* MtCC 7905. J Basic Microbiol 47:513–517
260. Wani PA, Khan MS, Zaidi A (2007) Effect of metal-tolerant plant growth-promoting Rhizobium on the performance of pea grown in metal-amended soil. Arch Environ Contam Toxicol 55:33–42
261. Someya N, Sato Y, Yamaguchi I, Hamamoto H, Ichiman Y, Akutsu K et al (2007) Alleviation of nickel toxicity in plants by a rhizobacterium strain is not dependent on its siderophore production. Commun Soil Sci Plant Anal 38:1155–1162
262. Juwarkar AA, Nair A, Dubey KV, Singh SK, Devotta S (2007) Biosurfactant technology for remediation of cadmium and lead contaminated soils. Chemosphere 10:1996–2002
263. Rajkumar M, Nagendran R, Lee KJ, Lee WH, Kim SZ (2006) Influence of plant growth promoting bacteria and Cr^{6+} on the growth of Indian mustard. Chemosphere 62:741–748
264. Shilev S, Fernandez A, Benlloch M, Sancho ED (2006) Sunflower growth and tolerance to arsenic is increased by the rhizospheric bacteria *Pseudomonas fluorescens*. In: Morel J-L, Echevarria G, Goncharova N (eds) Phytoremediation of metal-contaminated soils. Springer, Netherlands, pp 315–326
265. Farwell AJ, Vesely S, Nero V, Rodriguez H, Shah S, Dixon DG et al (2006) The use of transgenic canola (Brassica napus) and plant growth-promoting bacteria to enhance plant biomass at a nickel-contaminated field site. Plant Soil 288:309–318
266. Sheng XF, Xia JJ (2006) Improvement of rape (*Brassica napus*) plant growth and cadmium uptake by cadmium-resistant bacteria. Chemosphere 64:1036–1042
267. Wu CH, Wood TK, Mulchandani A, Chen W (2006) Engineering plant-microbe symbiosis for rhizoremediation of heavy metals. Appl Environ Microbiol 72:1129–1134
268. Vivas A, Biro B, Ruíz-Lozanoa JM, Azcon R (2006) Two bacterial strains isolated from a Zn-polluted soil enhance plant growth and mycorrhizal efficiency under Zn toxicity. Chemosphere 52:1523–1533
269. Ashour EH, El-Mergawi RA, Radwan SMA (2006) Efficiency of Pseudomonas to phytoremediate nickel by canola (*Brassica napus* L.). J Appl Sci Res 2:375–382

270. Reed MLE, Glick BR (2005) Growth of canola (*Brassica napus*) in the presence of plant growth-promoting bacteria and either copper or polycyclic aromatic hydrocarbons. Can J Microbiol 51:1061–1069
271. Belimov AA, Hontzeas N, Safronova VI, Demchinskaya SV, Piluzza G, Bullitta S et al (2005) Cadmium-tolerant plant growth-promoting rhizobacteria associated with the roots of Indian mustard (*Brassica juncea* L. Czern.). Soil Biol Biochem 37:241–250
272. Dell'Amico E, Cavalca L, Andreoni V (2005) Analysis of rhizobacterial communities in perennial Graminaceae from polluted water meadow soil, and screening of metal-resistant, potentially plant growth-promoting bacteria. FEMS Microbiol Ecol 52:153–162. https://doi.org/10.1016/j.femsec.2004.11.005
273. Di Gregorio S, Lampis S, Vallini G (2005) Selenite precipitation by a rhizospheric strain of *Stenotrophomonas* sp. isolated from the root system of *Astragalus bisulcatus*: a biotechnological perspective. Environ Int 31:233–241
274. Carrillo-Castañeda 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 26:1801–1814
275. Abou-Shanab RA, Angle JS, Delorme TA, Chaney RL, van Berkum P, Moawad H et al (2003) Rhizobacterial effects on nickel extraction from soil and uptake by *Alyssum murale*. New Phytol 158:219–222
276. Vivas A, Azcón R, Biró B, Barea JM, Ruiz-Lozano JM (2003) Influence of bacterial strains isolated from lead-polluted oil and their interactions with arbuscular mycorrhizae on the growth of *Trifolium pratense* L. under lead toxicity. Can J Microbiol 49:577–588
277. Nie L, Shah S, Burd GI, Dixon DG, Glick BR (2002) Phytoremediation of arsenate contaminated soil by transgenic canola and the plant growth-promoting bacterium *Enterobacter cloacae* CAL2. Plant Physiol Biochem 40:355–361
278. Lodewyckx C, Taghavi S, Mergeay M, Vangronsveld J, Clijsters H, van der Lelie D (2001) The effect of recombinant heavy metal resistant endophytic bacteria in heavy metal uptake by their host plant. Int J Phytoremediation 3:173–187
279. Whiting SN, de Souza MP, Terry N (2001) Rhizosphere bacteria mobilize Zn for hyperaccumulation by *Thlaspi caerulescens*. Environ Sci Technol 35:3144–3150
280. Burd GI, Dixon DG, Glick BR (2000) Plant growth promoting bacteria that decrease heavy metal toxicity in plants. Can J Microbiol 46:237–245
281. Burd GI, Dixon DG, Glick BR (1998) A plant growth promoting bacterium that decreases nickel toxicity in seedlings. Appl Environ Microbiol 64:3663–3668
282. Sharma P, Pandey S (2014) Status of phytoremediation in world scenario. Int J Environ Bioremediat Biodegrad 2:178–191
283. Barrutia O, Epelde L, García-Plazaola JI, Garbisu C, Becerril JM (2009) Phytoextraction potential of two *Rumex acetosa* L. accessions collected from metalliferous and non-metalliferous sites: effect of fertilization. Chemosphere 74:259–264
284. Burges A, Epelde L, Blanco F, Becerril J, Garbisu C (2017) Ecosystem services and plant physiological status during endophyte-assisted phytoremediation of metal contaminated soil. Sci Total Environ 584–585:329–338
285. Buscaroli A (2017) An overview of indexes to evaluate terrestrial plants for phytoremediation purposes (Review). Ecol Indicators 82:367–380
286. Barceló J, Poschenrieder C (2003) Phytoremediation: principles and perspectives. Contrib Sci 2:333–344 Institut d'Estudis Catalans, Barcelona
287. Fiorentino N, Fagnano M, Adamo P, Impagliazzo A, Mori M, Pepe O et al (2013) Assisted phytoextraction of heavy metals: compost and trichoderma effects on giant reed (*Arundo donax* L) uptake and soil N-cycle microflora. Ital J Agron 8:244–250
288. Gou ZH, Miao XF (2010) Growth changes and tissues anatomical characteristics of giant reed (*Arundo donax* L,) incontaminated soil with arsenic, cadmium and lead. J Cent South Univ Technol 17:770–777
289. Shiri M, Rabhi M, Abdelly C, El Amrani A (2015) The halophytic model plant *Thellungiella salsuginea* exhibited increased tolerance to phenanthrene-induced stress in comparison

with the glycophitic one *Arabidopsis thaliana*: application for phytoremediation. Ecol Eng 74:125–134

290. Ghosh M, Singh SP (2005) A review on phytoremediation of heavy metals and utilization of its byproducts. Appl Ecol Environ Res 3:1–18
291. Brooks RR, Chambers MF, Nicks LJ, Robinson BH (1999) Phytomining. Trends Plant Sci 1:359–362
292. Bridgwater AV, Meier M, Radlein D (1999) An over view of fast pyrolysis of biomass. Org Geochem 30:1479–1493
293. Lasat MM (2000) Phytoextraction of metals from contaminated soil: a review of plant/soil/metal interaction and assessment of pertinent agronomic issues. J Hazard Subst Res 2:1–25
294. Raskin I, Ensley BD (2000) Phytoremediation of toxic metals: using plants to clean up the environment. Wiley-Interscience, New York
295. Prasad MNV, Freitas H (2003) Metal hyperaccumulation in plants: biodiversity prospecting for phytoremediation technology. Electron J Biotechnol 6:275–321
296. Evangelou MW, Ebel M, Schaeffer A (2007) Chelate assisted phytoextraction of heavy metals from soil. Effect, mechanism, toxicity, and fate of chelating agents. Chemosphere 68:989–1003
297. Alkorta I, Hernández-Allica J, Becerril JM, Amezaga I, Albizu I, Onaindia M et al (2004) Chelate-enhanced phytoremediation of soils polluted with heavy metals. Rev Environ Sci Biotechnol 3:55–70
298. Leštan D, Luo C, Li X (2008) The use of chelating agents in the remediation of metal contaminated soils: a review. Environ Pollut 153:3–13
299. Kos B, Leštan D (2004) Soil washing of Pb, Zn and Cd using biodegradable chelator and permeable barriers and induced phytoextraction by *Cannabis sativa*. Plant Soil 263:43–51
300. Wu LH, Luo YM, Christie P, Wong MH (2003) Effects of EDTA and low molecular weight organic acids on soil solution properties of a heavy metal polluted soil. Chemosphere 50:819–822
301. Postrigan BN, Knyazev AV, Kuluev BRO, Yakhin I, Chemeris AV (2012) The activity of synthetic pseudophytochelating gene in tobacco plants. Fiziol Rastenii 59:303–308
302. Wood JL, Tang C, Franks AE (2016) Microbial associated plant growth and heavy metal accumulation to improve phytoextraction of contaminated soils. Soil Biol Biochem 103:131–137. https://doi.org/10.1016/j.soilbio.2016.08.021
303. Ali N, Masood S, Mukhtar T, Kamran MA, Rafique M, Munis MFH et al (2015) Differential effects of cadmium and chromium on growth, photosynthetic activity, and metal uptake of *Linum usitatissimum* in association with *Glomus intraradices*. Environ Monit Assess 187:1–11
304. Wu Q-S, Zou Y-N, He X-H (2010) Contributions of arbuscular mycorrhizal fungi to growth, photosynthesis, root morphology and ionic balance of citrus seedlings under salt stress. Acta Physiol Plant 32:297–304
305. Piotrowski JS, Rillig MC (2008) Succession of arbuscular mycorrhizal fungi: patterns, causes, and considerations for organic agriculture. Adv Agron 97:111–130
306. Renker C, Blanke V, Rstler B, Heinrichs J, Buscot FO (2004) Diversity of cryptococcus and dioszegia yeasts (*Basidiomycota*) inhabiting arbuscular mycorrhizal roots or spores. FEMS Yeast Res 4:597–603
307. Shahabivand S, Maivan HZ, Goltapeh EM, Sharifi M, Aliloo AA (2012) The effects of root endophyte and arbuscular mycorrhizal fungi on growth and cadmium accumulation in wheat under cadmium toxicity. Plant Physiol Biochem 60:53–58
308. Wang FY, Lin XG, Yin R (2007) Effect of arbuscular mycorrhizal fungal inoculation on heavy metal accumulation of maize grown in a naturally contaminated soil. Int J Phytoremediation 9:345–353
309. Li H, Ye ZH, Chan WF, Chen XW, Wu FX, Wu SC, Wong MH (2011) Can arbuscular mycorrhizal fungi improve grain yield, as uptake and tolerance of rice grown under aerobic conditions? Environ Pollut 159:2537–2545

310. Li T, Liu MJ, Zhang XT, Zhang HB, Sha T, Zhao ZW (2011) Improved tolerance of maize (*Zea mays* L.) to heavy metals by colonization of a dark septate endophyte (DSE) Exophiala pisciphila. Sci Total Environ 409:1069–1074
311. Bai Y, Liang J, Liu R, Hu C, Qu J (2014) Metagenomic analysis reveals microbial diversity and function in the rhizosphere soil of a constructed wetland. Environ Technol 35:2521–2527
312. Dell'Amico E, Cavalca L, Andreoni V (2008) Improvement of *Brassica napus* growth under cadmium stress by cadmium-resistant rhizobacteria. Soil Biol Biochem 40:74–84
313. Ma Y, Rajkumar M, Freitas H (2009) Improvement of plant growth and nickel uptake by nickel resistant-plant-growth promoting bacteria. J Hazard Mater 166:1154–1161
314. Sumi H, Kunito T, Ishikawa Y, Sato T, Park HD, Nagaoka K, Aikawa Y (2015) Plant roots influence microbial activities as well as cadmium and zinc fractions in metal-contaminated soil. Chem Ecol 31:105–110
315. Bedini S, Turrini A, Rigo C, Argese E, Giovannetti M (2010) Molecular characterization and glomalin production of arbuscular mycorrhizal fungi colonizing a heavy metal polluted ash disposal island, downtown Venice. Soil Biol Biochem 42:758–765
316. Khade HW, Adholeya A (2009) Arbuscular mycorrhizal association in plants growing on metal-contaminated and noncontaminated soils adjoining Kanpur tanneries, Uttar Pradesh, India. Water Air Soil Pollut 202:45–56
317. Fomina MA, Alexander IJ, Colpaert JV, Gadd GM (2005) Solubilization of toxic metal minerals and metal tolerance of mycorrhizal fungi. Soil Biol Biochem 37:851–866
318. Finlay R, Wallander H, Smits M, Holmstrom S, van Hees P, Lian B et al (2009) The role of fungi in biogenic weathering in boreal forest soils. Fungal Biol Rev 23:101–106
319. Van Schöll L, Kuyper TW, Smits MM, Landeweert R, Holffland E, van Breemen N (2008) Rock-eating mycorrhizas: their role in plant nutrition and biogeochemical cycles. Plant and Soil 303:35–47
320. Achakzai AK, Liasu MO, Popoola OJ (2012) Effect of mycorrhizal inoculation on the growth and phytoextraction of heavy metals by maize grown in oil contaminated soil. Pak J Bot 44:221–230
321. Punamiya P, Datta R, Sarkar D, Barber S, Patel M, Das P (2010) Symbiotic role of *Glomus mosseae* in phytoextraction of lead in vetiver grass [*Chrysopogon zizanioides* (L.)]. J Hazard Mater 177:465–474. https://doi.org/10.1016/j.jhazmat.2009.12.056
322. Körpe DA, Aras S (2011) Evaluation of copper-induced stress on eggplant (*Solanum melongena* L.) seedlings at the molecular and population levels by use of various biomarkers. Mutat Res 719:29–34
323. Márquez-García B, Horemans N, Cuypers A, Guisez Y, Córdoba F (2011) Antioxidants in Erica andevalensis: a comparative study between wild plants and cadmium-exposed plants under controlled conditions. Plant Physiol Biochem 49:110–115
324. Liu H, Yuan M, Tan S, Yang X, Lan Z, Jiang Q et al (2015) Enhancement of arbuscular mycorrhizal fungus (*Glomus versiforme*) on the growth and Cd uptake by Cd-hyperaccumulator *Solanum nigrum*. Appl Soil Ecol 89:44–49
325. Marques AP, Oliveira RS, Rangel AO, Castro PM (2006) Zinc accumulation in *Solanum nigrum* is enhanced by different arbuscular mycorrhizal fungi. Chemosphere 65:1256–1263
326. Marques AP, Oliveira RS, Rangel AO, Castro PM (2008) Application of manure and compost to contaminated soils and its effect on zinc accumulation by Solanum nigrum inoculated with arbuscular mycorrhizal fungi. Environ Pollut 151:608–620
327. Chen BD, Li XL, Tao HQ, Christie P, Wong MH (2003) The role of arbuscular mycorrhiza in zinc uptake by red clover growing in a calcareous soil spiked with various quantities of zinc. Chemosphere 50:839–846
328. Ker K, Charest C (2010) Nickel remediation by AM-colonized sunflower. Mycorrhiza 20:399–406
329. Sheoran V, Sheoran A, Poonia P (2016) Factors affecting phytoextraction: a review. Pedosphere 26:148–166

330. Kuffner M, De Maria S, Puschenreiter M, Fallmann K, Wieshammer G, Gorfer M et al (2010) Bacteria associated with Zn and Cd-accumulating *Salix caprea* with differential effects on plant growth and heavy metal availability. J Appl Microbiol 108:1471–1484
331. Sessitsch A, Puschenreiter M (2008) Endophytes and rhizosphere bacteria of plants growing in heavy metal contaminated soil. In: Dion P, Nautiyal CS (eds) Microbiology of extreme soils. Springer, Berlin
332. van der Lelie D, Corbisier P, Diels L, Gilis A, Lodewyckx C, Mergeay M et al (2000) The role of bacteria in the phytoremediation of heavy metals. In: Terry N, Bañuelos GS (eds) Phytoremediation of contaminated soil and water. Lewis Publishers (CRC Press), Boca Raton, FL, pp 265–281
333. Cabello-Conejo MI, Becerra-Castro C, Monterroso C, Prieto-Fernández A, Mench M, Kidd PS 2011 Effects of rhizobacterial inoculation on biomass and nickel concentration in Alyssum pintodasilvae. In: Proceedings of the 11th international conference on the biogeochemistry of trace elements (ICOBTE), 2011 July 4–7, Florence, Italy
334. Guo J, Tang S, Ju X, Ding Y, Liao S, Song N (2011) Effects of inoculation of a plant growth promoting rhizobacterium *Burkholderia sp*. D54 on plant growth and metal uptake by a hyperaccumulator *Sedum alfredii* Hance grown on multiple metal contaminated soil. World J Microbiol Biotechnol 27:2835–2844
335. Li WC, Ye ZH, Wong MH (2007) Effects of bacteria on enhanced metal uptake of the Cd/Zn hyperaccumulating plant, *Sedum alfredii*. J Exp Bot 58:4173–4182
336. Kim JO, Lee YW, Chung J (2013) The role of organic acids in the mobilization of heavy metals from soil. KSCE J Civil Eng 17:1596–1602
337. Li W, Ye Z, Wong M (2009) Metal mobilization and production of short-chain organic acids by rhizosphere bacteria associated with a Cd/Zn hyperaccumulating plant, *Sedum alfredii*. Plant Soil 326:453–467
338. Küpper H, Mijovilovich A, Meyer-Klaucke W, Kroneck PMH (2004) Tissue- and age-dependent differences in the complexation of cadmium and zinc in the cadmium/zinc hyperaccumulator *Thlaspi caerulescens* (Ganges ecotype) revealed by X-ray absorption spectroscopy. Plant Physiol 134:748–757
339. Glick BR (2004) Teamwork in phytoremediation. Nat Biotechnol 22:526–527
340. Braud A, Jézéquel K, Bazot S, Lebeau T (2009) Enhanced phytoextraction of an agricultural Cr-,Hg- and Pb-contaminated soil by bioaugmentation with siderophore producing bacteria. Chemosphere 74:280–286
341. Hider RC, Kong X (2010) Chemistry and biology of siderophores. Nat Prod Rep 27:637–657
342. Braud A, Jézéquel K, Vieille E, Tritter A, Lebeau T (2006) Changes in extractability of Cr and Pb in a polycontaminated soil after bioaugmentation with microbial producers of biosurfactants, organic acids and siderophores. Water Air Soil Pollut 6:3–4
343. Venkatesh NM, Vedaraman N (2012) Remediation of soil contaminated with copper using rhamnolipids produced from *Pseudomonas aeruginosa* MTCC 2297 using waste frying rice bran oil. Ann Microbiol 62:85–91
344. Haferburg G, Kothe E (2010) Metallomics: lessons for metalliferous soil remediation. Appl Microbiol Biotechnol 87:1271–1280
345. Taghavi S, Garafola C, Monchy S, Newman L, Hoffman A, Weyens N et al (2009) Genome survey and characterization of endophytic bacteria exhibiting a beneficial effect on growth and development of poplar. Appl Environ Microbiol 75:748–757
346. Garcia de Salamone IE, Hynes RK, Nelson LM (2005) Role of cytokinins in plant growth promotion by rhizosphere bacteria. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, The Netherlands, pp 173–195
347. Patten CL, Glick BR (2002) Role of Pseudomonas putida indole acetic acid in development of host plant root system. Appl Environ Microbiol 48:3795–3801
348. Ortiz Castro R, Valencia Cantero E, Lopez Bucio J (2008) Plant growth promotion by *Bacillus megaterium* involves cytokinin signaling. Plant Signal Behav 3:263–265

349. Cabello-Conejo MI, Prieto-Fernandez T, Kidd PS (2014) Exogenous treatments with phytohormones can improve growth and nickel yield of hyperaccumulating plants. Sci Total Environ 494–495:1–8
350. Hadi F, Bano A, Fuller MP (2010) The improved phytoextraction of lead (Pb) and the growth of maize (*Zea mays* L.): the role of plant growth regulators (GA3 and IAA) and EDTA alone and in combinations. Chemosphere 80:457–462
351. Shilev SI, Ruso J, Puig A, Benlloch M, Jorrin J, Sancho E (2001) Rhizospheric bacteria promote sunflower (*Helianthus annus* L.) plant growth and tolerance to heavy metals. Minerva Biotechnol 13:37–39
352. Ghosh P, Rathinasabapathi B, Ma LQ (2011) Arsenic-resistant bacteria solubilized arsenic in the growth media and increased growth of arsenic hyperaccumulator *Pteris vittata* L. Bioresour Technol 102:8756–8761
353. Sun LN, Zhang YF, He LY, Chen ZJ, Wang QY, Qian M et al (2010) Genetic diversity and characterization of heavy metal-resistant-endophytic bacteria from two copper tolerant plant species on copper mine wasteland. Bioresour Technol 101:501–509
354. He CQ, Tan GE, Liang X, Du W, Chen YL, Zhi GY et al (2010) Effect of Zn-tolerant bacterial strains on growth and Zn accumulation in *Orychophragmus violaceus*. Appl Soil Ecol 44:1–5
355. 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 326:453–467
356. He LY, Chen Z-J, Ren G-D, Zhang Y-F, Qian M, Sheng X-F (2009) Increased cadmium and lead uptake of a cadmium hyperaccumulator tomato by cadmium-resistant bacteria. Exotoxicol Environ Saf 72:1343–1348
357. Kumar KV, Singh N, Behl HM, Srivastava S (2008) Influence of plant growth promoting bacteria and its mutant on heavy metal toxicity in *Brassica juncea* grown in fly ash amended soil. Chemosphere 72:678–683
358. Abou-Shanab RA, Ghanem K, Ghanem N, Al-Kolaibe A (2008) The role of bacteria on heavy-metal extraction and uptake by plants growing on multi-metal-contaminated soils. World J Microbiol Biotechnol 24:253–262
359. 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 72:157–164
360. Safronova VI, Stepanok VV, Engqvist GL, Alekseyev YV, Belimov AA (2006) Root-associated bacteria containing 1-aminocyclopropane-1-carboxylate deaminase improve growth and nutrient uptake by pea genotypes cultivated in cadmium supplemented soil. Biol Fertil Soils 42:267–272
361. Duponnois R, Kisa M, Assigbetse K, Prin Y, Thioulouse J, Issartel M et al (2006) Fluorescent pseudomonads occurring in Macrotermes subhyalinusmound structures decrease Cd toxicity and improve its accumulation in sorghum plants. Sci Total Environ 370:391–400
362. Wu SC, Cheung KC, Luo YM, Wong MH (2006) Effects of inoculation of plant growth promoting rhizobacteria on metal uptake by *Brassica juncea*. Environ Pollut 140:124–135. https://doi.org/10.1016/j.envpol.2005.06.023
363. Di Gregorio S, Barbafieri M, Lampis S, Sanangelantoni AM, Tassi E, Vallini G (2006) Combined application of Triton X-100 and *Sinorhizobium sp* Pb002 inoculum for the improvement of lead phytoextraction by *Brassica juncea* in EDTA amended soil. Chemosphere 63:293–299
364. Zaidi S, Usmani S, Singh BR, Musarrat J (2006) Significance of *Bacillus subtilis* strain SJ-101 as a bioinoculant for concurrent plant growth promotion and nickel accumulation in *Brassica juncea*. Chemosphere 64:991–997
365. De Maria S, Rivelli AR, Kuffner M, Sessitsch A, Wenzel WW, Gorfer M et al (2011) Interactions between accumulation of trace elements and major nutrients in *Salix caprea* after inoculation with rhizosphere microorganisms. Chemosphere 84:1256–1261