Chapter 4
Plant Assisted Bioremediation of Heavy Metal Polluted Soils

Sumita Chandel, Rouf Ahmad Dar, Dhanwinder Singh, Sapna Thakur, Ravneet Kaur, and Kuldip Singh

Abstract Industrial and anthropogenic activities are the major reason for heavy metal pollution. To date, thousands of hectares of farmland globally and in India specifically have been contaminated by heavy metals. This has adversely affected the crop productivity, soil microbial diversity and eventually deteriorated the soil quality. Soil quality is closely associated with crop quality, human health and welfare. Therefore, the remediation of these metal-polluted soils becomes imperative. Conventional remediation methods like precipitation, oxidation/reduction, filtration, evaporation and adsorption etc. are energy demanding or require a large number of chemical reagents and are associated with possible production of secondary pollutants. Fortunately, some microorganisms with the capability to induce resistance to heavy metals, and reduce or adsorb them in non-toxic form can be used for possible bioremediation

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S. Chandel (✉) · D. Singh · K. Singh
Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, India
e-mail: Sumita-coasoil@pau.edu

D. Singh
e-mail: dhanwinder@pau.edu

K. Singh
e-mail: kuldip@pau.edu

R. A. Dar
Department of Microbiology, Punjab Agricultural University, Ludhiana, Punjab, India
e-mail: roufdar-mb@pau.edu

S. Thakur
Department of Forestry and Natural Resources, Punjab Agricultural University, Ludhiana, Punjab, India
e-mail: sapnathakur@pau.edu

R. Kaur
Department of Botany, Punjab Agricultural University, Ludhiana, Punjab, India
e-mail: ravneet-bot@pau.edu

R. A. Dar
Department of Industrial Microbiology, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, India

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of polluted soils, thus representing an economical and environment-friendly remediation method. These microbes detoxify the heavy metals, clean up the environment and increase the soil fertility, but, the adsorbed or converted metal still remains in the soil is the problem associated with it. Phytoremediation can be another option for detoxification of heavy metal polluted soils. However, phytoremediation alone has its limitations. Hence, the most effective way of remediation of heavy metal polluted soils is an integrated approach that involves both plants and microbes. Understanding the whole mechanism of plant assisted bioremediation along with bioavailability, uptake, translocation, sequestration and different defence mechanisms will help to develop heavy metal stress-resistant cultivars and highly efficient plant species for phytoremediation in harmony with microflora through genetic engineering technologies. Hence, this chapter will provide an understanding of plant assisted bioremediation, the fate of heavy metals in plant and soil, different plant defence mechanisms and potential microflora for plant assisted bioremediation.

Keywords Bioremediation · Heavy metal pollution · Microflora · Phytoextraction · Soil fertility

4.1 Introduction: Background of Heavy Metal Pollution

Heavy metals being toxic and bioaccumulative in nature, are environmental pollutants with prolonged persistence in the environment, thus leading to detrimental effects on floral wealth and human health (Rzymski et al. 2014). They are metals possessing a specific density of more than 5 g cm^{-3} and have adverse impacts on the life and environment (Järup 2003). Some metals known as micronutrients, (copper, iron, manganese, molybdenum, nickel and zinc) play a vital role in the normal functioning of plant cells such as biosynthesis of nucleic acids, chlorophyll, carbohydrates, secondary metabolites, stress resistance and maintenance of biological membranes as well as overall growth of the plants (Rengel 2004). However, when their internal concentration transcends a certain threshold limit, they negatively influence plant growth and become toxic, forming a bell-shaped dose–response relationship (Marschner 1995). Moreover, the concentration of heavy metals is generally location-specific, subjected to the source of individual pollutants.

As per the World Health Organization (WHO), the common toxic ‘heavy metals’ of public health concern are arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb), selenium (Se), manganese (Mn), copper (Cu) and molybdenum (Mo). The standards for heavy metals in soil, plant and water as per Bureau of Indian standards (BIS) and WHO have been presented in Table 4.1.

Table 4.1 Normal and critical range of heavy metals in soil, plant and water

Heavy metal (s)	Normal range in soil (mg kg^{-1})	Critical soil total concs (mg kg^{-1})	Normal range in plant (mg kg^{-1})	Critical concentration in plants	Permissible limit in water (mg L^{-1})
Arsenic	0.1–40	20–50	0.02–7	5–20	0.01
Cadmium	0.01–2.0	3–8	0.1–2.4	5–3	0.003
Cobalt	0.5–65	25–50	0.02–1	15–50	0.05
Chromium	5–1500	75–100	0.03–14	5–30	0.05
Mercury	0.01–0.5	0.3–15	0.005–0.17	1–3	0.001
Nickel	2–750	100	0.02–5	10–100	0.02
Lead	2–300	100–400	0.2–20	30–300	0.01
Selenium	0.1–5	5–10	0.0001–0.2	5–30	0.01
Manganese	20–10,000	1500–3000	20–1000	300–500	0.3
Copper	2–250	60–125	5–20	20–100	1.5
Molybdenum	0.1–40	2–10	0.03–5	10–50	0.07

Data from Bowen (1979), Kabata-Pendias and Pendias (1984), BIS (2012)

4.1.1 World Status

Rapid industrialization and exponential increase in the human population has increased the discharge of massive loads of heavy metal pollutants in the environment (Zhang et al. 2020). Globally, around 500 M ha of our land resources are facing the problem of soil contamination ended up with higher concentrations of heavy metals compared to the regulatory levels (Liu et al. 2018). Industries and other human activities discharge approximately 2 million tons/day of sewage and effluents into the water bodies making them unfit for various agricultural and other activities. Fly ash dumping sites of coal-based thermal power stations are also a major source of heavy metal pollution around the world (Pandey and Singh 2010; Pandey 2020). In developing nations, the situation is more critical where about 90% of sewage and 70% of industrial wastes (generally untreated/partially treated) are being discharged into surface water resources (Anonymous 2010). Over the past few years, the annual global release of heavy metals has surpassed 0.2 lacs MT for Cadmium, 9.3 lacs MT for Copper, 7.83 lacs MT for lead and 1.35 lacs MT for Zinc (Thambavani and Prathipa 2012). Further, heavy metal poisoning has become a universal public health concern. Heavy metal pollution in soils also has tremendously impacted the global economy, which has annually been estimated to be beyond US$10 billion.

4.1.2 *Indian Status*

The data available on the nature and extent of metal pollution and its impact assessment on the plant, soil and human health is not very conclusive in India. However, as per Indian central pollution control board (CPCB 2009), approximately 38,254 megaliters per day (MLD) of sewage and 25,000 MLD of untreated industrial wastewater generated from urban areas are released into the surface water bodies, wreaking degradation of the quality of water resources. Bhardwaj (2005) has estimated that by 2050, wastewater generation in India is going to be around 1,22,000 MLD. The utilization of such wastewater loaded surface water sources for irrigation purposes in agricultural fields has magnified the heavy metals concentrations in soils of agricultural fields particularly those situated in the vicinity of urban areas (Saha and Panwar 2013). However, the heavy metal accumulation in the soils will vary depending upon the source, concentration and duration of application (Rattan 2005). Usage of sewage water as irrigation for 20 years successively may result in significant accumulation of zinc (2.1 times), copper (1.7 times), iron (1.7 times), nickel (63.1%) and lead (29%) in the soils as compared to soils irrigated with tube well water (Simmons 2006). Such unrestricted transfer of heavy metals in arable land through wastewater irrigation will trigger more metal uptake by crops and will enter the food chain (Rattan 2002).

4.2 Sources of Heavy Metal Pollution

Geogenic and anthropogenic activities are mainly responsible for heavy metal pollution in the environment. Geogenic processes such as biogenic, terrestrial, volcanic processes, erosion, leaching and meteoric are the main sources of heavy metals in the environment (Muradoglu et al. 2015). While, industrialization, urbanization and modernization of the agricultural sector are substantially contributed to the release of heavy metal pollutants into the surrounding which gets deposited on the soil through natural processes of sedimentation and precipitation. In addition, anthropogenic processes such as irrigation with sewage and industrial wastewater, mining activities, fly ash disposal, excessive application of pesticides and fertilizers, have disturbed the natural balance of geochemical cycles, which in turn has resulted in the entry of heavy metals into the soil (Zhang et al. 2011; Dixit et al. 2015). The major contributors of heavy metals in the environment are listed in Table 4.2.

4.3 Plant Assisted Bioremediation: Techniques/Strategies

Plant assisted bioremediation involves the symbiotic relationship between rhizospheric microorganisms and the plant roots (Kumar et al. 2017). The symbiotic relationship intensifies bioavailability of the heavy metals and stimulates absorption capacity of the roots. Remediation of metal-polluted soil by soil microbes especially the rhizospheric population is known as rhizoremediation (Kuiper et al. 2004). Rhizoremediation involving plant growth-promoting rhizobia, mycorrhiza and other microorganisms is very efficient in promoting plant biomass and thus its efficiency to stabilize and remediate metal-polluted soil (Jing et al. 2007). Plant roots release exudates, may be enzymatic or non-enzymatic that modify the soil environment and habitat to numerous microorganisms. Rhizosphere plays a great role in the remediation of metal polluted soil. Heavy metals can only be transformed via several processes such as sorption, methylation, complexation or change in valence oxidation state, affecting their mobility and bioavailability. Microbes have an important role in the processes like carbon sequestration, plant growth, productivity and phytoremediation. Microorganisms (bacteria, fungi and microalgae) along with plants are the potential agents of bioremediation. They enhance the plant growth through different enzymatic activities, nitrogen fixation and reducing the ethylene production (Pandey and Singh 2019). Bacteria respond to the heavy metals and the molecules generated through oxidative stress in different ways. These are entrapped in the capsules, transported through heavy metals by the cell membrane, absorbed on the cell walls, precipitated or oxidized/reduced (Singh et al. 2010). The microbial response to heavy metals is important in harnessing them as potential candidates for remediation of metal polluted soils (Hemambika et al. 2011). Plant growth-promoting bacteria (PGPB) also known as growth-promoting agents are now assessed for their metal detoxifying potential in remediating metal-polluted soils (Ahemad 2014). Fungi are important as

Table 4.2 Major sources of heavy metals

Heavy metal (s)	Contributors of heavy metals in the environment
Arsenic	Volcanic eruptions, semiconductors, smelting coal mines, power plants, petroleum refining, metal adhesives, ammunition, wood preservatives, pesticides and herbicides, animal feed additives
Copper	Biosolids electroplating, mining activities, petroleum refining and smelting operations
Cadmium	Geogenic sources, metal smelting and refining process, combustion of fossil fuels, fertilizers, sewage sludge
Chromium	Sewage sludge, solid wastes, electroplating, tanning industries
Lead	Mining and smelting of metalliferous ores, leaded gasoline combustion, sewage and industrial waste, paints
Mercury	Volcanic eruptions, wild forest fires, emissions from industries producing caustic soda, combustion of coal, peat and wood
Selenium	Coal mining, oil refineries, fossil fuels, glass manufacturing industry, varnish and pigment formulation
Nickel	Volcanic eruptions, forest fire, landfilling operations, oceanic gaseous exchange, weathering of soils and geological processes
Zinc	Smelting and refining industries, mining operations, electroplating industry, bio solids

Source Lone et al. (2008)

these augment the phytoremediation by changing the bioavailability of metal through different ways like modifying the pH of the soil, production of different chelators, and controlling the redox reaction etc. (Ma et al. 2011a, b). Also, a high surface-to-volume ratio make bacteria a potential biosorbing agents. While, the plants absorb these metals and translocate them to various plant tissues and organs. Plants remediate the heavy metal polluted soil by adopting different techniques/strategies such as phytoextraction, phytostabilization, phytovolatilization, phytostimulation (Pandey and Bajpai 2019; Pathak et al. 2020). These are described as:

Phytoextraction: Phytoextraction is the process of the uptaking and storing of heavy metals from the soil by the plants (McGrath 1998). There are two fundamental ways of phytoextraction:

- **Natural**: The natural way of removal of heavy metals by the plants, also known as unassisted phytoremediation.
- **Assisted**: Microbes, plant hormones and chelating agents assist the plant in the remediation of heavy metal polluted soils (Malik et al. 2022).

Natural phytoremediation can be accomplished by either (1) hyperaccumulator plants or (2) genetic engineering of the plant with certain characteristics of hyperaccumulators for the accomplishment of phytoextraction (Chaney et al. 2005). The hyperaccumulator plants are the plants whose tissues can contain certain heavy metals from 1000 to 10,000 mg kg^{-1} (Black 1995). They can collect and concentrate the heavy metals in the harvestable tissues, biomass without affecting the plant growth. The heavy metal concentration in the hyperaccumulator plants is approximately 100 times higher compared to the ordinary plants. It is approximately 1000 mg kg^{-1} for arsenic and nickel, 100 mg kg^{-1} for cadmium and 10,000 mg kg^{-1} for zinc and manganese. The most prominent examples of hyperaccumulator plants are *Arabidopsis*, *Alyssum, Noccaea and the members of* Brassicaceae family.

Phytostabilization: Phytostabilization involves complexation, precipitation, sorption or metal reduction (Ghosh and Singh 2005). Plants restrict the movement of the metals in the roots by the assimilation, aggregation, adsorption and precipitation. They also help to avoid movement of the metals through water, wind, drainage and dispersion of soil (USEPA 1999). The phytostabilization stabilizes the metal contaminant rather than translocating it to the edible parts, that in turn can reach human beings (Prasad and Freitas 2003). In this, there is the aggregation of metal by roots or root exudates that immobilize and lower the accessibility of the soil pollutants. Chromium and lead are toxic metals that are remediated by phytostabilization. The proficiency of the phytostabilization is increased by the addition of nutrients to soil viz. lime and phosphate. *Brassica juncea* has been reported to be an efficient Phytostabilizer as it accumulates chromium in the roots (Bluskov and Arocena 2005).

Phytovolatilization: The release of metal pollutants to the atmosphere by the plants in altered or unaltered form after metabolic and transpirational pull is called phytovolatilization (USEPA 1999). Selenium, arsenic and mercury are the main metal pollutants that can be remediated through phytovolatilization (Dietz and Schnoor 2001).

4.4 Significance of Plant Assisted Bioremediation of Heavy Metal in Agriculture

Agriculture is the main backbone of the Indian economy and socio-political stability. With approximately 7% of the growth, Indian economy is the 7th largest in the world. The contribution of agriculture and its allied sectors was 51.81% during 1950–51, which declined to 18.20% by 2013–2014 and now it is approximately 14.39% (2018–19). These figures are still higher than most of the countries. Soil quality is one of the main contributing factors for sustainable agriculture. Sustainability is defined as the living within the regenerative capacity of the biosphere (Wackernagel et al. 2002). Inappropriate agricultural management practices, excessive use of a large number of chemicals, insecticides, pesticides, sludge and manure are attributing declination of soil quality. Developmental activities such as industrialization, urbanization and transportation are competing with natural resources, and impacting soil quality and biodiversity (Godfray et al. 2010). Despite several adverse effects of industries on the environment, they are considered important because of the unlimited human desires. The dependency of agriculture and industries on each other and their impact on the environment and human life is depicted in Fig. 4.1. Different anthropogenic activities have become the main reason for the deterioration of natural resources (soil + water). In the long run, polluted soil and water will not be suitable to grow the food which will directly or indirectly impact the socio-economic condition of the country (Saha et al. 2017). In the agroecosystem, agriculture and industries are the main reason for

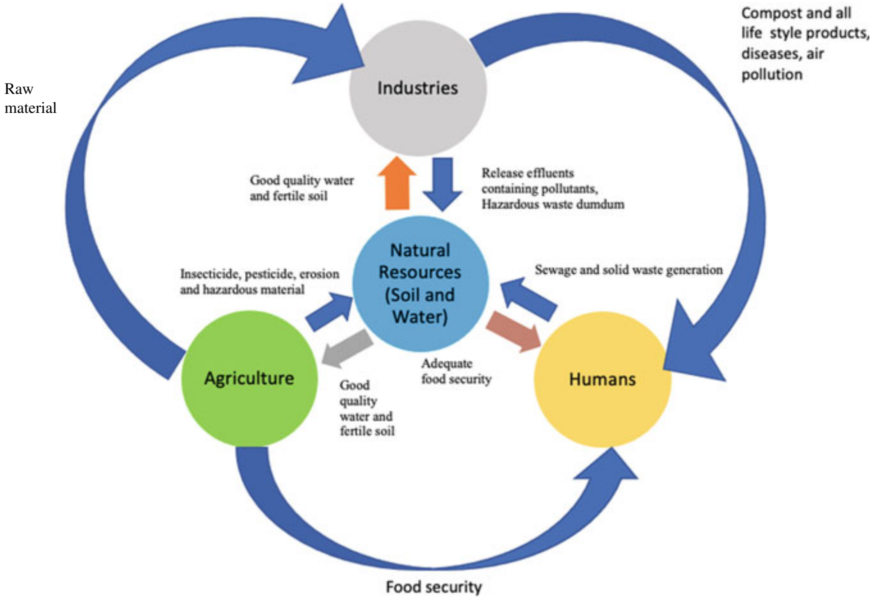

Fig. 4.1 Relationship of agriculture and industrial activities affecting natural resources and humans

soil pollution by heavy metals such as cadmium, chromium, lead, arsenic, nickel and mercury. Introduction of the above metals in the soil environment and their impact on soil is quite alarming, as:

- Entry of these metals in the agroecosystem results in degradation of soil structure and affects moisture retention in the soil profile.
- Heavy metals interact with soil components, microorganisms (nitrogen transformation, mineralization/immobilization etc.), root cells and affect the transformation of soil nutrients and their uptake.
- Build-up of salinity problem in the polluted soil along with the effect on water and nutrient uptake.
- Heavy metals lead to alkalinity development, result in more ammonia volatilization losses.
- The agronomic efficiency and partial factor productivity of polluted soil are normally lower than the unpolluted soil.
- The shelf life of the crops irrigated with industrial wastewater is lower than irrigated with fresh water.
- Heavy metal pollution results in huge ecological disturbances

4.5 Role of Microflora and Flora in Plant Assisted Bioremediation

Plant assisted bioremediation is an eco-friendly approach, encompassing the complex phenomenon of interaction between the microbes and plant genotype with its biotic and abiotic environment. The most important components of plant assisted bioremediation consist the in situ selection of genotypes and symbiotic microorganisms in the rhizosphere (having the capability of degrading the organic contaminants completely). Further, the identification of candidate genes and alleles linked with biochemical and physiological processes also has a key role in the development of a potential plant assisted bioremediation strategy. High levels of metal extraction and translocation to shoots and organic degradation are keys to develop an efficient phytoremediation measure. A most promising approach to substitute the costly remediation technologies is the use of plants assisted by microbes to clean up heavy metal polluted soils and water (Malik et al. 2022). Therefore, the selection of appropriate microbes and plant species is a prerequisite for effective remediation of heavy metal pollution.

4.5.1 Potential Microbes Involved in Bioremediation

Microorganisms help in the uptake of heavy metals through both active (bioaccumulation) and passive (adsorption) modes. Microbes (bacteria, fungi and algae) have been utilized to remediate the contaminated sites. The high surface to volume ratio, ubiquitous nature, the capability of growing in extreme conditions and active chemisorption sites make bacteria a potential candidate for bioremediation (Srivastava et al. 2015; Mosa et al. 2016). Higher absorption, uptake and recovery capacity of fungi make them suitable biosorbents for the remediation of toxic metals (Fu et al. 2012). Also, algae compared to other biosorbents produce high biomass. The high sorption capacity of algae and the presence of various metal binding chemical groups like hydroxyl, carboxyl, phosphate and amide make them a suitable contender for remediation of heavy metals (Abbas et al. 2014). The microorganisms involved in bioremediation of heavy metals are summarized in Table 4.3.

Numerous researchers have reported bacterial accumulation and sorption along with other plant growth promoting features responsible for the enhanced plant growth in polluted soils (Ma et al. 2011a, b; Kumar et al. 2009). Higher accumulation of heavy metals in plants without having any phytotoxicity is due to decreased internal availability of metals or metalloids and higher rhizospheric plant bioavailability (Deng et al. 2013a, b; Weyens et al. 2010). Nickle uptake by *Alyssum murale* was significantly enhanced by *Sphingomonas macrogoltabidus*, *Microbacterium liquefaciens* and *Microbacterium arabinogalactanolyticum* inoculation compared to the un-inoculated control (Abou-Shanab et al. 2003). Correspondingly, the inoculation of *Phaseolus vulgaris* with *Pseudomonas putida* KNP9 protected it from metal toxicity (lead and cadmium) and improved its growth with respect to controls (Tripathi et al. 2005). Therefore, the application of metal remediating plant growth-promoting bacteria (PGPB) along with plant growth promoting activities makes the remediation process more effective and efficient (Glick 2012). The utilization of the mining sites with the higher concentration of heavy metals is a global challenge to environmental sustainability (Ahirwal and Pandey 2021). In this direction, researchers demonstrated that the *Pseudomonas aeruginosa*-HMR1 removes heavy metals and exhibits plant growth-promoting attributes. Thus, the *P. aeruginosa*-HMR1 can be used for the restoration of mining lands for forestry, ornamental plants and agricultural purposes (Bhojiya et al. 2021).

Fungi have been found to have more tolerance to metals than bacteria (Deng and Cao 2017; Deng et al. 2013a). Fungi easily reach the microsites that are not accessible to the plant roots and thus can compete with other microbes for food and metal uptake. These protect the plant roots from directly interacting with metals and increase the soil hydrophobicity, thus hindering metal transport. Moreover, the extended mycelia formation by fungi also makes them suitable for bioremediation. In metal-polluted soils, various fungi like *Aspergillus, Trichoderma* and the arbuscular mycorrhizae (AM) have demonstrated the capacity to improve the phytoremediation process (Deng et al. 2011, 2013a). These fungi have high capability of immobilization of toxic/heavy metals by forming either the insoluble compounds, chelation or through biosorption. The fungal species and ecotype greatly affect phytoremediation efficiency. Some examples of bioremediation of heavy metals are given in Table 4.4.

Table 4.3 Potential microbes for remediation of heavy metal pollution

Microorganisms	Metal	Metal concentration (Initial) (mg L^{-1})	Efficiency (%) or Sorption capacity (mg g^{-1})	References
Bacteria				
Bacillus laterosporus	Cd	1000	159.5	Zouboulis et al. (2004)
Bacillus licheniformis	Cd	1000	142.7	Zouboulis et al. (2004)
Desulfovibrio desulfuricans	Cu	100	98.2	Kim et al. (2015)
Acinetobacter sp.	Cr	16	87%	Bhattacharya et al. (2019)
Bacillus subtilis	Cr	0.57	99.60%	Kim et al. (2015)
Methylobacterium organophilum	Pb		18%	Kim et al. (1996)
Cellulosimicrobium sp. (KX710177)	Pb	50	99.33%	Bharagava and Mishra (2018)
Staphylococcus sp.	Cu	100	98.20%	Kim et al. (2015)
Flavobacterium sp.	Cu	1.194	20.30%	Kumaran et al. (2011)
Micrococcus sp.		100	65.00%	Jafari et al. (2015)
Enterobacter cloacae	Pb	7.2	2.3	Kang et al. (2005)
Pseudomonas aeruginosa	Co	58.93	8.92	Kang et al. (2005)
	Ni	58.69	8.26	
Pseudomonas sp.	Cu	300	5.52	Rajkumar et al. (2008)
	Zn	275	3.66	
Fungi				
Aspergillus niger	Pb Cr(VI)	100 50	34.4 6.6	Dursun et al. (2003)
Phanerochae techrysosporium	Pb	100	88.16	Iqbal and Edyvean (2004)
	Zn	100	39.62	
Rhizopus oryzae	Cu	100	34	Fu et al. (2012)
Sphaerotilus natans	Cr	200	60%	Kumar et al. (2017)
Saccharomyces cerevisiae (Y)	Cr	570.25	95%	Benazir et al. (2010)
Aspergillus versicolor	Cu	50	29.06%	Tas et al. (2010)
Algae				

(continued)

Table 4.3 (continued)

Microorganisms	Metal	Metal concentration (Initial) (mg L^{-1})	Efficiency (%) or Sorption capacity (mg g^{-1})	References
Codium vermilara	Ni	147	13.2	Romera et al. (2007)
Lessonia nigrescens	Ar(V)	200	45.2	Hansen et al. (2006)
Sargassum muticum	Sb	10	5.5	Ungureanuet al. (2015)
Spirogyra sp.	Pb	200	140	Gupta and Rastogi (2008)
Chlorella vulgaris	Cu	50 mg dm^{-3}	97.70%	Goher et al. (2016)
Spirulina sp.	Cu	5	81.20%	Mane and Bhosle (2012)
Nostoc sp.	Pb	1	99.60%	Kumaran et al. (2011)
	Cd	1	95.40%	Kumaran et al. (2011)
	Ni	1	88.23%	Kumaran et al. (2011)

4.5.2 Potential Plants Involved in Bioremediation

The potential phytoextractive plant species has the ability to accumulate the high content of the metals into the aboveground biomass without showing any toxicity symptoms. Their potential of phytoextraction can be enhanced by the use of fast-growing hyperaccumulator tree species with extensive root systems, thus ensuring its economic and environmental feasibility. Remarkable genetic variability has been reported to exist among plants of Salicaceae species adapted to soil of varying level metal contaminants (Dickinson and Pulford 2005; Puschenreiter et al. 2010; Marmiroli et al. 2011; Yang et al. 2015). In addition to this, adoption of native fast growing tree species may provide us with a better possible solution. Some of the plants suitable for plant assisted bioremediation are given in Table 4.5.

4.6 Mechanism of Plant Assisted Bioremediation

The mechanism for the plant assisted bioremediation involves bioavailability, uptake, translocation, sequestration and different defence mechanism that can help to develop heavy metal stress-resistant cultivars and highly efficient plant species

Table 4.4 Plant assisted microflora involved in bioremediation of heavy metals

Microorganisms	Plant	Heavy metals	Role/effect	Reference
Rhizobium sp. strains E20-8 and NII-1	*Pisum sativum* L	Cd	Remediates Cd pollution through various mechanisms like cytoplasmic sequestration, periplasmic allocation, extracellular immobilization and biotransformation	Cardoso et al. (2018)
*Microbacterium*sp. NE1R5,*Curtobacterium*sp. NM1R1	*Brassica nigra*	As, Zn, Cu, Pb	Enhancement of seed germination and root development	Román-Ponce et al. (2017)
Thiobacillus thiooxidans	*Gladiolus grandiflorus* L	Cd, Pb	Uptake and accumulation of Cd and Pb increases along with enhanced root length, plant height and dry biomass	Mani et al. (2016)
Pseudomonas brassicacearum, Rhizobium leguminosarum	*Brassica juncea*	Zn	Attenuates metal toxicity and promotes metal chelation	Adediran et al. (2015)
Pseudomonas sp.	Soybean, mungbean, wheat	Ni, Cd, Cr	Promotion of growth	Gupta et al. (2002)
*Sinorhizobium*sp. Pb002	*Brassica juncea*	Pb	Lead phytoextraction efficiency is enhanced by *B. juncea* plants	Di Gregorio et al. (2006)
Pseudomonas sp. A3R3	*Alyssum serpyllifolium, Brassica juncea*	Ni	More biomass (*B. juncea*) and Ni content (*A. serpyllifolium*) in plants grown in Ni-stressed conditions	Ma et al. (2011a, b)
*Bradyrhizobium*sp. 750, *Pseudomonas cytis*sp.,*Ochrobactrum*	*Lupinus luteus*	Cu, Cd, Pb	Enhanced the accumulation of metals	Dary et al. (2010)
Pseudomonas aeruginosa, Pseudomonas fluorescens, Ralstoniametallidurans	Maize	Cr, Pb	Accelerated soil metal mobilization and increased uptake of Cr and Pb	Braud et al. (2009)
*Bacillus weihenstephanensis*strain SM3	*Helianthus annuus*	Ni, Cu, Zn	Accelerated Cu and Zn accumulation in plants, also increased the water soluble Ni, Cu and Zn concentrations in soil with their metal mobilizing potential	Rajkumar et al. (2008)
*Achromobacterxylosoxidans*strain Ax10	*Brassica juncea*	Cu	Enhanced Cu uptake by plants	Ma et al. (2009)

(continued)

Table 4.4 (continued)

Microorganisms	Plant	Heavy metals	Role/effect	Reference
*Glomerales*species *Rhizophagus* *Funneliformis* *Claroideoglomus*	*Lactuca sativa* *Daucus carota*	Sb	Increased its uptake and accumulation in plants particularly in roots	Pierart et al. (2018)
Funneliformismosseae, *Rhizophagusirregularis,* *Claroideoglomuslamellosum*	*Ricinus communis*	Cr(III), Cr(VI)	Reduction of Cr(VI) concentration in soils	Gil-Cardeza et al. (2018)
AM fungi	*Solanum melongena*	Pb, As, Cd	AM increased metal (loids) uptake and biomass	Chaturvedi et al. (2018)
Glomus mosseae	*Cajanus cajan*	Cd, Pb	Lead distribution pattern seems to be changed by fungal symbiont in extra radical hyphae of fungi, roots and shoots. Inoculation of fungal cultures in pigeon pea demonstrated the bioremediation potential by assisting it to grow in heavily metal-contaminated soils	Garg and Aggarwal (2011)
Scleroderma citrinum	*Pinus sylvestris* L	Zn, Cd, Pb	Reduction in translocation of Zn, Cd, or Pb from roots to shoots in pine seedlings	Krupa and Kozdrój (2007)
Bacillus thuringiensis GDB-1	*Alnus firma*	Cd, Ni, As, Cu, Pb, Zn	Promoted accumulation of metal(loid)s (As, Cu, Pb, Ni and Zn)	Babu et al. (2013)

for phytoremediation in harmony with microflora through genetic engineering technologies.

4.6.1 Bioavailability

It is defined as a part of the total elemental concentration available to plants that determines the uptake and accumulation of heavy metal ions in plants. Heavy metals exist in soils with several degrees of fractions i.e. soil solution form, soluble metal complexes and free metal ions forms. Several factors that determine the bioavailability of heavy metal elements are environmental conditions (moisture, temperature and oxidation state), soil properties (pH and organic matter) and enhanced biological activity by microbes (Yang et al. 2012; Bravin et al. 2012). These factors regulate the release of heavy metals into the soil and influence the plant uptake from soils. Environmental factors like high temperature enhance the physical, chemical and biological activities in soil–plant system, while precipitation and rainfall are known

Table 4.5 Potential plants for remediation of heavy metal pollution from soil

Plant species	Metal	Reference
Alyssum spp., Phyllanthus serpentines, Isatispinnatiloba, Berkheyacoddii	Nickel (Ni)	Li et al. (2003), Bani et al. (2010), Chaney et al. (2010), Mesjasz-Przybyłowicz et al. (2004), Altinözlü et al. (2012)
Azolla pinnata, Solanum photeinocarpum, Thlaspicaerulescens, Rorippaglobosa, Turnip landraces, Prosopis laevigata	Cadmium (Cd)	Rai (2008), Zhang et al. (2011), Lombi et al. (2001), Wei et al. (2008), Li et al. (2016), Buendía-González et al. (2010)
Pteris spp., Corrigiolatelephiifolia, Eleocharis acicularis, Azolla carobiniana	Arsenic (As)	Srivastava et al. (2006), Sakakibara et al. (2011), Garcia-Salgado et al. (2012)
Eleocharis acicularis, Aeolanthusbiformifolius, Ipomoea alpine, Haumaniastrumkatangense, Pteris vittata	Copper (Cu)	Sakakibara et al. (2011), Chaney et al. (2010), Mitch (2002), Sheoran et al. (2009), Wang et al. (2012)
Pteris vittata	Chromium (Cr)	Kalve et al. (2011)
Thlaspicaerulescens, Eleocharis acicularis, Thlaspicalaminare, Deschampsiacespitosa	Zinc (Zn)	Cunningham and Ow (1996), Sakakibara et al. (2011), Sheoran et al. (2009), Kucharski et al. (2005)
Medicago sativa, Brassica spp.,Thlaspirotundifolium Helianthus annuus, Euphorbia cheiradenia, Betula occidentalis, Deschampsiacespitosa	Lead (Pb)	Koptsik (2014), Cunningham and Ow (1996), Chehregani and Malayeri (2007), Kucharski et al. (2005)
Lecythisollaria, Astragalus racemosus	Selenium (Se)	Marques et al. (2009)
Schima superba, Macadamia neurophyllaMaytenusbureavianaAlyxiarubricaulis	Manganese (Mn)	Yang et al. (2012), Sheoran et al. (2009), Marques et al. (2009), Chaney et al. (2010)
Achillea millefolium, Marrubium vulgare, Rumex induratus, Hordeum spp., Festuca rubra, Helianthus tuberosus, Poa pratensis, Armoracia lapathifolia, Brassica juncea	Mercury (Hg)	Wang et al. (2012), Rodriguez et al. (2003), Sas-Nowosielska et al. (2008)

to accelerate plant growth and development. High soil moisture content regulates the movement of water-soluble trace elements during bioremediation. Soil properties, viz., pH, organic matter/organic carbon and cation exchange capacity (CEC) are the important factors that control the bioavailability of cations in soil. Soils with higher organic matter and high pH will form complex with heavy metals more firmly and become less available to plants for uptake and accumulation. Acidification of the rhizosphere is considered to increase the metal accumulation potential of plants raised on heavy metal contaminated soils. At acidic pH, heavy metals are found in free ionic forms and are more bioavailable, but at the basic pH metals form insoluble metal complexes with phosphates and carbonates (Sandarin and Hoffman 2007; Rensing and Maier 2003). Biological activities within the soil–plant system alter the bioavailability of metal elements. Microbes in the rhizosphere can produce chelating compounds, enhance the key nutrient uptake and also the availability of soil heavy metals (Rajkumar et al. 2012). Some plants secrete the organic components that form soluble complexes with heavy metal ions in soils. These soluble complex formations promote the mobility of heavy metals in soils. Yang et al. (2012) reported that root exudates include various organic acids and amino acids viz., oxalic acid, citric acid, tartaric acid, succinic acid, aspartic acid and glutamic acid, that form heavy metal soluble complexes and increase the mobility of Cd, Cu, Zn and Pb in soils (Fig. 4.2).

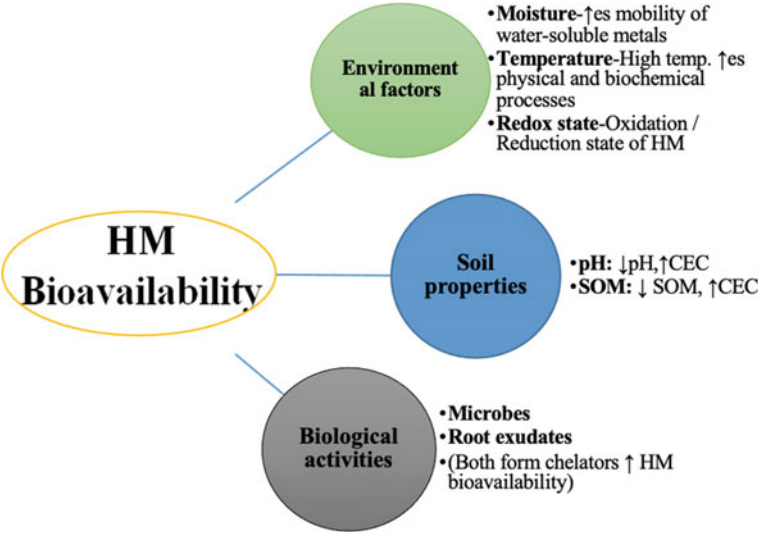

Fig. 4.2 Bioavailability of the heavy metals (HM) to plants

4.6.2 Plant Uptake

The movement of heavy metals in soils depends upon precipitation, redox potential, absorption/ adsorption and its complexation/methylation responses mediated by microbes along with plants (Kumar et al. 2017). The mechanism of plant metal uptake, rejection, translocation and sequestration is specific and highly variable within the plant varieties (Lone et al. 2008). Plants adopt two main strategies to combat heavy metal stress by either reduce metal uptake or increase vacuolar sequestration. The heavy metal is bioactivated by the root microbe’s interaction first which leads to root absorption and further compartmentalization.

(i) *Bioactivation of metals by root-microbe interaction*

Several studies depicted the positive interaction of microorganisms with plant species in the rhizosphere (Dakora and Phillips 2002; Kuiper et al 2004). Plant growth promoting rhizobacteria increase the bioavailability of metal ions by dissolving them via changing the chemical properties (pH, redox state, organic matter) of soils in the rhizosphere and modify the heavy metal speciation in the root zone (Jing et al. 2007). They solubilize the ions like phosphate, siderophore and increase acid production (Kumar et al. 2017). During heavy metal stress, mycorrhizae release natural acids that enhance zinc solubility and its mobility, ultimately playing a significant role to strengthen plant survival rate (Giasson et al. 2008).

Bacterial endophytes are considered to be beneficial for host plants usually during stress conditions, because they regulate the plant growth promoting mechanisms like phytohormone production by activating enzymes viz., 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase, ethylene and Indole acetic acid (IAA) (Hardoim et al. 2008; Rajkumar et al. 2012). Endophytes also known to enhance nitrogen fixation and phosphate availability in rhizosphere, hence helps to recover the plant during heavy metal (HM) stress conditions (Kuklinsky-Sobral et al. 2004).

(ii) *Root absorption and compartmentalization*

The transport of nutrients and heavy metals from soils to plant roots occurs via symplastic and apoplastic transport. In symplastic transport heavy metals enter the root cells through the plasma membrane of the endodermis of the root. While in apoplastic transport, it enters the root apoplast via spacing within the cells. Generally, heavy metals and nutrient ions cross the membranes only with the aid of naturally occurring membrane transport proteins (Fig. 4.3). The abundance of these proteins depends upon tissue type and environmental conditions. If a small amount of nutrients is present in soils, then the plant requires high-affinity transporters for uptake; whereas if the nutrients in the soil are present in high concentrations (e.g. agricultural soils with fertilizers), then low-affinity transporters would be more useful for plant uptake (Cailliatte et al. 2010).

Several transporter families have been reported in plants such as heavy metal ATPase (HMA), natural resistance and macrophage proteins (NRAMP), Zrt, Irt-like proteins (ZIP) etc. (Table 4.6). In the cytosol, toxic metals rapidly bind to chelators

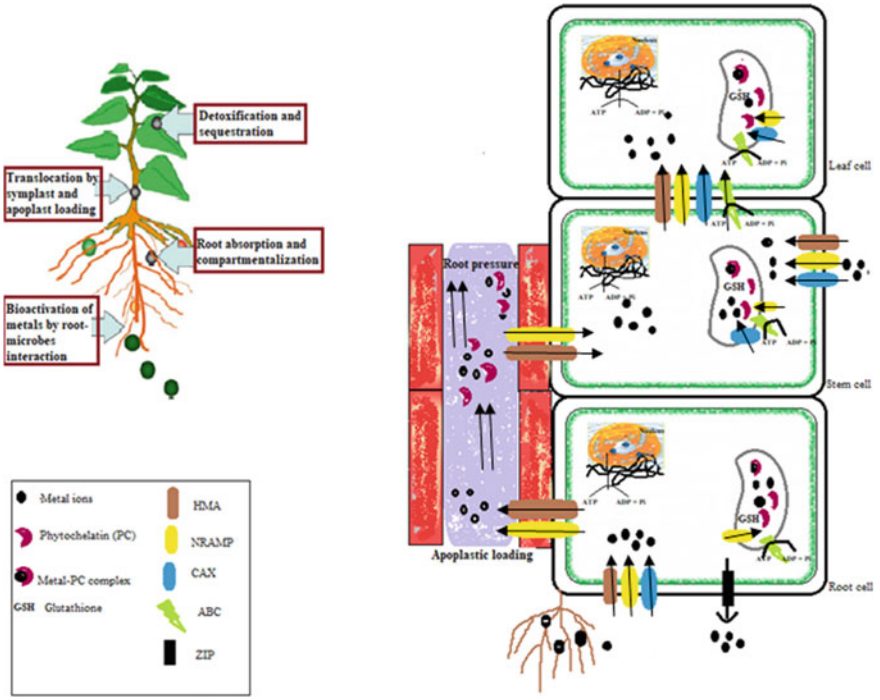

Fig. 4.3 Uptake of heavy metal and its compartmentalization in various plant part through different transporter proteins

and are transferred to the vacuole for sequestration. Ingle et al. (2005) observed that histidine is involved in Ni-chelation in root cells and helps plant to tolerate Ni toxicity. Cr (III) in root cells is chelated with acetate and sequestered in the vacuole (Bluskov and Arocena 2005).

4.6.3 Translocation

Heavy metal transporters are required for translocation of metallic ions from root symplast to xylem apoplast due to endodermal barrier (casparian strips) in the root. The translocation of heavy metal ions depends on two factors: root pressure and leaf transpiration (Kumar et al. 2017).

(i) *Root symplast to apoplast through xylem tissues*

Xylem loading of metals from root symplast is an important phenomenon making the plant to tolerate heavy metal toxicity instead of promoting its accumulation in root cells that would inactivate the enzymes involved in metabolic processes. Cation

Table 4.6 Metal transporters involved in heavy metal uptake, transport and sequestration during phytoremediation (Bhargava et al. 2012)

Transporter family	Transporter gene	Plant species	Metal transported	References
Natural resistance-associated macrophage proteins (NRAMP)	*nramp1* *nramp1-3* *nramp4*	*Malus baccata* *Lycopersicon esculentum* *Thlaspi japonicum*	Fe (Iron) Fe Iron) Fe (Iron)	Xiao et al. (2008), Bereczky et al. (2003), Mizuno et al. (2005)
Fe-regulated transporter (IRT)	*irt1* *irt1-2* *irt1-2*	*A. thaliana* *T. caerulescens* *L. esculentum*	Fe (Iron) Fe (Iron) Fe (Iron)	Kerkeb et al. (2008), Schikora et al. (2006), Plaza et al. (2007), Bereczky et al. (2003)
Zn-regulated transporter (ZRT)	*Zip* *zip1-12* *zip4* *znt1-2*	*Medicago truncatula* *A. thaliana* *O. sativa* *T. caerulescens*	Zn (Zinc) Zn (Zinc) Zn (Zinc) Zn (Zinc)	Lopez-Millan et al (2004), Roosens et al. (2008), Ishimaru et al. (2005), Van de Mortel et al (2006)
P-type ATPase	*hma9* *hma8* *hma3* *hma4*	*Oryza sativa* *Glycine max* *A. thaliana* *A. halleri*	Cu (Copper), Zn (Zinc), Cd (Cadmium), Cu (Copper) Co (Copper), Zn (Zinc), Cd (Cadmium), Pb (Lead), Cd (Cadmium)	Lee et al. (2007), Bernal et al. (2007), Morel et al. (2008), Courbot et al. (2007)
Copper transporter	*copt1*	*A. thaliana*	Cu (Copper)	Sancenon et al. (2004), Andres-Colas et al. (2010)
Yellow stripe-like (YSL)	*Ysl3* *Ysl2*	*T. caerulescens* *A. thaliana*	Fe (Iron), Ni (Nickel) Fe (Iron), Cu (Copper)	Gendre et al. (2006), DiDonato et al. (2004)
Cation diffusion facilitator (CDF)	*mtp1* *mtp1* *mtp1* *mtp1*	*Thlaspi goesingense* *A. thaliana* *A. halleri* *Nicotiana tabacum*	Zn (Zinc), Ni (Nickel) Zn (Zinc) Zn (Zinc) Zn (Zinc), Co (Cobalt)	Kim et al. (2004), Kawachi et al. (2008), Willems et al. (2007), Shingu et al. (2005)

diffusion facilitator (CDF) type of proteins conveys a broad array of metal divalent ions from cytoplasm toward the outer cell parts and even within the subcellular compartments (Hanikenne et al. 2005). HMA2 proteins are energy-dependent transporters, despite having selective nature they also get activated by analogue metal ions. Hussain et al. (2004) isolated HMA2 and HMA4 transporters in *Arabidopsis* for Zn transportation within cellular compartments and homeostasis. Milner and Kochain (2008) deciphered the importance of HMA2 and HMA4 genes in metal loading into the xylem.

(ii) *Root apoplast to aerial (stem and leaves) tissues*

Hyper accumulator plants rapidly translocate the absorbed metal ions from the root to the above-ground parts, while non-accumulators accumulate heavy metals only in their root portions. Heavy metals can be stored in root vacuoles. Due to the limited space and high heavy metal concentration in the soil matrix, it gets translocated to shoot tissue where sequestration and detoxification rate is comparatively high (Kumar et al. 2017). Generally, metals are stored in only chelated form but are transported from one cellular compartment to other in free ionic state according to the selectivity of transporter proteins (Ortiz et al. 1995). Research experiments showed that hyperaccumulator plants accumulate high concentration of heavy metals in stem and leaf vacuoles than the root tissues. In the leaf tissues, high amount of metals accumulates in epidermal tissues compared to the cortical and vascular tissues (Kupper et al. 2001; Kumar et al. 2017).

4.6.4 Sequestration/Detoxification

To cope up with heavy metal stress, plants adapt different survival strategies like compartmentalization, exclusion, complexation and synthesis of binding proteins (metallothioneins and phytochelatins). Heavy metal toxicity inside the plant cell gets detoxified by complex formation and compartmentalization to make them less available to metabolic active sites. Organic acids, glutathione precursor of phytochelatins and metallothiones play a significant role in detoxification/sequestration. Phytochelatins (PC) have an imperative role to detox cadmium in fungi and plants through conjugation. Glutathione enhances the PC synthesis and thus more PC-metal complex formation in the vacuole which ultimately enhances cadmium tolerance in plants (Lee et al. 2003).

In plants, different heavy metal ions (Cu, Hg, Zn, Pb, Cd) stimulate the enzyme, γ-glutamyl-cysteinyl dipeptidyl transpeptidase (PC synthase) for phytochelatin synthesis which results in glutathione conversion (GSH) to phytochelatin (Fig. 4.4). These phytochelatins are produced from glutathione (GSH) through oxidation and reduction reactions. The metal ion binds to cysteine sulfhydryl residues of phytochelatins and its sequestration occurs inside the vacuole (Zhu et al 2004; Kumar et al. 2017). In hyperaccumulator plants, toxic effects of Ni were overcome by enhancing GSH-dependent antioxidant mechanism that protects the plant from

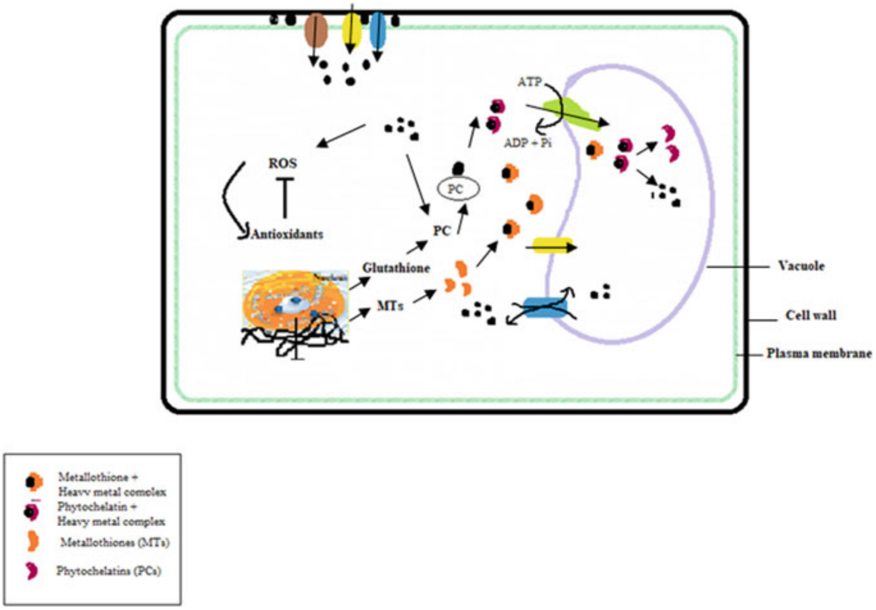

Fig. 4.4 Sequestration and detoxification of heavy metals (HM) in plant cell

oxidative damage (Freeman et al. 2005). Metallothiones are metal-binding proteins that modulate the concentration of metals inside the cell by binding heavy metal ions to cysteine and thiol groups (Khan et al. 2004). Mn^{2+} metal detoxification involves uptake of ions from the plasma membrane, binding with malate and transportation through tonoplast to vacuole where Mn unbinds from malate and form complex with oxalate (Memon et al. 2001).

Heavy metal toxicity hindered the functional group of important molecules that disrupt the metabolic enzyme activity and consequently inhibit or suppress photosynthetic rate, respiration rate and all physiological and biochemical processes of plants (Gupta et al. 2015; Ali et al. 2013). Naturally, plants develop various defense mechanisms against heavy metal stress inside the plant body which include compartmentalization reduction, suppression of high-affinity phosphate transport system, sequestration and translocation (Zhao et al. 2009). When metal ions cross enter into plant tissues by crossing these barriers then various cellular defense mechanisms (as a second line of defense viz., ROS production, antioxidants) are initiated to detox the adverse effect of noxious heavy metals (Silva and Matos 2016).

4.7 Conclusion and Future Prospects

The pollution due to heavy metals is of great concern because of its potential impact on human and animal health. It is imperative to protect the natural resources and biodiversity, by using cheaper and effective technologies. In phytoremediation, the plants have to retain the pollutant in their root or other parts by producing large biomass and microbes converting toxic forms of heavy metals to non-toxic forms. But till now no plant is known to fulfil both these criteria. At the heavily contaminated sites with both organic and inorganic pollutants, there is a limitation of plant growth and microbial activity, thus having reduced plant assisted bioremediation efficiency. Recent progress in molecular, biochemical and plant physiology fields provides a strong scientific base for achieving this goal. During the last decade, substantial efforts have been made by the researchers to identify plant hyperaccumulators, bioremediators for heavy metals and their mechanism of uptake, translocation. There is a huge genetic variation in different plant species, even among the cultivars of the same species. So, research must be carried out to study the mechanism of metal uptake, accumulation, exclusion, translocation and compartmentation for each species as they play a specific role in phytoremediation. Further, research is needed to study metal uptake at the cellular level including influx and efflux of different metals by different cell organelles and membranes.

- There is a need of microbial profiling of rhizosphere under controlled and field conditions to examine the antagonistic and synergistic effects of different metal ions in soil and polluted waters.
- Selected essential rhizosphere microorganisms and microbial strains able to degrade toxic pollutants can be studied in the natural habitat. Molecular techniques will further help in elucidating the fate and effect of these selected strains in the soil environment.
- Standardization of the methods for heavy metal recovery from the hyperaccumulator plants will allow the detection of the new strains of the micro-organisms who can degrade or reduce the toxic metals to non-toxic metals as well as improve the fertility status of the soil.

References

Abbas SH, Ismail IM, Mostafa TM, Sulaymon AH (2014) Biosorption of heavy metals: a review. J Chem Sci Technol 3(4):74–79

Abou-Shanab RA, Angle JS, Delorme TA, Chaney RL, van Berkum P, Moawad H, Ghanem K, Ghozlan HA (2003) Rhizobacterial effects on nickel extraction from soil and uptake by Alyssum murale. New Phytol 158:219–224

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

Ahemad M (2014) Phosphate solubilizing bacteria-assisted phytoremediation of metalliferous soils: a review. 3 Biotech. https://doi.org/10.1007/s13205-014-0206-0

Ahirwal J, Pandey VC (2021) Restoration of mine-degraded land for sustainable environmental development. Restor Ecol 29(4):e13268. https://doi.org/10.1111/rec.13268

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

Altinözlü H, Karagöz A, Polat T, Ünver I (2012) Nickel hyperaccumulation by natural plants in Turkish serpentine soils. Turk J Bot 36:269–280. https://doi.org/10.3906/bot-1101-10

Andres-Colas N, Perea-Garcia A, Puig S, Penarrubia L (2010) Deregulated copper transport affects Arabidopsis development especially in the absence of environmental cycles. Plant Physiol 153:170–184

Anonymous (2010) World Water Day, United Nations

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

Bani A, Pavlova D, Echevarria G, Mullaj A, Reeves RD, Morel JL, Sulçe S (2010) Nickel hyperaccumulation by the species of Alyssum and Thlaspi (Brassicaceae) from the ultramafic soils of the Balkans. Bot Serb 34:3–14

Benazir JF, Suganthi R, Rajvel D, Pooja MP, Mathithumilan B (2010) Bioremediation of chromium in tannery effluent by microbial consortia. African J Biotech 9:3140–3143

Bereczky Z, Wang HY, Schubert V, Ganal M, Bauer P (2003) Differential regulation of Nramp and IRT metal transporter genes in wild type and iron uptake mutants of tomato. J Bio Chem 278:24697–24704

Bernal M, Testillano PS, Alfonso M, Del Carmen RM, Picorel R, Yruela I (2007) Identification and subcellular localization of the soybean copper P1B-ATPase GmHMA8 transporter. J Struct Biol 158:146–158

Bharagava RN, Mishra S (2018) Hexavalent chromium reduction potential of *Cellulosimicrobium* sp. isolated from common effluent treatment plant of tannery industries. Ecotoxicol Environ Safety 147:102–109

Bhardwaj RM (2005) Status of wastewater generation and treatment in India. IWG-Env, International work session on water statistics, Vienna, p 9. Available at http://unstats.un.org/unsd/environment/envpdf/pap_wasess3b6india.pdf

Bhargava A, Carmona FF, Bhargava M et al (2012) Approaches for enhanced phytoextraction of heavy metals. J Environ Manage 105:103–120

Bhattacharya A, Gupta A, Kaur A, Malik D (2019) Alleviation of hexavalent chromium by using microorganisms: insight into the strategies and complications. Water Sci Technol 79.3:411–424. https://doi.org/10.2166/wst.2019.060

Bhojiya AA, Joshi H, Upadhyay SK, Srivastava AK, Pathak VV, Pandey VC, Jain D (2021) Screening and optimization of zinc removal potential in Pseudomonas aeruginosa—HMR1 and its plant growth-promoting attributes. Bull Environ Contam Toxicol. https://doi.org/10.1007/s00128-021-03232-5

BIS (2012) Indian standard for drinking water, Bureau of Indian Standards (IS-10500), New Delhi

Black H (1995) Absorbing possibilities: phytoremediation. Environ Health Perspect 103:1106–1108

Bluskov S, Arocena JM (2005) Uptake, distribution, and speciation of chromium in Brassica juncea. Int J Phytoremediation 7:153–165

Bowen HJM (1979) Environmental chemistry of the elements. Academic press, London

Braud A, Jézéquel K, Bazot S and Lebeau T (2009) Enhanced phytoextraction of an agricultural Cr-, Hg- and Pb-contaminated soil by bioaugmentation with siderophore producing bacteria. Chemosphere 74: 280–286.

Bravin MN, Garnier C, Lenoble V, Gerard F, Dudal Y, Hinsinger P (2012) Root-induced changes in pH and dissolved organic matter binding capacity affect copper dynamic speciation in the rhizosphere. Geochim Cosmochim Ac 84:256–268

Buendía-González L, Orozco-Villafuerte J, Cruz-Sosa F, Barrera-Díaz C, Vernon-Carter E (2010) Prosopis laevigataa potential chromium (VI) and cadmium (II) hyperaccumulator desert plant. Bioresour Technol 101:5862–5867. https://doi.org/10.1016/j.biortech.2010.03.027

Cailliatte R, Schikora A, Briat JF, Mari S, Curie C (2010) High affinity manganese uptake by the metal transporter nramp1 is essential for Arabidopsis growth in low manganese conditions. Plant Cell 22:904–917

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

Chaney RL, Angle JS, McIntosh MS, Reeves RD, Li YM, Brewer EP, Chen KY, Roseberg RJ, Perner H, Synkowski EC, Broadhurst CL, Wang S, Baker AJ (2005) Using hyperaccumulator plants to phytoextract soil Ni and Cd. Z Naturforsch C 60:190–198

Chaney RL, Broadhurst CL, Centofanti T (2010) Phytoremediation of soil trace elements. In: Hooda PS (ed) Trace elements in soils chichester. John Wiley & Sons, Inc. pp 311–352

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

Chehregani A, Malayeri BE (2007) Removal of heavy metals by native accumulator plants. Int J Agric Biol 9:462–465

Courbot M, Willems G, Motte P, Arvidsson S, Roosens N, Saumitou-Laprade P, Verbruggen N (2007) A major quantitative trait locus for Cd tolerance in Arabidopsis halleri colocalizes with HMA4, a gene encoding a heavy metal ATPase. Plant Physiol 144:1052–1065

CPCB (2009) Comprehensive environmental assessment of industrial clusters. Ecological impact assessment series: EIAS/5/2009–2010. Central pollution control board, ministry of environment and forests, Govt. of India, New Delhi

Cunningham SD, Ow DW (1996) Promises and prospects of phytoremediation. Plant Physiol 110:715. https://doi.org/10.1104/pp.110.3.715

Dakora FD, Phillips DA (2002) Root exudates as mediators of mineral acquisition in low-nutrient environments. Plant Soil 13:35–47

Dary M, Chamber-Pérez MA, Palomares AJ, Pajuelo E (2010) In situ phytostabilisation of heavy metal polluted soils using Lupinus luteus inoculated with metal resistant plant-growth promoting rhizobacteria. J Hazard Mater 177: 323–330

Deng Z, Cao L (2017) Fungal endophytes and their interactions with plants in phytoremediation: a review. Chemosphere 168:1100–1106

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

Deng Z, Zhang R, Shi Y, Hu L, Tan H, Cao L (2013a) Characterization of Cd-, Pb-, Zn-resistant endophytic Lasiodiplodiasp. 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

Deng Z, Zhang R, Shi Y, Hu L, Tan H, Cao L (2013b) Enhancement of phytoremediation of Cd- and Pb-contaminated soils by self-fusion of protoplasts from endophytic fungus Mucor sp. CBRF59. Chemosphere 91:41–47

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

Dickinson NM, Pulford ID (2005) Cadmium phytoextraction using short-rotation coppice Salix: the evidence trail. Environ Int 31:609–613

DiDonato RJ, Roberts LA, Sanderson T, Eisley RB, Walker EL (2004) Arabidopsis yellow stripe-Like2 (YSL2): a metal-regulated gene encoding a plasma membrane transporter of nicotianamine metal complexes. Plant J 39:403–414

Dietz AC, SchnoorJL (2001) Advances in phytoremediation. Environmental health perspectives 109(suppl 1):163–168

Dixit R, Wasiullah MD, Pandiyan K, Singh UB, Sahu A, Shukla R, Singh BP, Rai JP, Sharma PK, Lake H, Paul D (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability 7:2189–2212. https://doi.org/10.3390/su7022189

Dursun A, Uslu G, Cuci Y, Aksu Z (2003) Bioaccumulation of copper(II), lead(II) and chromium(VI) by growing Aspergillus niger. Process Biochem 38:1647–1651

Freeman JL, Michael WP, Nieman K, Salt DE (2005) Nickel and cobalt resistance engineered in Escherichia coli by overexpression of serine acetyltransferase from the nickel hyperaccumulator plant Thlaspigoes ingense. Appl Environ Microbiol 12:8627–8633

Fu YQ, Li S, Zhu HY, Jiang R, Yin LF (2012) Biosorption of copper(II) from aqueous solution by mycelial pellets of Rhizopus oryzae. Afr J Biotechnol 11:1403–1411

Garcia-Salgado S, Garcia-Casillas D, Quijano-Nieto MA, Bonilla-Simon MM (2012) Arsenic and heavy metal uptake and accumulation in native plant species from soils polluted by mining activities. Water Air Soil Pollut 223:559–572

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

Gendre D, Czernic P, Conéjéro G, Pianelli K, Briat JF, Lebrun M, Mari S (2006) TcYSL3, a member of the YSL gene family from the hyperaccumulator Thlaspi caerulescens, encodes a nicotianamine- Ni/Fe transporter. Plant J 49:1–15

Ghosh M, Singh SP (2005) A review on phytoremediation of heavy metals and utilization of its byproducts. Appl Ecol Environ Res 3:1–18

Giasson P, Karam A, Jaouich A (2008) Arbuscular mycorrhizae and alleviation of soil stresses onplant growth. In: Siddiqui ZA, Akhtar MS, Futai K (eds) Mycorrhizae: sustainable agriculture and forestry. Springer, Dordrecht, pp 99–134

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

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Hindawi Publishing Corporation, Scientifica

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Goher ME, El-Monem AMA, Abdel-Satar AM, Ali MH, Hussian AEM, Napíorkowska-Krzebietke A (2016) Biosorption of some toxic metals from aqueous solution using nonliving algal cells of Chlorella vulgaris. J Elementol 21(3):703–714

Gupta VK, Rastogi A (2008) Biosorption of lead from aqueous solutions by green algae Spirogyra species: kinetics and equilibrium studies. Jhazardous Mater 152(1):407–414

Gupta A, Meyer JM, Goel R (2002) Development of heavy metal resistant mutants of phosphate solubilizing Pseudomonas sp. NBRI4014 and their characterization. CurrMicrobiol 45:323–332

Gupta VK, Nayak A, Agarwal S (2015) Bioadsorbents for remediation of heavy metals: current status and their future prospects. Environ Eng Res 20:1–18

Hanikenne M, Kramer U, Demoulin V, Baurain D (2005) A comparative inventory of metal transporters in the green alga Chlamydomonas reinhardtiiand the red alga Cyanidioschizonmerolae. Plant Physiol 137:428–446

Hansen HK, Ribeiro A, Mateus E (2006) Biosorption of arsenic (V) with Lessonia nigrescens. Miner Eng 19(5):486–490

Hardoim PR, Overbeek LS, Elsas JD (2008) Properties of bacterial endophytes and their proposed role in plant growth. Trends Microbiol 16:63–471

Hemambika B, Rani MJ, Kannan VR (2011) Biosorption of heavy metals by immobilized and dead fungal cells: a comparative assessment. J Ecol Nat Environ 3:168–175

Hussain SA, Palmer DH, Moon S, Rea DW (2004) Endocrine therapy and other targeted therapies for metastatic breast cancer. Expert Rev Anticancer Ther 4:1179–1195

Ingle RA, Mugford ST, Rees JD, Campbell MM, Smith JAC (2005) Constitutively high expression of the histidine biosynthetic pathway contributes to nickel tolerance in hyperaccumulator plants. Plant Cell 17:2089–2106

Iqbal M, Edyvean R (2004) Biosorption of lead, copper and zinc ions on loofa sponge immobilized biomass of Phanero chaetechrysosporium. Miner Eng 17:217–223

Ishimaru Y, Suzuki M, Kobayashi T, Takahashi M, Nakanishi H, Mori S, Nishizawa NK (2005) OsZIP4, a novel zinc-regulated zinc transporter in rice. J Exp Bot 56:3207–3214

Jafari SA, Cheraghi S, Mirbakhsh M, Mirza R, Maryamabadi A (2015) Employing response surface methodology for optimization of mercury bioremediation by Vibrio parahaemolyticus PG02 in coastal sediments of Bushehr, Iran. CLEAN Soil, Air, Water 43(1):118–126

Järup L (2003) Hazards of heavy metal contamination. Br Med Bull 68:167–182. https://doi.org/10.1093/bmb/ldg032

Jing YD, Zhen Li HE, Yang XE (2007) Role of soil rhizobacteria in phytoremediation of heavy metal contaminated soils. J Zhejiang Univ Sci B 8:192–207

Kabata-Pendias A, Pendias H (1984) Trace elements in soils and plants. CPRC Press, Boca Raton, Fla

Kalve S, Sarangi BK, Pandey RA, Chakrabarti T (2011) Arsenic and chromium hyperaccumulation by an ecotype of Pteris vittata—prospective for phytoextraction from contaminated water and soil. Curr Sci India 100:888–894

Kang S, Lee J, Kim K (2005) Metal removal from wastewater by bacterial sorption: kinetics and competition studies. Environ Technol 26:615–624

Kawachi M, Kobae Y, Mimura T, Maeshima M (2008) Deletion of a histidine-rich loop of AtMTP1, a vacuolar Zn2þ/Hþ antiporter of Arabidopsis thaliana, stimulates the transport activity. J Biol Chem 283:8374–8383

Kerkeb L, Mukherjee I, Chatterjee I, Lahner B, Salt DE, Connolly EL (2008) Iron-induced turnover of the arabidopsis iron-regulated transporter1 metal transporter requires lysine residues. Plant Physiol 146:1964–1973

Khan FI, Husain T, Hejazi R (2004) An overview and analysis of site remediation technologies. J Environ Manag 71:95–112

Kim SY, Kim JH, Kim CJ, Oh DK (1996) Metal adsorption of the polysaccharide produced from Methylobacterium organophilum. Biotech Lett 18(10):1161–1164

Kim D, GustinJL LB, Persans MW, Baek D, Yun DJ, Salt DE (2004) The plant CDF family member TgMTP1 from the Ni/Zn hyperaccumulator Thlaspigoesingenseacts to enhance efflux of Zn at the plasma membrane when expressed in Saccharomyces cerevisiae. Plant J 39:237–251

Kim IH, Choi JH, Joo JO, Kim YK, Choi JW, Oh BK (2015) Development of a microbe-zeolite carrier for the effective elimination of heavy metals from seawater. J Microbiol Biotechnol 25:1542–1546

Koptsik G (2014) Problems and prospects concerning the phytoremediation of heavy metal polluted soils: a review. Eurasian Soil Sci 47:923–939. https://doi.org/10.1134/S1064229314090075

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

Kucharski R, Sas-Nowosielska A, Małkowski E, Japenga J, Kuperberg J, Pogrzeba M et al (2005) The use of indigenous plant species and calcium phosphate for the stabilization of highly metal-polluted sites in southern Poland. Plant Soil 273:291–305. https://doi.org/10.1007/s11104-004-8068-6

Kuiper I, Lagendijk EL, Bloemberg GV, Lugtenberg BJJ (2004) Rhizoremediation: a beneficial plant-microbe interaction. Mol Plant-Microbe Interact 17:6–15

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 6:1244–1251

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

Kumar SS, Kadier A, Malyan SK, Ahmad A, Bishnoi NR (2017) Phytoremediation and rhizoremediation: uptake, mobilization and sequestration of heavy metals by plants. In: Singh DP (ed) Plant-Microbe interactions in agro-ecological perspectives Springer, pp 367–394. https://doi.org/10.1007/978-981-10-6593-4_15

Kumaran NS, Sundaramanicam A, Bragadeeswaran S (2011) Adsorption studies on heavy metals by isolated cyanobacterial strain (nostoc sp.) from uppanar estuarine water, southeast coast of India. J Appl Sci Res 7(11):1609–1615

Kupper H, Lombi E, Zhao FJ, Wieshammer G, McGrath SP (2001) Cellular compartmentation of Ni in the hyperaccumulators Alyssum lesbiacum A. Bertoloniiand Thlaspigoesingense. J Exp Bot 52:2291–2300

Lee S, Moon JS, Ko TS, Petros D, Goldsbrough PB, Korban SS (2003) Over expression of Arabidopsis phytochelatin synthase paradoxically leads to hypersensitivity to cadmium stress. Plant Physiol 131:656–663

Lee S, Kim YY, Lee Y, An G (2007) Rice P1B-type heavy-metal ATPase, OsHMA9, is a metal efflux protein. Plant Physiol 145:831–842

Li YM, Chaney R, Brewer E, Roseberg R, Angle JS, Baker A, Reeves R, Nelkin J (2003) Development of a technology for commercial phytoextraction of nickel: economic and technical considerations. Plant Soil 249:107–115

Li X, Zhang X, Yang Y, Li B, Wu Y, Sun H et al (2016) Cadmium accumulation characteristics in turnip landraces from China and assessment of their phytoremediation potential for contaminated soils. Front Plant Sci 7:1862. https://doi.org/10.3389/fpls.2016.01862

Liu LW, Li W, Song WP, Guo MX (2018) Remediation techniques for heavy metal–contaminated soils: principles and applicability. Sci Total Environ 633:206–219. https://doi.org/10.1016/j.scitotenv.2018.03.161

Lombi E, Zhao FJ, Dunham SJ, McGrath SP (2001) Phytoremediation of heavy metal-contaminated soils: natural hyperaccumulation versus chemical enhanced phytoextraction. J Environ Qual 30:1919–1926

Lone MI, He ZL, Stoffella PJ, Yang XE (2008) Phytoremediation of heavy metal polluted soils and water: progresses and perspectives. J Zhejiang Univ-Sci. B (biomed Biotechnol) 9:210–220. https://doi.org/10.1631/jzus.B0710633

Lopez-Millan AF, Ellis DR, Grusak MA (2004) Identification and characterization of several new members of the ZIP family of metal ion transporters in Medicago truncatula. Plant Mol Biol 54:583–596

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

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

Ma Y, Rajkumar M, Luo Y, Freitas H (2011b) Inoculation of endophytic bacteria on host and non-host plants-effects on plant growth and Ni uptake. J Hazard Mater 195:230–237

Malik G, Hood S, Majeed S, Pandey VC (2022). Understanding assisted phytoremediation: potential tools to enhance plant performance. In: Pandey VC (eds) Assisted phytoremediation. Elsevier, Amsterdam, pp 1–24. https://doi.org/10.1016/B978-0-12-822893-7.00015-X

Mane PC, Bhosle AB (2012) Bioremoval of some metals by living Algae Spirogyra sp. and Spirullina sp. from aqueous solution. Int J Environ Res 6(2):571–576

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

Marmiroli M, Pietrini F, Maestri E, Zacchini M, Marmiroli N, Massacci A (2011) Growth, physiological and molecular traits in Salicaceae trees investigated for phytoremediation of heavy metals and organics. Tree Physiol 31:1319–1334

Marques AP, Rangel AO, Castro PM (2009) Remediation of heavy metal contaminated soils: phytoremediation as a potentially promising clean-up technology. Crit Rev Env Sci Technol 39:622–654. https://doi.org/10.1080/10643380701798272

Marschner H (1995) Mineral nutrition of higher plants. Oxford University Press, London

McGrath SP (1998) Phytoextraction for soil remediation. In: Brooks RR (ed) Plants that hyperaccumulate heavy metals. CABI Publishing, Wallingford, pp 261–287

Memon A, Aktoprakligil D, Ozdemir Z, Vertii A (2001) Heavy metal accumulation and detoxification mechanism in plants. Turk J Bot 25:111–121

Mesjasz-Przybyłowicz J, Nakonieczny M, Migula P, Augustyniak M, Tarnawska M, Reimold U et al (2004) Uptake of cadmium, lead nickel and zinc from soil and water solutions by the nickel hyperaccumulator Berkheyacoddii. Acta BiolCracoviensia Ser Bot 46:75–85

Milner MJ, Kochian LV (2008) Investigating heavy-metal hyperaccumulation using Thlaspi caerulescensas a model system. Ann Bot 102:3–13

Mitch ML (2002) Phytoextraction of toxic metals: a review of biological mechanism. J Environ Qual 31:109–120. https://doi.org/10.2134/jeq2002.1090

Mizuno T, Usui K, Horie K, Nosaka S, Mizuno N, Obata H (2005) Cloning of three ZIP/NRAMP transporter genes from a Ni hyperaccumulator plant Thlaspi japonicum and their Ni 2þ-transport abilities. Plant Physiol Biochem 43:793–801

Morel M, Crouzet J, Gravot A, Auroy P, Leonhardt N, Vavasseur A, Richaud P (2008) AtHMA3, a P1B-ATPase allowing Cd/Zn/Co/Pb vacuolar storage in Arabidopsis. Plant Physiol 149:894–904

Mosa KA, Saadoun I, Kumar K, Helmy M, Dhankher OP (2016) Potential biotechnological strategies for the cleanup of heavy metals and metalloids. Frontiers Plant Sci 7:303. https://doi.org/10.3389/fpls.2016.00303

Muradoglu F, Gundogdu M, Ercisli S, Encu T, Balta F, Jaafar HZE, Zia-Ul-Haq M (2015) Cadmium toxicity affects chlorophyll a and b content, antioxidant enzyme activities and mineral nutrient accumulation in strawberry. Biol Res 48:1–7. https://doi.org/10.1186/S40659-015-0001-3

Ortiz DF, Theresa R, McCue KF, Ow DW (1995) Transport of metal-binding peptides by HMT1, a fission yeast ABC-type vacuolar membrane protein. J Biol Chem 270(9):4721–4728

Pandey VC (2020) Phytomanagement of fly ash. Elsevier (Authored book), ISBN: 9780128185445. https://doi.org/10.1016/C2018-0-01318-3, pp 334

Pandey VC, Bajpai O (2019) Phytoremediation: from theory towards practice. In: Pandey VC, Bauddh K (eds) Phytomanagement of polluted sites. Elsevier, Amsterdam, pp 1–49. https://doi.org/10.1016/B978-0-12-813912-7.00001-6

Pandey VC, Singh V (2019) Exploring the potential and opportunities of recent tools for removal of hazardous materials from environments. In: Pandey VC, Bauddh K (eds) Phytomanagement of polluted sites. Elsevier, Amsterdam, pp 501–516. https://doi.org/10.1016/B978-0-12-813912-7.00020-X

Pandey VC, Singh N (2010) Impact of fly ash incorporation in soil systems. Agr Ecosyst Environ 136:16–27. https://doi.org/10.1016/j.agee.2009.11.013

Pathak S, Agarwal AV, Pandey VC (2020) Phytoremediation—a holistic approach for remediation of heavy metals and metalloids. In: Pandey VC, Singh V (eds) Bioremediation of pollutants. Elsevier, Amsterdam, pp 3–14. https://doi.org/10.1016/B978-0-12-819025-8.00001-6

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

Plaza S, Tearall KL, Zhao FJ, Buchner P, McGrath SP, Hawkesford MJ (2007) Expression and functional analysis of metal transporter genes in two contrasting ecotypes of the hyperaccumulator Thlaspi caerulescens. J Exp Bot 58:1717–1728

Prasad MNV, Freitas HM (2003) Metal hyperaccumulation in plants—biodiversity prospecting for phytoremediation technology. Electron J Biotechnol 6:285–321

Puschenreiter M, Türktaş M, Sommer P, Wieshammer G, Laaha G, Wenzel WW, Hauser MT (2010) Differentiation of metallicolous and non-metallicolous Salix caprea populations based on phenotypic characteristics and nuclear microsatellite (SSR) markers. Plant, Cell Environ 33:1641–1655

Rai PK (2008) Phytoremediation of Hg and Cd from industrial effluents using an aquatic free floating macrophyte Azolla pinnata. Int J Phytorem 10:430–439

Rajkumar M, Ma Y, Freitas H (2008) Characterization of metalresistant plant-growth promoting Bacillus weihenstephanensis isolated from serpentine soil. Portugal J Basic Microbiol 48:500–508

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

Rattan RK (2002) Heavy metals in environments-Indian scenario. Fertil News 47:21–40

Rattan RK (2005) Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. Agric Ecosys Environ 109:310–322

Rengel Z (2004) Heavy metals as essential nutrients. In: Prasad MNV (ed) Heavy metal stress in plants, 2nd edn. Springer, Berlin

Rensing C, Maier RM (2003) Issues underlying use of biosensors to reduce measure bioavailability. Ecotoxicol Environ Sat 56:140–147

Rodriguez L, Lopez-Bellido F, Carnicer A, Alcalde-Morano V (2003) Phytoremediation of mercury-polluted soils using crop plants. Fresen Environ Bull 9:328–332. https://doi.org/10.1007/s11356-019-06563-3

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

Romera E, González F, Ballester A, Blázquez M, Munoz J (2007) Comparative study of biosorption of heavy metals using different types of algae. BioresourTechnol 98:3344–3353

Roosens NH, Willems G, Saumitou-Laprade P (2008) Using Arabidopsis to explore zinc tolerance and hyperaccumulation. Trends Plant Sci 13:208–215

Rzymski P, Niedzielski P, Poniedziałek B, Klimaszyk P (2014) Bioaccumulation of selected metals in bivalves (Unionidae) and Phragmites australis inhabiting a municipal water reservoir. Environ Monitor Asses 186:3199–3212. https://doi.org/10.1007/s10661-013-3610-8

Saha JK, Panwar NR (2013) Environmental pollution in the country in relation to soil quality and human health. In: Manna MC, Biswas AK, Chaudhary RS, Lakaria BL, Rao AS (eds) Kundu S. IISS contribution in frontier areas of soil research, Indian Institute of Soil Science, Bhopal, India, pp 281–306

Saha JK, Selladurai R, Coumar MV, Dotaniya ML, Kundu S, Patra AK (2017) Soil pollution-an emerging threat to agriculture. Springer. pp 1–9

Sakakibara M, Ohmori Y, Ha NTH, Sano S, Sera K (2011) Phytoremediation of heavy metal contaminated water and sediment by Eleocharis acicularis. Clean Soil Air Water 39:735–741

Sancenon V, Puig S, Mateu-Andres I, Dorcey E, Thiele DJ, Penarrubia L (2004) The Arabidopsis copper transporter COPT1 functions in root elongation and pollen development. J Bio Chem 279:15348–15355

Sandarin TR, Hoffman DR (2007) Bioremediation of organic and metal contaminated environments: effects of metal toxicity, speciation and bioavailability or biodegradation. Environ Bioremd Technol 1–34

Sas-Nowosielska A, Galimska-Stypa R, Kucharski R, Zielonka U, Małkowski E, Gray L (2008) Remediation aspect of microbial changes of plant rhizosphere in mercury contaminated soil. Environ Monit Assess 137:101–109. https://doi.org/10.1007/s10661-007-9732-0

Schikora A, Thimm O, Linke B, Buckhout TJ, Müller M, Schmidt W (2006) Expression, localization, and regulation of the iron transporter LeIRT1 in tomato roots. Plant Soil 284:101–108

Sheoran V, Sheoran A, Poonia P (2009) Phytomining: a review. Miner Eng 22:1007–1019. https://doi.org/10.1016/j.mineng.2009.04.001

Shingu Y, Kudo T, Ohsato S, Kimura M, Ono Y, Yamaguchi I, Hamamoto H (2005) Characterization of genes encoding metal tolerance proteins isolated from Nicotiana glauca and Nicotiana tabacum. Biochem Biophys Res Commun 331:675–680

Silva P, Matos M (2016) Assessment of the impact of aluminum on germination, early growth and free proline content in Lactuca sativa L. Ecotoxicol Environ Saf 131:151–156

Simmons RW (2006) Impact of wastewater irrigation on Cd and Pb concentrations in rice straw and paragrass

Singh V, Chauhan PK, Kanta R, Dhewa T, Kumar V (2010) Isolation and characterization of Pseudomonas resistant to heavy metals contaminants. Int J Pharm Sci Rev Res 3:164–167

Srivastava M, Ma LQ, Santos JAG (2006) Three new arsenic hyperaccumulating ferns. Sci Total Environ 364:24–31

Srivastava S, Agrawal SB, Mondal MK (2015) A review on progress of heavy metal removal using adsorbents of microbial and plant origin. Environ Sci Pollu Res 22(20):15386–15415

Tastan BE, Ertûgrul S, Dönmez G (2010) Efectivebioremoval of reactive dye and heavy metals by Aspergillus versicolor. Bioresource Technol 10(3):870–876

Thambavani DS, Prathipa V (2012) Quantitative assessment of soil metal pollution with principal component analysis, geo accumulation index and enrichment index. Asian J Environ Sci 7(2):125–134

Tripathi M, Munot HP, Shouch Y, Meyer JM, Goel R (2005) Isolation and functional characterization of siderophore-producing lead- and cadmium-resistant Pseudomonas putida KNP9. Curr Microbiol 5:233–237

Ungureanu G, Santos S, Boaventura R, Botelho C (2015) Biosorption of antimony by brown algae S. muticum and A. nodosum. Environ Eng Manag J 14:455–463

USEPA (1999) Report on bioavailability of chemical wastes with respect to the potential for soil remediation. T28006: QT-DC-99-003260

van de Mortel JE, Villanueva LA, Schat H, Kwekkeboom J, Coughlan S, Moerland PD, Loren V, van Themaat E, Koornneef M, Aarts MGM (2006) Large expression differences in genes for iron and Zn homeostasis, stress response, and lignin biosynthesis distinguish roots of Arabidopsis thaliana and the related metal hyperaccumulator Thlaspicaerulescens. Plant Physiol 142:1127–1147

Wackernagel M, Schulz B, Deumling D et al (2002) Tracking the ecological overshoot of the human economy. PNAS, Proc Nat Acad Sci 99:9266–9271

Wang J, Feng X, Anderson CW, Xing Y, Shang L (2012) Remediation of mercury contaminated sites–a review. J Hazard Mater 221:1–18. https://doi.org/10.1016/j.jhazmat.2012.04.035

Wei S, Zhou Q, Saha UK (2008) Hyperaccumulative characteristics of weed species to heavy metals. Water Air Soil Pollut 192:173–181

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

Willems G, Drager DB, Courbot M, Gode C, Verbruggen N, Saumitou- Laprade P (2007) The genetic basis of Zn tolerance in the metallophyte Arabidopsis halleri ssp. Halleri (Brassicaceae): an analysis of quantitative trait loci. Genetics 176:659–674

Xiao H, Yin L, Xu X, Li T, Han Z (2008) The Iron-regulated transporter, MbNRAMP1, isolated from Malus baccatais involved in Fe, Mn and Cd trafficking. Ann Bot 102:881–889

Yang JX, Liu Y, Ye ZH (2012) Root-Induced changes of pH, Eh, Fe(II) and fractions of Pb and Zn in rhizosphere soils of four wetland plants with different radial oxygen losses. Pedosphere 22:518–527

Yang J, Li K, Zheng W, Zhang H, Cao X, Lan Y, Yang C, Li C (2015) Characterization of early transcriptional responses to cadmium in the root and leaf of Cd-resistant Salix matsudanaKoidz. BMC Genomics 16:705

Zhang X, Xia H, Li Z, Zhuang P, Gao B (2011) Identification of a new potential Cd-hyperaccumulator Solanum photeinocarpum by soil seed bank-metal concentration gradient method. J Hazard Mater 189:414–419

Zhang M, Xian S, Xu J (2020) Heavy metal pollution in the East China sea: a review. Mar Pollut Bull 159:111473

Zhao FJ, Ma JF, Meharg AA, McGrath SP (2009) Arsenic uptake and metabolism in plants. New Phytol 181:777–794

Zhu YG, Kneer R, Tong YP (2004) Vacuolar compartmentalization: a second-generation approach to engineering plants for phytoremediation. Trends Plant Sci 9:7–9

Zouboulis A, Loukidou M, Matis K (2004) Biosorption of toxic metals from aqueous solutions by bacteria strains isolated from metal-polluted soils. Process Biochem 39:909–916