Chapter 7
Phytoremediation of Lead Present in Environment: A Review

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Abstract Lead (Pb) is a heavy metal used in various industrial processes, so its levels are considerably increased in the soil, sediments, surface water, and groundwater. Pb is a non-biodegradable and persistent environmental pollutant that causes toxicity in humans, plants, animals, and microorganisms. Phytoremediation is a clean, eco-friendly, and cost-effective technology to remove Pb from aquatic and terrestrial environments. This technology uses plants to remove, immobilize, and contain Pb through phytoextraction, phytostabilization, and rhizofiltration. This chapter describes the characteristics of plants used in phytoremediation, focusing on the mechanisms employed by the plants to assist in the removal or immobilization of Pb. Moreover, it shows the state of the art on phytoremediation assisted by microorganisms for enhancing phytoremediation of Pb-polluted soils.

Keywords Phytoextraction · Phytostabilization · Rhizofiltration · Microbial-assisted phytoremediation

7.1 Introduction

Lead (Pb) is a soft, malleable, bluish-gray metal located in group IV of the periodic table of elements (Al-Fartusie and Mohssan 2017). Pb occurs naturally in the soil at a concentration from 0.002 to 0.2 mg/kg, while in fresh waters, from 0.001 to 0.010 mg/L, worldwide (Carrillo-Chávez et al. 2006). The presence of Pb in the environment can be from natural or anthropogenic sources (Li et al. 2012). The primary natural sources of Pb are weathering and erosion of lead-rich rocks, forest fires, and

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volcanic eruptions (Zhang et al. 2019). While anthropogenic Pb results from mining, smelting, leaded gasoline combustion, coal burning, and industrial production of pigments, lead-acid batteries, cable sheathing, ammunition, alloys, solder, and pipes (Ballantyne et al. 2018; Eichler et al. 2015). Both natural and anthropogenic Pb sources have caused a significant increase in their levels in the environment (Zhang et al. 2019). For example, high Pb concentration has been detected in arable lands of Ireland (Nag and Cummins 2022), urban agricultural soils of Cameroon (Aboubakar et al. 2021), and in the arable soil in Southwest China (Wu et al. 2018).

Pb is a non-biodegradable and persistent pollutant that exerts toxic effects on plants, animals, and microorganisms at low concentrations (Wong and Li 2004; Abdelkrim et al. 2020; Rahman and Singh 2019). Pb ranks second on the list of hazardous substances according to the U.S. Agency for Toxic Substances and Disease Registry (ATSDR 2022). In humans, Pb causes haematological and cardiovascular disorders, kidney dysfunction, gastrointestinal disease, and central nervous system damage (Rahimpoor et al. 2020; Khanam et al. 2020; Rahman and Singh 2019). Lead also affects brain development in children, causing behavioural changes and lowering IQ score (Heidari et al. 2022).

Different physical and chemical methods have been developed to remove Pb from contaminated sites. These methods include soil washing, landfilling, vitrification, electrokinetic treatments, surface capping, encapsulation, and soil flushing (Liu et al. 2018; Song et al. 2017). Besides, bioremediation has been proposed as an eco-sustainable alternative for removing natural and anthropogenic Pb from soils, sediments, surface water, and groundwater (Bala et al. 2022). In this technology, living organisms such as bacteria, fungi, microalgae, or plants are used to degrade or transform environmental contaminants into non-toxic forms (Vidali 2001). According to the application site, bioremediation techniques have been classified as in situ or ex situ (He et al. 2021). In situ techniques are carried out directly at the contaminated site, while ex situ techniques are applied outside the contaminated site (Boopathy 2000).

7.2 Phytoremediation: Definition and Strategies

Phytoremediation is an in situ bioremediation technology that uses plants to degrade, immobilize, neutralize, and contain environmental contaminants (Wang et al. 2017). Phytoremediation has been successfully applied to clean up heavy metals, radionuclides, petroleum hydrocarbons, explosives, pesticides, pharmaceutical and personal care products (PPCPs) from aquatic and terrestrial environments (Jee 2016; Kurade et al. 2021). Plants perform phytoextraction, phytovolatilization, phytostabilization, rhizofiltration, phytodegradation, and phytostimulation to remove xenobiotics (Alsafran et al. 2022).

Phytoextraction or phytoaccumulation is used to remove heavy metals and other inorganic compounds from soil and sediment to the aerial parts of plants. In this process occurs the absorption of contaminants by the plant roots, translocation through stems, and their accumulation in shoots and leaves (Mahar et al. 2016; Etim 2012).

Phytostabilization or phytoimmobilization is a strategy in which a plant species reduces the mobility of pollutants and decreases its bioavailability for other plants or microorganisms (Alsafran et al. 2022). In this strategy, heavy metals and other inorganic compounds are adsorbed on root cell walls, absorbed within root tissues, or immobilized as non-toxic forms in the rhizosphere through mechanisms including sorption, precipitation, complexation, or metal valence reduction (Rai et al. 2021; Etim 2012; Yan et al. 2020).

Rhizofiltration is a hydroponic-based phytoremediation technique that uses plant roots to eliminate pollutants from the impacted aquatic environments (Srivastava et al. 2021). In this strategy, heavy metals and other inorganic compounds are adsorbed or precipitated on the root surface or absorbed in the roots (Kristanti et al. 2021).

Phytovolatilization is a strategy in which plants uptake environmental contaminants, transform them into volatile forms, and release them into the atmosphere through transpiration (Etim 2012). This process is applied for the treatment of some metals and metalloids such as arsenic (As), selenium (Se), and mercury (Hg) (Rai et al. 2021). This strategy is controversial because the pollutants are not destroyed but transferred to the atmosphere, where they can be redeposited (Mahar et al. 2016).

Phytodegradation is when plants uptake, store, metabolize or mineralize organic contaminants in their tissues (Rai et al. 2021). The phytodegradation process requires degrading enzymes involved in various metabolic processes and enzymes such as nitrilase, nitroreductase, peroxidase, dehalogenase, oxygenase, and laccases (Chatterjee et al. 2013).

Phytostimulation is a strategy in which plants and microorganisms localized in the rhizosphere degrade organic contaminants (Rai et al. 2021). In this strategy, plants secrete root exudates and metabolites that stimulate the growth of degrading microorganisms (Favas et al. 2014).

7.3 Phytoremediation of Lead

Rhizofiltration, phytostabilization, and phytoextraction are the main strategies for Pb removal from polluted environments. Phytostabilization and phytoextraction are applicable for the remediation of Pb in soils and sediments, while rhizofiltration is used for the remediation of surface water, groundwater, and wastewater (Yan et al. 2020; Otte and Jacob 2006).

7.3.1 Phytostabilization of Lead

Phytostabilization reduces the Pb migration from contaminated to non-contaminated soils (Alsafran et al. 2022; Bolan et al. 2011). In this process, the immobilization of Pb can occur by either adsorption on root cell walls or Pb precipitation in the rhizosphere (Ashraf et al. 2015; Arshad et al. 2016).

The bioavailability of Pb in the soil depends on its speciation, which is influenced by various factors such as pH, redox potential, organic matter, sulphur, and carbonate contents (Olaniran et al. 2013; John and Leventhal 1995). Besides, plant roots play an essential role in the metal and nutrient solubility in the soil (Wenzel et al. 1999). The metabolic activity of the plant roots can change the pH, the redox conditions, concentrations of Dissolved Organic Matter (DOM), and microbial activity in the rhizosphere, which enhance the uptake of nutrients such as iron (Fe), phosphorus (P), and zinc (Zn) or immobilize non-essential metals (Li et al. 2021; Seshadri et al. 2015; Rai et al. 2021). For example, *Pelargonium* × *hortorum* L.H. Bailey increased the DOM content and acidified the rhizosphere soil in response to Pb (Manzoor et al. 2020). Root exudation is one of the most critical factors affecting the physicochemical characteristics of the soil (Li et al. 2011b). The root exudates are a mixture of metabolites, including sugars, amino acids, and organic acids, produced by plants and secreted to the soil (Vives-Peris et al. 2020). These compounds can affect the bioavailability of Pb in the rhizosphere (Li et al. 2021; Seshadri et al. 2015). For example, the waterlogged (*Oenanthe javanica* DC.) and yellow melon (*Cucumis melo* L.) roots release citric acid and others organic acids to the rhizosphere which form soluble Pb–organic complexes (Liu and Luo 2019; Irias Zelaya et al. 2020). Similarly, organic acids secreted by pea plants (*Pisum sativumpea* L.) favour the formation of stable metal complexes in the root region (Austruy et al. 2014).

Pb precipitates have also been observed in the root of *Pelargonium* cultivars, Indian mustard (*Brassica juncea*), and two poplar species (Arshad et al. 2016; Yang et al. 2021; Shi et al. 2021). In *Pelargonium* cultivars, Pb precipitates on the root surface in the form of αPbO, $PbOH^+$, carbonates, and ferrite derivatives (Arshad et al. 2016). On the other hand, in the Indian mustard root cells, Pb precipitates as lead phosphate $Pb_3(PO_4)_2$, pyromorphite $Pb_5(PO_4)_3(OH, Cl)$, and other Pb phosphates (Yang et al. 2021). Similarly, *Populus* × *canescens* and *P. nigra* precipitate the Pb as phosphates and oxalates in their roots (Shi et al. 2021).

Pb immobilization in the root can be due to the interaction between the heavy metal ions and the components of the root cell wall (Krzesłowska 2011). The cell wall is the first structure of root cells to come in contact with heavy metals and is involved in ions metal binding (Parrotta et al. 2015). The cell wall's main components are polysaccharide such as cellulose, hemicellulose (HC), and pectin which play an important role in Pb binding in cell walls (Zhang et al. 2021a; Sumranwanich et al. 2018). Pb adsorption by different cell wall components has been reported previously in tea (*Camellia sinensis* L.) and *Athyrium wardii* (Hook.) roots. In the cell wall of tea plant roots, the most significant amount of Pb is adsorbed mainly by cellulose and lignin (68.42%), followed by pectin (20%) and HC2 (5.26%) (Wang et al. 2015). On the other hand, pectin and HC are the primary binding sites for Pb in root cell walls of *A. wardii* (Zhan et al. 2020). The Pb-binding capacity of cell wall polysaccharides is attributed mainly to the presence of carboxyl (–COOH) and hydroxyls (–OH) groups (Sumranwanich et al. 2018; Wang et al. 2015; Zhan et al. 2020).

Previous studies have reported that Pb increases the biosynthesis of polysaccharides in some plant species' root cell walls. For instance, Pb induced pectin and hemicellulose production in root cell walls of tall fescue (*Festuca arundinacea* Schreb) (Zhang et al. 2020), *A. wardii* (Zhan et al. 2020), *Populus* × *canescens*, and *P. nigra* (Shi et al. 2021), which may be a mechanism of tolerance to Pb stress of these plants.

In the phytostabilization process, the plant roots take up Pb ions or Pb-soluble complexes from the rhizosphere and accumulate them internally (Yan et al. 2020). The Pb within root tissue can be associated with the cell wall in apoplastic space or immobilized intracellularly in vacuoles, limiting Pb translocation from roots to shoots (Yan et al. 2020; Rahman et al. 2022; Wierzbicka 1998).

In signal grass (*Brachiaria decumbens*), Indian mustard (*B. juncea*), and *Neyraudia reynaudiana* it have been observed that most Pb precipitates in the cell wall as insoluble deposits inside the roots (Kopittke et al. 2008; Zhou et al. 2016; Yang et al. 2021). Pb mainly exists as lead phosphate precipitates [$Pb_5(PO_4)_3(OH, Cl)$, and $Pb_3(PO_4)_2$] in the Indian mustard roots cells (Yang et al. 2021). Insoluble deposits of chloropyromorphite [$Pb_5(PO_4)_3Cl$] in root cells have also been observed in signal grass (*B. decumbens*) roots (Kopittke et al. 2008).

Vacuolar sequestration of Pb in radicular cells limits its translocation within plants (Sharma and Dubey 2005). Vacuoles are the largest organelle of plant cells and play an essential function in the heavy metal detoxification (Sharma et al. 2016). In this organelle, intracellular Pb is stored by complexation with organic acids and sulfur-rich peptides known as phytochelatins (Zhang et al. 2018; Singh et al. 2017; Zhao et al. 2015). In addition to cell walls, the vacuoles are one of the main storage sites of Pb in *Allium sativum* and *N. reynaudiana* roots (Jiang and Liu 2010; Zhou et al. 2016). Approximately, 31.2–41.3% of total Pb is stored in the vacuoles of roots *A. wardii* (Hook.) (Zhao et al. 2015).

7.3.2 Phytoextraction of Lead

Phytoextraction is a method used to reduce Pb levels in soil and sediments. This method requires Pb uptake by plant roots, root-to-shoot translocation, and intracellular compartmentalization of Pb in aerial tissues (Yan et al. 2020). These processes are dependent on plant species, variety, genotype, environmental conditions, and Pb bioavailability in the soil (Asare et al. 2023).

The first step in Pb accumulation is the Pb uptake by the root (Gong et al. 2022). The Pb ions from the soil are absorbed by the root epidermal cells and can be transported inside the root by apoplastic or symplastic pathways (He et al. 2023; Zhou et al. 2018). In the apoplastic pathway, Pb in the extracellular fluid is transferred from one cell wall to another, whereas in the symplastic pathway, the Pb ions cross the plasma membrane and transfer cell to cell through channels called plasmodesmata (Pasricha et al. 2021). As Pb is not an essential element, plants do not have a specific channel for Pb uptake, so it has been suggested that Pb enter the plant cells via channels or transporters for other essential cations (Peralta-Videa et al. 2009; Gong et al. 2022). Different proteins have been associated with Pb transport across the membrane, such as AtCNGC1 (cyclic nucleotide-gated channel 1), NtCBP4 (Plasma membrane Calmodulin-Binding Protein 4), and OsNRAMP5 (Natural Resistance-Associated Macrophage Proteins 5) (Arazi et al. 1999; Sunkar et al. 2000; Chang et al. 2022). In tobacco (*Nicotiana tabacum*) and *Arabidopsis thaliana*, two cation channels for K^+ and Ca^{2+} called NtCBP4 and AtCNGC1, respectively, have been associated with Pb uptake across the plant plasma membrane and Pb accumulation (Arazi et al. 1999; Sunkar et al. 2000). On the other hand, the OsNRAMP5, a divalent metal transporter, is associated with transporting intracellular Pb in rice (*Oryza sativa*) roots (Chang et al. 2022). Once inside the root cells, Pb is associated with amino acids and organic acids and can be translocated to shoots and leaves by the xylem (Gall and Rajakaruna 2013; Pourrut et al. 2013).

At the shoot level, intracellular Pb is detoxified by metal-binding ligands such as phytochelatins and metallothioneins (Mitra et al. 2014; Pourrut et al. 2011; Eapen and D'Souza 2005). Phytochelatins (PC) are oligopeptides that contain glutamic acid (Glu), cysteine (Cys), and glycine (Gly) [$(\gamma\text{–Glu–Cys})_n\text{–Gly}$ ($n = 2 - 11$)], whose synthesis is catalyzed by phytochelatin synthase (PCS) from glutathione (Scarano and Morelli 2002; Gupta et al. 2013b). While metallothionein (MT) are low-molecular-weight proteins (7–10 kDa) with 9–16 cysteine residues that are encoded by a family of MT genes (Eapen and D'Souza 2005; Cobbett and Goldsbrough 2002). Previous studies have reported that the plants synthesize PC and MT in response to Pb stress. For example, it has been observed that Pb exposure induces the synthesis of PC in *Salvinia minima* Baker, Dwarf bamboo (*Sasa argenteostriata*), and coontail (*Ceratophyllum demersum* L.) (Jiang et al. 2020; Estrella-Gómez et al. 2009; Mishra et al. 2006), and increases the expression of MT genes in tomato (*Lycopersicon esculentum*), *Bruguiera gymnorrhiza*, and rice (*O. sativa*) plants (Kim and Kang 2018; Kisa et al. 2017; Huang and Wang 2009).

In the cytoplasm of shoot cells, PC and MT binding to intracellular Pb and form stable complexes. The PC–Pb complex is finally transported into the vacuole, where it is stored (Andra et al. 2009; Inouhe et al. 2012).

7.3.3 Rhizofiltration of Lead

Rhizofiltration is a technique used to remove Pb from surface water, groundwater, and effluents with low levels of contaminants (Ekta and Modi 2018; Jadia and Fulekar 2009). Similarly, to the phytostabilization process, in the rhizofiltration, the Pb ions can be absorbed within root tissues (Kristanti et al. 2021; Rawat et al. 2012), adsorbed by root cell walls (Ho et al. 2021), or immobilized in the root surface (Delgado-González et al. 2021; Dushenkov et al. 1995).

In aquatic and wetland plants, iron plaque plays an essential role in the sequestration of heavy metals in the roots (Tripathi et al. 2014). The Fe plaques are deposits of different iron oxides and hydroxides on the root surface (Tripathi et al. 2014; Khan et al. 2016). The presence of ferrihydrite [$Fe_{4\text{–}5}(OH,O)_{12}$], lepidocrocite [$\gamma\text{–FeOOH}$], siderite [$FeCO_3$], and goethite [FeO(OH)] has been observed in the Fe plaques of *Oenanthe javanica*, *Phalaris arundinacea*, and *Vallisneria americana* (Liu and Luo 2019; Hansel et al. 2001; St-Cyr et al. 1993). These Fe (hydr)oxides are result of oxidation of ferrous iron (Fe^{2+}) in the rhizosphere by the oxygen loss from the roots, and the biological activity of microorganisms (Tripathi et al. 2014; Khan et al. 2016). Previous studies have reported that iron plaque can sequester Pb on the root surface (Zandi et al. 2022). In rice (*O. sativa*), the most significant amount of plant taken Pb (> 60%) is stored in the iron plaque of the root (Cheng et al. 2014; Ma et al. 2013). Similarly, most of the total Pb uptake (50–60%) performed by *Phalaris arundinacea* L. and *Carex cinerascens* Kukenth. plants was found in the iron plaque, and only small amounts was found in roots and shoots (Liu et al. 2015, 2016). The Pb–binding capacity of Fe plaques is attributed mainly to the Pb's specific and high affinity for iron (hydr)oxides (Hansel et al. 2001).

7.3.4 Potential Plants for Phytoremediation of Pb

The concentration of heavy metals in plants determines the success of phytoremediation; therefore, selecting suitable plant species is crucial in phytoextraction, phytostabilization, and rhizofiltration efficiency (Yan et al. 2020; Gupta et al. 2013a).

Hyperaccumulator plants can potentially remove Pb from the soil through phytoextraction (Lone et al. 2008). Pb hyperaccumulators are plants able to grow in contaminated soils with heavy metals and accumulate more than 1000 mg/kg of Pb in aerial organs without show phytotoxicity signs (Sytar et al. 2021; Manara et al. 2020). However, Pb hyperaccumulation in plants is uncommon because Pb ions are easily precipitated in the rhizosphere, limiting their uptake by roots and the translocation to shoots (Baker and Brooks 1989). In the Global Hyperaccumulator Database (http://hyperaccumulators.smi.uq.edu.au/collection/), *Alyssum wulfenianum*, *Noccaeae rotundifolium* subsp. *cepaeifolium*, *Polycarpaea synandra*, *Sesbania drummondii*, *Armeria maritima* var. *Halleri*, *Dactyloctenium aegyptium*, *Microstegium ciliatum*, *Polygala umbonata*, and *Spermacoce mauritiana* plants, belonging to seven families, have been identified as Pb hyperaccumulators (Reeves et al. 2018). Although these plants accumulate high concentrations of Pb, hyperaccumulator plants are small and present slow growth, which limits their use in the phytoremediation process (Saifullah et al. 2009; Yan et al. 2020).

Different fast-growing crops with high biomass production, like sorghum (*Sorghum bicolor* L.), sunflower (*Helianthus annuus* L.), and corn (*Zea mays*) have been studied to remove Pb from lead contaminated soil under field conditions (Cheng et al. 2015; Zehra et al. 2020; Yuan et al. 2019). Despite the lower concentrations of Pb in their tissues, the total metal remotion exerted by these plants can be like levels reached by hyperaccumulator plants (Van Slycken et al. 2008).

Native plants grown on heavy metal contaminated sites are another option for Pb remediation. These plant species can survive, grow, and reproduce under metal stress better than plants introduced from other environments (Midhat et al. 2019;

Yoon et al. 2006). Several studies have evaluated the phytoremediation potential of native plants growing in heavy metal-contaminated sites (Table 7.1). For example, Salazar and Pignata (2014) studied the vegetal community growing around a lead smelter plant in Argentina. On the other hand, Mahdavian et al. (2017) and Nouri et al. (2011) investigated plants colonizing a lead–zinc mining area in Iran. In Marocco, Midhat et al. (2019) and Hasnaoui et al. (2020) identified metal-tolerant native plant species from three abandoned mining sites and a contaminated site near a Pb/Zn mining area, respectively. In these sites, some plants belonging to the Asparagaceae, Asteraceae, Brassicaceae, Cucurbitaceae, Cyperaceae, Euphorbiaceae, Fabaceae, Gramineae, Lamiaceae, Liliaceae, Resedaceae, and Tamaricaceae families have been observed (Table 7.1).

The phytoremediation potential of plants can be estimated using Bioconcentration Factors (BCF) and Translocation Factors (TF) (Rolón-Cárdenas et al. 2022). The BCF is the ratio between the heavy metal content in the plant roots and the substrate (Zou et al. 2012; Lorestani et al. 2011). Various native plant species like *Artemisia sieberi* Besser, *Fortuynia bungei* Boiss., *Astragalus durandianus* Aitch. & Baker, *Mentha longifolia* L., and *Allium umbilicatum* Boiss. have showed BCF > 1 for Pb (Table 7.1), indicating the potential of these plants to be used in Pb phytostabilization (Lorestani et al. 2013).

On the other hand, TF is the ratio of heavy metal content in the shoots and the roots (Midhat et al. 2019; Lorestani et al. 2011). Values TF > 1 for Pb has been reported in different native plants such as *Lactuca viminea* (L.) J. Presl & C. Presl, *Scariola orientalis* (Boiss.) Sojak, *Scolymus hispanicus*, *Cyperus iria*, *Juncellus serotinus*, *Euphorbia macroclada* Boiss., *Echinophora platyloba* DC., *Paspalum paspaloides*, *Phragmites australis*, *Reseda alba*, and *Tamarix ramosissima* Ledeb. (Table 7.1). This TF value indicates high efficiency in Pb translocation from the roots to the shoots and, therefore, their potential to be used in phytoextraction (Midhat et al. 2019).

Rhizofiltration uses heavy metal tolerant plants with a fibrous root system and large surface areas to 'filter' Pb ions in solution (Chatterjee et al. 2013; Nedjimi 2021). Different aquatic plants have been studied to remove Pb from water through rhizofiltration (Kafle et al. 2022). For example, *Alternanthera sessilis*, *Enhydra fluctuans*, *Pistia stratiotes*, *Salvinia cucullata*, *Typha latifolia*, and *Vetiveria zizanioides* can remove between 84 and 99% of Pb from solution and accumulate into root and shoot (Das et al. 2021; Parven et al. 2022; Veselý et al. 2011; Alonso-Castro et al. 2009; Singh et al. 2015). Some terrestrial plants such as Indian mustard (*B. juncea*), *Cosmos sulphureus* Cav., sunflower (*H. annuus* L.), *Iris lactea* var. *chinensis*, and *Talinum paniculatum* are also suitable for rhizofiltration due to they remove high amount of Pb from the hydroponic medium and accumulate it in roots and shoots (Liu et al. 2000; Aftab et al. 2021; Seth et al. 2011; Han et al. 2008; dos Reis et al. 2022).

The plants used for rhizofiltration are first cultivated in hydroponic conditions to favour the root system development, later transferred to the contaminated water source, and finally harvested when the root of plants are saturated with contaminants (Mansoor et al. 2022; Yan et al. 2020).

Table 7.1 Native plants growing on heavy metal contaminated sites

Family	Plant	Pb concentration (mg/kg)			Factors		References
		Soil	Root	Shoot	TF	BCF	
Asparagaceae	*Asparagus horridus* L.	10,813.1	45.2	15.2	0.3	0.004	Midhat et al. (2019)
Asteraceae	*Artemisia sieberi* Besser	127.4	345.2	106.2	0.3	2.71	Mahdavian et al. (2017)
Asteraceae	*Bidens pilosa* L.	11,936.0	741.0	59.8	0.1	0.06	Salazar and Pignata (2014)
Asteraceae	*Lactuca viminea* (L.) J. Presl & C. Presl	1077.5	149.2	201.7	1.4	0.14	Midhat et al. (2019)
Asteraceae	*Scariola orientalis* (Boiss.) Sojak	1204.0	9017.0	9140.0	1.0	7.49	Nouri et al. (2011)
Asteraceae	*Scolymus hispanicus*	7792.9	798.7	972.7	1.2	0.10	Hasnaoui et al. (2020)
Asteraceae	*Tagetes minuta* L.	2645.0	30.7	20.0	0.7	0.01	Salazar and Pignata (2014)
Brassicaceae	*Fortuynia bungei* Boiss.	127.0	1720.1	73.0	0.0	13.54	Mahdavian et al. (2017)
Cucurbitaceae	*Citrullus colocynthis* (L.) Schrader	6156.7	94.4	38.4	0.4	0.02	Midhat et al. (2019)
Cyperaceae	*Cyperus iria*	40.8	35.5	54.0	1.5	0.87	Li et al. (2011a)
Cyperaceae	*Juncellus serotinus*	155.0	67.9	91.0	1.3	0.44	Li et al. (2011a)
Euphorbiaceae	*Euphorbia gedrosiaca*	564.9	332.1	52.1	0.2	0.59	Mahdavian et al. (2017)
Euphorbiaceae	*Euphorbia hirta*	283.0	30.6	13.9	0.5	0.11	Li et al. (2011a)
Euphorbiaceae	*Eupatorium inulifolium* Kunth	11,936.0	441.0	52.2	0.1	0.04	Salazar and Pignata (2014)
Euphorbiaceae	*Euphorbia macroclada* Boiss.	9451.0	3809.0	8095.0	2.1	0.40	Nouri et al. (2011)
Fabaceae	*Astragalus durandianus* Aitch. & Baker	241.0	1189.5	137.0	0.1	4.94	Mahdavian et al. (2017)

(continued)

Table 7.1 (continued)

Family	Plant	Pb concentration (mg/kg)			Factors		References
		Soil	Root	Shoot	TF	BCF	
Fabaceae	*Hedysarum spinosissimum*	6445.1	983.6	253.9	0.3	0.15	Hasnaoui et al. (2020)
Fabaceae	*Lotus corniculatus*	12,223.8	1493.0	832.4	0.6	0.12	Hasnaoui et al. (2020)
Gramineae	*Echinophora platyloba* DC.	10,426.0	1421.0	10,121.0	7.1	0.14	Nouri et al. (2011)
Gramineae	*Paspalum paspaloides*	186.0	18.0	50.5	2.8	0.10	Li et al. (2011a)
Gramineae	*Phragmites australis*	174.0	1.3	8.3	6.3	0.01	Li et al. (2011a)
Lamiaceae	*Mentha longifolia* L.	58.0	2168.9	125.0	0.1	37.39	Mahdavian et al. (2017)
Liliaceae	*Allium umbilicatum* Boiss.	25.0	1257.6	80.0	0.1	50.30	Mahdavian et al. (2017)
Resedaceae	*Reseda alba* L.	9535.0	1743.0	703.0	0.4	0.18	Nouri et al. (2011)
Resedaceae	*Reseda alba*	13,487.6	322.7	1607.5	5.0	0.02	Hasnaoui et al. (2020)
Tamaricaceae	*Tamarix ramosissima* Ledeb.	10,401.0	130.0	2010.0	15.5	0.01	Nouri et al. (2011)

7.4 Microbial-Assisted Pb Phytoremediation

Soil microorganisms fulfill essential ecosystem processes since they regulate biogeochemical cycles and decompose organic matter to maintain soil fertility (Basu et al. 2021). Plants establish associations with different types of soil microorganisms like bacteria and fungi which contribute to the host adaptation to environmental conditions (Gan et al. 2017; Narula et al. 2012). The rhizosphere is the zone of the soil around the plants' roots where occurs intense biological activity during the plant-soil-microorganism interactions (More et al. 2019; Pathan et al. 2020).

Rhizobacteria and epiphytic bacteria are a broad group of soil bacteria that colonize the area around the roots, and the root surface, respectively (Taulé et al. 2021). While the endophytic bacteria colonize the internal plant tissues without causing adverse effects on their host plants (Ma et al. 2011).

Plant-associated microorganisms play an essential role in the metal phytoremediation process. These microorganisms can promote plant growth, reduce metal phytotoxicity, modify metal uptake and accumulation in the plant, and increase metal bioavailability in soil or water (Ma et al. 2016; Rajkumar et al. 2012). For example, two rhizospheric bacteria identified as *Bacillus proteolyticus* and *B. licheniformis*, increased the biomass of *Solanum nigrum* plants growing in heavy metal-contaminated soil, and the total Pb content in roots and shoots (He et al. 2020). Under axenic conditions, a rhizospheric arsenic-resistant bacteria also increased Pb concentration in the root of *Pteris vittata* (Manzoor et al. 2019). An endophytic microbial consortium isolated from three native plants increased Pb accumulation in roots and shoots of *B. juncea*, and Pb concentration in sunflower (*H. annuus*) roots (Pietrini et al. 2021).

In recent years, it has been demonstrated the potential of in situ plant-bacteria interaction for promote plant growth under Pb stress and Pb removal from water and contaminated sites. In an agricultural field contaminated with Pb and Cd, a consortium of four heavy metals resistant bacteria (*Rhizobium leguminosarum*, *Bacillus simplex*, *Luteibacter* sp. and, *Variovorax* sp.) increased plant length, dry biomass, nodule number of *Lathyrus sativus* plants, and enhance Pb accumulation in roots in comparison with uninoculated plants (Abdelkrim et al. 2020). Endophyte bacteria *Pseudomonas putida* RE02 reduced the mortality percentage of *Trifolium repens* seedlings under metal stress and improved Pb uptake by *T. repens* plants grown in heavy metal contaminated tailings (Liu et al. 2021).

In a constructed wetland, a consortium of five rhizobacteria (*Bacillus cereus*, *B. pumilus*, *B. subtilis*, *Brevibacillus choshinensis*, and *Rhodococcus rhodochrous*) increased Pb sorption by *Scirpus grossus* plants from contaminated water (Tangahu et al. 2022).

Bacterial communities can improve growth and tolerance to metal stress in host plants by producing phytohormones and enzyme 1–aminocyclopropane–1–carboxylate (ACC) deaminase which reduces ethylene production (Kong and Glick 2017; Sharma 2021). These bacteria also promote plant growth and favour nutritional status by improving the absorption of water and nutritive elements such as nitrogen (N), phosphorus (P), and iron (Fe) through mechanisms like nitrogen fixation, P-solubilization, and siderophores production (Ma et al. 2011; Etesami 2018; Manoj et al. 2020).

Like bacteria, fungi have also been evaluated to increase phytoremediation efficiency. Arbuscular Mycorrhizae (AM) are fungal endophytes that colonize the internal root tissues of higher plants (Deng and Cao 2017; Gaur and Adholeya 2004). AM fungi have also been shown to promote plant growth under Pb stress and increase Pb accumulation in plants. For example, *Funneliformis mosseae*, *Claroideoglomus etunicatum*, and *Rhizophagus intraradices*, promote the growth of the soybean (*Glycine max* L.) exposed to 100 and 300 mg/kg Pb, and increase Pb accumulation in the roots compared to non-inoculated plants (Adeyemi et al. 2021). *F. mosseae* inoculation also increased Pb accumulation in root and dry weights of *Bidens parviflora* under Pb stress (Yang et al. 2022). Similarly, *Rhizophagus irregularis* increases the shoot biomass of *Medicago truncatula* under Pb stress (800 mg/kg), and enhances the Pb concentration and content in its roots (Zhang et al. 2021b).

Arbuscular mycorrhizae inoculation may increase the Pb tolerance of the host plant and accumulation in the roots through immobilization of Pb ions by the root cell wall or by the fungal cells (Zhang et al. 2010, 2021c). *R. irregularis* inoculation induced pectin and hemicellulose production in root cell walls of *M. truncatula*, which increases the Pb immobilization (Zhang et al. 2021c). On the other hand, in maize (*Z. mays*) plants inoculated with AM fungi, the most significant amount of Pb in roots is localized in the hyphal wall and within fungal cells (Zhang et al. 2010).

7.5 Conclusion

Rhizofiltration, phytostabilization, and phytoextraction are the main phytoremediation strategies for Pb removal from polluted environments. In the phytostabilization and rhizofiltration process, the Pb ions can be precipitated in the rhizosphere, immobilized on root cell walls, or sequestered on the root surface. In contrast, in phytoextraction, the Pb is uptake by plant roots, translocated from roots to shoots, and accumulated in aerial tissues. The Pb hyperaccumulator plants, fast-growing crops with high biomass production, and the native plants growing on heavy metal contaminated sites have been used to remove Pb from the soil, while the aquatic and terrestrial plants with fibrous root systems are suitable for Pb removal of surface water, and groundwater. The plant-associated microorganisms like bacteria and fungi could be used as an alternative to improve the Pb phytoextraction efficiency.

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