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Removal of Heavy Metals in Contaminated Soil by Phytoremediation Mechanism: a Review

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Abstract The rapid development of industrial sector has increased the heavy metal pollution issue recently, as the need of various metals is increasing for manufacturing purpose. These metals are the natural components that can be found in soil, but contamination happens when the concentration of these metals are high in soil due to anthropogenic activities. Several remediation techniques such as physical method, thermal desorption, chemical, and electrokinetic remediation are used to remediate the soil contaminated by heavy metals recently. As these remediation technologies have limitation on cost, effectiveness, and environmental friendly remediation issue, phytoremediation is then attracting the attention from various researchers due to its advantages of efficient, cost-effective, and eco-friendly remediation method. The mechanisms of phytoremediation are phytoextraction, phytostabilization, phytovolatilization, phytodegradation, phytodesalination, rhizofiltration, rhizodegradation, and phytoevaporation. However, these mechanisms were affected by several factors such as the plant species, properties of medium, bioavailability of metal, and the addition of chelating agent. The type of plant utilized for phytoremediation (metallophytes) is categorized as metal indicators, metal excluders, and metal hyperaccumulators. This review article comprehensively discusses the source and effect of heavy metal on human health as well as phytoremediation techniques and mechanism during the heavy metal removal.

Keywords Phytoremediation · Environmental pollutant · Toxicology · Heavy metal · Metallophytes plant

1 Introduction

The rapid development of the industrial sector has increased the heavy metal pollution issue recently, as the need for various metals is increasing for manufacturing purposes. Heavy metals such as copper, lead, zinc, cadmium, chromium, and arsenic are widely used by agriculture and industries and are highly toxic at very low concentrations. These metals are the natural components that can be found in soil, but contamination happens when the concentration of these metals are high in soil due to the mining and smelting activities (Tchounwou et al. 2012). This issue has become a worldwide concern as the heavy metal can enter the food chain and eventually cause adverse health impacts on humans (Fig. 1). Besides, a human can also expose to the heavy metal in the soil through inhalation of particulate matter and direct contact with the contaminated soil (Ali et al. 2013). Table 1 gives toxicity level, anthropogenic sources of heavy metals, and its effect on human health. Thus, recovery and remediation of the contaminated sites are required to prevent the health impact on humans. During the time when there is no advanced technology to carry out soil remediation, the

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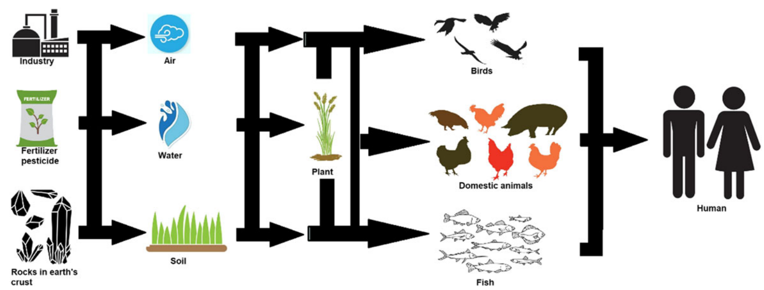

Fig. 1 Source of heavy metal and their pathway in the environment

heavy metal–contaminated soils are controlled using on-site management or being excavated and disposed of a landfill site. However, this method does not solve the heavy metal contamination issue, but only involve the migration of the heavy metal–contaminated soil from the contaminated site to landfill. With the development of remediation techniques and technologies, several chemical and physical methods have been used to remediate the contaminated site recently. However, these methods require a high cost and are technically complicated to apply (Tangahu et al. 2011). These methods can also cause disturbance of native soil microflora and irreversible changes in soil properties by degrading the valuable component of soils. Moreover, the chemical technologies can produce secondary pollution problems, which a large volume of sludge will be generated and hence, increase the cost for sludge management (Rakhshaee et al. 2009).

As an effective, eco-friendly, cost-effective, and easy-to-apply remediation method, phytoremediation has gained enormous interest from the researchers for soil remediation. Phytoremediation is a treatment method that utilized plants and the associated soil microbes to remove the contaminants in the environment (Ali et al. 2013). The plant used to remove the contaminant is not affecting the topsoil; thus, this method does not disturb the ecosystem and is environment-friendly (Cristaldi et al. 2017). Heavy metals can be in the form of free metal ions and soluble metal complexes in the soil. Besides, they can also precipitate hydroxides, oxides, carbonate, and embedded into a silicate mineral structure. The bioavailability of the heavy metals is important in order to let the heavy metal contaminant be absorbed by the plant roots through phytoremediation techniques. However, the solubility of the metals can affect the bioavailability of heavy metals in soil (Cristaldi et al. 2017; Tangahu et al. 2011; Tchounwou et al. 2012). This paper aims to overview the phytoremediation concept and discusses the use of several mechanisms to phytoremediate the heavy metal–contaminated soil. Several factors that affect the mechanisms uptake were also reviewed.

2 Current Trend of Heavy Metal Remediation Techniques

With the increment of urbanization and industrialization, the cases of soil contaminated by heavy metals have increased rapidly and become a threat to food safety, ecological environment, and sustainable development of the agriculture sector (Yao et al. 2012). Thus, soil remediation is essential to avoid the adverse impact, reduce the risk to the environment from toxic metals, and ensure a safe environment for future generations (Cristaldi et al. 2017). Several remediation techniques such as soil replacement method, thermal desorption, chemical leaching, and electrokinetic remediation are used to remediate the soil contaminated by heavy metals recently (Table 2).

Soil replacement method is a soil remediation method that dilutes the concentration of the contaminant in the soil and then increases the soil's environmental capacity. Soil spading, soil replacement, and new soil importing are the three concepts used in this method. Soil spading is a technique that carries out natural degrading of the contaminant in the soil by digging and spreading the contaminated soil to reduce the concentration of the contaminant (Derakhshan Nejad et al. 2018; Yao et al. 2012). Soil replacement is a method that can be applied for small area-contaminated soil by removing the contaminated soil and replacing with the new and clean soil. This method requires treatment for the replaced soil to inhibit second pollution (Paz-Ferreiro et al. 2018; Yao et al. 2012). New soil importing is also a method to dilute the contaminated soil by adding a large amount of clean soil, covering, and mixing with the contaminated soil. This method is

Table 1 Source and effect of heavy metal for human health

Toxicity level	Heavy metals	Sources	Harmful effect	References
High poisonous	As	Antipyretics, antiseptics, caustics, antispasmodics, herbicides, fungicides, insecticides, paint, and cosmetics	Carcinogen, cellular damage and cell death	Chen and Olsen (2016)
	Cd	Batteries, ceramics, electronic and metal-finishing industries, electroplating industries, pigments, petroleum products, textiles, insecticides, solders, television sets, metallurgical industries	Causing irreversible damage to the renal tubules, which are involved in the mechanisms of nutrient reabsorption	Pulford and Watson (2003); Rubio et al. (2018)
	Hg	Mining and coal combustion, medical waste	Neurotoxin which impairs brain function, cause damage to kidney and lung	Clarkson and Magos (2006); Rodrigues et al. (2012)
	Pb	Melting and smelting of ores, exhaust from automobiles, fertilizer, pesticide, additive in pigment and gasoline, urban soil waste	Respiratory diseases and heart, brain and kidney damage	Zulfiqar et al. (2019)
	Se	Electronics, paint industry, glass industry, ceramics, metallurgy, chemical industry, and pharmaceutics and in agriculture	Acute toxicity in respiratory, gastrointestinal, cardiovascular difficulties and hypertension, or chronic toxicity	Etteieb et al. (2020)
	Zn	Galvanizing iron and steel, construction, siding, apparatus housings, office hardware, heating and ventilation conduits, vehicle, and building enterprises for roofing	Diarrhea, liver failure, bloody urine, icterus, kidney failure, stomach cramps, abdominal cramps, epigastric pain	Vardhan et al. (2019)
Moderately poisonous	Co	Metal industry, construction industry, cosmetics and jewelry, medical exposure	Neurological, cardiovascular, and endocrine	Leyssens et al. (2017)
	Cr	Leather tanning, metallurgy, electroplating, and refractory	Ulcerations, dermatitis, and allergic skin reactions	Almeida et al. (2019)
	Cu	Electronic chips, batteries, cell phones, semiconductors, water pipes, fertilizer industry, pulp, and paper industry, fungicides, insecticides, catalysts, and metal processing products	Epigastric torment, gastrointestinal bleeding, diarrhea, spewing, tachycardia, hematuria, respiratory challenges, hemolytic anemia	Vardhan et al. (2019)
	Ni	Mining, smelting, emissions from vehicles, disposal of household, municipal and industrial waste, steel manufacturing and cement industry	Lung irritation, lung inflammation (pneumonia), and emphysema	Schaumlöffel (2012)
Low poisonous	Ba	Ore mining and refining	Damage to the cardiovascular, renal, respiratory, hematological, nervous, and endocrine systems	Lu et al. (2019)
	Mn	Mining and metallurgical industries	Manganese neurotoxicity	Nelson et al. (2018)
	Sr	Thermal power plants, ferrous metallurgy enterprises, non-ferrous metallurgy enterprises, and chemical industry	Destruction of the whole body (general toxic effect)	Mironyuk et al. (2019)

Table 2 Current bioremediation techniques for heavy metal removal

Techniques	Principles	Pollutant	Reference
Natural attenuation	The use of natural processes to contain or reduce the amount of pollutants at contaminated sites	Cu, Pb, Zn	Agnello et al. (2016)
Soil flushing	The application of aqueous solutions in the soil to solubilize contaminants	Cd, Pb	Lee et al. (2011)
Soil washing	A technique of using liquid or chemical additive to washing the soil, scrubbing the soil, and then separating the clean soils from contaminated soil and washwater	Cd	Mu'azu et al. (2018)
Thermal desorption	The use of heat/high-temperature condition to increase the volatility of contaminants in order to remove them from the solid matrix	Hg	Back et al. (2020)
Electrokinetic	The use of direct electric current to remove contaminant particles from the soil by electric potential	Cu, Zn, Cr, Pb, Ni, Mn	Tang et al. (2017)
Oxidation	The application of chemical oxidants into the subsurface soil to oxidize and degrade organic contaminants	Cu, Zn, Pb, Cd, Cr	Guo and Zhou (2020)
Solidification	A technique that pollutants are rendered immobile by reactions with additives or processes	Pb, Zn, Cd	Xia et al. (2019)
Vitrification	A technique of using electricity to heat-contaminated soil sufficiently to produce an inert glass product.	Pb, Zn, Zr	Dellisanti et al. (2009)
Incineration	The application of combustion of contaminants contained in waste materials.	Zn, Cd, Pb, Cu	Atanes et al. (2019)
Biostimulation	A technique to stimulate existing bacteria in soil to increase their capability in bioremediation	Cu	Chen and Achal (2019)
Bioaugmentation	The use of additional bacterial cultures to speed up the rate of degradation of a contaminant in soil	Pb and Zn	Sprocati et al. (2012)
Bioleaching	A technique of using microorganisms to extract metals from contaminated soil	Ni, Cu, Zn	Wu et al. (2020)
Rhizoremediation	A process where microorganisms degrade soil contaminants in the rhizosphere	Cr	Ontañon et al. (2014)
Phytoremedition	A techniques of using living plants to clean up soil, air, and water contaminated with hazardous contaminants	Cd, Ni, Zn, Pb, and Cu	Doni et al. (2015)

decreasing the toxic effect on the environment effectively, but it is expensive, required big working volume and only appropriate for small-scale severely contaminated soil treatment. Besides, the executing of earthworks when using the soil replacement method may also disturb the ecosystem within the soil (Yao et al. 2012).

Thermal desorption is a remediation method that volatilizes the heavy metals such as mercury and metalloid arsenic by heating the contaminated soil using a microwave, steam, and infrared radiation. The vacuum negative pressure or carrier gas is then being used to collect and remove the volatilized heavy metals (Derakhshan Nejad et al. 2018; Paz-Ferreiro et al. 2018). The two types of thermal desorption are high-temperature desorption, which carried out with temperature between 320 and 560 °C, and low-temperature desorption, which carried out with temperature between 90 and 320 °C. The advantage of this remediation technology is having a simple process to carry out soil remediation. However, the devices used to carry out thermal desorption are expensive and required long desorption time (Yao et al. 2012).

A remediation technique that leaches the contaminant from the soil is called soil washing or chemical leaching. This method uses liquids that contain chelation agents, freshwater, and other solvents to wash the contaminated soil with mechanical processes (Tampouris et al. 2001; Yao et al. 2012). The environmental and health effects and the ability to solubilize specific contaminants are the factors to select the solvents used. By using this method, the heavy metal content in the soil is transferred from the soil to the liquid and formed leachate. The leachate is then comprising the chelation agents, surfactant, and inorganic eluent such as the heavy metals. This remediation method requires multiple mechanical processes to remove the contaminants in the soil. For example, the soil has to go through physical washing first, then only remove the contaminants through several stages of the chemical extraction process. The soil also needs to be heated up to 200 °F by using a volume of reduction washing unit and be washed with a surfactant, water, and other solvents. Researchers have found that ethylenediaminetetraacetic acid (EDTA) is an effective chelation agent for soil washing. However, this chelation agent is expensive and bad in biological degradability (Derakhshan Nejad et al. 2018; Paz-Ferreiro et al. 2018; Yao et al. 2012).

Soil treatment method which uses an electric field gradient to remediate the contaminated soil is called electrokinetic remediation. This method generates a low electric field by inserting two electrodes in the contaminated soil (Derakhshan Nejad et al. 2018). Electromigration, electrophoresis, or electroosmotic flow is then becoming the driving force to transport the contaminants from soil to electrodes. The contaminants can then be removed when they adsorb or precipitate at the electrode. This treatment method suits for the treatment of low permeable soil has low cost and is easy to install and operate (Acar and Alshawabkeh 1993; Virkutyte et al. 2002). As the application of this treatment method does not destroy the natural ecosystem in the soil, it is considered an environmentally friendly method. Nevertheless, the treatment efficiency of this method is low and cannot control well the pH value of the soil system. Moreover, the current flow will be diverted when there are buried metal objects in the soil and thus, requires a longer time for remediation. The presence of a high amount of unknown contaminants will also affect the effectiveness of electrokinetic remediation. As these remediation technologies have a limitation on cost, effectiveness, and environmentally friendly remediation issue, phytoremediation is then attracting the attention of various researchers due to its advantages of efficient, cost-effective, and eco-friendly remediation methods (Derakhshan Nejad et al. 2018; Yao et al. 2012).

3 Techniques of Phytoremediation

Phytoremediation defines as the use of the plant to render the soil and water harmless by adsorbing or degrading the contaminants. This remediation method is a biological remediation method as the plant is the biological component used to treat the contaminated environment. Phytoremediation is a cost-effective remediation method as it involves only little manpower. Besides, the esthetically pleasant characteristic of phytoremediation method has made it be a remediation method that is well accepted by surrounding residents. Phytoremediation is classified as an environmentally friendly method as it reduces the risk of contaminant dispersion and protects the original ecotype by avoiding the excavation of the contaminated sites (Cristaldi et al. 2017; Derakhshan Nejad et al. 2018). Phytoremediation is also being applied for the purpose of risk containment and phytoextraction of valuable metals such as nickel, thallium, and gold. Moreover, previous researchers have also found the economic value for applying phytoremediation on durable land as the land can be used to cultivate crops with higher market value when the soil quality is improved through phytoextraction (Vangronsveld et al. 2009). The mechanisms of phytoremediation are phytoextraction, phytostabilization, phytovolatilization, phytodegradation, phytodesalination, rhizofiltration, rhizodegradation, and phytoevaporation (Table 3). The mechanisms involved in the remediation of heavy metal–contaminated soil are shown in Fig. 2.

3.1 Phytoextraction

Phytoextraction or phytoaccumulation is performed by a plant when the roots of the plant absorb the contaminants from soil or water, transport, and accumulate the contaminants in the aboveground biomass such as shoots and leaves. The plant that is used to carry out phytoextraction should have high ability in producing high biomass or accumulating the contaminants (Lei et al. 2018; Sterckeman et al. 2019; Suman et al. 2018). Hyperaccumulator species are the desirable plants to be used for performing phytoextraction as they have a high ability to accumulate the contaminants (Cristaldi et al. 2017). However, the plant species that can produce high biomass but accumulate less can also be used to execute phytoextraction (Li et al. 2018; Nakajima et al. 2019). The effectiveness of the plant species in metal phytoextraction is determined through the ratio of metal concentrations in the soil and the plant. The plants that carry out phytoextraction are then be harvested and incinerated. The ash produced from the incineration will be sent to landfill for disposal, and thus, the contaminants in the soil are removed. However, the low bioavailability of metal in soil and low absorption rate of metal will limit the performance of phytoextraction. Besides, the effectiveness of phytoextraction will also be lowered when the metals are held within the roots instead of being transported to the shoots and leaves (Barman et al. 2000; Cristaldi et al. 2017; He et al. 2018; Suman et al. 2018).

Table 3 Techniques of phytoremediation

Techniques	Principles	Plant species	References
Rhizofiltration	The removal of pollutants from environment by adsorption or precipitation on the roots, or for adsorption of contaminants around the root zone	*Helianthus annuus*; *Phaseolus vulgaris*	Lee and Yang (2010)
Phytostabilization	Application of plants for stabilization of contaminants in soils	*Deschampsia cespitosa*; *Piptatherum miliaceum*; *Picea abies*	Padmavathiamma and Li (2007); Conesa et al. (2007); Brunner et al. (2008)
Phytoextraction	The uptake of pollutants from soil or water by plant roots and their translocation and accumulation in aboveground biomass	*Thlaspi caerulescens*; *Populus alba*; *Morus alba*	Prasad and Freitas (2003); Rafati et al. (2011)
Phytovolatilization	The pollutants are absorbed at root level, transported through the xylem, and released into the atmosphere from the aerial parts of plant in less toxic forms as a result of metabolic modification	*Caulanthus* sp.	Wang et al. (2012)
Phytodesalination	Removal of excess salts from saline soils by plants	*Hordeum vulgare*; *Artemisia argyi*; *Salsola collina*	Rabhi et al. (2010); Zorrig et al. (2012)
Rhizodegradation	Purification of polluted waters due to absorption, concentrating, and precipitation of metals by plant roots	*Carex pendula*	Ghosh (2010)
Phytoevaporation	The uptake of pollutants from soil or water by plant roots, convert it to volatile form, and subsequent release into the atmosphere (for organic pollutants and some heavy metals)	*Brassica juncea*	Padmavathiamma and Li (2007)

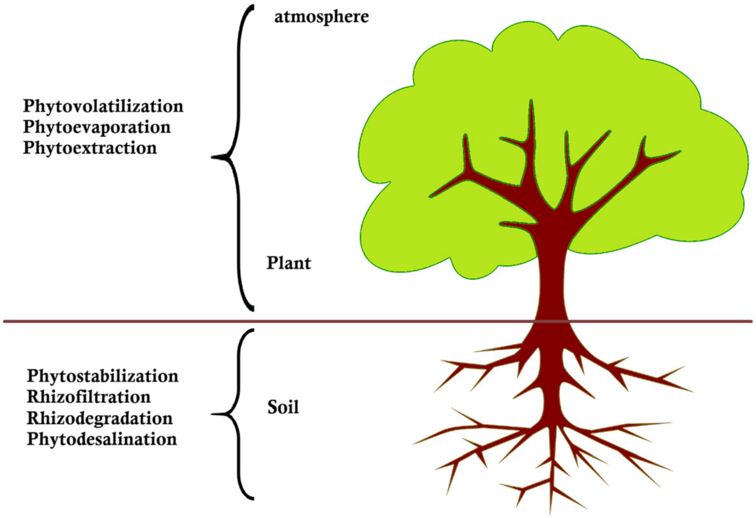

Fig. 2 Phytoremediation mechanisms involved for heavy metal contaminants

3.2 Phytostabilization

The absorption of heavy metals on the roots or precipitation of heavy metals within the rhizosphere that limits the mobility of the contaminants in the soil is known as phytostabilization. In this process, the plant that is being used to carry out phytostabilization alters the soil chemistry and hence, facilitates the absorption and precipitation processes of heavy metals in soil (Basharat et al. 2018; Garcia-Sanchez et al. 2018; Zhang et al. 2009). Moreover, the special redox enzymes excreted by the plants during phytostabilization process converts the heavy metals in soil into a less toxic state (Ali et al. 2013). This method was well practiced at the metal mining–contaminated site. The phytostabilization process inhibits further percolation and mobilization of metal contaminants, and therefore prevents groundwater contamination. However, this method is only a management strategy as it inactivates and stabilizes the heavy metals, but not removing them from the soil or water (Ali et al. 2013; Liphadzi et al. 2005).

3.3 Phytovolatilization

Phytovolatilization is the process that absorbs the contaminants from soil, transports the contaminants through the xylem, converts the contaminants into less toxic and volatile form, and releases them into the atmosphere. Phytovolatilization has been widely used to remove metals like mercury and selenium, as these metals have high volatility (Cristaldi et al. 2017; Wang et al. 2012). Previous studies found that *Astragalus racemosus* can convert the selenium into dimethyl diselenide through phytovolatilization process, while *Arabidopsis thaliana* can convert Hg^{2+} into Hg^0, which increases the volatility of mercury. However, the surrounding temperature and light intensity can influence the ability of the leaf tissues on releasing the mercury to the atmosphere (Parker et al. 1991; Rugh et al. 1996; Wang et al. 2012). Moreover, Liphadzi et al. (2005) have also found that the transpiration rate of the plant can affect the effectiveness of phytovolatilization (Liphadzi et al. 2005). Nevertheless, the edible product of the plant such as fruit may also contain the contaminants, as a result of accumulation and translocation when executing phytovolatilization. Another drawback of phytovolatilization is that it does not fully remove the contaminants, as the contaminants are only transformed into less toxic form and transferred from soil to atmosphere (Ali et al. 2013).

3.4 Rhizofiltration

The process which plants adsorb and precipitate the organic and inorganic contaminants on the roots to remove them from the contaminated wastewater, groundwater, and surface water is known as rhizofiltration. Characteristics such as hypoxia tolerant, metal tolerant, and large absorption surface area are the main factors to choose the suitable plant to apply rhizofiltration (Cristaldi et al. 2017; Zhang et al. 2009). As a comparison with aquatic plants, terrestrial plants are more desirable plants to perform in situ or ex situ rhizofiltration as they have a more fibrous system and developed roots that provides larger surface areas for absorption (Cristaldi et al. 2017). A success case of rhizofiltration is the use of *Phaseolus vulgaris* and *Helianthus annuus* to remove uranium from contaminated groundwater. The uranium removal result by the plants through rhizofiltration has an efficiency of more than 90%, and the uranium is accumulated at the root. The necessity of first cultivation in a greenhouse and pH adjustment are the downsides of this mechanism (Sharma & Pandey 2014). Moreover, the plants used to carry out rhizofiltration have to be harvested and disposed of when the root adsorption capacity reaches a maximum (Cristaldi et al. 2017; Lee and Yang 2010; Perez-Palacios et al. 2017).

3.5 Rhizodegradation

Rhizodegradation is performed when the microorganisms in the rhizosphere degrade the organic contaminants in the soil. The examples of microorganisms that carry out rhizodegradation are fungi, bacteria, and yeasts (Ely and Smets 2017; Wang et al. 2017). There are more microorganisms present in the rhizosphere than on the ground surface. The exudates that are secreted by the plants contain amino acids, carbohydrates, and flavonoids. The nutrient-containing exudates provide nitrogen and carbon sources to the microorganisms in the rhizosphere and thus, enhance the metabolic activities of the microorganisms by 10–100 times higher (Ali et al. 2013; Cristaldi et al. 2017). The efficiency of extraction and removal of contaminants are then increased due to the nutrient-rich environment. Besides, the enzymes released by the plants also help in stimulating the growth of the soil microbes and degrading the organic contaminants in the soil (Leung et al. 2013; Yadav et al. 2010). Other studies found that the large surface area provided by the roots of the plant aids in the microbial growth by providing more oxygen. However, the efficiency of rhizodegradation is lowered in the deep soil of 20 cm depth onwards. Moreover, the physical structure of the soil will limit the growth of the roots towards the deeper soil (Cunningham and Ow 1996).

4 Plants for Phytoremediation of Heavy Metals

As plants require macronutrients and micronutrients for growth, plants will take up metals like copper, zinc, nickel, and iron from the soil. The plant root system takes up the metals through active mechanisms such as the transportation of protein with the cell membrane and passive mechanisms such as transpiration. The common non-accumulator plants only take up less than 10 mg/L of micronutrients, which is a sufficient amount for their metabolic needs. However, the growth of the plant will be affected when the plant is cultivated on the soil with a high concentration of heavy metals. This is because the high concentration of heavy metals in soil is phytotoxic. However, plants that can be used to carry out phytoremediation are known as metallophytes. The three types of metallophytes are metal indicators, metal excluders, and metal hyperaccumulators (Bani et al. 2009; Pignattelli et al. 2012; Sakakibara et al. 2011; Zalewska and Danowska 2017). The list of metallophytes plants is shown in Table 4.

Plant that takes up a high concentration of heavy metals from the soil and accumulates them in the shoots and leaves is known as metal indicators. Thus, the shoot and leaves have an uptake high concentration of heavy metals, which can reflect the heavy metal concentration in soil. The plants are eventually died-off due to the metal toxicity as a result of continuous uptake of heavy metals. As the metal indicator plants are good in the absorption of the contaminants, these plants are used to indicate the possible heavy metal presented in the soil. Metal excluders are plants that cease the transportation of the absorbed heavy metals to their aboveground tissues but accumulate the absorbed heavy metals at their roots. Previous studies confirmed that metal excluders are efficient to perform phytostabilization (Alkorta et al. 2010; Fatnassi et al. 2015; Gil-Loaiza et al. 2016; Guo et al. 2014) .

Metal hyperaccumulators are plants that can take up and accumulate a high concentration of heavy metals in the plant foliage. The plant can only be classified as metal hyperaccumulator when it can remain healthy and not showing any signs of toxicity, after accumulating the concentrate heavy metals. The metal hyperaccumulators use the accumulated heavy metals in their tissues for ecological and physiological functions. Metal hyperaccumulators are widely used to perform phytoremediation as the metal hyperaccumulators will make the heavy metal–accumulated leaves unpalatable, and hence, evade the herbivores such as caterpillars from consuming it. This shows that the metal hyperaccumulators not only can protect themselves from consuming by predators but also aid in the prevention of heavy metals entering the food chain. The other

Table 4 List of metallophytes

Categories	Plant species	Accumulation	References
Metal excluder	*Silene paradoxa*	As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn	Pignattelli et al. (2012)
	Bidens pilosa	As, Cd	Sun et al. (2009)
Metal indicator	*Chara baltica*, *Cladophora* spp., *Coccotylus truncatus*, *Furcellaria lumbricalis*, *Polysiphonia fucoides*, *Stuckenia pectinata*, and *Zanichellia palustris*	Pb, Cd, Hg, Ni	Zalewska and Danowska (2017)
	Phragmites australis, *Typha capensis*, *Spartina maritima*	Cd, Cu, Pb, and Zn	Phillips et al. (2015)
	Patella vulgata and *Fucus serratus*	Cd, Co, Cr, Cu, Fe, Ni, Pb, Zn	Miramand and Bentley (1992)
	Ricinus communis	Ni	Çelik and Akdaş (2019)
Metal hyperaccumulator	*Eleocharis acicularis*	Cu, Zn, Cd, As	Sakakibara et al. (2011)
	Alyssum murale	Ni	Bani et al. (2009)
	Deschampsia cespitosa	Pb, Cd, Zn	Kucharski et al. (2005)
	Haumaniastrum robertii	Co	Chaney et al. (2010)
	Erato polymnioides	Hg	Chamba et al. (2017)
	Brassica juncea, *Medicago sativa*	Au	Bali et al. (2010)
	Macadamia neurophylla	Mn	Sheoran et al. (2009)
	Pteris vittata	Cr, Hg	Wang et al. (2012)

advantage of using metal hyperaccumulators for phytoremediation is, bio-ore of some commercial value may be produced from the metal hyperaccumulators that have accumulated a high level of heavy metals, and thus, reducing some costs of soil treatment (Briskine et al. 2017; Dipu et al. 2012; Li et al. 2017; Midhat et al. 2017; Peng et al. 2017; Sidhu et al. 2017).

5 Factors Affect Phytoremediation

The three main mechanisms of phytoremediation for heavy metal removal are phytostabilization, phytoextraction, and phytovolatilization. Phytostabilization limits the mobility of the heavy metal from entering the food chain; phytoextraction adsorbs the heavy metal from the soil and accumulate in the plant tissues; and, phytovolatilization volatilizes the heavy metals from the soil and releases them to the atmosphere in less toxic or non-hazardous form. However, these mechanisms may affect by several factors such as the plant species, properties of a medium, the bioavailability of metal, and the addition of chelating agent (Desai et al. 2019; Kang et al. 2018; Kozminska et al. 2018; Li et al. 2019; Tangahu et al. 2011).

5.1 Plant Species

Suitable plant species must be chosen before carrying out phytoremediation on heavy metal–contaminated soil. A plant that considers to have high efficiency of phytoextraction technique needs to achieve a high accumulation of heavy metals and produce large amounts of biomass. Moreover, the characteristics of the plant species also affect uptake efficiency (Tangahu et al. 2011; Tchounwou et al. 2012; Wang et al. 2012).

5.2 Properties of Medium

Researchers have reported that agronomical practices such as pH adjustment and addition of fertilizers can improve the efficiency of phytoremediation. A few studies show that the pH, amount of organic matter, and phosphorus content in the soil can affect the plants on lead absorption. The soil pH that is adjusted to a level of 6.5 to 7.0 with lime can reduce the lead uptake by plants (Kang et al. 2018; Tangahu et al. 2011; Vangronsveld et al. 2009).

5.3 Bioavailability of Metal

The efficiency of phytoextraction is critically affected by the bioavailability of heavy metals in the soil. The phytoextraction of lead is highly affected by low bioavailability. A few parameters can affect the bioavailability of heavy metals such as the soil pH, soil redox potential, and amount of organic matter, clay, and oxide minerals in the soil. The metal concentration in the soil solution can be reduced by the increment of soil pH, due to the complexation of metals by functional groups of organic matter and oxides. Besides, the extent of the metal complexation with organic C-based ligands in the soil is influenced by the pH control and hence, affected the solubility of heavy metals (Ali et al. 2013; Bondarenko et al. 2008; Borgmann and Norwood 2002; Jonnalagadda and Rao 1993; Liphadzi et al. 2005). Soil redox potential is an essential factor that affects the heavy metal transformation, solubility, and uptake by plants. Research shows that metals with higher oxidation states such as iron and manganese have lower solubility. Moreover, the mobility of metals is limited when the solubilized metals undergo re-precipitation and thus, affects the absorption and uptake by plants. A high amount of organic matter, clay, or oxides can decrease the bioavailability of metals in soil, as the metal cations react with these components that have high cation exchange capacity and high specific areas. Some heavy metals will become non-exchangeable as a result of binding to the humic substances in the inner-sphere complexes (Bourgeault et al. 2011; Cao et al. 2008; Dean 2010; Duval 2013).

5.4 Addition of Chelating Agents

The addition of biodegradable physicochemical factors such as chelating agents and micronutrients can increase the uptake of heavy metals by the plants and stimulate the heavy metal uptake capacity of the microbial community in and around the plant. Remediation periods through phytoremediation will be shorter when the rate of heavy metal uptake by plants increases, and thus, the cost of remediation will reduce. Chelating agents are required in alkaline soils that have a level of pH above 5.5 to 6, as the alkaline soils decrease the bioavailability of heavy metals (Ali and Hadi 2015; Bala and Thukral 2011; Gomez-Garrido et al. 2018; Tahmasbian and Safari Sinegani 2016).

6 Disposal of Metal-Accumulating Plant Waste

One of the vital concerns about phytoremediation is the handling and disposal of the metal-accumulating plants. Proper management and disposal of metal-accumulating plants must be carried out to prevent potential risks. These plants must be harvested and either disposed of or recycled in compliance with applicable regulations as the metal-accumulating plants are considered hazardous waste. The metal concentrations in the plants will determine whether the plants need to be landfilled or perform metal reclamation through pyrolysis of biomass, smelting, or extraction. The value of the reclaimed metals from the biomass of the plants may offset the cost of remediation. The resulting ash from the incinerated plant must be disposed to hazardous waste landfills, while radioactively contaminated plants must be disposed of as radioactive waste. The handling of plants before disposal is significant as some species such as *Brassica juncea* become crumbly, dry, and flaky after harvesting, thus, may become a source of secondary emissions of the metals that they have adsorbed and absorbed (Gomes et al. 2016; Szczygłowska et al. 2011).

7 Conclusion

Effective remediation on heavy metal–contaminated soil is necessary as this environmental problem could bring serious health impact to humans. Due to the limitation of physical and chemical remediation methods such as expensive, disturbance of native soil ecosystem, irreversible changes in soil properties, and creation of secondary pollution problems, phytoremediation becomes a better choice of technology to remediate the heavy metal–contaminated soil. The main mechanisms of phytoremediation are phytostabilization, phytoextraction, and phytovolatilization. Several factors such as a selection of plant species, properties of a medium, the bioavailability of metal, and the addition of chelating agents are important to enhance the efficiency and success rate of phytoremediation technology. Metal hyperaccumulators are usually being used to perform phytoremediation. These plants can accumulate large amount of concentrated heavy metals in their biomass and remain healthy. According to Hall (2002), heavy metal–tolerant plants can also protect themselves from metal toxicity through detoxification strategies. These plants have several mechanisms such as chelation, presence at the cellular and subcellular levels that are involved in the sequestration, or detoxification of toxic heavy metals (Hall 2002). The buildup of toxic metals around the sensitive organelles in the cell is then being prevented by chelation and hence, avoiding damages to the plant cells (Hall 2002). One of the significant advantages of phytoremediation is that it can avoid the accumulated metals entering the food chain, by making the leaves unpalatable and evade the herbivorous from consuming them. Besides, metal reclamation from the metal-accumulated plants may help in offsetting the remediation cost. However, climate and hydrologic conditions such as flooding and drought will be the challenges for future research on phytoremediation (Derakhshan Nejad et al. 2018). Climate condition is also varying from one place to another, and thus, the plant growth and performance of phytoremediation will be affected.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Acar, Y. B., & Alshawabkeh, A. N. (1993). Principles of electrokinetic remediation. *Environmental Science & Technology, 27*, 2638–2647.

Agnello, A. C., Bagard, M., van Hullebusch, E. D., Esposito, G., & Huguenot, D. (2016). Comparative bioremediation of heavy metals and petroleum hydrocarbons co-contaminated soil by natural attenuation, phytoremediation, bioaugmentation and bioaugmentation-assisted phytoremediation. *Science of the Total Environment, 563-564*, 693–703.

Ali, N., & Hadi, F. (2015). Phytoremediation of cadmium improved with the high production of endogenous phenolics and free proline contents in Parthenium hysterophorus plant treated exogenously with plant growth regulator and chelating agent. *Environmental Science and Pollution Research, 22*, 13305–13318.

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. *Chemosphere, 91*, 869–881.

Alkorta, I., Becerril, J. M., & Garbisu, C. (2010). Phytostabilization of metal contaminated soils. *Review in Environmental Health, 25*, 135–146.

Almeida, J. C., Cardoso, C. E. D., Tavares, D. S., Freitas, R., Trindade, T., Vale, C., & Pereira, E. (2019). Chromium removal from contaminated waters using nanomaterials–A review. *TrAC Trends in Analytical Chemistry, 118*, 277–291.

Atanes, E., Cuesta-García, B., Nieto-Márquez, A., & Fernández-Martínez, F. (2019). A mixed separation-immobilization method for soluble salts removal and stabilization of heavy metals in municipal solid waste incineration fly ash. *Journal of Environmental Management, 240*, 359–367.

Back, S.-K., Lee, E.-S., Seo, Y.-C., & Jang, H.-N. (2020). The effect of NaOH for the recovery of elemental mercury from simulated mixture wastes and waste sludge from an industrial process using a thermal desorption process. *Journal of Hazardous Materials, 384*, 121291.

Bala, R., & Thukral, A. K. (2011). Phytoremediation of Cr(VI) by Spirodela polyrrhiza (L.) Schleiden employing reducing and chelating agents. *International Journal of Phytoremediation, 13*, 465–491.

Bali, R., Siegele, R., & Harris, A. T. (2010). Phytoextraction of Au: Uptake, accumulation and cellular distribution in Medicago sativa and Brassica juncea. *Chemical Engineering Journal, 156*, 286–297.

Bani, A., Echevarria, G., Mullaj, A., Reeves, R., Morel, J. L., & Sulçe, S. (2009). Nickel Hyperaccumulation by Brassicaceae in serpentine soils of Albania and Northwestern Greece. *Northeastern Naturalist, 16*, 385–404.

Barman, S. C., Sahu, R. K., Bhargava, S. K., & Chaterjee, C. (2000). Distribution of heavy metals in wheat, mustard, and weed grown in field irrigated with industrial effluents. *Bulletin of Environmental Contamination and Toxicology, 64*, 489–496.

Basharat, Z., Novo, L. A. B. & Yasmin, A. (2018). Genome editing weds CRISPR: What is in it for phytoremediation? *Plants (Basel), 7*.

Bondarenko, O., Rolova, T., Kahru, A., & Ivask, A. (2008). Bioavailability of Cd, Zn and Hg in soil to nine recombinant luminescent metal sensor bacteria. *Sensors (Basel), 8*, 6899–6923.

Borgmann, U., & Norwood, W. P. (2002). Metal bioavailability and toxicity through a sediment core. *Environmental Pollution, 116*, 159–168.

Bourgeault, A., Gourlay-France, C., Priadi, C., Ayrault, S., & Tusseau-Vuillemin, M. H. (2011). Bioavailability of particulate metal to zebra mussels: Biodynamic modelling shows that assimilation efficiencies are site-specific. *Environmental Pollution, 159*, 3381–3389.

Briskine, R. V., Paape, T., Shimizu-Inatsugi, R., Nishiyama, T., Akama, S., Sese, J., & Shimizu, K. K. (2017). Genome assembly and annotation of Arabidopsis halleri, a model for heavy metal hyperaccumulation and evolutionary ecology. *Molecular Ecology Resource, 17*, 1025–1036.

Brunner, I., Luster, J., Günthardt-Goerg, M. S., & Frey, B. (2008). Heavy metal accumulation and phytostabilisation potential of tree fine roots in a contaminated soil. *Environmental Pollution, 152*, 559–568.

Cao, A., Cappai, G., Carucci, A., & Lai, T. (2008). Heavy metal bioavailability and chelate mobilization efficiency in an assisted phytoextraction process. *Environmental Geochemistry and Health, 30*, 115–119.

Çelik, Ö., & Akdaş, E. Y. (2019). Tissue-specific transcriptional regulation of seven heavy metal stress-responsive miRNAs and their putative targets in nickel indicator castor bean (R. communis L.) plants. *Ecotoxicology and Environmental Safety, 170*, 682–690.

Chamba, I., Rosado, D., Kalinhoff, C., Thangaswamy, S., Sánchez-Rodríguez, A., & Gazquez, M. J. (2017). Erato polymnioides–A novel Hg hyperaccumulator plant in

ecuadorian rainforest acid soils with potential of microbe-associated phytoremediation. *Chemosphere, 188*, 633–641.
Chaney, R. L., Broadhurst, C. L., & Centofanti, T. (2010). Phytoremediation of soil trace elements. In P. S. Hooda (Ed.), *Trace elements in soils* (pp. 311–352). Chichester: John Wiley & Sons.
Chen, X., & Achal, V. (2019). Biostimulation of carbonate precipitation process in soil for copper immobilization. *Journal of Hazardous Materials, 368*, 705–713.
Chen, A. Y.-Y., & Olsen, T. (2016). Chromated copper arsenate-treated wood: A potential source of arsenic exposure and toxicity in dermatology. *International journal of women's dermatology, 2*, 28–30.
Clarkson, T. W., & Magos, L. (2006). The toxicology of mercury and its chemical compounds. *Critical Reviews in Toxicology, 36*, 609–662.
Conesa, H. M., Schulin, R., & Nowack, B. (2007). A laboratory study on revegetation and metal uptake in native plant species from neutral mine tailings. *Water, Air, and Soil Pollution, 183*, 201–212.
Cristaldi, A., Conti, G. O., Jho, E. H., Zuccarello, P., Grasso, A., Copat, C., & Ferrante, M. (2017). Phytoremediation of contaminated soils by heavy metals and PAHs. *A brief review. Environmental Technology & Innovation, 8*, 309–326.
Cunningham, S. D., & Ow, D. W. (1996). Promises and prospects of phytoremediation. *Plant Physiology, 110*, 715–719.
Dean, J. R. (2010). Heavy metal bioavailability and bioaccessibility in soil. *Methods in Molecular Biology, 599*, 15–36.
Dellisanti, F., Rossi, P. L., & Valdrè, G. (2009). In-field remediation of tons of heavy metal-rich waste by Joule heating vitrification. *International Journal of Mineral Processing, 93*, 239–245.
Derakhshan Nejad, Z., Jung, M. C., & Kim, K. H. (2018). Remediation of soils contaminated with heavy metals with an emphasis on immobilization technology. *Environmental Geochemistry and Health, 40*, 927–953.
Desai, M., Haigh, M., & Walkington, H. (2019). Phytoremediation: Metal decontamination of soils after the sequential forestation of former opencast coal land. *Sci Total Environ, 656*, 670–680.
Dipu, S., Kumar, A. A., & Thanga, S. G. (2012). Effect of chelating agents in phytoremediation of heavy metals. *Remediation Journal, 22*, 133–146.
Doni, S., Macci, C., Peruzzi, E., Iannelli, R., & Masciandaro, G. (2015). Heavy metal distribution in a sediment phytoremediation system at pilot scale. *Ecological Engineering, 81*, 146–157.
Duval, J. F. (2013). Dynamics of metal uptake by charged biointerphases: Bioavailability and bulk depletion. *Physical Chemistry Chemical Physics, 15*, 7873–7888.
Ely, C. S., & Smets, B. F. (2017). Bacteria from wheat and cucurbit plant roots metabolize PAHs and aromatic root exudates: Implications for rhizodegradation. *International Journal of Phytoremediation, 19*, 877–883.
Etteieb, S., Magdouli, S., Zolfaghari, M., & Brar, S. (2020). Monitoring and analysis of selenium as an emerging contaminant in mining industry: A critical review. *Science of the Total Environment, 698*, 134339.
Fatnassi, I. C., Chiboub, M., Saadani, O., Jebara, M., & Jebara, S. H. (2015). Phytostabilization of moderate copper contaminated soils using co-inoculation of Vicia faba with plant growth promoting bacteria. *Journal of Basic Microbiology, 55*, 303–311.
Garcia-Sanchez, M., Kosnar, Z., Mercl, F., Aranda, E., & Tlustos, P. (2018). A comparative study to evaluate natural attenuation, mycoaugmentation, phytoremediation, and microbial-assisted phytoremediation strategies for the bioremediation of an aged PAH-polluted soil. *Ecotoxicology and Environmental Safety, 147*, 165–174.
Ghosh, S. (2010). Wetland macrophytes as toxic metal accumulators. *International Journal of Environmental Sciences, 1*, 523–528.
Gil-Loaiza, J., White, S. A., Root, R. A., Solis-Dominguez, F. A., Hammond, C. M., Chorover, J., & Maier, R. M. (2016). Phytostabilization of mine tailings using compost-assisted direct planting: Translating greenhouse results to the field. *Science of the Total Environment, 565*, 451–461.
Gomes, M. A. D. C., Hauser-Davis, R. A., de Souza, A. N., & Vitória, A. P. (2016). Metal phytoremediation: General strategies, genetically modified plants and applications in metal nanoparticle contamination. *Ecotoxicology and Environmental Safety, 134*, 133–147.
Gomez-Garrido, M., Mora Navarro, J., Murcia Navarro, F. J., & Faz Cano, A. (2018). The chelating effect of citric acid, oxalic acid, amino acids and Pseudomonas fluorescens bacteria on phytoremediation of Cu, Zn, and Cr from soil using Suaeda vera. *International Journal of Phytoremediation, 20*, 1033–1042.
Guo, J., & Zhou, Y. (2020). Transformation of heavy metals and dewaterability of waste activated sludge during the conditioning by Fe2+-activated peroxymonosulfate oxidation combined with rice straw biochar as skeleton builder. *Chemosphere, 238*, 124628.
Guo, P., Wang, T., Liu, Y., Xia, Y., Wang, G., Shen, Z., & Chen, Y. (2014). Phytostabilization potential of evening primrose (Oenothera glazioviana) for copper-contaminated sites. *Environmental Science and Pollution Research, 21*, 631–640.
Hall, J. L. (2002) Cellular mechanisms for heavy metal detoxification and tolerance. *Journal of Experimental Botany, 53* (366), 1–11.
He, H., Dong, Z., Pang, J., Wu, G. L., Zheng, J., & Zhang, X. (2018). Phytoextraction of rhenium by lucerne (Medicago sativa) and erect milkvetch (Astragalus adsurgens) from alkaline soils amended with coal fly ash. *Science of the Total Environment, 630*, 570–577.
Jonnalagadda, S. B., & Rao, P. V. (1993). Toxicity, bioavailability and metal speciation. *Comparative Biochemistry and Physiology - Part C, 106*, 585–595.
Kang, W., Bao, J., Zheng, J., Xu, F., & Wang, L. (2018). Phytoremediation of heavy metal contaminated soil potential by woody plants on Tonglushan ancient copper spoil heap in China. *International Journal of Phytoremediation, 20*, 1–7.
Kozminska, A., Wiszniewska, A., Hanus-Fajerska, E., & Muszynska, E. (2018). Recent strategies of increasing metal tolerance and phytoremediation potential using genetic transformation of plants. *Plant Biotechnology Report, 12*, 1–14.
Kucharski, R., Sas-Nowosielska, A., Małkowski, E., Japenga, J., Kuperberg, J. M., Pogrzeba, M., & Krzyżak, J. (2005). The use of indigenous plant species and calcium phosphate for the stabilization of highly metal-polluted sites in southern Poland. *Plant and Soil, 273*, 291–305.

Lee, M., & Yang, M. (2010). Rhizofiltration using sunflower (Helianthus annuus L.) and bean (Phaseolus vulgaris L. var. vulgaris) to remediate uranium contaminated groundwater. *Journal of Hazardous Materials, 173*, 589–596.

Lee, Y.-C., Kim, E. J., Ko, D. A., & Yang, J.-W. (2011). Water-soluble organo-building blocks of aminoclay as a soil-flushing agent for heavy metal contaminated soil. *Journal of Hazardous Materials, 196*, 101–108.

Lei, M., Wan, X., Guo, G., Yang, J., & Chen, T. (2018). Phytoextraction of arsenic-contaminated soil with Pteris vittata in Henan Province, China: Comprehensive evaluation of remediation efficiency correcting for atmospheric depositions. *Environmental Science and Pollution Research, 25*, 124–131.

Leung, H.-M., Wang, Z.-W., Ye, Z.-H., Yung, K.-L., Peng, X.-L., & Cheung, K.-C. (2013). Interactions between arbuscular mycorrhizae and plants in phytoremediation of metal-contaminated soils: A review. *Pedosphere, 23*, 549–563.

Leyssens, L., Vinck, B., Van Der Straeten, C., Wuyts, F., & Maes, L. (2017). Cobalt toxicity in humans—A review of the potential sources and systemic health effects. *Toxicology, 387*, 43–56.

Li, L. Z., Tu, C., Wu, L. H., Peijnenburg, W. J., Ebbs, S., & Luo, Y. M. (2017). Pathways of root uptake and membrane transport of Cd(2+) in the zinc/cadmium hyperaccumulating plant Sedum plumbizincicola. *Environmental Toxicology and Chemistry, 36*, 1038–1046.

Li, J. T., Gurajala, H. K., Wu, L. H., van der Ent, A., Qiu, R. L., Baker, A. J. M., Tang, Y. T., Yang, X. E., & Shu, W. S. (2018). Hyperaccumulator plants from China: A synthesis of the current state of knowledge. *Environmental Science and Technology, 52*, 11980–11994.

Li, X., Wang, X., Chen, Y., Yang, X., & Cui, Z. (2019). Optimization of combined phytoremediation for heavy metal contaminated mine tailings by a field-scale orthogonal experiment. *Ecotoxicology and Environmental Safety, 168*, 1–8.

Liphadzi, M. S., Kirkham, M. B., & Musil, C. F. (2005). Phytoremediation of soil contaminated with heavy metals: A technology for rehabilitation of the environment. *South African Journal of Botany, 71*, 24–37.

Lu, Q., Xu, X., Liang, L., Xu, Z., Shang, L., Guo, J., Xiao, D., & Qiu, G. (2019). Barium concentration, phytoavailability, and risk assessment in soil-rice systems from an active barium mining region. *Applied Geochemistry, 106*, 142–148.

Midhat, L., Ouazzani, N., Esshaimi, M., Ouhammou, A., & Mandi, L. (2017). Assessment of heavy metals accumulation by spontaneous vegetation: Screening for new accumulator plant species grown in Kettara mine-Marrakech, Southern Morocco. *International Journal of Phytoremediation, 19*, 191–198.

Miramand, P., & Bentley, D. (1992). Heavy metal concentrations in two biological indicators (Patella vulgata and Fucus serratus) collected near the French nuclear fuel reprocessing plant of La Hague. *Science of the Total Environment, 111*, 135–149.

Mironyuk, I., Tatarchuk, T., Vasylyeva, H., Naushad, M., & Mykytyn, I. (2019). Adsorption of Sr(II) cations onto phosphated mesoporous titanium dioxide: Mechanism, isotherm and kinetics studies. *Journal of Environmental Chemical Engineering, 7*, 103430.

Mu'azu, N. D., Haladu, S. A., Jarrah, N., Zubair, M., Essa, M. H., & Ali, S. A. (2018). Polyaspartate extraction of cadmium ions from contaminated soil: Evaluation and optimization using central composite design. *Journal of Hazardous Materials, 342*, 58–68.

Nakajima, H., Fujimoto, N., Yamamoto, Y., Amemiya, T., & Itoh, K. (2019). Response of secondary metabolites to Cu in the Cu-hyperaccumulator lichen Stereocaulon japonicum. *Environmental Science and Pollution Research, 26*, 905–912.

Nelson, M., Adams, T., Ojo, C., Carroll, M. A., & Catapane, E. J. (2018). Manganese toxicity is targeting an early step in the dopamine signal transduction pathway that controls lateral cilia activity in the bivalve mollusc Crassostrea virginica. *Comparative Biochemistry and Physiology - Part C, 213*, 1–6.

Ontañon, O. M., González, P. S., Ambrosio, L. F., Paisio, C. E., & Agostini, E. (2014). Rhizoremediation of phenol and chromium by the synergistic combination of a native bacterial strain and Brassica napus hairy roots. *International Biodeterioration & Biodegradation, 88*, 192–198.

Padmavathiamma, P. K., & Li, L. Y. (2007). Phytoremediation technology: Hyper-accumulation metals in plants. *Water, Air, and Soil Pollution, 184*, 105–126.

Parker, D. R., Page, A. L., & Thomason, D. N. (1991). Salinity and boron tolerances of candidate plants for the removal of selenium from soils. *Journal of Environmental Quality, 20*, 157–164.

Paz-Ferreiro, J., Gascó, G., Méndez, A., & Reichman, S. M. (2018). Soil pollution and remediation. *International Journal of Environmental Research and Public Health, 15*, 1657.

Peng, J. S., Wang, Y. J., Ding, G., Ma, H. L., Zhang, Y. J., & Gong, J. M. (2017). A pivotal role of cell wall in cadmium accumulation in the Crassulaceae hyperaccumulator Sedum plumbizincicola. *Molecular Plant, 10*, 771–774.

Perez-Palacios, P., Agostini, E., Ibanez, S. G., Talano, M. A., Rodriguez-Llorente, I. D., Caviedes, M. A., & Pajuelo, E. (2017). Removal of copper from aqueous solutions by rhizofiltration using genetically modified hairy roots expressing a bacterial Cu-binding protein. *Environmental Technology, 38*, 2877–2888.

Phillips, D. P., Human, L. R. D., & Adams, J. B. (2015). Wetland plants as indicators of heavy metal contamination. *Marine Pollution Bulletin, 92*, 227–232.

Pignattelli, S., Colzi, I., Buccianti, A., Cecchi, L., Arnetoli, M., Monnanni, R., Gabbrielli, R., & Gonnelli, C. (2012). Exploring element accumulation patterns of a metal excluder plant naturally colonizing a highly contaminated soil. *Journal of Hazardous Material, 227-228*, 362–369.

Prasad, M. N. V. & Freitas, H. M. D. O. (2003). Metal hyperaccumulation in plants-Biodiversity prospecting for phytoremediation technology.

Pulford, I. D., & Watson, C. (2003). Phytoremediation of heavy metal-contaminated land by trees–a review. *Environment International, 29*, 529–540.

Rabhi, M., Ferchichi, S., Jouini, J., Hamrouni, M. H., Koyro, H.-W., Ranieri, A., Abdelly, C., & Smaoui, A. (2010). Phytodesalination of a salt-affected soil with the halophyte Sesuvium portulacastrum L. to arrange in advance the requirements for the successful growth of a glycophytic crop. *Bioresource Technology, 101*, 6822–6828.

Rafati, M., Khorasani, N., Moattar, F., Shirvany, A., Moraghebi, F., & Hosseinzadeh, S. (2011). Phytoremediation potential of Populus alba and Morus alba for cadmium, chromuim and nickel absorption from polluted soil. *International Journal of Environmental Research, 5*, 961–970.

Rakhshaee, R., Giahi, M., & Pourahmad, A. (2009). Studying effect of cell wall's carboxyl–carboxylate ratio change of Lemna minor to remove heavy metals from aqueous solution. *Journal of Hazardous Materials, 163*, 165–173.

Rodrigues, S. M., Henriques, B., Reis, A. T., Duarte, A. C., Pereira, E., & Römkens, P. F. A. M. (2012). Hg transfer from contaminated soils to plants and animals. *Environmental Chemistry Letters, 10*, 61–67.

Rubio, C., Paz, S., Tius, E., Hardisson, A., Gutierrez, A. J., Gonzalez-Weller, D., Caballero, J. M., & Revert, C. (2018). Metal contents in the most widely consumed commercial preparations of four different medicinal plants (aloe, senna, ginseng, and ginkgo) from Europe. *Biological Trace Element Research, 186*, 562–567.

Rugh, C. L., Wilde, H. D., Stack, N. M., Thompson, D. M., Summers, A. O., & Meagher, R. B. (1996). Mercuric ion reduction and resistance in transgenic Arabidopsis thaliana plants expressing a modified bacterial merA gene. *Proceedings of the National Academy of Sciences of the United States of America, 93*, 3182–3187.

Sakakibara, M., Ohmori, Y., Ha, N. T. H., Sano, S., & Sera, K. (2011). Phytoremediation of heavy metal-contaminated water and sediment by Eleocharis acicularis. *CLEAN – Soil, Air, Water, 39*, 735–741.

Schaumlöffel, D. (2012). Nickel species: Analysis and toxic effects. *Journal of Trace Elements in Medicine and Biology, 26*, 1–6.

Sharma, P., Pandey, S. (2014) Status of Phytoremediation in World Scenario. *International Journal of Environmental Bioremediation & Biodegradation, 2.4* (2014), 178–191

Sheoran, V., Sheoran, A. S., & Poonia, P. (2009). Phytomining: A review. *Minerals Engineering, 22*, 1007–1019.

Sidhu, G. P. S., Singh, H. P., Batish, D. R., & Kohli, R. K. (2017). Tolerance and hyperaccumulation of cadmium by a wild, unpalatable herb Coronopus didymus (L.) Sm. (Brassicaceae). *Ecotoxicology and Environmental Safety, 135*, 209–215.

Sprocati, A. R., Alisi, C., Tasso, F., Marconi, P., Sciullo, A., Pinto, V., Chiavarini, S., Ubaldi, C., & Cremisini, C. (2012). Effectiveness of a microbial formula, as a bioaugmentation agent, tailored for bioremediation of diesel oil and heavy metal co-contaminated soil. *Process Biochemistry, 47*, 1649–1655.

Sterckeman, T., Gossiaux, L., Guimont, S., & Sirguey, C. (2019). How could phytoextraction reduce Cd content in soils under annual crops? Simulations in the French context. *Science of the Total Environment, 654*, 751–762.

Suman, J., Uhlik, O., Viktorova, J., & Macek, T. (2018). Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment? *Frontiers in Plant Science, 9*, 1476.

Sun, Y.-B., Zhou, Q.-X., Liu, W.-T., An, J., Xu, Z.-Q., & Wang, L. (2009). Joint effects of arsenic and cadmium on plant growth and metal bioaccumulation: A potential Cd-hyperaccumulator and As-excluder Bidens pilosa L. *Journal of Hazardous Materials, 165*, 1023–1028.

Szczygłowska, M., Piekarska, A., Konieczka, P., & Namieśnik, J. (2011). Use of brassica plants in the phytoremediation and biofumigation processes. *International Journal of Molecular Sciences, 12*, 7760–7771.

Tahmasbian, I., & Safari Sinegani, A. A. (2016). Improving the efficiency of phytoremediation using electrically charged plant and chelating agents. *Environmental Science and Pollution Research, 23*, 2479–2486.

Tampouris, S., Papassiopi, N., & Paspaliaris, I. (2001). Removal of contaminant metals from fine grained soils, using agglomeration, chloride solutions and pile leaching techniques. *Journal of Hazardous Materials, 84*, 297–319.

Tang, J., He, J., Liu, T., Xin, X., & Hu, H. (2017). Removal of heavy metal from sludge by the combined application of a biodegradable biosurfactant and complexing agent in enhanced electrokinetic treatment. *Chemosphere, 189*, 599–608.

Tangahu, B. V., Sheikh Abdullah, S. R., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering, 2011*, 31.

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Experientia supplementum, 101*, 133–164.

Vangronsveld, J., Herzig, R., Weyens, N., Boulet, J., Adriaensen, K., Ruttens, A., Thewys, T., Vassilev, A., Meers, E., Nehnevajova, E., van der Lelie, D., & Mench, M. (2009). Phytoremediation of contaminated soils and groundwater: Lessons from the field. *Environmental Science and Pollution Research, 16*, 765–794.

Vardhan, K. H., Kumar, P. S., & Panda, R. C. (2019). A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. *Journal of Molecular Liquids, 290*, 111197.

Virkutyte, J., Sillanpää, M., & Latostenmaa, P. (2002). Electrokinetic soil remediation—Critical overview. *Science of the Total Environment, 289*, 97–121.

Wang, J., Feng, X., Anderson, C. W. N., Xing, Y., & Shang, L. (2012). Remediation of mercury contaminated sites–A review. *Journal of Hazardous Materials, 221-222*, 1–18.

Wang, J., Song, X., Wang, Y., Bai, J., Li, M., Dong, G., Lin, F., Lv, Y., & Yan, D. (2017). Bioenergy generation and rhizodegradation as affected by microbial community distribution in a coupled constructed wetland-microbial fuel cell system associated with three macrophytes. *Science of the Total Environment, 607-608*, 53–62.

Wu, C., Jiang, M., Hsieh, L., Cai, Y., Shen, Y., Wang, H., Lin, Q., Shen, C., Hu, B., & Lou, L. (2020). Feasibility of bioleaching of heavy metals from sediment with indigenous bacteria using agricultural sulfur soil conditioners. *Science of the Total Environment, 703*, 134812.

Xia, W.-Y., Du, Y.-J., Li, F.-S., Li, C.-P., Yan, X.-L., Arulrajah, A., Wang, F., & Song, D.-J. (2019). In-situ solidification/stabilization of heavy metals contaminated site soil using a dry jet mixing method and new hydroxyapatite based binder. *Journal of Hazardous Materials, 369*, 353–361.

Yadav, R., Arora, P., Kumar, S., & Chaudhury, A. (2010). Perspectives for genetic engineering of poplars for enhanced phytoremediation abilities. *Ecotoxicology, 19*, 1574–1588.

Yao, Z., Li, J., Xie, H., & Yu, C. (2012). Review on remediation technologies of soil contaminated by heavy metals. *Procedia Environmental Sciences, 16*, 722–729.

Zalewska, T., & Danowska, B. (2017). Marine environment status assessment based on macrophytobenthic plants as bio-indicators of heavy metals pollution. *Marine Pollution Bulletin, 118*, 281–288.

Zhang, H., Dang, Z., Zheng, L. C., & Yi, X. Y. (2009). Remediation of soil co-contaminated with pyrene and cadmium by growing maize (Zea mays L.). *International Journal of Environmental Science & Technology, 6*, 249–258.

Zorrig, W., Rabhi, M., Ferchichi, S., Smaoui, A., & Abdelly, C. (2012). Phytodesalination : A solution for salt-affected soils in arid and semi-arid regions. *Journal of Arid Land Studies, 22*, 299–302.

Zulfiqar, U., Farooq, M., Hussain, S., Maqsood, M., Hussain, M., Ishfaq, M., Ahmad, M., & Anjum, M. Z. (2019). Lead toxicity in plants: Impacts and remediation. *Journal of Environmental Management, 250*, 109557.