

Review article**Phytoremediation: Stratagem Against Heavy Metal Contamination****Arpita Mishra, Reena Josephine Chellaiah Mesiadhas, Sangeetha Menon*, Bhagyalakshmi Unnikrishnan and Ayisha Simla***Department of Life Sciences, Kristu Jayanti College, K Narayanpura, Kothanur, Bangalore, Karnataka, 560077, India*

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Abstract

The concentration of heavy metals in soil has significantly risen due to a number of natural and anthropogenic processes. Heavy metals are indigestible by plants, persisting in the environment, can enter the diet through agricultural crops, and ultimately accumulate in the human body through biomagnification. Additionally, their toxic properties have caused a serious problem for both human well-being and the biosphere. This makes remediation of contaminated soil a vital issue. Serious drawbacks to many physical and chemical techniques employed in remediation include high cost, labor-intensive nature, change in soil qualities, and disruption of the soil's natural microbiota. Phytoremediation is a practical and ecologically favorable mitigation solution for the cost-effective revegetation of heavy metal-polluted soil. It involves reducing the negative impacts or levels of contaminants in the environment by utilizing plants and associated soil microbes. Furthermore, genetically engineered plants or microbes are used in combination with plants to enhance their capacity for phytoremediation. To increase efficiency, it is important to know the underlying mechanism behind the buildup of heavy metals and plant tolerance. In this review, we have tried to discuss the ways in which plants absorb, move, and eliminate heavy metals from the environment. We have attempted to focus on techniques that improve the efficiency of phytoremediation solutions aided by genetic engineering and microbes.

Keywords: heavy metals; biomagnification; soil contamination; phytoremediation; genetic engineering

1. Introduction

Heavy metals are a class of metallic chemical elements that have relatively large densities, atomic weights, and atomic numbers. The most prevalent heavy metals/metalloids are zinc (Zn), copper (Cu), nickel (Ni), mercury (Hg), lead (Pb), arsenic (As) and cadmium (Cd). These heavy metals/metalloids can be found in both biological and inorganic sources, including sewage sludge, metal smelting and mining, and chemical fertilizers (especially

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phosphate compounds), and fossil fuels (Alloway, 2013; Rafique & Tariq, 2016; Hatamian et al., 2018; Souri et al., 2018). They are found in a variety of environmental matrixes at extremely low concentrations (parts per billion to less than 10 parts per million), classified as trace elements (Zhang et al., 2019). Heavy metals, including As, Hg, Cd, Cu and Zn are highly noxious due to their oxidative stress and their persistence in human body. They pose serious health hazards because of their toxicity, which is dependent on the heavy metal type, concentration, and oxidation state (Table 1) (Su et al., 2014; Hatamian et al., 2019). Heavy metal-polluted soil can be restored using several techniques. Actions like cleaning soil and application of an electric field mostly depend on physio-chemical or mechanical processes (Wuana & Okieimen, 2011). While these methods are considered effective in eliminating dangerous metals from the environment, their application may be costly and challenging, and it can significantly alter the properties of soil and its productivity. Using plants to absorb and eliminate elemental contaminants or reducing their persistence in soil is known as phytoremediation (Cunningham & Ow, 1996). It is a "green" method to remove toxic metals from tainted water and soil. Radionuclides and organic contaminants are also eliminated by this technique (Raskin et al., 1997; Ali et al., 2013). In addition to existing physical and chemical techniques, this approach can be utilized to eliminate excess heavy metals from the soil (Garbisu & Alkorta, 2001; McGrath et al., 2001). Phytoremediation includes several techniques like phytoextraction, rhizofiltration, and phytodegradation. This review gives a comprehensive understanding of phytoremediation, and its components and the mechanism of action. Reducing the possibility of releasing or introducing toxins into the environment is the main goal of remediation of contaminated soil. Soil properties, extent of contamination, regulatory restrictions, available technology, and financial investment all play a role in choosing the best remediation technique (Zheng et al., 2024). Table 1 lists a few plants employed in heavy metal remediation.

2. Sources of Soil-based Heavy Metals

Even though heavy metals are known to be components of soil, their presence in plants and soil can have several detrimental effects on the environment, plants, animals, and microbes (Lasat, 1999; Bhunia et al., 2017). Heavy metals get into the soil largely through man-made and natural activities. The major natural processes are erosion, volcanic activity, and mineral weathering. Human activities that are the major anthropogenic sources of contamination include pesticide and fertilizer use, mining, smelting, electroplating, air pollution, industrial discharge, sludge disposal and vehicle emissions (Figure 1) (Souri et al., 2019; Fattahi et al., 2021).

3. Mechanism of Detoxification

Plants protect themselves from the harmful effects of heavy metals through avoidance or tolerance (Figure 2) (Dalvi & Bhalerao, 2013).

3.1 Avoidance

The term "heavy metal avoidance strategy" refers to the ability of plants to limit the uptake of heavy metals and inhibit their entry into root cells. This is an extracellular first layer of defense and acts via several mechanisms, including metal ion precipitation, metal exclusion, and root sorption. A number of root exudates have the ability to change the pH

Table 1. List of key plants used for heavy metal remediation

Heavy Metal	Effect on Health	Sources	Plant Species used in Remediation	Reference
Mercury	CNS injuries, Renal dysfunction, GI ulceration, Hepatotoxicity	Medical waste and release of Au- Ag from coal combustion	<i>Cicer arietinum</i> , <i>Hordeum spp.</i> <i>Silene vulgaris</i>	Rodriguez et al., 2003; Wang et al., 2012
Lead	Brain damage, liver malfunction, decreased lung capacity malfunction of heart	Emissions caused by burning fuel, pesticides, herbicides	<i>Brassica juncea</i> , <i>Brassica nigra</i> , <i>Helianthus annuus</i>	Koptsik, 2014
Cadmium	Renal failure, respiratory illnesses	Mining and smelting, the use of phosphate fertilizers, sewage sludge application, and industrial process like electroplating and manufacturing	<i>Azolla pinnata</i> , <i>Arabis gemmifera</i>	Kristanti et al., 2021
Copper	Damage to the kidney and brain, cirrhosis of liver, intestinal irritation	Pesticides, Fertilizers	<i>Ipomoea alpine</i> , <i>Pteris vittata</i>	Sakakibara et al., 2011; Wang et al., 2012; Sheoran et al., 2009; Wuana & Okieimen, 2011
Chromium	Hair loss	Tanneries, industry, fly ash	<i>Pteris vittate</i> , <i>Brachiaria mutia</i> , <i>Leptochloa fusca</i>	Kalve et al., 2011; Salem et al., 2000
Nickel	Allergy, cancer, neurotoxicity, genotoxicity, nephrotoxicity, hepatotoxicity	Automobile battery steel alloys, household appliances	<i>Phyllanthus serpeni</i> , <i>Alyssum murale</i>	Cunningham Ow, 1996; Chaney et al., 2010; Bani et al., 2010; Khan et al., 2007; Das et al., 2008
Arsenic	Allergic dermatitis nephrotoxicity, hepatotoxicity.	Semiconductors, petroleum refining	<i>Corrigiola telephifolia</i> , <i>Pteris spp.</i>	Kalve et al., 2011
Zinc	nephrotoxicity, hepatotoxicity.	Electroplating, smelting and refining	<i>Noccaea caerulescens</i> , <i>Eleocharis acicularis</i>	Sakakibara et al., 2011

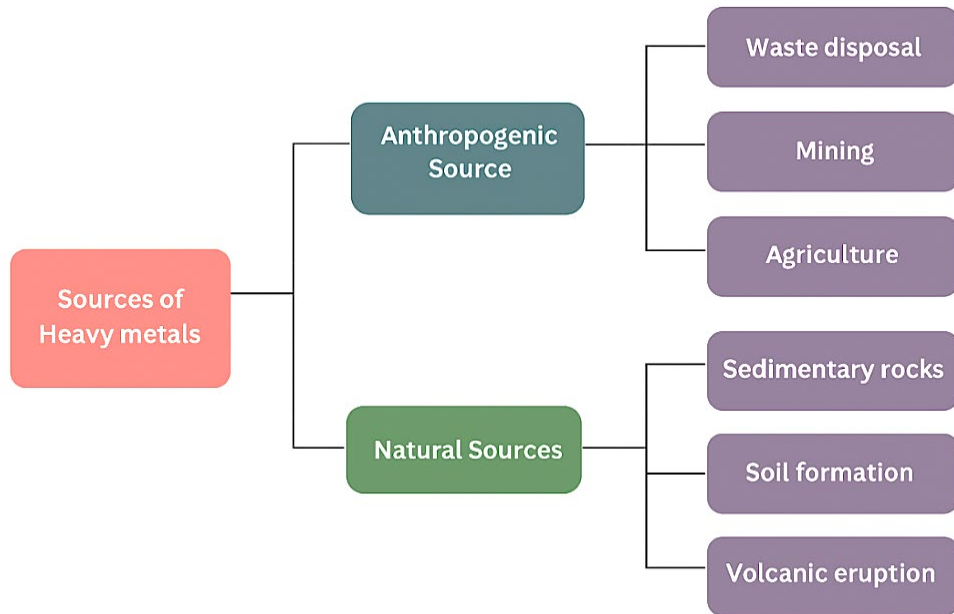


Figure 1. Sources of heavy metals in nature

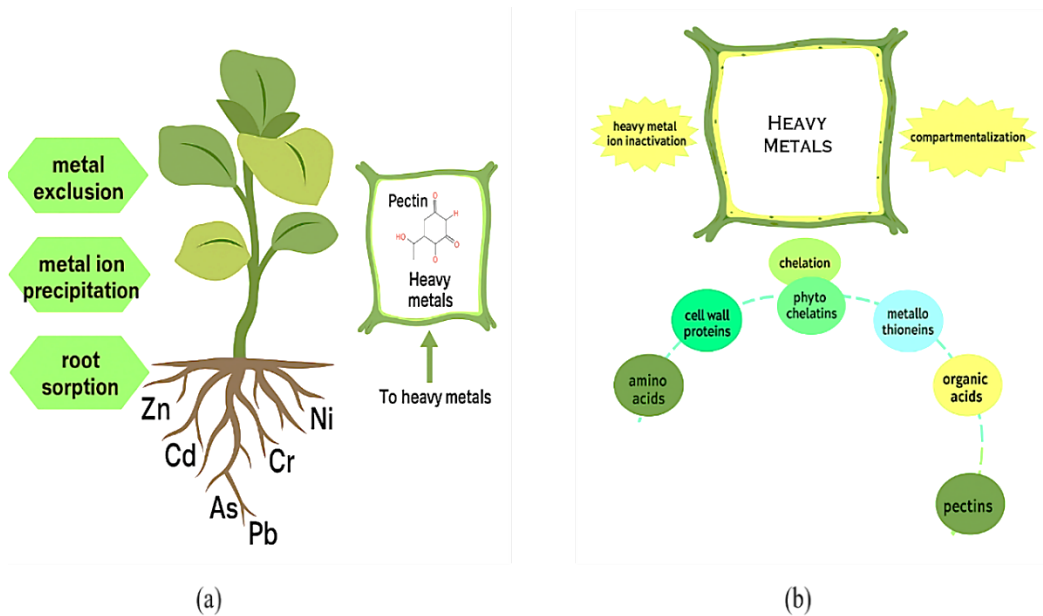


Figure 2. Mechanism of detoxification of heavy metal: (a) Avoidance (b) Tolerance

of the rhizosphere, precipitating heavy metals and thus limiting negative consequences (Dalvi & Bhalerao, 2013; Souri & Hatamian, 2019). To prevent harmful heavy metals from being absorbed and transported from root to shoot, metal exclusion method separates the root and shoots systems. Arbuscular mycorrhizae can limit heavy metal uptake via absorption, adsorption, or chelation in the rhizosphere (Dhalaria et al., 2020). These processes limit the concentration of heavy metals that can enter the roots. Plants may survive excessive level of heavy metals by using the protective layer of their cell walls (Memon & Schröder, 2009). Pectins are anionic heteropolysaccharides that contain polygalacturonic acids. Carboxylic groups on these galacturonic acid units are negatively charged that can bind to positively charged heavy metals ions. By acting as a cation exchanger, the cell wall keeps heavy metal ions outside of the cell (Ernst et al., 1992).

3.2 Tolerance

Plants have a tolerance mechanism in place to address the buildup of hazardous heavy metal ions that can enter plant cytoplasm. These mechanisms act as the cell's second line of defense, performing a range of functions such as chelation, compartmentalization, and heavy metal ion inactivation (Dalvi & Bhalerao, 2013). The organic materials used in heavy metal ion chelation include amino acids, cell wall proteins, phytochelatins (PCs), metallothioneins (MTs), organic acids, and pectins (Hall, 2002; Sharma & Dietz, 2006; Gupta et al., 2013). When heavy metals interact with organic acids in cells, their bioavailability to plants decreases, preventing the metals from staying as unbound ions within the cytosol. For example, citric acid promotes Ni chelation in *T. goesingense* leaves (Krämer et al., 2000). During chelation, heavy metals are continually transported from the cytoplasm to inactive regions such as vacuoles and are safely maintained there.

4. Methods of Phytoremediation

During phytoremediation, green plants remove, sequester, or retain dangerous substances from polluted water and soil (Pivetz et al., 2019). It employs a variety of methods for breaking down, removing, or immobilizing contaminants. The methods include rhizofiltration and phytoextraction for accumulation, phytovolatilization for dissipation, phytostabilization and hydraulic control for immobilization, and phytodegradation and rhizodegradation for decomposition (Pivetz, 2001). Plants may employ some of these strategies to reduce soil and water pollution, depending on the toxins. Some of the methods used in phytoremediation are discussed in Figure 3.

4.1 Phytostabilization

Metal-contaminated soil is inactivated via a plant-based technique called phytostabilization, phytorestitution, and phytoimmobilization (Bolan et al., 2011). These techniques involve the use of heavy metal tolerant plants to keep heavy metals out of groundwater by limiting their biological availability and movement (Epelde et al., 2009; Khalid et al., 2017). This approach chemically and physically immobilizes metal pollutants by amending various additives into the soil (Wuana & Okieimen, 2011). The most

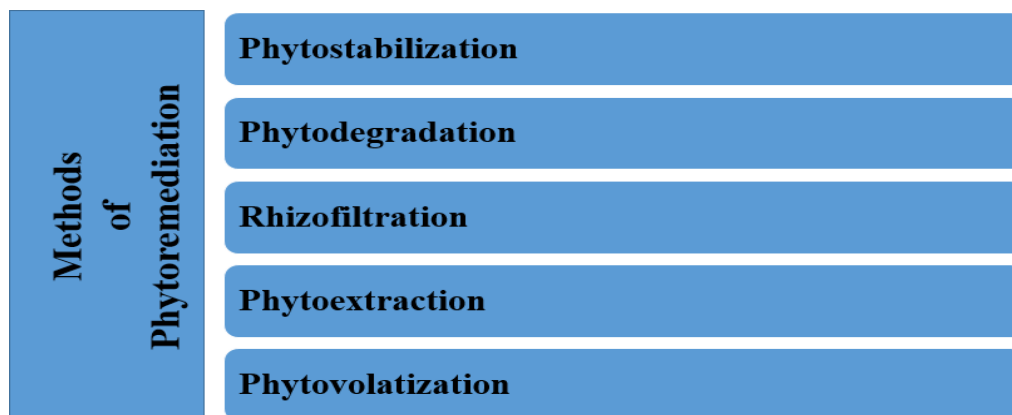


Figure 3. Various approaches to phytoremediation

productive soil additions for immobilizing heavy metals include clay minerals, biosolids, and organic matter (Flathman & Lanza, 1998). Given that metal pollutants are persistent in the soil after phytostabilization, it is therefore considered as a temporary process. Examples of plants include *Acanthus ilicifolius*, *Agrostis capillaris*, *Arundo donax*, *Iris lactea*, *Dahlia pinnata*, *Salix purpurea* (Lone et al., 2008)

4.2 Phytodegradation

Phytodegradation is the process by which pollutants are absorbed by plants and transformed into less toxic substances. Pesticides, chlorinated solvents, and other pollutants that are both organic and inorganic can be decomposed by these methods (Newman & Reynolds, 2004). The capability to degrade chemicals varies with the species and is dependent on the plant's phytochemical characteristics (Khandare & Govindwar, 2015). Water hyacinth has been shown to remove pollutants from industrial wastewater (Paz-Alberto & Sigua, 2013). Enzymes involved in the process include nitrilase, laccase, dehalogenase, peroxidase, and nitroreductase. The plant *Myriophyllum aquaticum* (aquatic) that produces nitroreductase enzyme, reduced the concentration of trinitrotoluene (TNT) in the soil within one week (Hoehamer et al., 2006). Lately, genetically modified plants such as *Liliodendron tulipifera* and *Brassica juncea* have been utilized for phytoremediation (Kärenlampi et al., 2000). Few other plants include *Populus* spp., *Nitella* spp., *Armoracia rusticana*, *Spirodela polyrhiza* and *Salix* spp. (Mahjoub, 2013).

4.3 Rhizofiltration

Rhizofiltration is a technique used to recover wastewater and low- polluted ground and surface fluids by using plant roots (Mukhopadhyay & Maiti, 2010). Plants are first cultivated to have a big root system before being moved to the contaminated site. Apart from roots, the techniques where shoots and seedlings are used are termed as caulofiltration and blastofiltration, respectively. These methods reduce the quantity of toxins discharged into groundwater by absorbing, precipitating, or adsorbing them. *Salvinia minima*, *Eichhornia crassipes*, *Hydrilla verticillata*, *Ceratophyllum demersum*, *Azolla pinnata*, *Lemna minor* are few examples of the plants utilizing rhizofiltration to remediate the polluted soil (Kristanti et al., 2021).

4.4 Phytoextraction

Through their roots, plants absorb pollutants from the soil, water, or sediments. These pollutants are then carried to the biomass above ground, where they are built up in areas like the shoots and other plant components that can be eaten. The effectiveness of phytoextraction as a potential environmental cleansing technique depends on a few parameters, including heavy metal speciation, soil characteristics, heavy metal bioavailability, and the plant's capacity to absorb metals and accumulate aboveground components (Yan et al., 2020). The fundamental concept of phytoextraction for contaminated environments is to grow appropriate plant species close by, harvest the heavy metal-containing biomass and then refine the material to reduce its size and density. The resulting heavy metal-enriched biomass has high concentrations of contaminant metals; it is either carefully removed as harmful waste or, if economically feasible, used for trace element re-extraction (Sheoran et al., 2009; Suman et al., 2018). The method is widely used for maintaining soil properties and lowering the levels of metal pollutants in the roots and shoots of plants (Van Nevel et al., 2007). *Arabidopsis thaliana*, *Brassica juncea*, *Crotalaria juncea*, *Cynodondactylon*, *Parthenium integrifolium*, *Phragmitis communis*, *Bixa orellana*, and *Lemna valdiviana* are among the plants that are used for phytoextraction (Zhuang et al., 2007; Saraswat & Rai, 2009).

4.5 Phytovolatilization

Heavy metal pollutants are taken up by plants through a process called phytovolatilization, which transforms them into volatile, non-toxic forms through transpiration. Certain hazardous metals, including arsenic and mercury, can decompose into volatile compounds like mercuric oxide and dimethyl selenide. This bioremediation technique is still problematic since the converted mercuric oxide and dimethyl selenide discharged into the surroundings continue to affect biological systems (Sakakibara et al., 2010). Heavy metal absorption has been shown to occur in musk grass (*Chara canescens*), Indian mustard (*Brassica juncea*), and *Arabidopsis thaliana*, which then releases the metals into the atmosphere in gaseous form (Ghosh & Singh, 2005). Due to its long half-life of over 327,000 years, selenium pollution in the soil poses a serious environmental risk and phytovolatilization can be used to degrade it (Sharma et al., 2015). Similarly, mercury from the soil is absorbed through roots and converted into a volatile form and eventually transpired. Since there is minimal chance that the gaseous volatilized products would return to or near the site, one way to conceptualize phytovolatilization is as a long-term site solution. Other examples include *Polypogon monspeliensis*, *Juncus effuses*, *Phragmites australis*, *Myriophyllum brasiliense*, *Juncus xiphioides*, *Typha latifolia* (Kafle et al., 2022).

Although there are various methods of phytoremediation, the technique to be used for any type of remediation will depend on its applicability and the type of pollutants involved. Table 2 summarizes the advantages and disadvantages of various phytoremediation techniques.

5. Factors affecting Phytoremediation

Heavy metal phytoremediation is influenced by numerous factors. One of the most crucial elements in the phytoremediation process is the selection of plant species. Plant species with large biomass results in increased efficiency in phytoremediation. Examples of plants

Table 2. Comparison of various phytoremediation techniques

Phytoremediation Technique	Description	Key Advantages	Key Disadvantages
Phytoextraction	Plants accumulate contaminants (typically heavy metals) in their harvestable shoots.	Cost-effective; aesthetically pleasing; reduces waste volume; potential for metal recovery.	Slower process (years); limited to shallow contamination; plant specific; biomass disposal required.
Phytostabilization	Plants reduce contaminant mobility in soil/water through root absorption, adsorption, or precipitation.	Prevents contaminant migration (leaching, erosion); reduces bioavailability; effective for large areas; rapid vegetative cover.	Contaminants remain in situ; regular monitoring required; does not remove contaminants; may require soil amendments.
Phytovolatilization	Plants absorb contaminants (e.g., volatile organic compounds, some metals like Se, Hg) and release them into the atmosphere as less harmful volatile forms.	Contaminants are removed from soil/water; can be effective for large, diffuse contamination.	Contaminants are released into atmosphere (potential air pollution); less control over contaminant fate; not suitable for all contaminants.
Phytodegradation	Plants or their associated microorganisms break down organic contaminants within plant tissues (rhizosphere or endophytic).	Destroys contaminants completely; effective for various organic pollutants; less invasive.	Slower process; limited to specific organic compounds; effectiveness depends on plant-microbe interactions.
Rhizofiltration	Plant roots (usually in hydroponic systems) absorb, adsorb, or precipitate contaminants from wastewater.	Effective for treating industrial effluents/wastewater; faster than terrestrial methods; can treat large volumes of water.	Requires hydroponic setup; root biomass disposal needed; sensitive to high contaminant concentrations; requires pH control.

utilized for phytoremediation of contaminated soils include sunflower, sorghum, and maize. Research has shown that root zone, rooting depth, the quantity of contaminants that are transmitted from roots to shoots, as well as plant species, all influence each other. pH significantly impacts phytoremediation capacity, as it influences the adsorption of environmental pollutants. High soil pH increases the efficiency of adsorption, with metal pollutants being temporarily less soluble (Souri & Hatamian, 2019). Microbial activity in the rhizosphere impacts plant growth and metal absorption. Phosphate solubilizing bacteria has shown to amplify Cd bioavailability and phytoextraction in *Brassica juncea*. Concentration of heavy metals and their chemical characteristics in soil affect phytoremediation too, as it competes with micronutrients like P, Ca, Mg, or Fe making it more difficult for plants to absorb or break down pollutants (Hatamian et al., 2020). Factors that limit pollutant uptake or prevent plant growth may make some sites unsuitable for phytoremediation (Figure 4) (Ahmad et al., 2024).

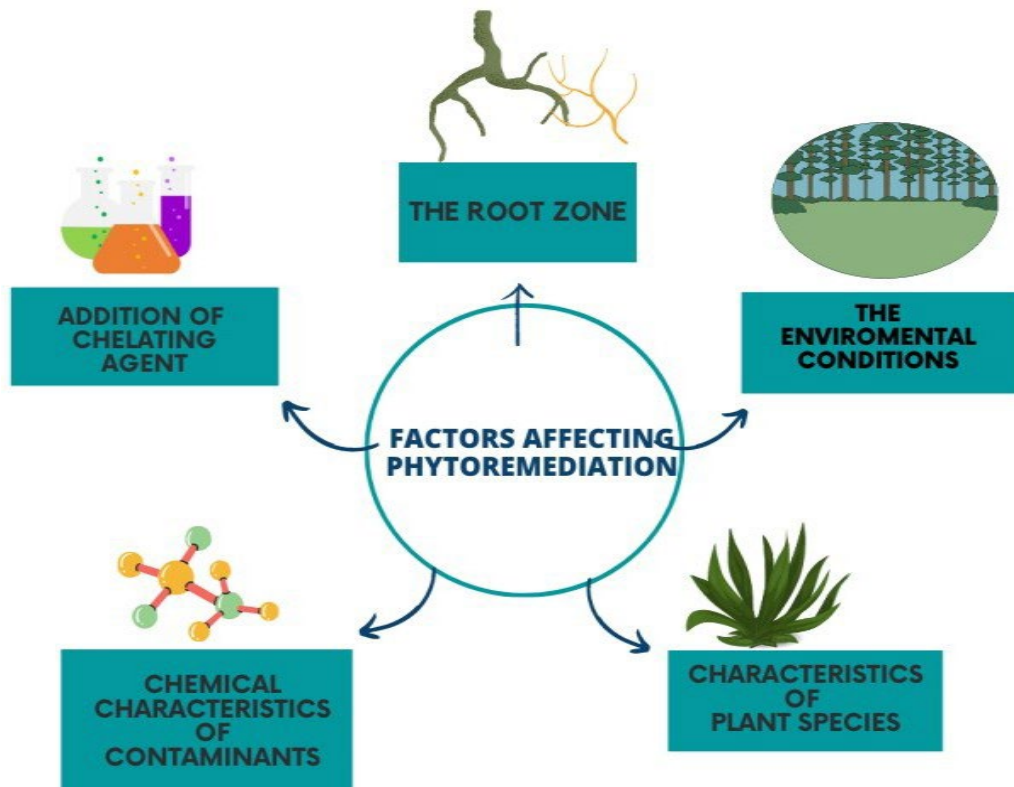


Figure 4. Factors affecting bioremediation

6. Recent Advances in Phytoremediation

6.1 Genetically engineered plants

The process of phytoremediation is improved by the use of genetically modified plants (Heaton et al., 1998; Eapen & D'Souza, 2005). Hyper-accumulator plants that have

undergone genetic modification may yield increased biomass production and soil metal extraction (Gisbert et al., 2003). Genetically engineered *Arabidopsis* demonstrated increased ability to accumulate lead, cadmium, and mercury, among other heavy metals. *Thlaspi goesingense* metal tolerance protein 1 (TgMTP1 transporter gene) has been suggested to play an important role in Zn hyperaccumulation in *T. goesingense* (Gustin et al., 2009). Similarly, AtZAT/AtMTP1 gene from *Arabidopsis*, which codes for a vacuolar zinc transporter, affects zinc detoxification (Van der Zaal et al., 1999). The OsMTP1 transporter from rice, expressed in tobacco showed enhanced metal tolerance (Menguer et al., 2013). Transgenic tobacco overexpressing rice metal tolerance protein gene OsMTP1 demonstrated a markedly higher tolerance to Cd in terms of cell survival, lipid peroxidation, membrane stability, and biomass and plant growth (Das et al., 2016). A transgenic *Arabidopsis* plant expressing mercuric ion-binding protein (MerP) exhibited superior metal-accumulating capacity (Hsieh et al., 2008).

6.2 Phytohormone-assisted phytoremediation

The process known as "plant growth regulators (PGR)-assisted phytoremediation" presents a viable way to lessen the accumulation of heavy metals in tissues of plants. Numerous investigations have demonstrated the ways in which these phytohormones may augment heavy metals accumulation and strengthen plant resistance and tolerance to stress. For example, the addition of auxin has demonstrated potential to increase tolerance to Cd in tomato seedlings (Liu et al., 2024). Moreover, it has shown that by preventing the absorption of Cd, the detrimental effects of Cd stress in *Trigonella foenum-graecum* can be lessened by adding 10 and 100mM IAA to nutritional solutions, which controlled the ascorbate-glutathione cycle (Bashri & Prasad, 2016). Furthermore, it has demonstrated that supplementing *Solanum nigrum* with 1000 mgL⁻¹ gibberellic acid 3 (GA3) greatly increased the plant's biomass and phytoremediation effectiveness (Ji et al., 2015). Likewise, it has been noted that the application of 5, 10, and 15 µM ABA can lessen the negative effects of Cd on the development of mung bean (*Vigna radiate*) plants (Zhao et al., 2023). Controlling antioxidative defense systems and preventing membrane lipid peroxidation were connected to this growth-promoting effect of ABA.

6.3 Microbial-assisted phytoremediation

Plant growth-promoting bacteria (PGPB) primarily enhance plant growth and tolerance to stress, and also helps in the breakdown, immobilization, or transformation of contaminants like heavy metals, pesticides, and hydrocarbons, aiding the process of remediation. These microbes can break down toxic materials or change them into simpler forms (Zulfiqar et al., 2023). Numerous PGPB have been shown to enhance the capacity of plants root systems to absorb heavy metals. For example, *Arthrobacter* infected *Ocimum gratissimum* helps remove Cd from soil by promoting its uptake through roots (Prapagdee & Khonsue, 2015). The detoxification of heavy metals depends on these microorganisms because they release a variety of chemicals such as organic acids and siderophores (chelators) that raise the heavy metal availability and reduce soil pH (Pande et al., 2022). It was observed that *Pseudomonas* sp. LK9-inoculated *Solanum nigrum* showed a 46% increase in Cd absorption (Chen et al., 2014). Moreover, a variety of bacteria release polymeric substances, including glomalin and polysaccharides, which lessen heavy metal mobility and aid in phytostabilization. In particular, PGPR are essential to phytoremediation

procedures because they can increase the pace at which plants detoxify, encourage the release of root enzymes that hasten the breakdown of pollutants, or pH change in the soil.

6.4 AMF inoculation-assisted phytoremediation

Through their connections with their host plants' roots, arbuscular mycorrhizal fungi (AMF), a kind of mutualistic fungus, increases the amount of phosphorus available. AMF produces chelating compounds to immobilize heavy metals by lowering the pH of the soil and/or changing the root exudate (Ma et al., 2022). For instance, the use of AMF decreased the pH and chemical fractions of the Cd-polluted soil, which greatly elevated phytoavailability and Cd buildup in the tissues of the roots and shoots (Wang et al., 2020). Alternatively, phytoextraction of heavy metals may be made possible by enhanced plant growth and increased absorption in the rhizosphere. For instance, by preventing Cd from being transported to aerial sections, AMF injections significantly boosted Cd tolerance in *Cassia alata* (Silva et al., 2018). The mutually beneficial connection between *Glomus mosseae* fungus and *Festuca arundinacea* plants promoted metallothionein and ABC transporter gene expression in addition to increasing Ni translocation (Shabani et al., 2016).

6.5 Earthworm-assisted phytoremediation

Earthworms, which are sometimes referred to as "ecosystem engineers", are essential for improving soil conditions, cycling nutrients, and breaking down organic matter. Since earthworms help to reduce soil pH, more nutrients and heavy metals are available in the rhizosphere under their activity (Cao et al., 2015). They achieve this by using their gut flora to secrete specific organic acids like fulvic and humic acids. Incorporating earthworms into the culture medium improves *Solanum nigrum*'s ability to detoxify lead (Pb). The capability for phytoextraction through *Canavalia ensiformis* plants was increased when *Rhizoglyphus musclarum* and earthworms (*Eisenia andrei*) were combined with sandy soil polluted with Cu (Santana et al., 2019). Moreover, combining *Eisenia fetida* earthworm with *Brassica juncea* plants greatly increased the effectiveness of Cd detoxification (Kaur et al., 2018).

6.6 Nanoparticles-assisted phytoremediation

One novel and creative method to improve the effectiveness of heavy metal removal is to use nanoparticles (NPs) (Zhou et al., 2020). As such, these particles possess the capacity to augment phytoremediation via several mechanisms, including but not limited to adsorption or redox processes involving heavy metals, encouraging plant development, or assisting heavy metal phytoremediation (Moharem et al., 2019; Cao et al., 2020). Through electrostatic adsorption, nanoparticles can help plants stabilize heavy metals, among many other chemical interactions. Through their interactions with rhizospheric fungi and bacteria, NPs can stimulate plant development. Several studies have shown how beneficial nanoparticles are for improving phytoremediation. For instance, it has been shown that introducing nano-TiO₂ particles to soil polluted with Cd improves soybean's (*Glycine max*) capacity to extract Cd (Ike et al., 2007).

7. Challenges of Phytoremediation

Phytoremediation is now being widely used because of its practical, affordable, and environmentally beneficial qualities. However, it suffers from several disadvantages over

conventional cleanup techniques (Adeoye et al., 2022). It is a labor-intensive procedure that might take years to complete and depends on biological cycles to rebuild soil. It may also include numerous crop cycles. Even though it can reduce phytotoxicity and encourage plant development in mildly to moderately contaminated areas, major limitations include shallow root depth, insufficient aboveground biomass, and sluggish plant growth. Hyperaccumulator plants may collect massive amounts of metals but their limited biomass and slow development rate make them less successful (Skuza et al., 2022). Metal-related soil pollutants are difficult for plants to absorb due to their limited bioavailability. Many synthetic chelating compounds, such as citric acid, EGTA, EDTA, CDTA, and DTPA, which are commonly utilized to address metal mobilization and bioavailability issues, have drawn criticism for their toxicity, non-biodegradability, and persistence in the soil. Furthermore, climate and temperature parameters are required for plants to participate in long-term phytoremediation (Mahar et al., 2016). Significant logistical problems also arise in the management, preservation, and appropriate disposal of phyto-biomass generated from metals. Compaction and composting can result in less phyto-biomass bulk and less transportation expenses, but they can also cause more dissolved metal-organic compound leaching. Harvested biomass decomposes naturally if it is disposed of in unlined landfills or kept on-site in uncovered stacks. The removal of biomass from hyperaccumulators is a crucial bottleneck, according to Sas-Nowosielska et al. (2004). According to the study, basic landfilling raises the possibility of uncontrolled leaching, in which organic acids created during plant decomposition make heavy metals more soluble and mobile, perhaps contaminating groundwater. According to Ghosh & Singh (2005), phytoremediation may result in "trophic transfer" in the absence of a specific disposal chain. Toxins like lead and cadmium can infiltrate the food chain and biomagnify in higher predators when local fauna grazes on the metal-enriched plants. Although it is a popular technique for reducing the amount of contaminated biomass, incineration poses serious threats to air quality. In his investigation on the thermal treatment of metal-contaminated willow, Keller et al. (2005) discovered that although the volume is decreased by 90%, certain metals, such as zinc and cadmium, can volatilize at high temperatures. These metals are discharged into the air as fine particles in the absence of sophisticated scrubbers. There is a logistical window for environmental mishaps when significant amounts of "hot" (very contaminated) biomass are transported from a location to a processing plant. Reducing volume is frequently the aim of disposal, but this leads to a "waste-within-waste" issue. It is challenging and costly to locate landfills capable of handling such high quantities of particular toxins, which results in "orphan waste" that is kept in temporary storage indefinitely. Thus, maintaining the long-term management of phyto-biomass in phytoremediation continues to be a major concern.

8. Conclusions

Food safety and agricultural production are seriously threatened by heavy metal pollution because of its detrimental impacts and rapid ecological spread. Numerous strategies have arisen to reduce contamination from heavy metals and restore damaged soil have been researched. With its many benefits and track record of successfully restoring heavy metal-contaminated soil, phytoremediation is unique among physicochemical methods. There are currently hundreds of heavy metal hyperaccumulating plants identified, making this one of the most straightforward kinds of phytoremediation. In addition to other techniques, reducing the soil's pH can make metals more bioavailable and bio-augmented acidified manure can enhance plant absorption of heavy metals. Moreover, phytoremediation can recover important metals from heavily polluted places while simultaneously enhancing the

quality of the soil. By creating plants with enhanced ability to collect the heavy metals, genetic engineering and molecular science research might greatly increase the effectiveness of phytoremediation. To improve soil remediation and metal accumulation in plants, this strategy can be enhanced by adding chelating agents and microorganisms to increase the bioavailability of heavy metals. More investigation is necessary to completely comprehend how different catalysts affect the effectiveness of phytoremediation, increasing their suitability for environmental restoration. Numerous plant species have significant possibilities for heavy metal bioaccumulation and can be used successfully in phytoremediation initiatives, according to earlier studies.

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10. Authors' Contributions

All the authors have contributed equally to drafting the manuscript. Arpita Mishra: wrote the initial draft; Reena Josephine C M: edited the manuscript; Sangeetha Menon: literature review, edited and revised the manuscript; Bhagyalakshmi Unnikrishnan: literature review and wrote the initial draft; Ayisha S: literature review and wrote the initial draft.

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11. Conflicts of Interest

Regarding the publishing of this paper, the author or authors state that they have no conflicts of interest.

References

- Adeoye, A. O., Adebayo, I. A., Afodun, A. M., & Ajijolakewu, K. A. (2022). Benefits and limitations of phytoremediation: Heavy metal remediation review. In R. A. Bhat, F. M. P. Tonelli, G. H. Da, & K. Hakeem (Eds.). *Phytoremediation: Biotechnological Strategies for Promoting Invigorating Environs* (pp. 227-238). Academic Press. <https://doi.org/10.1016/C2020-0-03410-9>
- Ahmad, I., Alserae, H., Zhu, B., Zahoor, A., Farooqi, Z. U. R., Mihoub, A., Ain, Q. U. & Radicetti, E., (2024). Phytoremediation of cadmium: A review. In A. K. Jha, & N. Kumar (Eds.). *Cadmium toxicity in water: Challenges and solutions* (pp. 75-99). Springer water Book series. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-54005-9_5.
- Ali, G., Khan, H., & Sajad, E. (2013). Phytoremediation of heavy metals-concepts and applications. *Chemosphere*, 91(7), 869-881. <https://doi.org/10.1016/j.chemosphere.2013.01.075>
- Alloway, B. J. (2013). Sources of heavy metals and metalloids in soils. In B. Alloway (Ed.). *Heavy metals in soils. Environmental pollution, Vol 22* (pp. 11-50). Springer. https://doi.org/10.1007/978-94-007-4470-7_2

- Bani, A., Plavlova, G., & Morel, J. L. (2010). Nickel hyperaccumulation by the species of *Alyssum* and *Thlaspi* (Brassicaceae) from the ultramafic soils of the Balkans. *Botanica Serbica*, 34, 3-14.
- Bashri, G., & Prasad, S. M. (2016). Exogenous IAA differentially affects growth, oxidative stress and antioxidants system in Cd stressed *Trigonella foenum-graecum* L. seedlings: Toxicity alleviation by up-regulation of ascorbate-glutathione cycle. *Ecotoxicology and Environmental Safety*, 132, 329-338. <https://doi.org/10.1016/j.ecoenv.2016.06.015>
- Bhunia, P. (2017). Environmental toxicants and hazardous contaminants: Recent advances in technologies for sustainable development. *Journal of Hazardous, Toxic and Radioactive Waste*, 21(4), Article 02017001. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000366](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000366)
- Bolan, N. S., Park, J. H., Robinson, B., Naidu, R., & Huh, K. Y. (2011). Phytostabilization: a green approach to contaminant. In D.L. Sparks (Ed.). *Advances in agronomy* (pp. 145-204). Elsevier. <https://doi.org/10.1016/B978-0-12-385538-1.00004-4>
- Cao, J., Ji, D., & Wang, C. (2015). Interaction between earthworms and arbuscular mycorrhizal fungi on the degradation of oxytetracycline in soils. *Soil Biology and Biochemistry*, 90, 283-292. <https://doi.org/10.1016/j.soilbio.2015.08.020>
- Cao, F., Dai, H., Hao, P. F., & Wu, F. (2020). Silicon regulates the expression of vacuolar H (+)-pyrophosphatase 1 and decreases cadmium accumulation in rice (*Oryza sativa* L). *Chemosphere*, 240, Article 124907. <https://doi.org/10.1016/j.chemosphere.2019.124907>
- 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). Wiley-Blackwell. <https://doi.org/10.1002/9781444319477.ch14>
- Chen, L., Luo, S., Li, X., Wan, Y., Chen, J., & Liu, C. (2014). Interaction of Cd-hyperaccumulator *Solanum nigrum* L. and functional endophyte *Pseudomonas* sp. Lk9 on soil heavy metals uptake. *Soil Biology and Biochemistry*, 68, 300-308. <https://doi.org/10.1016/j.soilbio.2013.10.021>
- Cunningham, S. D., & Ow, D. W. (1996). Promises and prospects of phytoremediation. *Plant Physiology*, 110(3), 715-719. <https://doi.org/10.1104/pp.110.3.715>
- Dalvi, A. A., & Bhalerao, S. A. (2013). Response of plants towards heavy metal toxicity: An overview of avoidance, tolerance and uptake mechanism. *Annals of Plant Sciences*, 2(9), 362-368.
- Das, K. K., Das, S. N., & Dhundasi, S. A. (2008). Nickel, its adverse health effects & oxidative stress. *The Indian Journal of Medical Research*, 128(4), 412-425. Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/19106437>.
- Das, N., Bhattacharya, S., & Maiti, M. K. (2016). Enhanced cadmium accumulation and tolerance in transgenic tobacco overexpressing rice metal tolerance protein gene OsMTP1 is promising for phytoremediation. *Plant Physiology and Biochemistry*, 105, 297-309. <https://doi.org/10.1016/j.plaphy.2016.04.049>
- Dhalaria, R., Kumar, D., Kumar, H., Nepovimova, E., Kuča, K., Islam, M., & Verma, R. (2020). Arbuscular mycorrhizal fungi as potential agents in ameliorating heavy metal stress in plants. *Agronomy*, 10(6), Article 815. <https://doi.org/10.3390/agronomy10060815>
- Eapen, S., & D'Souza, S. F. (2005). Prospects of genetic engineering of plants for phytoremediation of toxic metals. *Biotechnology Advances*, 23(2), 97-114. <https://doi.org/10.1016/j.biotechadv.2004.10.001>
- Epelde, L., Becerril, J. M., Mijangos, I., & Garbisu, C. (2009). Evaluation of the efficiency of a phytostabilization process with biological indicators of soil health. *Journal of Environmental Quality*, 38(5), 2041-2049. <https://doi.org/10.2134/jeq2009.0006>
- Ernst, W. H. O., Verkleij, J. A. C., & Schat, H. (1992). Metal tolerance in plants. *Acta Botanica Neerlandica*, 41(3), 229-248. <https://doi.org/10.1111/j.1438-8677.1992.tb01332.x>

- Fattahi, B., Arzani, K., Souri, M.K. & Barzegar, M. (2021). Morphological and phytochemical responses to cadmium and lead stress in coriander (*Coriandrum sativum* L.). *Industrial Crops and Products*, 171(1), Article 113979. <https://doi.org/10.1016/j.indcrop.2021.113979>
- Flathman, P. E., & Lanza, G. R. (1998). Phytoremediation: Current views on an emerging green technology. *Journal of Soil Contamination*, 7(4), 415-432. <https://doi.org/10.1080/10588339891334438>
- Garbisu, C., & Alkorta, I. (2001). Phytoextraction: A cost-effective plant-based technology for the removal of metals from the environment. *Bioresource Technology*, 77(3), 229-236. [https://doi.org/10.1016/S0960-8524\(00\)00108-5](https://doi.org/10.1016/S0960-8524(00)00108-5)
- Ghosh, M., & Singh, S. P. (2005). A review on phytoremediation of heavy metals and utilization of its byproducts. *Applied Ecology and Environmental Research*, 3(1), 1-18. https://doi.org/10.15666/aeer/0301_001018
- Gisbert, C., Ros, R., De Haro, A., Walker, D. J., Bernal, P., Serrano, M., & Navarro-Aviñó, R. (2003). A plant genetically modified that accumulates Pb is especially promising for phytoremediation. *Biochemical and Biophysical Research Communications*, 303(2), 440-445. [https://doi.org/10.1016/s0006-291x\(03\)00349-8](https://doi.org/10.1016/s0006-291x(03)00349-8)
- Gupta, D. K., Vandenhove, H., & Inouhe, M. (2013). Role of phytochelatin in heavy metal stress and detoxification mechanisms in plants. In D. Gupta, F. Corpas & J. Palma (Eds.). *Heavy Metal Stress in Plants* (pp. 73-94). Springer. https://doi.org/10.1007/978-3-642-38469-1_4
- Gustin, J. L., Loureiro, M. E., Kim, D., Na, G., Tikhonova, M., & Salt, D. E. (2009). MTP1-dependent Zn sequestration into shoot vacuoles suggests dual roles in Zn tolerance and accumulation in Zn-hyperaccumulating plants. *The Plant Journal*, 57, 1116-1127. <https://doi.org/10.1111/j.1365-313X.2008.03754.x>
- Hall, J. L. (2002). Cellular mechanisms for heavy metal detoxification and tolerance. *Journal of Experimental Botany*, 53(366), 1-11. <https://doi.org/10.1093/jexbot/53.366.1>
- Hatamian, M., Nejad, R., Kafi, A., Souri, M., & Shahbazi, M. K. (2018). Interactions of lead and nitrate on growth characteristics of ornamental Judas tree (*Cercis siliquastrum*). *Open Agriculture*, 3, 386-392. <https://doi.org/10.1515/opag-2018-0070>
- Hatamian, M., Nejad, R., Kafi, A., Souri, M., & Shahbazi, M. K. (2019). Growth characteristics of ornamental Judas tree (*Cercis siliquastrum* L.) seedling under different concentrations of lead and cadmium in irrigation water. *Acta Scientiarum Polonorum Hortorum Cultus*, 18(2), 87-96. <https://doi.org/10.24326/asphc.2019.2.8>
- Hatamian, M., Nejad, A. R., Kafi, M., Souri, M. K., & Shahbazi, K. (2020). Nitrate improves hackberry seedling growth under cadmium application. *Heliyon*, 6(1), Article e03247. <https://doi.org/10.1016/j.heliyon.2020.e03247>
- Heaton, A. C. P., Rugh, C. L., Wang, N.-J., & Meagher, R. B. (1998). Phytoremediation of mercury- and methylmercury-polluted soils using genetically engineered plants. *Journal of Soil Contamination*, 7(4), 497-509.
- Hoehamer, C. F., Wolfe, N. L., & Eriksson, K. E. L. (2006). Differences in the biotransformation of 2, 4, 6-trinitrotoluene (TNT) between wild and axenically grown isolates of *Myriophyllum aquaticum*. *International Journal of Phytoremediation*, 8(2), 107-115. <https://doi.org/10.1080/15226510600678431>
- Hsieh, J. L., Chen, C. Y., Chiu, M. H., Chein, M. F., Chang, J. S., Endo, G., & Huang, C. C. (2009). Expressing a bacterial mercuric ion binding protein in plant for phytoremediation of heavy metals. *Journal of Hazardous Materials*, 161(2-3), 920-925. <https://doi.org/10.1016/j.jhazmat.2008.04.079>
- Ike, A., Sriprang, R., Ono, H., Murooka, Y., & Yamashita, M. (2007). Bioremediation of cadmium contaminated soil using symbiosis between leguminous plant and

- recombinant rhizobia with the MTL4 and the PCS genes. *Chemosphere*, 66(9), 1670-1676. <https://doi.org/10.1016/j.chemosphere.2006.07.058>
- Ji, P., Tang, X., Jiang, Y., Tong, Y., Gao, P., & Han, W. (2015). Potential of gibberellic acid 3 (GA3) for enhancing the phytoremediation efficiency of *Solanum nigrum* L. *Bulletin of Environmental Contamination and Toxicology*, 95(6), 810-814. <https://doi.org/10.1007/s00128-015-1670-x>
- Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, 8, Article 100203. <https://doi.org/10.1016/j.envadv.2022.100203>
- Kalve, S., Sarangi, B. K., Pandey, R. A., & Chakrabarti, T. (2011). Arsenic and chromium hyperaccumulation by an ecotype of *Pteris vittata* - prospective for phytoextraction from contaminated water and soil. *Current Science*, 100(6), 888-894.
- Kärenlampi, S., Schat, H., Vangronsveld, J., Verkleij, J. A. C., van der Lelie, D., Mergeay, M., & Tervahauta, A. I. (2000). Genetic engineering in the improvement of plants for phytoremediation of metal polluted soils. *Environmental Pollution*, 107(2), 225-231. [https://doi.org/10.1016/s0269-7491\(99\)00141-4](https://doi.org/10.1016/s0269-7491(99)00141-4)
- Kaur, P., Bali, S., Sharma, A., Vig, A. P., & Bhardwaj, R. (2018). Role of earthworms in phytoremediation of cadmium (Cd) by modulating the antioxidative potential of *Brassica juncea* L. *Applied Soil Ecology: A Section of Agriculture*, 124, 306-316. <https://doi.org/10.1016/j.apsoil.2017.11.017>
- Keller, C., Ludwig, C., Davoli, F., & Wochele, J. (2005). Thermal treatment of metal-enriched biomass produced from heavy metal phytoextraction. *Environmental Science & Technology*, 39(9), 3359-3367. <https://doi.org/10.1021/es0484101>
- Khalid, S., Shahid, M., Niazi, N. K., Murtaza, B., Bibi, I., & Dumat, C. (2017). A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of Geochemical Exploration*, 182, 247-268. <https://doi.org/10.1016/j.gexplo.2016.11.021>
- Khan, M. A., Ahmad, I., & Rahman, I. U. (2007). Effect of environmental pollution on heavy metals content of *Withania somnifera*. *Journal of the Chinese Chemical Society*, 54(2), 339-343. <https://doi.org/10.1002/jccs.200700049>
- Khandare, R. V., & Govindwar, S. P. (2015). Phytoremediation of textile dyes and effluents: Current scenario and future prospects. *Biotechnology Advances*, 33(8), 1697-1714. <https://doi.org/10.1016/j.biotechadv.2015.09.003>
- Koptsik, G. N. (2014). Problems and prospects concerning the phytoremediation of heavy metal polluted soils: a review. *Eurasian Soil Science*, 47, 923-939. <https://doi.org/10.1134/S1064229314090075>
- Krämer, U., Pickering, I. J., Prince, R. C., Raskin, I., & Salt, D. E. (2000). Subcellular localization and speciation of nickel in hyperaccumulator and non-accumulator *Thlaspi* species. *Plant Physiology*, 122(4), 1343-1354. <https://doi.org/10.1104/pp.122.4.1343>
- Kristanti, R. A., Ngu, W. J., Yuniarto, A., & Hadibarata, T. (2021). Rhizofiltration for removal of inorganic and organic pollutants in groundwater: a review. *Biointerface Research in Applied Chemistry*, 11, 12326-12347.
- Lasat, M. M. (1999). Phytoextraction of metals from contaminated soil: a review of plant/soil/metal interaction and assessment of pertinent agronomic issues. *Journal of Hazardous Substance Research*, 2(1), Article 5. <https://doi.org/10.4148/1090-7025.1015>
- Liu, H., Wu, Y., Cai, J., Chen, Y., Zhou, C., Qiao, C., & Wang, S. (2024). Effect of auxin on cadmium toxicity-induced growth inhibition in *Solanum lycopersicum*. *Toxics*, 12(5), Article 374. <https://doi.org/10.3390/toxics12050374>

- Lone, M. I., He, Z. L., Stoffella, P. J., & Yang, X. E. (2008). Phytoremediation of heavy metal polluted soils and water: progresses and perspectives. *Journal of Zhejiang University Science B*, 9(3), 210-220. <https://doi.org/10.1631/jzus.B0710633>
- Ma, Y., Ankit, Tiwari, J., & Baudh, K. (2022). Plant-mycorrhizal fungi interactions in phytoremediation of geogenic contaminated soils. *Frontiers in Microbiology*, 13, Article 843415. <https://doi.org/10.3389/fmicb.2022.843415>
- Mahar, A., Wang, P., Ali, A., Awasthi, M. K., Lahori, A. H., Wang, Q. & Zhang, Z. (2016). Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicology and Environmental Safety*, 126, 111-121. <https://doi.org/10.1016/j.ecoenv.2015.12.023>
- Mahjoub, B. (2013). Plants for soil remediation. In S. Gaspard & M. C. Ncibi (Eds.). *Biomass for sustainable applications: Pollution remediation and energy* (pp 106-143). The Royal Society of Chemistry. <https://doi.org/10.1039/9781849737142>
- McGrath, S. P., Zhao, F. J., & Lombi, E. (2001). Plant and rhizosphere processes involved in phytoremediation of metal-contaminated soils. *Plant and Soil*, 232, 207-214. <https://doi.org/10.1023/A:1010358708525>
- Memon, A. R., & Schröder, P. (2009). Implications of metal accumulation mechanisms to phytoremediation. *Environmental Science and Pollution Research*, 16, 162-175. <https://doi.org/10.1007/s11356-008-0079-z>
- Menguer, P. K., Farthing, E., Peaston, K. A., Ricachenevsky, F. K., Fett, J. P., & Williams, L. E. (2013). Functional analysis of the rice vacuolar zinc transporter OsMTP1. *Journal of Experimental Botany*, 64(10), 2871-2883. <https://doi.org/10.1093/jxb/ert136>
- Moharem, M., Elkhatib, E., & Mesalem, M. (2019). Remediation of chromium and mercury polluted calcareous soils using nanoparticles: Sorption-desorption kinetics, speciation and fractionation. *Environmental Research*, 170, 366-373. <https://doi.org/10.1016/j.envres.2018.12.054>
- Mukhopadhyay, S., & Maiti, S. K. (2010). Phytoremediation of metal mine waste. *Applied Ecology and Environmental Research*, 8(3), 207-222.
- Newman, L. A., & Reynolds, C. M. (2004). Phytodegradation of organic compounds. *Current Opinion in Biotechnology*, 15(3), 225-230. <https://doi.org/10.1016/j.copbio.2004.04.006>
- Pande, V., Pandey, S. C., Sati, D., Bhatt, P., & Samant, M. (2022). Microbial interventions in bioremediation of heavy metal contaminants in agroecosystem. *Frontiers in Microbiology*, 13, Article 824084. <https://doi.org/10.3389/fmicb.2022.824084>
- Paz-Alberto, A. M., & Sigua, G. C. (2013). Phytoremediation: A green technology to remove environmental pollutants. *American Journal of Climate Change*, 2(1), 71-86. <https://doi.org/10.4236/ajcc.2013.21008>
- Pivetz, B. E. (2001). *Phytoremediation of contaminated soil and ground water at hazardous waste sites*. https://www.epa.gov/sites/default/files/2015-06/documents/epa_540_s01_500.pdf
- Pivetz, S., Ali, Q., Zahir, Z. A., Ashraf, S., & Asghar, H. N. (2019). Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. *Ecotoxicology and Environmental Safety*, 174, 714-727. <https://doi.org/10.1016/j.ecoenv.2019.02.068>
- Prapagdee, B., & Khonsue, N. (2015). Bacterial-assisted cadmium phytoremediation by *Ocimum gratissimum* L. in polluted agricultural soil: a field trial experiment. *International Journal of Environmental Science and Technology*, 12(12), 3843-3852. <https://doi.org/10.1007/s13762-015-0816-z>
- Rafique, N., & Tariq, S. R. (2016). Distribution and source apportionment studies of heavy metals in soil of cotton/wheat fields. *Environmental Monitoring and Assessment*, 188(5), Article 309. <https://doi.org/10.1007/s10661-016-5309-0>

- Raskin, I., I., Smith, R. D., & Salt, D. E. (1997). Phytoremediation of metals: using plants to remove pollutants from the environment. *Current Opinion in Biotechnology*, 8(2), 221-226. [https://doi.org/10.1016/S0958-1669\(97\)80106-1](https://doi.org/10.1016/S0958-1669(97)80106-1)
- Rodriguez, L., Lopez-Bellido, F., Carnicer, A. & Alcalde, M. V. (2003). Phytoremediation of mercury-polluted soils using crop plants. *Fresenius Environmental Bulletin*, 12, 967-971.
- 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(8), 735-741. <https://doi.org/10.1002/clen.201000488>
- Salem, H. M., Eweida, E. A., & Farag, A. (2000). Heavy metals in drinking water and their environmental impact on human health. In *Proceedings of the International Conference for Environmental Hazards Mitigation* (pp. 542-556). Cairo University.
- Santana, N. A., Ferreira, P. A. A., Tarouco, C. P., Schardong, I. S., Antonioli, Z. I., Nicoloso, F. T., & Jacques, R. J. S. (2019). Earthworms and mycorrhization increase copper phytoextraction by *Canavalia ensiformis* in sandy soil. *Ecotoxicology and Environmental Safety*, 182, Article 109383. <https://doi.org/10.1016/j.ecoenv.2019.109383>
- Saraswat, S., & Rai, J. P. N. (2009). Phytoextraction potential of six plant species grown in multimetal contaminated soil. *Chemistry in Ecology*, 25(1), 1-11. <https://doi.org/10.1080/02757540802657185>
- Sas-Nowosielska, A., Kucharski, R., Malkowski, E., Pogrzeba, M., Kuperberg, M. & Kryński, K. (2004). Phytoextraction crop disposal — an unsolved problem. *Environmental Pollution*, 128, 373-379. <https://doi.org/10.1016/j.envpol.2003.09.012>
- Shabani, L., Sabzalian, M. R. & Mostafavi pour, S. (2016). Arbuscular mycorrhiza affects nickel translocation and expression of ABC transporter and metallothionein genes in *Festuca arundinacea*. *Mycorrhiza*, 26(1), 67-76. <https://doi.org/10.1007/s00572-015-0647-2>
- Sharma, S.S., & Dietz, K.J. (2006). The significance of amino acids and amino acid-derived molecules in plant responses and adaptation to heavy metal stress. *Journal of Experimental Botany*, 57(4), 711-726. <https://doi.org/10.1093/jxb/erj073>
- Sharma, S., Singh, B., & Manchanda, V. K. (2015). Phytoremediation: role of terrestrial plants and aquatic macrophytes in the remediation of radionuclides and heavy metal contaminated soil and water. *Environmental Science and Pollution Research*, 22, 946-962. <https://doi.org/10.1007/s11356-014-3635-8>
- Sheoran, V., Sheoran, A. S., & Poonia, P. (2009). Phytomining: A review. *Minerals Engineering*, 22(12), 1007-1019. <https://doi.org/10.1016/j.mineng.2009.04.001>
- Silva, J. R. R., Fernandes, A. R., Junior, M. L. S., Santos, C. R. C., & Lobato, A. K. S. (2018). Tolerance mechanisms in *Cassia alata* exposed to cadmium toxicity - potential use for phytoremediation. *Photosynthetica*, 56(2), 495-504. <https://doi.org/10.1007/s11099-017-0698-z>
- Skuzza, L., Szućko-Kociuba, I., Filip, E., & Bożek, I. (2022). Natural molecular mechanisms of plant hyperaccumulation and hypertolerance towards heavy metals. *International Journal of Molecular Sciences*, 23(16), Article 9335. <https://doi.org/10.3390/ijms23169335>
- Souri, M. K., Alipanahi, N., Hatamian, M., Ahmadi, M., & Tesfamariam, T., (2018). Elemental profile of heavy metals in garden cress, coriander, lettuce and spinach, commonly cultivated in Kahrizak, South of Tehran-Iran. *Open Agriculture*, 3(1), 32-37. <https://doi.org/10.1515/opag-2018-0004>
- Souri, M. K., & Hatamian, M. (2019). Aminochelates in plant nutrition; a review. *Journal of Plant Nutrition*, 42(1), 67-78. <https://doi.org/10.1186/s40538-019-0170-3>
- Souri, M. K., Hatamian, M., & Tesfamariam, T. (2019). Plant growth stage influences heavy metal accumulation in leafy vegetables of garden cress and sweet basil. *Chemical and Biological Technologies in Agriculture*, 6(1), Article 25. <https://doi.org/10.1186/s40538-019-0170-3>

- Su, C., Jiang, L., & Zhang, W. (2014). A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. *Environmental Skeptics and Critics*, 3(2), 24-38.
- 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, Article 1476. <https://doi.org/10.3389/fpls.2018.01476>
- Van Der Zaal, B. J., Neuteboom, L. W., Pinas, J. E., Chardonens, A. N., Schat, H., Verkleij, J. A., & Hooykaas, P. J. (1999). Overexpression of a novel Arabidopsis gene related to putative zinc-transporter genes from animals can lead to enhanced zinc resistance and accumulation. *Plant*, 119, 1047-1056. <https://doi.org/10.1104/pp.119.3.1047>
- Van Nevel, L., Mertens, J., Oorts, K., & Verheyen, K. (2007). Phytoextraction of metals from soils: how far from practice. *Environmental Pollution*, 150(1), 34-40. <https://doi.org/10.1016/j.envpol.2007.05.024>
- Wang, G., Wang, L., Ma, F., You, Y., Wang, Y., & Yang, D. (2020). Integration of earthworms and arbuscular mycorrhizal fungi into phytoremediation of cadmium-contaminated soil by *Solanum nigrum* L. *Journal of Hazardous Materials*, 389, Article 121873. <https://doi.org/10.1016/j.jhazmat.2019.121873>
- Wang, J., Feng, X., Anderson, C. W., Xing, Y., & Shang, L. (2012). Remediation of mercury contaminated sites—a review. *Journal of hazardous materials*, 221, 1-18. <https://doi.org/10.1016/j.jhazmat.2012.04.035>
- Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecology*, 2011, Article 402647. <https://doi.org/10.5402/2011/402647>
- Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science*, 11, Article 359. <https://doi.org/10.3389/fpls.2020.00359>
- Zhang, X., Yan, L., Liu, J., Zhang, Z., & Tan, C. (2019). Removal of different kinds of heavy metals by novel PPG-nZVI beads and their application in simulated storm water infiltration facility. *Applied Sciences*, 9(20), Article 4213. <https://doi.org/10.3390/app9204213>
- Zhao, Y., Wang, J., Huang, W., Zhang, D., Wu, J., Li, B., Li, M., Liu, L., & Yan, M. (2023). Abscisic-acid- regulated responses to alleviate cadmium toxicity in plants. *Plants*, 12(5), Article 1023. <https://doi.org/10.3390/plants12051023>
- Zheng, X., Lin, H., Du, D., Li, G., Alam, O., Cheng, Z., Liu, X., Jiang, S. & Li, J. (2024). Remediation of heavy metals polluted soil environment: A critical review on biological approaches. *Ecotoxicology and Environmental Safety*, 284, 116883. <https://doi.org/10.1016/j.ecoenv.2024.116883>
- Zhou, P., Adeel, M., Shakoor, N., Guo, M., Hao, Y., & Azeem, I., Rui, Y. (2020). Application of nanoparticles alleviates heavy metals stress and promotes plant growth: An overview. *Nanomaterials*, 11(1), Article 26. [10.3390/nano11010026](https://doi.org/10.3390/nano11010026)
- Zhuang, P., Yang, Q. W., Wang, H. B., & Shu, W. S. (2007). Phytoextraction of heavy metals by eight plant species in the field. *Water, Air, and Soil Pollution*, 184(1-4), 235-242. <https://doi.org/10.1007/s11270-007-9412-2>
- Zulfiqar, U., Haider, F. U., Maqsood, M. F., Mohy-Ud-Din, W., Shabaan, M., Ahmad, M., Kaleem, M., Ishfaq, M., Aslam, Z., & Shahzad, B. (2023). Recent advances in microbial-assisted remediation of cadmium- contaminated soil. *Plants*, 12(17), Article 3147. <https://doi.org/10.3390/plants12173147>