REVIEW

Phytoremediation of toxic metals and their post-remediation management approaches

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Abstract

Toxic metal contamination is a serious concern nowadays due to their persistence, toxicity, and bioaccumulation properties. These metals cause severe effects on human health and the environment, and even at low concentrations, they may contribute to severe diseases, including cancer. Phytoremediation is one of the eco-friendly and cost-effective methods for the remediation of toxic metals. Hyperaccumulator plants absorb and tolerate higher concentrations of toxic metals through various mechanisms, including chelation, antioxidant defense, compartmentalization, uptake, and storage in their tissues. The mitigation of toxic metal contamination through phytoremediation is a cost-effective approach. However, it must include thorough assessments of its impacts on herbivores and humans during and after the remediation process. Herbivores eating these hyperaccumulators may develop toxic metal accumulation, which could lead to neurological, developmental, and other disorders. Post-phytoremediation strategies for managing biomass include incineration, pyrolysis, gasification, and composting. Biomass management, such as thermal treatments like pyrolysis or biological methods like composting are used to prevent contaminants from re-entering the soil. However, the risk of secondary pollution persists if handling protocols are not strictly regulated. Though phytoremediation presents an encouraging solution to the problem of toxic metal pollution, successful phytoremediation projects require the management of post-remediation biomass. This review article focuses on the concept of phytoremediation of toxic metal contamination, including the mechanism of metal binding and sequestration in hyperaccumulator plants. It also focuses on sustainable strategies for environmental protection and economic feasibility to promote informed decision-making in phytotechnologies.

Keywords: Hyperaccumulator, Phytoextraction, Phytoremediation, Phytostabilization, Toxic metals

Introduction

The rapid industrial growth in recent decades has led to a substantial increase in the presence of toxic metals in the environment, raising significant concerns worldwide (Angon et al., 2024). Toxic metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), and mercury (Hg) persistently accumulate, posing risks and causing adverse effects on both plants and animals (Alsafran et al., 2021; Habiba et al., 2019; Xu et al., 2024). These metals enter the environment from different sources, both natural and human-made, including oil and gas industries, building infrastructure, mining, smelting practices, coal-fired power plants, synthetic fertilizers' production, agricultural practices, etc. (Al-Thani & Yasseen, 2020; Wan et al., 2024; Yan et al., 2020). In response to these challenges, understanding the dynamics of toxic metal accumulation in plants is crucial. Strategies for accumulation and tolerance depend on various factors, such as metal type and plant species. The excess accumulation of toxic metals in plants results in a reduction of stomatal conductance, transpiration rates, growth, disruptions in metabolism, etc. (Saifullah et al., 2014; Vasilachi et al., 2023).

Plants can remediate toxic metals through four key processes, i.e., exclusion, stabilization, removal, and distinct organ localization. Permissible accumulation limits are crucial, and beyond the permissible limits, toxic metals begin to accumulate and magnify within the food chain, which emphasizes the importance of environmental preventive measures (Abid et al., 2025; Sharma & Pandey, 2014; Singh & Kalamdhad, 2011; Wuana & Okieimen, 2011). Cadmium (Cd) exposure causes the Itai-itai disease in humans, and chromium (Cr) exposure causes cancer (Zohdi et al., 2012), and excess arsenic (As) may disrupt the immune system (Islam, 2023; Duruibe et al., 2007). Remediation of toxic metal sites is a top priority, because it reduces health-related risks and protects the soil from further degradation to sustain the production of food.

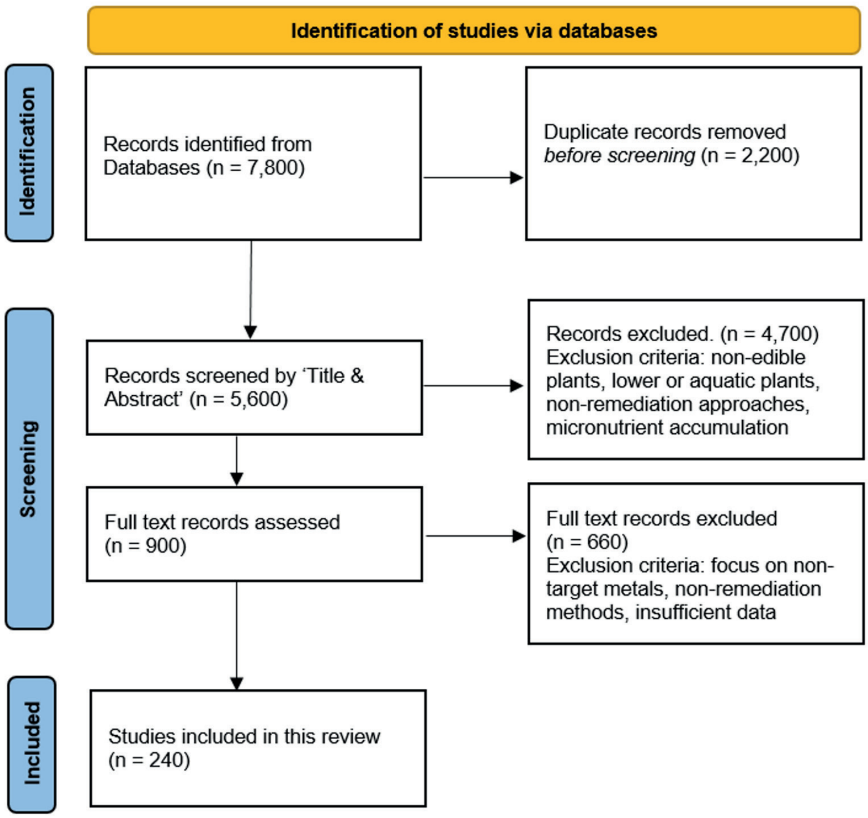
Consequently, there is an immediate need for the development of highly economical remediation technologies that are efficient and cost-effective. Global efforts to eliminate toxic metals often involve high costs and pose risks of environmental contamination. Phytoremediation is a promising environmental approach that effectively removes toxic metals from polluted soil in a sustainable and cost-effective way (Deng et al., 2024).

Phytoremediation with hyperaccumulator plants is an effective method in which plants use their root systems to stabilize, move, or translocate, or sequester nonessential metals from soil (Liu et al., 2020). It depends on a number of processes, including phytoextraction, phytovolatilization, phytostabilization, and phytofiltration to excrete or neutralize harmful pollutants (Kafle et al., 2022). Plants employ one or more of these mechanisms to minimize the toxic metals concentration in the soil. Despite this, toxic metals may persist in the edible parts of hyperaccumulator crops even after phytoremediation, posing risks to human health by entering the food chain. Thus, strict safety regulations to monitor metal levels in food items are crucial to preventing the consumption of contaminated vegetables, thereby protecting public health at the national and international levels.

The growing use of hyperaccumulator plants in pollution sites requires complete knowledge of post-phytoremediation processes to maintain the longevity of this remediation method. This review paper discusses the relationships between hyperaccumulator plants and the toxic metals they absorb and their possible health effects on human beings. It mainly deals with the identification and characterization of hyperaccumulator edible plants, mechanisms of action of phytoremediator plants, and the fate of pollutants in post-phytoremediation conditions. It also further highlighted the possibility of tapping into nature-based remediation that would benefit sustainable agriculture by utilizing natural detoxification methods.

Methodology

This review was conducted using a structured systematic review framework based on the PRISMA guidelines (Page et al., 2021). A comprehensive literature search was performed across multiple electronic databases, including PubMed, Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search covered studies published between 2000 and 2026. Boolean operators (AND, OR) were used with keywords such as: "phytoremediation", "heavy metals", "toxic metals", "hyperaccumulator plants", "phytoextraction", "phytostabilization", "phytovolatilization", "phytofiltration", "edible hyperaccumulators" "phytoremediation of heavy metals", and "Potentially Toxic Elements." To ensure a rigorous and focused review, the study was guided by specific inclusion and exclusion criteria designed to isolate the most relevant data. We prioritized peer-reviewed research articles and high-impact reviews that specifically investigated the remediation of toxic metalloids, namely Cadmium (Cd), Lead (Pb), Mercury (Hg), Arsenic (As), and Chromium (Cr) within terrestrial edible plants. This focus allows for a critical analysis of both the phytoremediation mechanisms and the subsequent food safety implications. Conversely, we excluded non-terrestrial species like aquatic plants and mosses, as well as studies centered solely on essential micronutrients (Zn, Fe, Cu) or purely technical remediation methods like bioadsorption, ensuring the findings remain applicable to soil-to-crop contamination scenarios. A total of 7800 records were initially identified. After removing duplicates, 5600 articles were screened based on title and abstract. Following a full-text assessment, 240 studies were included in the final analysis. A PRISMA flow diagram has been included (Figure 1) to illustrate the study selection process.



| **Figure 1**. PRISMA flow diagram for literature search of the study (Page et al., 2021).

Origin and impact of toxic metal contaminants on plant and human health

Toxic metals are metallic elements or metalloids that harm living organisms even at low exposure, typically having high density and atomic numbers above 20, though toxicity mainly depends on dose and chemical form. Although naturally occurring in soil, they can accumulate to high levels and cause toxicity in various living organisms, such as plants, animals, humans, and microbes (Ahmed et al., 2021). Essential metals such as Fe, Mn, Co, Zn, and Mo are required in trace amount and are crucial for supporting a broad range of biological processes (Bhattacharya et al., 2016), and also non-essential toxic metals, including Hg, As, Cd, Cr, and Pb are considered pollutants and are harmful to the environment (Sumiahadi & Acar 2018).

Toxic metals are consistently introduced into the soil and water through natural processes of the earth's crust. However, anthropogenic activities, such as industrial waste accumulation, urbanization, mining, atmospheric deposition, sludge dumping, smelting, electroplating, and the extensive use of pesticides and chemical fertilizers in agriculture containing toxic metals, have significantly increased their release into the ecosystem (Abdelsalam et al., 2019; Angon et al., 2024; Adamu et al., 2013). Many of these metals accumulate in plants, enter the food chain, and subsequently transfer to consumers, adversely affecting consumer health (Awa and Hadibarata, 2020). The different sources and impact of toxic metals on plants and human beings are shown below in Figure 2.

The exposure of plants to toxic metals induces changes in physiological and biochemical properties. Plants must evolve or adopt a sequence of methods to cope with the detrimental effects of toxic metals toxicity. For example, Imran et al. (2013) reported a reduction in plumule and radicle length in *Helianthus annuus* L. seedlings exposed to As. Additionally, As has been reported to reduce photosynthetic pigments, destroy chloroplast membranes, reduce enzyme activity, and modify nutrient balance and protein metabolism (Martínez-Castillo et al., 2022; Li et al., 2006; Singh et al., 2009; Ahsan et al., 2010. Similarly, Hernández et al. (2012) observed that AlfaAlfa roots exposed to toxic metals such as Hg and Cd induce oxidative stress and glutathione depletion. Furthermore, Chatterjee et al. (2004) reported that the accumulation of Pb caused negative impacts on biochemical and physiological processes responsible for grain quality in *Oryza sativa*. Pb not only disrupts cell organelle integrity, including the membrane stability index, but also lowers the concentration of chlorophyll in leaves and reduces the number and size of leaves, tillers, and inflorescence. The adverse effects of toxic metals are not only limited to the botanical world but also impact human health significantly. Plant exposure to these metals not only determines the physiology and biochemical reactions of plants, but also predetermines possible consequences of the impact on the wider ecosystem. High concentrations of toxic metals disrupt human metabolic processes, entering the body through food, skin contact, or inhalation. Park et al. (2004) have shown that exposure of human beings to dust and mist of hexavalent chromium Cr(VI) is associated with life risks of lung cancer and possible death. Postmenopausal breast cancer is more likely when people consume Cd-contaminated rice and other foods (Itoch et al., 2014). Similarly, As exposure causes different health issues such as respiratory, renal, neurological, and cardiovascular (Lin et al., 2013). Table 1 provides a summary of anthropogenic sources and adverse effects of selected toxic metals on plant and human health.

Toxic metal contaminants have complex interactions with plant physiology and human health, highlighting the need for a detailed understanding of these environmental challenges. The high level of

toxic metal concentration is a great threat to life. The cellular dynamics underlying the uptake of toxic metals in eukaryotic cells is essential to understand the mechanisms by which metals interact with living systems in providing an enlightenment on how these contaminants are absorbed, transported and detoxified in the cells.

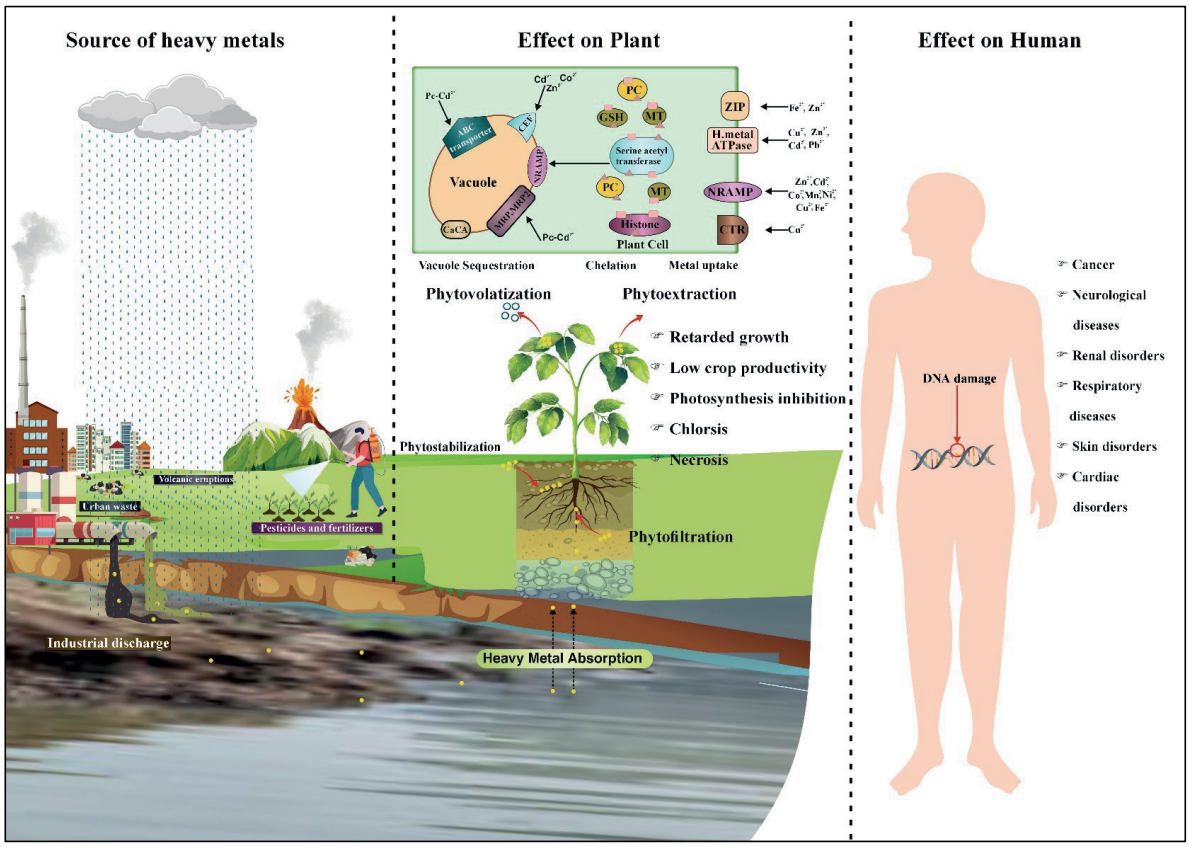


Figure 2. Sources of Toxic Metals and Their Impact on Plants and Human being.

Table 1. Human-induced origins and detrimental impact of specific Toxic metals on plant and human health.

Toxic Metals	Threshold limits (soil (mg/kg)	Source	Harmful impact on plant health	Harmful Impact on Human Health	References
Arsenic (As)	20	Industrial activities and trans-ferred by air Usage of pesticides and wood preserva-tives.	Disturb the normal functioning of plant metabolism. Stunted growth and low crop productivity.	Carcinogen, cellular damage, and cell death	Chen & Olsen, 2016; Kabir et al., 2016

Cadmium (Cd)	0.8	Batteries, ceramics, electronic and metal-finishing industries, electroplating industries, pigments, petroleum products, textiles, insecticides, television sets, metallurgical industries.	Decreases seed germination, lipid content, and plant growth. Disturb enzyme activities. Interfere with the symbiosis between microbes and plants. Increase plant predisposition to fungal invasion.	Causing irreversible damage to the renal tubules	Laghlim et al., 2015; Pulford & Watson 2003; Rubio et al., 2018; WHO 1996
Mercury (Hg)	0.1-1.0	Mining, petrochemical, painting industries, fertilizers, and medical instruments	Conflicts with electron transport. Disrupt oxidation reactions and the photosynthesis process.	Neurological and renal disorders	Rezae et al., 2005; Wang et al., 2012; Ha et al., 2017
Lead (Pb)	85	Melting and smelting of ores, automobiles, pesticides, urban soil waste	Reduces chlorophyll. Chlorosis, Necrosis. Inhibit root and shoot growth. Less biomass production. Affect seed germination.	Respiratory, cardiac, neurological, and renal disorders.	Laghlim et al., 2015; Zulfiqar et al., 2019; WHO 1996
Chromium (Cr)	100	Leather tanning, metallurgy, electroplating, and refractory	Stunted plant growth. Causes membrane damage Chlorosis Root damage.	Skin disorders	Laghlim et al., 2015; Almeidaa et al., 2019; WHO 1996

Toxic metal uptake and its intracellular dynamics in eukaryotic cells

Certain elements such as Zn, Cu, and Fe are essential micronutrients required in trace amounts, whereas metals such as Cd, Cr, Pb, Hg, and As have no known biological function and are toxic even at low concentrations and disturb biochemical and physiological activities by destabilizing the enzymatic reactions and acting reactively (Cheng et al., 2025; Tchounwou et al., 2012; Rahman et

al., 2012). Plants that exhibit a greater ability to absorb and transport the toxic metal into their shooting system are termed hyperaccumulators (Akinbile & Mbohwa, 2025). These plants have developed internal and complex mechanisms, including uptake, transportation, and detoxification of toxic metals. A comprehensive array of investigations has been undertaken on *Thlaspi caerulescens* and *Arabidopsis halleri*, by considering these as a model organism for elucidating toxic metal tolerance strategies (Milner & Kochian 2008; Frérot et al., 2010). Existing evidence claims that hyperaccumulation is attributed to the differential expression of shared genes in both hyperaccumulator and non-hyperaccumulator plants, rather than arising from the presence of novel genes (Verbruggen et al., 2009). The comprehensive elucidation of the intricate mechanisms governing toxic metal uptake, transportation, and detoxification in eukaryotic cells is further explained in the subsequent section.

Uptake and transport of toxic metals

Hyperaccumulator plants have a remarkable ability to absorb toxic elements, even under varied concentrations of toxic metals in the soil. This uptake process is influenced by multiple factors, including pH, soil moisture content, soil physical conditions, and the presence of organic substances (Tangahu et al., 2011). A study indicates that organic acid substances released from the rhizosphere impact the solubility of Cd by forming Cd complexes (Krishnamurti et al., 1997). Consequently, the pH and organic acid compounds released from a hyperaccumulator rhizosphere stimulate toxic metal absorption, thereby increasing their uptake (Pan et al., 2010). Additionally, transporters located in the plasma membrane play a crucial role in facilitating the uptake of toxic metal ions from the soil. Specifically, transporters from the ZIP family (ZRT–IRT-like proteins) are involved in the accumulation of toxic metals through the uptake and transport of various cations, such as Fe^{2+}, Mn^{2+}, and Zn^{2+}, from the root to the shoot (Guerinot 2000). Hyperaccumulator plants like *T. caerulescens* and *A. halleri* have increased Zn uptake in comparison to non-hyperaccumulator plant species, a phenomenon associated with increased expression of several ZIP family members in hyperaccumulators (Assunção et al., 2001). Another important metal transporter family, named P1B-type ATPases of toxic metal transporting ATPases (HMAs), is widely present across different taxa, dependent on the transportation of toxic metals such as Zn, Cd, Co, and Pb, playing an essential role in metal tolerance (Axelsen & Palmgren 2001; Williams & Mills 2005). The HMA4 transporter is involved in the translocation of Zn and Cd from the root to the shoot of the plant. The Cd and Zn efflux from the root system into xylem vessels enhanced the metal tolerance due to the overexpression of HMA4 (Verret et al., 2004). Further, NRAMPs (naturally resistant associated macrophage proteins), a type of transporters, utilize the proton gradient in the transmembrane to facilitate transportation of divalent cations like Mn^{2+} and Fe^{2+} to the cytoplasm (Cailliatte et al., 2010). It has been demonstrated that the iron transporter found at the plasma membrane of *Oryza sativa,* regulated by OsNramp1, exhibits Cd influx activity (Takahashi et al., 2011). Additionally, another type of transporter named the metal transporter proteins (MTPs) family are involved in the transportation of Zn and Ni towards the internal cell chamber and extracellular space (Gustin et al., 2011). Zn accumulation and its tolerance are regulated by MTP1, a vacuolar Zn^{2+}/H^{+} antiporter that is situated at both the vacuolar and plasma membrane (Desbrosses-Fonrouge et al., 2005). In *Thlaspi goesingense,* the members of the MTP family are engaged for Ni vacuolar storage (Persans et al., 2001). Furthermore, cation exchanger (CAX) transporters situated at the tonoplast are involved in vacuolar accumulation/sequestration of Cd (Sharma et al., 2016). The expression of CAX4 and CAX2 in *Nicotiana tabacum* plays an important role in Cd transport and its selectivity in tonoplast vesicles (Koren'Kov et al., 2007). Lead

(Pb) is available to plants through natural and anthropogenic sources. Several studies demonstrated that root hairs have a high capability to adsorb Pb due to its association with polysaccharides of root epidermal cells (Nareshkumar et al., 2015). Various plant species, including *Brassica juncea*, *Vigna unguiculata*, and *Festuca rubra*, have provided insights into the absorption of lead (Pb) on their root surfaces (Pourrut et al., 2011). Ca-permeable channels are the primary route through which Pb enters the root (Kumar et al., 2017). Transgenic tobacco plants overexpress a protein named calmodulin-binding protein 4 (NtCBP4), which has a possible role in Pb uptake across the plasma membrane (Zeng et al., 2015).

Detoxification / Efflux of toxic metal ions

Detoxification of toxic metals is an indispensable mechanism for phytoremediation (Thakur et al., 2016). In case there is excessive assembly of toxic metal ions in the cytosol, the plants are obligated to get rid of them through detoxification to minimize their detrimental effects (Manara 2012). This process works through chelation, where toxic metal ions bind with ligands to form stable complexes. In the cytoplasm, several organic and inorganic ligands are present to facilitate the chelation of toxic metal ions. The organic compounds, such as organic acids, amino acids, phytochelatins (PCs), and metallothioneins (MTs), are engaged in toxic metal ion chelation (Hall 2002; Sharma and Dietz 2006). Organic acids present inside the cells neutralize the effect of toxic metals as free ions in the cytoplasm by minimizing their bioavailability to plants. For instance, in the leaves of *T. goesingense,* citrate mediates the chelation of Ni (Krämer et al., 2000), whereas in the leaves of *Solanum nigrum,* acetic and citric acids bind to Cd (Sun et al., 2006). Moreover, chelation of Zn in *A. halleri* through malate organic acid (Sarret et al., 2002). Similarly, stress from toxic metals induces the accumulation of various types of amino acids. For instance, in *Arabidopsis thaliana,* the production of cysteine can be stimulated by Cd (Domínguez−Solís et al., 2004), whereas the production of proline is stimulated by high stress of Cd, Pb, Zn, and Cu (Roy and Bera 2002). These aforementioned amino acids have the competency to remove toxic metals through chelation inside the cells and xylem sap (Rai 2002). After chelation, toxic metal ligand complexes are actively transported from the cytosol into dormant compartments, such as the vacuole, where they are stored without any harmful effect (Tong et al., 2004). The harmful effects of toxic metals are reduced by sequestration and vacuolar compartmentalization that aids the flushing out of toxic metals from cellular sites involved in metabolic processes (Sheoran et al., 2010).

Furthermore, various genes are involved in the detoxification mechanism of toxic metals. For example, in *O. sativa* nodulin 26-like intrinsic protein 2:1 (OsNIP2:1) is involved in the uptake as well as removal of As^{3+} (Zhao et al., 2010). Similarly, *Saccharomyces cerevisiae* exhibits ACR3 proteins for the removal of As^{3+} (Wysocki et al., 1997). One of the transporters located at the plasma membrane of the cell, named P1B-type heavy metal ATPases (HMAs), play an essential role in metal homeostasis. For example, in *O. sativa*, OsHMA9 is associated with the efflux of various metals such as Zn, Pb, and Cu (Lee et al., 2007). The gene for the cucumber CsMTP9 member of the MTP family, is a plasma membrane-bound antiporter that effluxes Mn^{2+} and Cd^{2+} from the endodermis into the vascular tissue by the influx of hydrogen ions (Pedas et al., 2014). Apart from this, the detoxification of toxic metals in a hyperaccumulator also depends on gene overexpression associated with antioxidant activity, such as reduced glutathione (GSH), cysteine, and O-acetylserine (Anjum et al., 2008). A study revealed that in *Noccaea goesingense,* overexpression of NgSAT resulted in increased levels of GSH that help in the tolerance of Ni, Co, Zn (Freeman et al., 2004).

Toxic metal uptake and intracellular dynamics in eukaryotic cells involve complex mechanisms, but these strategies have limitations when environmental metal levels become too high. The insufficiency of these strategies highlights the need for more comprehensive remediation approaches. Phytoremediation technology has emerged as a promising and environmentally friendly, sustainable solution to combat the escalating challenges posed by toxic metal pollution. By leveraging the unique capabilities of hyperaccumulator plants, phytoremediation offers a green strategy that goes beyond intracellular processes, addressing the broader ecological impact of toxic metal contamination.

Phytoremediation technology: a green solution to the problem of toxic metal contamination

Phytoremediation is a feasible and eco-friendly green technology that can effectively reduce toxic metal pollution in soil. It is an environmentally friendly method because it reduces the risk of contaminant spread and maintains primary or individual ecotypes without excavation (Yan et al., 2020; Kafle et al., 2022; Cristaldi et al., 2017). The future of phytoremediation lies in harnessing the potential of hyperaccumulator plant species that can accumulate a wide range of toxic metals (Reeves et al., 2008). The new solution involves not only the use of hyperaccumulator plants but also rhizospheric microbes to transform, mobilize, or even sequester elemental pollutants within the soil (Cao et al., 2025; Liu et al., 2020). Hyperaccumulator plants, due to their remarkable competency, employ diverse mechanisms to absorb elemental pollutants from the environment, thus mitigating detrimental effects on consumers. The comprehensive details of hyperaccumulator plants are given below (Table 2 & S1)

Among these hyperaccumulator plants, the Brassicaceae family has gained recognition and is displaying its significance in the phytoremediation process, with numerous hyperaccumulator species. The extensive use of Brassicaceae in phytoremediation is also emphasized in various studies (Ali et al., 2017; Gurajala et al., 2019). Research found that *Brassica juncea* can absorb lead (Pb) at a concentration of 10300 mg/kg via phytoremediation (Koptsik 2014; Yan et al., 2020). The potential of other species, e.g., *B. carinata, B. napus, B. nigra, B. rapa, B. oleracea*, to accumulate toxic metals has been explored as well (Zeremsk et al., 2021). Moreover, varied species, including *Sedum alfredii*, which has a high capacity to accumulate Cd (Zhou and Qiu 2005), and *Trifolium alexandrinum*, can absorb toxic metals, including Cd, Pb, Cu, and Zn through phytoremediation (Ali et al., 2012), are also illustrations of the vast possibilities of this remediation process. The emerging popularity and societal acceptance of phytoremediation over the past decades' underscore soil remediation research.

Strategies of phytoremediation

The remediation of toxic metal-polluted soil through phytoremediation involves a number of plant-driven strategies. The effectiveness of these strategies is intricately linked to the metals' chemical composition, with the bioavailability of these pollutants playing a crucial role in achieving effective remediation outcomes (Usman et al., 2020). Phytoremediation encompasses a spectrum of techniques, including phytoextraction (or phytoaccumulation), phytofiltration, phytostabilization, and phytovolatilization (Aryal, 2024; Usman et al., 2018; Wei et al., 2021). Different phytoremediation strategies for toxic metals' removal are shown below (Figure 3).

Phytoextraction

Phytoextraction, a fundamental component of phytoremediation, involves the use of plants to absorb elemental pollutants or toxic metals from the soil through their root systems. These metals are subsequently translocated and accumulate in the aboveground parts of the plants (Jacob et al., 2018; Yan et al., 2020). This strategic approach has gained significance as an important method for reclaiming potentially toxic elements (PTEs) or toxic metals from contaminated soil (Ali et al., 2013; Sarwar et al., 2017). In this process, toxic metals undergo efficient extraction, accumulation, and transportation to the aerial parts of the plant. Notably, phytoextraction presents an advantageous alternative to other remediation methods, permitting the extraction of toxic metals from the aboveground plant components (Jeyasundar et al., 2021). Numerous plant species exhibit proficiency in the phytoextraction of specific toxic metals, exemplified by *Pteris vittata* for As and Cr (Salido et al., 2003), *Pelargonium hortorum* for Pb (Manzoor et al., 2020), and *Thlaspi caerulescens* for Cd and Zn (Cosio et al., 2004).

Phytostabilization

Phytostabilization involves the use of plant species with high metal tolerance to induce inactivation or immobilization of toxic metals, either within the roots or in the rhizosphere. This process is utilized to reduce the bioavailability of toxic metals, blocking their migration into the ecosystem and mitigating the entry of elemental pollutants into the food chain (Alsafran et al., 2022). The mechanism involves the stabilization of toxic metals in the soil through various processes, including the adsorption of metals by the root cell wall, reduction of metal valence in the rhizosphere, and sequestration of metals in the root tissue (Gerhardt et al., 2017; Kumpiene et al., 2012). Despite its advantageous properties, phytostabilization is less prevalent in practice compared to phytoextraction, mainly due to the temporary immobilization of toxic metals (Radziemska 2018). Various studies indicate that numerous plant species exhibit phytostabilization of potentially toxic elements, such as *Silene vulgaris* for Hg, Cd (Pérez-Sanz et al., 2012; Gardea-Torresdey et al., 2004), *Poa pratensis* for Hg (Sas-Nowosielsk et al., 2008), *Athyrium wardii* for Pb (Zhao et al., 2016), etc.

Phytofiltration

Phytofiltration is a method for extracting toxic metals from contaminated wastewater by using plant roots (rhizofiltration), shoots (caulofiltration), or seedlings (blastofiltration) (Jadia and Fulekar, 2009). In this technique, plant roots absorb or adsorb toxic metals, and root exudates play a pivotal role in altering the pH of the rhizosphere, leading to the precipitation of toxic metals on plant roots (Javed et al., 2019). Consequently, this process reduces the mobility of toxic metals in groundwater or surface water. For effective rhizofiltration, plants must possess characteristics such as a compact root system, hyperaccumulator traits, and high biomass production. Numerous aquatic plant species, including water hyacinth, *Azolla*, and duckweed, demonstrate proficiency in rhizofiltration (Hooda 2007). Additionally, terrestrial plants like *B. juncea* and *Helianthus annuus* exhibit rhizofiltration capabilities due to their dense hairy roots and ability to accumulate toxic metals (Dhanwal et al., 2017; Rezania et al., 2016).

Phytovolatilization

Phytovolatilization stands as a phytoremediation strategy wherein plants absorb toxic metal pollutants from the soil, subsequently converting them into volatile forms and releasing them into the atmosphere (Zhakypbek et al., 2024). This technique finds applicability for organic pollutants and specific potentially toxic elements such as Se, Hg, and As (Mahar et al., 2016). *B. juncea* is recognized as

a proficient phytovolatilizer of Se (Zhang et al., 2020). A distinctive advantage of phytovolatilization over other techniques lies in its capacity to extract toxic metals from the soil and disperse them in gaseous forms into the atmosphere. It is essential to note that phytovolatilization does not result in the complete removal of pollutants, as these toxic elements persist in the environment.

The list of different hyperaccumulator plants along with their methods used for the remediation of toxic metals is given in Table 2.

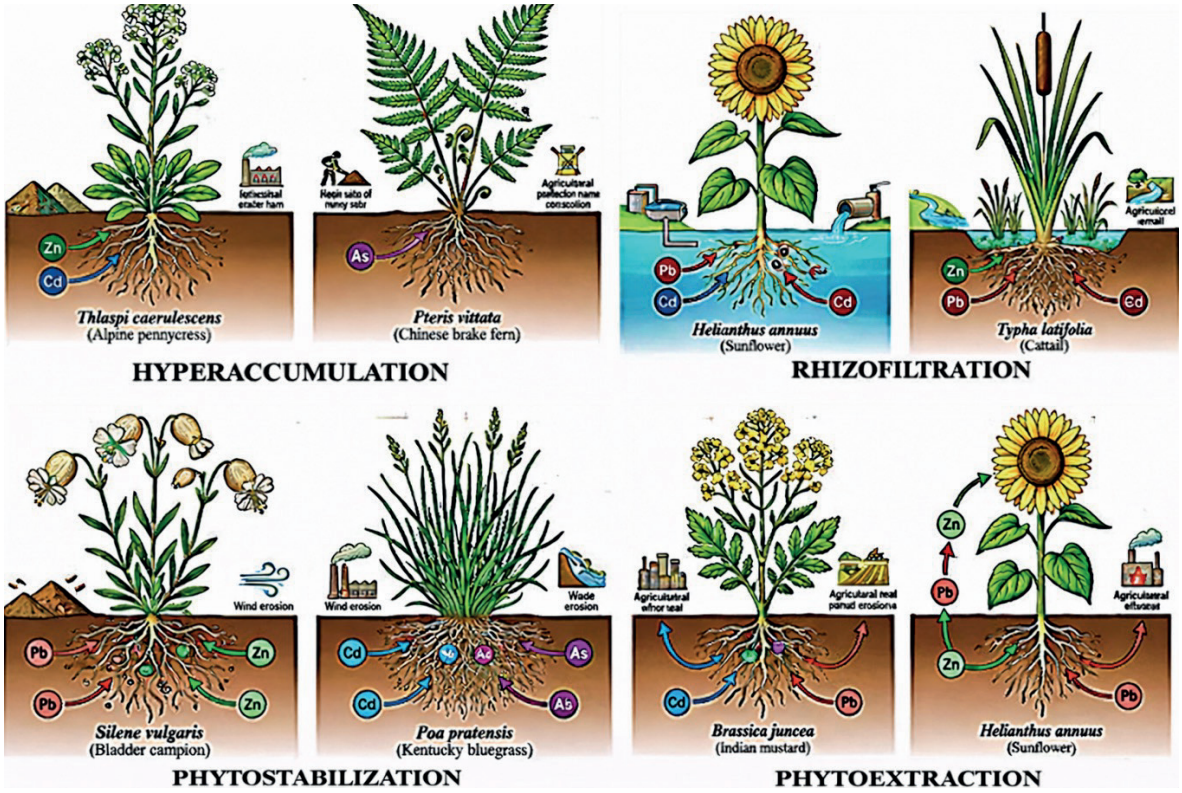


Figure 3. Different phytoremediation strategies for toxic metals removal.

Table 2. List of the top toxic metal accumulator plants along with their phytoremediation mechanism (Other accumulator plant details in Supplementary file S1).

S.No.	Plants Name	Family	Heavy metals	Max. concentration of H.M. accumulated (mg/kg)	Type of Plant	Mechanism of phytoremediation	Reference
1	*Solanum photeincarpum*	Solanaceae	Cd	544,132			Muthusaravanan et al., 2018
2	*Medicago sativa*	Fabaceae	Pb	43,300	Edible	Phytoextraction	Koptsik 2014
3	*Thlaspi caerulescens*	Brassicaceae	Zn	39,600	Edible	Phytoextraction	Cosio et al., 2004

4	*Dicoma nicco-lifera*	Asteraceae	Cr	30,000			Thangavel and Subbhuraam 2004
5	*Arabidopsis halleri*	Brassicaceae	Zn	30,000	Weed	Phytoextraction	Cosio et al., 2004
6	*Minuartia verna*	Caryophyllaceae	Pb	20,000	Perennial herb		Thangavel and Subbhuraam 2004
7	*Leptospermum scoparium*	Myrtaceae	Cr	20,000	Edible medicinal		Thangavel and Subbhuraam 2004
8	*Aeollanthus biformifolius*	Lamiaceae	Cu	13,700		Phytoextraction	Chaney et al., 2010
9	*Agrostis tenuis*	Poaceae	Pb	13,490	Weed		(Thangavel and Subbhuraam 2004.
10	*Ipomoea alpine*	Convolvulaceae	Cu	12,300	Weed	Phytoextraction	Lasat 2002
11	*Alyxia rubri-caulis*	Apocynaceae	Mn	11500		Phytoextraction	Koptsik 2014
12	*Phytolacca american*	Phytolaccaceae	Cd	10,700	Weed	Phytoextraction	Peng et al., 2008
13	*Brassica juncea*	Brassicaceae	Pb	10,300	Edible	Phytoextraction	Koptsik, 2014
14	*Pteris vittate*	Pteridoideae	Cr	10,232	Fern	Phytoextraction	Salido et al., 2003; Kalve et al., 2011
15	*Haumaniastrum roberti*	Lamiaceae	Co	10200		Phytoextraction	Sheoran et al., 2010; Lasat, 2002

The compiled dataset encompasses 120 hyperaccumulator plant species exhibiting diverse phytoremediation capabilities, including phytoextraction, rhizofiltration, and phytostabilization. Among these, 6 species are aromatic, 55 are edible, and 24 possess medicinal value. In terms of metal specificity, cadmium (Cd) hyperaccumulation is most prevalent (34 species), followed by lead (Pb) (22 species), arsenic (As) (8 species), mercury (Hg) (6 species), and selenium (Se) (3 species). Edible hyperaccumulators are predominantly distributed across the families Brassicaceae (18 species), Lamiaceae (11 species), and Asteraceae and Poaceae (7 species each). From the total dataset, top 15 metal hyperaccumulator plants (>10,000 mg/kg) are presented in Table 1 while the remaining 105 are provided in Supplementary File S1. Table 2 highlights key high-capacity accumulators, with *Solanum photeinocarpum* showing exceptionally high Cd accumulation (544,132 mg/kg). The findings emphasize phytoextraction as the dominant remediation mechanism across major plant families such as Solanaceae, Fabaceae, and Brassicaceae. Importantly, the inclusion of edible species like *Medicago sativa* and *Brassica juncea* underscores both their remediation potential and associated food safety concerns. Additionally, the dataset spans plants of varied utility, including medicinal species like *Prosopis laevigata* and common weeds such as *Phytolacca americana*, indicating that effective phytoremediation can be achieved across diverse ecological and functional plant groups.

Post-phytoremediation effects of toxic metals accumulator edible plants on consumers

Various technologies are being employed to eliminate toxic metals from contaminated soil, and phytoremediation stands out as a major one among them. This method relies on hyperaccumulator plant species known for their capacity to withstand toxic metals in the environment and contaminated soil. Hyperaccumulator plants demonstrate a high ability to translocate and accumulate toxic metals in roots and shoots. It facilitates the movement of toxic metals from roots to shoots for subsequent harvesting (Nedjimi, 2021). However, it's imperative to recognize the numerous limitations of phytoremediation for edible plants, as it may potentially have adverse effects on consumer health. One significant concern lies in the risk of unintended consequences related to the bioaccumulation process. Even though hyperaccumulator plants are adept at concentrating toxic metals, there is a possibility that certain contaminants might be stored in edible parts of the plant in forms that are still harmful to humans. Inadequate understanding of the complex interactions between different metals, soil conditions, and plant physiology could lead to the unintentional introduction of toxic elements into the food chain. Furthermore, the long-term effects of consuming hyperaccumulator plants need thorough examination, as chronic exposure to even low levels of certain toxic metals can have adverse health consequences. The success of phytoremediation with hyperaccumulator edible plants also depends on careful monitoring and management to prevent contamination of surrounding areas and water sources (Tamma et al., 2025). Thus, the understanding of the constraints and potential risks associated with utilizing these plants in edible crops is crucial.

In this context, several case studies have been explored to elucidate the post-phytoremediation negative impacts on consumers. One such case study involved *Colocasia esculenta*, a hyperaccumulator plant grown in mercury (Hg) contaminated soil. After 28 days of planting, the concentration of Hg in the soil decreased. However, the toxic metal Hg accumulated in the plant tissue, and the translocation factor (TF) was calculated, revealing higher TF in the shoot part compared to other plant parts. The average Hg concentration in this study was 42.7 µg/kg body weight, considerably exceeding the standard Hg value of 1.6 µg/kg body weight. This study suggests that the consumption of *C. esculenta* may pose toxicity risks to humans and be hazardous to human health (Asare et al., 2021). The exposure of Hg to humans may cause autoimmune disease, anxiety, hair loss, and fatigue (Ali et al., 2013). Another research study was conducted on *Ocimum basilicum* that was grown on metal-polluted soil. The levels of Cd and Pb were found beyond the permitted limit, i.e., 0.3 mg/kg and 10 mg/kg, respectively. The Cd and Pb accumulated in mature plant leaves are highly toxic. These toxic metals constitute a constraint for human consumption of the studied plant (Dinu et al., 2020). If Cd is consumed by humans, it can cause lung disease or accumulate in the kidneys & damage the filtration mechanism, and cause osteoporosis (Fatima et al., 2019). Similarly, if there is prolonged exposure to Pb, it may decrease the potency in males, affecting the cardiovascular and central nervous system (Debnath et al., 2019). There are several members of the family Brassicaceae, which include important vegetables consumed across the world and play a vital role in the human diet (Cartea et al., 2010). These vegetables, such as *B. oleracea*, *B. rapa*, *and B. napus,* absorb toxic metals from contaminated soil. A case study conducted on irrigated urban and industrial wastewater, soil, and vegetables for the presence of toxic metals revealed that the levels of $Cr^{2+,}$ $Pb^{2+,}$ and Cd^{2+} in vegetables exceeded the allowed threshold value, indicating the possible threat to human health, routing via food chain contamination (Mahmood & Malik et al., 2014). When the quantity of Cr reaches a significant level, it becomes toxic and carcinogenic to humans

(Achmad et al., 2017). Another empirical data explains that two varieties of *Brassica* crops, such as *B. oleracea* var. *Italica* (broccoli), and *B. oleracea* var. *Gemmifera* (Brussels sprouts), when irrigated with municipal wastewater, the concentration of toxic metals was found to be above the permissible limit. The value of toxic metals found in broccoli as: Ni 3.91– 4.15 mg/g, Pb 9.82–10.4 mg/g, whereas, in brussels sprouts, Cd 0.8–1.17 mg/g, Co 2.35–2.70 mg/g, and Ni 5.70–6.17 mg/g, which was found quite high. These aforementioned concentrations of toxic metals in Broccoli and Brussels sprouts are detrimental for human consumption (Kalavrouziotis et al., 2008). The highly polluted ecosystem by Ni gives rise to different pathogenic effects in humans, such as lung cancer, headache, nasal cancer, and epigenetic disorders (Genchi et al., 2020). Literature data have revealed that various crops, including *Z. mays* (corn), *Lycopersicon esculentum* (tomato), *B. oleracea* (cabbage), and *B. chinensis* (pakchoi), grown in soils contaminated with electronic wastes, exhibit varying levels of toxic metal accumulation. Specifically, it has been observed that *B. chinensis* accumulates high quantities of toxic metals such as Pb, Cd, and Cu above the established threshold limits. The elevated presence of these toxic metals, namely Pb, Cd, and Cu, can lead to multiple chronic diseases or comorbidities in humans. This accumulation poses a risk as these contaminants may enter the food chain, posing health threats to consumers. (Liu et al., 2012; Liu et al., 2012a). Therefore, caution is advised to prevent the adverse health effects associated with the consumption of crops grown in soils contaminated with electronic waste.

In light of the findings presented in the aforementioned studies, it is essential to recognize the potential risks associated with the consumption of hyperaccumulator plants used in phytoremediation strategies. The elevated concentration of toxic metals in the edible parts of these plants poses health hazards to consumers, necessitating an urgent need to effectively address these issues. Considering the intricate interplay between environmental sustainability, agricultural practices, and human health, the following section explores proposed solutions to mitigate the adverse effects of utilizing hyperaccumulator plants and provides insights into achieving a balance between phytoremediation efforts and safeguarding public health. In conclusion, although the use of hyperaccumulator edible plants for phytoremediation is an innovative approach, the potential negative impacts on consumers and ecosystems underscore the importance of thorough research, regulation, and responsible implementation to ensure the overall success and safety of this strategy.

Strategies for sustainable management of hyperaccumulator plant biomass: post-phytoremediation

Phytoremediation contributes to soil stabilization by eliminating pollutants, improving the quality of soil, and deterring soil erosion (Aftab et al., 2021; Afzal et al., 2019). The successful use of these phyto-technologies, which are environmentally friendly, however, depends on the effectiveness of the post-phytoremediation measures regarding the biomass containing toxic metals (Khan et al., 2021). Several technologies target this problem by placing the accent on the economic valorization of biomass by means of bioenergy production (Gomes 2012). Incineration, pyrolysis, gasification, combustion, and composting are some of the techniques used in the treatment of contaminated biomass.

Incineration

It is the process of burning forced air with the combustion reaction to the biomass of the plant that contains toxic metals, and it is a process of high-pressure oxidation. The product of this process is lighter ash, which is easy to transport and store. But, incineration creates fly ash that has hazardous toxic metals that cause secondary pollution. According to Wu et al. (2021), the total weight of *S. al-*

feradii declined to 58.6 percent following the procedure of incineration. Furthermore, Hazotte et al. (2020) found that the Ni hyperaccumulator plant, *Odontarrhena chalcidica,* generated ash with Ni content of 13.5g/kg compared to the fresh biomass with Ni content of about 10 g/kg. Generally, as the temperature for incineration rises, the rate of toxic metal vaporization will also increase, leading to a higher concentration of toxic metals in fly ash. As the toxic metal content in fly ash surpasses the permissible limit set by authorities, therefore, fly ash is unsuitable for subsequent reuse. Meanwhile, Zhu et al. (2019) revealed that by increasing the incineration temperature, leaching of toxic metals might be reduced. Additives such as kaolin, zeolite, and montmorillonite are used to increase the retrieval of toxic metals in bottom ash and reduce the transportation to gas-phase fly ash. Lu et al. (2015) showed that the addition of kaolin in fly ash removed 91.2 and 88.1% of Cd and Zn, respectively, from the fly ash, with the increased sequestration efficacy attributed to physical and chemical adsorption mechanisms of toxic metal sequestration during incineration.

Pyrolysis

Another technique that is being used to manage contaminated hyperaccumulated plant biomass is pyrolysis. Pyrolysis is the oxygen-free degradation of hyperaccumulated biomass of plants at elevated temperatures, which yields bio-oil, biochar, and pyrolysis gases (H_2, CO_2, CO) depending on the time and temperature (Tayibi et al., 2021). Although effective, a couple of challenges are present in pyrolysis, such as high operational costs and technological complexity. The potential offsets to economic impact are possible products such as biochar and bio-oil. However, (Alcazar-Ruiz et al., 2022). Hyperaccumulator biochar presents a necessity to assess the authenticity of toxic metals' toxicity. Zhang et al. (2021) carried out research on the hyperaccumulator plant *Sedum plumbizincicola* for Cd and Zn by pyrolysis treatment to determine the pyrolysis risk assessment on biochar towards the environment. They demonstrated that 80.95 percent Cd and 95.56% Zn recovery were achieved at a pyrolysis temperature of 350 ^{o}C, and this highlighted the high efficiency of the pyrolysis treatment in enclosing the toxic metals in the biochar. Certain additives, such as calcium dihydrogen phosphate, sodium hydroxide, calcium carbonate, and iron (III) chloride, are able to mitigate the amount of toxic metals leeching throughout the process of pyrolysis to stable compounds (Liu et al., 2020; Liu et al., 2020a). Pyrolysis of the cotton stalk biomass was catalyzed by additives, like potassium carbonate, that accelerated the rate of the reaction, leading to a remarkable increase in the lead (Pb) content by 51.5 to 93.4%, an effect due to the formation of a stable lead hydroxide (Wang et al., 2021). The disadvantages of pyrolysis are that it requires low moisture (<10%) to achieve favorable yields and calorific values, and high expenses on rehabilitating blocked pipelines because of tar formation, which inhibits its adoption at an industrial scale.

Gasification

It is an important process in the search for sustainability in the management of hyperaccumulator plant biomass following phytoremediation. The process entails exposing solid substances to high temperatures, which causes them to convert into syngas, a mix of carbon monoxide and hydrogen. Significantly, the generated syngas are utilized in gas turbines or fuel cells to generate electricity. Cui et al. (2018) have shown that the gasification of the *Sedum alfredii* in a range of temperatures, 500 to 800 ^{o}C produced a syngas with an optimal ratio of hydrogen and carbon monoxide (1.26 to 2.46), which was later used in the Fischer Tropsch process in producing a sustainable fuel. The transformation and migration of toxic metal content in the biomass plant in the gasification process should be thoroughly studied to ensure the sustainability of the phytoremediation efforts. Duan et al. (2017) studied the behavior of transformation of arsenic (As) in ladder brake (*Pteris vittata* L.) during gas-

ification, revealing a significant release of about 60% of As at a temperature of 600 °C. Additionally, Zhang et al. (2019 & 2019a) highlighted the advantages of incorporating iron oxide compounds during the gasification of stonecrop (*Sedum plumbizincicola*) and ladder brake (*Pteris vittata* L.), enhancing gas yields of hydrogen and carbon monoxide while efficiently removing toxic metals using activated carbon. To secure the sustainable management of hyperaccumulator plant biomass, it is crucial to conscientiously tackle the challenges linked to the formation of excessive tar dust containing toxic metals during the gasification process. Such challenges can lead to energy waste, reduced gasification efficiency, as well as corrosion and blockage of gas pipelines (Cui et al., 2018).

Compaction

Apart from the above-mentioned methods, compaction emerges as an alternative disposal method for the post-phytoremediation sustainable management of hyperaccumulator plant biomass. This is carried out by pressing the contaminated plant biomass, and the subsequent collection of the leachates separately. The resulting particulate discarded products, however, have a large quantity of toxic metals, which require additional treatment as hazardous waste at an appropriate disposal site. It is interesting to note that assessment studies have not been done on the recovery of valuable toxic metals by utilizing the leachate obtained during the compaction of contaminated plant biomass (Oladoye et al., 2022). Further research activities can be very helpful in trying to come up with a way to retrieve toxic metals in the collected leachate to add to the overall sustainability of hyperaccumulator plant biomass handling techniques.

Composting

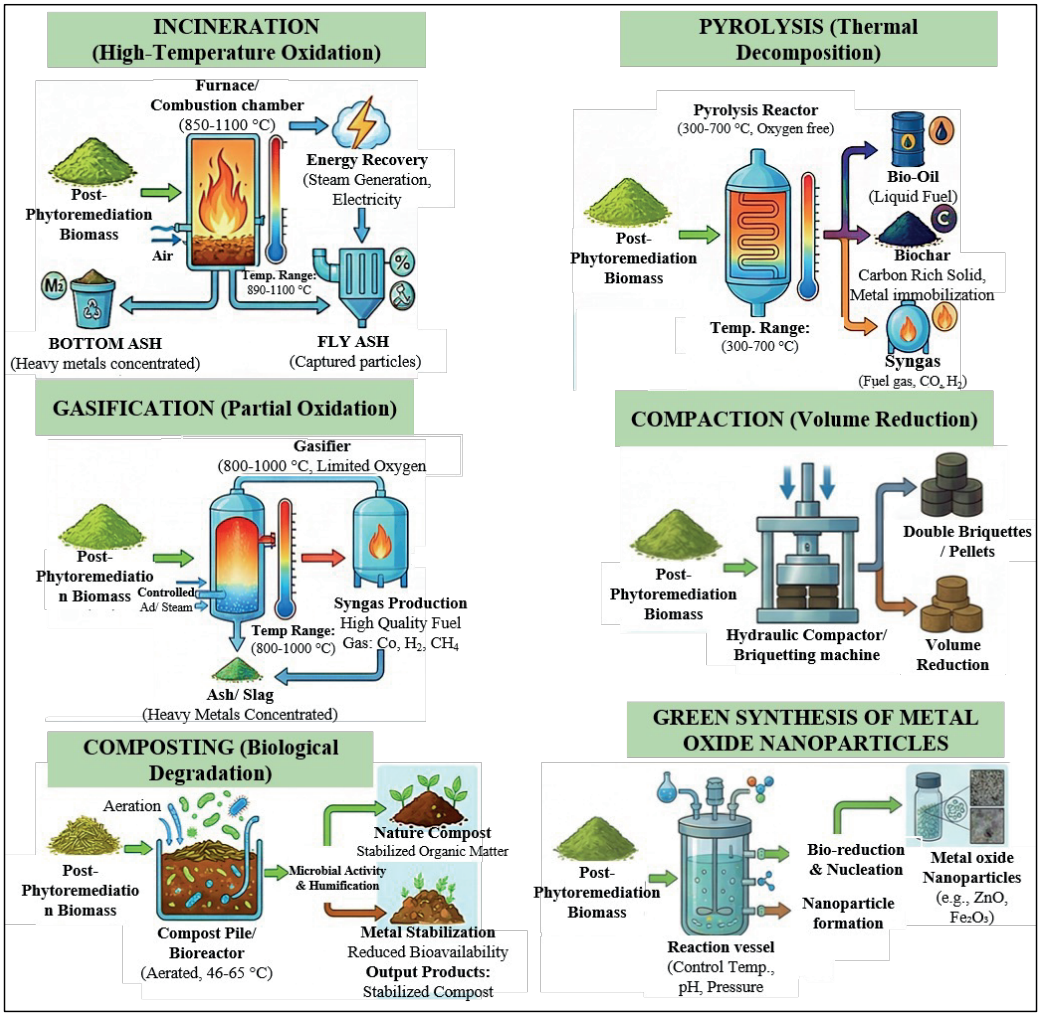
It is another methodology that is used in the sustainable management of hyperaccumulator plant biomass. The biochemical conversion of concentrated and compacted toxic metal-enriched portions of the plant biomass. Composting is done by reducing the volume and weight through the digestion process. This procedure promises to be cost-effective in transportation. Although it has historically been used on agricultural waste, regardless of the current application, compost processing is vulnerable to the remobilization of toxic metals due to microbial activities and solid waste (leachates). An appropriate confinement procedure is of the utmost concern to reduce the potential of leaching toxic metals (Viaene et al., 2016; Mohanty, 2016; Muthusaravanan et al., 2020). Song and Park (2017) conducted a research study that included the development of compost made with the plant biomass of *Phragmites australis* and *Typha angustifolia* after phytoremediation. The outcome of this process was better soil qualities, in particular, soil moisture. Microbial decomposition was found to increase nitrogen availability, which is beneficial to plant growth. Even though the biomass of hyperaccumulator plants that have undergone phytoremediation may be utilized as compost to increase the fertility of soil, more studies are required since the biomass of plants is structurally complex and is degraded by microbial communities in a diverse way (Wei et al., 2012).

Metal oxide nanoparticles synthesis

The green synthesis of metal oxide nanoparticles (MONP) through the utilization of phytoremediation plants has gradually emerged as a novel approach for managing the biomass generated after the phytoremediation process. Wang et al. (2016) accomplished the successful synthesis of zinc oxide nanoparticles using the Zn hyperaccumulator, *S. alfredii*. The resulting zinc oxide nanoparticles demonstrated the ability of photocatalytic degradation. Even though little to no research activity is being carried out on the theme of green synthesis of MONP using hyperaccumulator plants endowed with toxic metals following phytoremediation. Current research efforts are more focused on giving general accounts of the incorporation of plant extracts and phytochemicals into green synthetic processes, without explaining the mechanisms underlying these reactions. Therefore, transition-

ing bench-scale production of green-synthesized MONP to an industrial scale might be challenging unless proper direction of engineering factors, such as a stoichiometric ratio and mass balance, is provided (Ying et al., 2022). In addition to this, the quality of MONP produced by the green synthesis process using hyperaccumulator plants may also vary widely in terms of size and shape. This fluctuation may pose a challenge in industrial application, where the deliberate control of the particle size and crystallinity of the production process is of high necessity (Xu et al., 2020). Therefore, conventional synthesis processes remain popular and widely used by industries.

In summary, the effective application of phytotechnologies in consideration of post-phytoremediation solutions to toxic metals contaminated biomass depends on the efficacy of diverse approaches. Among them, incineration, pyrolysis, gasification, combustion, and composting address the issue of money-making, sustainable biomass valorization by means of bioenergy. There are critical issues in dealing with post-phytoremediation strategies that must be resolved to facilitate the sustainable management of hyperaccumulator plant biomass, which should not only be environmentally beneficial but also economically sustainable. Figure 4 shows the post-phytoremediation biomass management strategies. Further research and technological innovations also contribute to the further optimization of these strategies and their general applicability in real practice.



| **Figure 4.** Post-phytoremediation biomass management strategies.

Challenges and future prospects

Phytoremediation is widely recognized as a cost-effective and environmentally sustainable approach for remediating toxic metal-contaminated soils; however, its large-scale application remains constrained by several biological, environmental, and operational limitations (Ali et al., 2013; Mahar et al., 2016; Yan et al., 2020). A major challenge lies in its inherently slow remediation rate, as metal uptake typically requires multiple growing cycles and is strongly influenced by climatic conditions, soil chemistry, and plant developmental stages (Mohamed et al., 2025). While hyperaccumulator species demonstrate exceptional capacity for metal sequestration, their practical applicability is often limited by low biomass production, creating a trade-off between accumulation efficiency and total metal removal (Eissa et al., 2025). Furthermore, phytoremediation efficiency is highly metal-specific. It is generally more effective for relatively mobile elements such as Cd, Ni, and Zn, whereas its performance is significantly reduced for poorly mobile metals like Pb and Cr (Yan et al., 2020). This limitation is compounded by soil-related factors, including low metal bioavailability, variable pH, high organic matter content, and the presence of competing ions (Mocek-Płóciniak et al., 2023). Although soil amendments can enhance metal mobility and uptake, their application remains controversial, as they may increase the risk of metal leaching and secondary contamination (Wang et al., 2020). These contrasting findings highlight that phytoremediation outcomes are highly site-specific and require careful optimization rather than generalized application. Plant physiological responses to contaminated environments further complicate remediation efficiency. Exposure to high metal concentrations often induces phytotoxic effects such as reduced leaf area, impaired photosynthesis, and stunted growth, ultimately limiting biomass production and metal uptake (Jarin et al., 2025).

Beyond in-field limitations, post-remediation biomass management represents a critical and often underestimated challenge. The accumulation of high metal concentrations in harvested plant tissues effectively transforms biomass into hazardous waste (Yan et al., 2020). If not properly managed, this biomass can act as a secondary source of pollution through metal leaching or atmospheric release. Although incineration is commonly employed, it requires strict regulatory control, and the resulting metal-rich ash must be safely disposed of or processed for recovery (Mohamed et al., 2025). In regions lacking adequate infrastructure or regulatory frameworks, these logistical and economic constraints significantly hinder large-scale implementation.

Despite these limitations, phytoremediation continues to hold strong future potential, particularly with the integration of emerging technologies. Advances in genetic engineering, including CRISPR-based genome editing and molecular breeding, offer opportunities to develop plant varieties with enhanced metal tolerance, deeper root systems, and increased biomass production (Oubohssaine & Dahmani, 2024). Similarly, rhizosphere engineering, through plant growth-promoting rhizobacteria and mycorrhizal associations, has shown promise in improving metal bioavailability while reducing plant stress (Karnwal et al., 2025). Emerging interdisciplinary approaches further expand the scope of phytoremediation. Nanotechnology, precision agriculture, and remote sensing can enhance remediation efficiency and enable real-time monitoring (Gao et al., 2021; Mahmud et al., 2025). In addition, phytomining offers a novel pathway for recovering valuable metals such as Ni and Co, transforming remediation into a resource-generating process (Eissa et al., 2025). However, the economic feasibility and large-scale applicability of such approaches remain insufficiently explored. While phytoremediation holds significant promise, its successful implementation will depend on addressing key technical, ecological, and regulatory challenges. Future efforts must integrate biological innovations

with safe biomass management strategies and robust policy frameworks to enable its transition from experimental application to a scalable solution for contaminated land restoration.

Conclusion

Phytoremediation has emerged as a promising, eco-friendly approach for mitigating toxic metal contamination in soils, with several plant species demonstrating significant potential for metal uptake and sequestration. This review highlights that while hyperaccumulator plants, particularly those with high biomass and efficient translocation capacity, can effectively remove or immobilize contaminants such as Cd, Pb, As, and Cr, their performance is highly species-specific and influenced by environmental factors, including soil chemistry and metal bioavailability. A critical insight from this analysis is that phytoremediation does not eliminate metals but redistributes them into plant biomass. This shift necessitates careful post-harvest management, as metal-enriched biomass constitutes a secondary source of contamination if improperly handled. Contrary to earlier generalized assumptions, practices such as uncontrolled composting or open burning are not safe disposal strategies, as they may lead to metal leaching into soil and groundwater or atmospheric emissions. Instead, controlled approaches such as pyrolysis, gasification, or regulated incineration should be prioritized to minimize environmental and health risks. The use of edible plants in phytoremediation presents a complex risk–benefit scenario. Although such species may offer practical advantages in terms of cultivation and biomass yield, the accumulation of toxic metals in edible tissues poses significant food safety concerns. Therefore, their application must be strictly restricted to non-food purposes unless metal concentrations are demonstrably below established international safety limits (e.g., WHO/FAO guidelines). Comprehensive risk assessment frameworks and continuous monitoring are essential before considering their deployment in contaminated sites. Despite notable progress, several research gaps remain. There is a lack of long-term, field-scale validation studies, limited standardization in biomass disposal protocols, and insufficient integration of phytoremediation with advanced technologies such as genetic engineering, rhizosphere manipulation, and nanotechnology. Future research should focus on developing high-efficiency, high-biomass plant systems, improving metal bioavailability, and establishing clear regulatory and safety guidelines for both application and biomass management. The most critical takeaway from this review is that while phytoremediation offers a sustainable remediation strategy, its success depends not only on plant performance but also on the safe handling of contaminated biomass and careful consideration of human health risks, particularly when edible plant species are involved.

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References

Abdelsalam, I. M., Elshobary, M., Eladawy, M. M., & Nagah, M. (2019). Utilization of multi-tasking non-edible plants for phytoremediation and bioenergy source: A review. *Phyton, 88*(2), 69. https://doi.org/10.32604/phyton.2019.06831

Abid, H., Mahroof, S., Ahmad, K. S., Sadia, S., Iqbal, U., Mehmood, A., Shehzad, M. A., Basit, A., Tahir, M. M., Awan, U. A., Almutairi, K. F., Elansary, H. O., & Moussa, I. M. (2025). Harnessing native plants for sustainable heavy metal phytoremediation in crushing industry soils of Muzaffarabad. *Environmental Technology & Innovation, 38*, 104141. https://doi.org/10.1016/j.eti.2025.104141

Achmad, R. T., & Auerkari, E. I. (2017). Effects of chromium on the human body. *Annual Research & Review in Biology*, 1–8. https://doi.org/10.9734/ARRB/2017/33462

Adamu, H., Uzairu, A., & Harrison, G. F. (2013). Assessment of trace metals in sewage water and sludge from River Kubanni drainage basin. *African Journal of Biotechnology, 12*(1), 49–55. https://

doi.org/10.5897/AJB08.1075

Aftab, N., Saleem, K., Khan, A. H. A., Butt, T. A., Mirza, C. R., Hussain, J., Farooq, G., Tahir, A., Yousaf, S., Zafar, M. I., Nawaz, I., & Iqbal, M. (2021). *Cosmos sulphureus* Cav. is more tolerant to lead than copper and chromium in hydroponics system. *International Journal of Environmental Science and Technology, 18*, 2325–2334. https://doi.org/10.1007/s13762-020-02981-w

Afzal, M., Arslan, M., Müller, J. A., Shabir, G., Islam, E., Tahseen, R., Anwar-ul-Haq, M., Hashmat, A. J., Iqbal, S., & Khan, Q. M. (2019). Floating treatment wetlands as a suitable option for large-scale wastewater treatment. *Nature Sustainability, 2*(9), 863–871. https://doi.org/10.1038/s41893-019-0350-y

Ahmed, S. F., Kumar, P. S., Rozbu, M. R., Chowdhury, A. T., Nuzhat, S., Rafa, N., Mahlia, T. M. I., Ong, H. C., & Mofijur, M. (2021). Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil. *Environmental Technology & Innovation, 25*, 102114. https://doi.org/10.1016/j.eti.2021.102114

Ahsan, N., Lee, D.-G., Kim, K.-H., Alam, I., Lee, S.-H., Lee, K.-W., Lee, H., & Lee, B.-H. (2010). Analysis of arsenic stress-induced differentially expressed proteins in rice leaves by two-dimensional gel electrophoresis coupled with mass spectrometry. *Chemosphere, 78*(3), 224–231. https://doi.org/10.1016/j.chemosphere.2009.11.004

Aishwarya, S., Venkateswarlu, N., Chandramouli, K., & Vijaya, T. (2014). Role of endophytic fungi in the restoration of heavy metal contaminated soils. *Indo American Journal of Pharmaceutical Research, 4*, 5427–5436.

Akinbile, B. J., & Mbohwa, C. (2025). Incorporating hyperaccumulating plants in phytomining, remediation and resource recovery: Recent trends in the African region: A review. *RSC Sustainability, 3*(4), 1652–1671. https://doi.org/10.1039/D5SU00021A

Alaribe, F. O., & Agamuthu, P. (2015). Assessment of phytoremediation potentials of *Lantana camara* in Pb-impacted soil with organic waste additives. *Ecological Engineering, 83*, 513–520. https://doi.org/10.1016/j.ecoleng.2015.07.001

Alcazar-Ruiz, A., Ortiz, M. L., Dorado, F., & Sanchez-Silva, L. (2022). Gasification versus fast pyrolysis bio-oil production: A life cycle assessment. *Journal of Cleaner Production, 336*, 130373. https://doi.org/10.1016/j.jclepro.2022.130373

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals: Concepts and applications. *Chemosphere, 91*(7), 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075

Ali, H., Naseer, M., & Sajad, M. A. (2012). Phytoremediation of heavy metals by *Trifolium alexandrinum*. *International Journal of Environmental Sciences, 2*(3), 1459–1469. https://doi.org/10.6088/ijes.00202030031

Ali, Z., Waheed, H., Gul, A., Afzal, F., Anwaar, K., & Imran, S. (2017). Brassicaceae plants: Metal accumulation and their role in phytoremediation. In *Oilseed crops: Yield and adaptation under environmental stress* (pp. 207–223). https://doi.org/10.1002/9781119048800.ch11

Almeida, J. C., Cardoso, C. E., Tavares, D. S., Freitas, R., Trindade, T., Vale, C., & Pereira, E. (2019). Chromium removal from contaminated waters using nanomaterials: A review. *Trends in Analytical Chemistry, 118*, 277–291. https://doi.org/10.1016/j.trac.2019.05.005

Alsafran, M., Usman, K., Ahmed, B., Rizwan, M., Saleem, M. H., & Al Jabri, H. (2022). Understanding the phytoremediation mechanisms of potentially toxic elements: A proteomic overview of recent advances. *Frontiers in Plant Science, 13*, 881242. https://doi.org/10.3389/fpls.2022.881242

Alsafran, M., Usman, K., & Al Jabri, H. (2021). Ecological and health risks assessment of potentially toxic metals and metalloids contaminants: A case study of agricultural soils in Qatar. *Toxics, 9*(2), 35. https://doi.org/10.3390/toxics9020035

Al-Thani, R. F., & Yasseen, B. T. (2020). Phytoremediation of polluted soils and waters by native Qatari plants: Future perspectives. *Environmental Pollution, 259*, 113694. https://doi.org/10.1016/j.envpol.2019.113694

Angelova, V. R., Grekov, D. F., Kisyov, V. K., & Ivanov, K. I. (2015). Potential of lavender (*Lavandula vera* L.) for phytoremediation of soils contaminated with heavy metals. *International Journal of Agricultural and Biosystems Engineering, 9*(5), 522–529.

Angelova, V. R., Ivanova, R. V., Todorov, G. M., & Ivanov, K. I. (2016). Potential of *Salvia sclarea* L. for phytoremediation of soils contaminated with heavy metals. *International Journal of Agricultural and Biosystems Engineering, 10*(12), 780–790.

Angon, P. B., Islam, M. S., KC, S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon, 10*(7), e28357. https://doi.org/10.1016/j.heliyon.2024.e28357

Anjum, N. A., Gill, S. S., Ahmad, I., Pacheco, M., Duarte, A. C., Umar, S., Khan, N. A., & Pereira, M. E. (2012). The plant family Brassicaceae: An introduction. In N. A. Anjum et al. (Eds.), *The plant family Brassicaceae: Contribution towards phytoremediation* (pp. 1–33). Springer. https://doi.org/10.1007/978-94-007-3913-0_1

Anjum, N. A., Umar, S., Ahmad, A., Iqbal, M., & Khan, N. A. (2008). Sulphur protects mustard (*Brassica campestris* L.) from cadmium toxicity by improving leaf ascorbate and glutathione. *Plant Growth Regulation, 54*, 271–279. https://doi.org/10.1007/s10725-007-9251-6

Anjum, N. A., Umar, S., & Iqbal, M. (2014). Assessment of cadmium accumulation, toxicity, and tolerance in Brassicaceae and Fabaceae plants: Implications for phytoremediation. *Environmental Science and Pollution Research, 21*, 10286–10293. https://doi.org/10.1007/s11356-014-2889-5

Arshad, M., Silvestre, J., Pinelli, E., Kallerhoff, J., Kaemmerer, M., Tarigo, A., Shahid, M., Guiresse, M., Pradere, P., & Dumat, C. (2008). A field study of lead phytoextraction by various scented *Pelargonium* cultivars. *Chemosphere, 71*(11), 2187–2192. https://doi.org/10.1016/j.chemosphere.2008.02.013

Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. *Heliyon, 10*(19), e38683. https://doi.org/10.1016/j.heliyon.2024.e38683

Asare, D. A., Anderson, E., Amosah, M. E., Ntiri-Bekoh, R., & Ofori-Sarpong, G. (2021). Assessing the toxicity of *Colocassia esculenta* (cocoyam plant) grown on mercury-contaminated soil. *Ghana Mining Journal, 21*(2), 46–54. https://doi.org/10.4314/gm.v21i2.6

Assunção, A. G., Martins, P. D., De Folter, S., Vooijs, R., Schat, H., & Aarts, M. G. (2001). Elevated expression of metal transporter genes in three accessions of the metal hyperaccumulator *Thlaspi caerulescens*. *Plant, Cell & Environment, 24*(2), 217–226. https://doi.org/10.1111/j.1365-

3040.2001.00666.x

Awa, S. H., & Hadibarata, T. (2020). Removal of heavy metals in contaminated soil by phytoremediation mechanism: A review. *Water, Air, & Soil Pollution, 231*(2), 47. https://doi.org/10.1007/s11270-020-4426-0

Axelsen, K. B., & Palmgren, M. G. (2001). Inventory of the superfamily of P-type ion pumps in *Arabidopsis*. *Plant Physiology, 126*(2), 696–706. https://doi.org/10.1104/pp.126.2.696

Barlow, R., Bryant, N., Andersland, J., & Sahi, S. (2000). Lead hyperaccumulation by *Sesbania drummondii*. In *Proceedings of the 2000 Conference on Hazardous Waste Research* (pp. 112–114).

Bhattacharya, P. T., Misra, S. R., & Hussain, M. (2016). Nutritional aspects of essential trace elements in oral health and disease: An extensive review. *Scientifica, 2016*. https://doi.org/10.1155/2016/5464373

Bozdoğan Sert, E., Türkmen, M., & Çetin, M. (2019). Heavy metal accumulation in rosemary leaves and stems exposed to traffic-related pollution near Adana-İskenderun Highway (Hatay, Turkey). *Environmental Monitoring and Assessment, 191*, 1–12. https://doi.org/10.1007/s10661-019-7714-7

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*(3), 559–568. https://doi.org/10.1016/j.envpol.2007.07.006

Buendía-González, L., Orozco-Villafuerte, J., Cruz-Sosa, F., Barrera-Díaz, C. E., & Vernon-Carter, E. J. (2010). *Prosopis laevigata*: A potential chromium (VI) and cadmium (II) hyperaccumulator desert plant. *Bioresource Technology, 101*(15), 5862–5867. https://doi.org/10.1016/j.biortech.2010.03.027

Cailliatte, R., Schikora, A., Briat, J. F., Mari, S., & Curie, C. (2010). High-affinity manganese uptake by the metal transporter NRAMP1 is essential for *Arabidopsis* growth in low manganese conditions. *The Plant Cell, 22*(3), 904–917. https://doi.org/10.1105/tpc.109.073023

Cao, X., Dong, Q., Mao, L., Yang, X., Wang, X., & Zou, Q. (2025). Enhanced phytoextraction technologies for the sustainable remediation of cadmium-contaminated soil based on hyperaccumulators: A review. *Plants, 14*(1), 115. https://doi.org/10.3390/plants14010115

Cartea, M. E., Francisco, M., Soengas, P., & Velasco, P. (2010). Phenolic compounds in *Brassica* vegetables. *Molecules, 16*(1), 251–280. https://doi.org/10.3390/molecules16010251

Chand, S., Singh, G., Rajkumari, & Patra, D. D. (2016). Performance of rose-scented geranium (*Pelargonium graveolens*) in heavy metal-polluted soil vis-à-vis phytoaccumulation of metals. *International Journal of Phytoremediation, 18*(8), 754–760. https://doi.org/10.1080/15226514.2015.1131236

Chaney, R. L., Broadhurst, C. L., & Centofanti, T. (2010). Phytoremediation of soil trace elements. In *Trace elements in soils* (pp. 311–352). https://doi.org/10.1002/9781444319477.ch14

Chatterjee, C., Dube, B. K., Sinha, P., & Srivastava, P. (2004). Detrimental effects of lead phytotoxicity on growth, yield, and metabolism of rice. *Communications in Soil Science and Plant Analysis, 35*(1–2), 255–265. https://doi.org/10.1081/CSS-120027648

Chehregani, A., & Malayeri, B. E. (2007). Removal of heavy metals by native accumulator plants.

International Journal of Agriculture and Biology, 9(3), 462–465.

Chen, A. 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*(1), 28–30. https://doi.org/10.1016/j.ijwd.2016.01.002

Chen, H.-L., Su, H.-J., Guo, Y.-L., Liao, P.-C., Hung, C.-F., & Lee, C.-C. (2006). Biochemistry examinations and health disorder evaluation of Taiwanese living near incinerators and with low serum PCDD/Fs levels. *Science of the Total Environment, 366*(2–3), 538–548. https://doi.org/10.1016/j.scitotenv.2005.11.004

Chen, Y., Shen, Z., & Li, X. (2004). The use of vetiver grass (*Vetiveria zizanioides*) in the phytoremediation of soils contaminated with heavy metals. *Applied Geochemistry, 19*(10), 1553–1565. https://doi.org/10.1016/j.apgeochem.2004.02.003

Cheng, Y., Zhao, Y., Chen, C., & Zhang, F. (2025). Heavy metals toxicity: Mechanism, health effects, and therapeutic interventions. *MedComm, 6*(9), e70241. https://doi.org/10.1002/mco2.70241

Chinmayee, M. D., Mahesh, B., Pradesh, S., Mini, I., & Swapna, T. S. (2012). Assessment of phytoremediation potential of invasive weed *Amaranthus spinosus* L. *Applied Biochemistry and Biotechnology, 167*, 1550–1559. https://doi.org/10.1007/s12010-012-9657-0

Cosio, C., Martinoia, E., & Keller, C. (2004). Hyperaccumulation of cadmium and zinc in *Thlaspi caerulescens* and *Arabidopsis halleri* at the leaf cellular level. *Plant Physiology, 134*(2), 716–725. https://doi.org/10.1104/pp.103.031948

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. https://doi.org/10.1016/j.eti.2017.08.002

Cui, X., Shen, Y., Yang, Q., Kawi, S., He, Z., Yang, X., & Wang, C. H. (2018). Simultaneous syngas and biochar production during heavy metal separation from Cd/Zn hyperaccumulator (*Sedum alfredii*) by gasification. *Chemical Engineering Journal, 347*, 543–551. https://doi.org/10.1016/j.cej.2018.04.133

Dasgupta, S., Satvat, P. S., & Mahindrakar, A. B. (2011). Ability of *Cicer arietinum* (L.) for bioremoval of lead and chromium from soil. *International Journal of Technical Engineering Systems, 24*, 338–341.

de la Rosa, G., Peralta-Videa, J. R., Montes, M., Parsons, J. G., Cano-Aguilera, I., & Gardea-Torresdey, J. L. (2004). Cadmium uptake and translocation in tumbleweed (*Salsola kali*), a potential Cd-hyperaccumulator desert plant species: ICP/OES and XAS studies. *Chemosphere, 55*(9), 1159–1168. https://doi.org/10.1016/j.chemosphere.2004.01.028

Debnath, B., Singh, W. S., & Manna, K. (2019). Sources and toxicological effects of lead on human health. *Indian Journal of Medical Specialities, 10*(2), 66. https://doi.org/10.4103/INJMS.INJMS_30_18

Deng, S., Zhang, X., Zhu, Y., & Zhuo, R. (2024). Recent advances in phyto-combined remediation of heavy metal pollution in soil. *Biotechnology Advances, 72*, 108337. https://doi.org/10.1016/j.biotechadv.2024.108337

Desbrosses-Fonrouge, A. G., Voigt, K., Schröder, A., Arrivault, S., Thomine, S., & Krämer, U. (2005).

Arabidopsis thaliana MTP1 is a Zn transporter in the vacuolar membrane which mediates Zn detoxification and drives leaf Zn accumulation. *FEBS Letters, 579*(19), 4165–4174. https://doi.org/10.1016/j.febslet.2005.06.046

Dhanwal, P., Kumar, A., Dudeja, S., Chhokar, V., & Beniwal, V. (2017). Recent advances in phytoremediation technology. In *Advances in environmental biotechnology* (pp. 227–241). Springer. https://doi.org/10.1007/978-981-10-4041-2_14

Dhiman, S. S., Zhao, X., Li, J., Kim, D., Kalia, V. C., Kim, I.-W., Kim, J. Y., & Lee, J.-K. (2017). Metal accumulation by sunflower (*Helianthus annuus* L.) and the efficacy of its biomass in enzymatic saccharification. *PLOS ONE, 12*(4), e0175845. https://doi.org/10.1371/journal.pone.0175845

Dinu, C., Vasile, G. G., Buleandra, M., Popa, D. E., Gheorghe, S., & Ungureanu, E. M. (2020). Translocation and accumulation of heavy metals in *Ocimum basilicum* L. plants grown in a mining-contaminated soil. *Environmental Science and Pollution Research, 20*, 2141–2154. https://doi.org/10.1007/s11368-019-02550-w

Domínguez-Solís, J. R., López-Martín, M. C., Ager, F. J., Ynsa, M. D., Romero, L. C., & Gotor, C. (2004). Increased cysteine availability is essential for cadmium tolerance and accumulation in *Arabidopsis thaliana*. *Plant Biotechnology Journal, 2*(6), 469–476. https://doi.org/10.1111/j.1467-7652.2004.00092.x

Duan, L., Li, X., Jiang, Y., Lei, M., Dong, Z., & Longhurst, P. (2017). Arsenic transformation behaviour during thermal decomposition of *Pteris vittata*, an arsenic hyperaccumulator. *Journal of Analytical and Applied Pyrolysis, 124*, 584–591. https://doi.org/10.1016/j.jaap.2017.01.013

Duruibe, J. O., Ogwuegbu, M. O., & Egwurugwu, J. N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences, 2*(5), 112–118.

Ehsan, M., Santamaría-Delgado, K., Alderete-Chavez, A., De la Cruz-Landero, N., Jaén-Contreras, D., & Molumeli, P. A. (2009). Phytostabilization of cadmium-contaminated soils by *Lupinus uncinatus* Schldl. *Spanish Journal of Agricultural Research, 7*(2), 390–397. https://doi.org/10.5424/sjar/2009072-430

Eissa, M. A. (2025). Phytoremediation of heavy metal-contaminated soils: Evaluating agronomic crops, hyperaccumulators, and halophytes. *Soil and Sediment Contamination: An International Journal*, 1–19. https://doi.org/10.1080/15320383.2025.2591202

Fatima, G., Raza, A. M., Hadi, N., Nigam, N., & Mahdi, A. A. (2019). Cadmium in human diseases: It's more than just a mere metal. *Indian Journal of Clinical Biochemistry, 34*, 371–378. https://doi.org/10.1007/s12291-019-00839-8

Fiorentino, N., Ventorino, V., Rocco, C., Cenvinzo, V., Agrelli, D., Gioia, L., Di Mola, I., Adamo, P., Pepe, O., & Fagnano, M. (2017). Giant reed growth and effects on soil biological fertility in assisted phytoremediation of an industrial polluted soil. *Science of the Total Environment, 575*, 1375–1383. https://doi.org/10.1016/j.scitotenv.2016.09.220

Francesconi, K., Visoottiviseth, P., Sridokchan, W., & Goessler, W. (2002). Arsenic species in an arsenic hyperaccumulating fern, *Pityrogramma calomelanos*: A potential phytoremediator of arsenic-contaminated soils. *Science of the Total Environment, 284*(1–3), 27–35. https://doi.org/10.1016/S0048-9697(01)00854-3

Freeman, J. L., Persans, M. W., Nieman, K., Albrecht, C., Peer, W., Pickering, I. J., & Salt, D. E. (2004). Increased glutathione biosynthesis plays a role in nickel tolerance in *Thlaspi* nickel hyperaccumulators. *The Plant Cell, 16*(8), 2176–2191. https://doi.org/10.1105/tpc.104.023036

Frérot, H., Faucon, M., Willems, G., Godé, C., Courseaux, A., Darracq, A., Verbruggen, N., & Saumitou-Laprade, P. (2010). Genetic architecture of zinc hyperaccumulation in *Arabidopsis halleri*: The essential role of QTL × environment interactions. *New Phytologist, 187*(2), 355–367. https://doi.org/10.1111/j.1469-8137.2010.03295.x

Gao, F., Shen, Y., Sallach, J. B., Li, H., Liu, C., & Li, Y. (2021). Direct prediction of bioaccumulation of organic contaminants in plant roots from soils with machine learning models based on molecular structures. *Environmental Science & Technology, 55*(24), 16358–16368. https://doi.org/10.1021/acs.est.1c02376

García-Salgado, S., García-Casillas, D., Quijano-Nieto, M. A., & Bonilla-Simón, M. M. (2012). Arsenic and heavy metal uptake and accumulation in native plant species from soils polluted by mining activities. *Water, Air, & Soil Pollution, 223*, 559–572. https://doi.org/10.1007/s11270-011-0882-x

Gardea-Torresdey, J. L., Peralta-Videa, J. R., Montes, M., de la Rosa, G., & Corral-Díaz, B. (2004). Bioaccumulation of cadmium, chromium, and copper by *Convolvulus arvensis* L.: Impact on plant growth and uptake of nutritional elements. *Bioresource Technology, 92*(3), 229–235. https://doi.org/10.1016/j.biortech.2003.10.002

Garg, N., Singla, P., & Bhandari, P. (2015). Metal uptake, oxidative metabolism, and mycorrhization in pigeonpea and pea under arsenic and cadmium stress. *Turkish Journal of Agriculture and Forestry, 39*(2), 234–250. https://doi.org/10.3906/tar-1406-121

Gautam, M., Pandey, D., & Agrawal, M. (2017). Phytoremediation of metals using lemongrass (*Cymbopogon citratus* (DC.) Stapf.) grown under different levels of red mud in soil amended with biowastes. *International Journal of Phytoremediation, 19*(6), 555–562. https://doi.org/10.1080/15226514.2016.1267701

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human health and environmental toxicology. *International Journal of Environmental Research and Public Health, 17*(3), 679. https://doi.org/10.3390/ijerph17030679

Gerhardt, K. E., Gerwing, P. D., & Greenberg, B. M. (2017). Taking phytoremediation from proven technology to accepted practice. *Plant Science, 256*, 170–185. https://doi.org/10.1016/j.plantsci.2016.11.016

Ghosh, A., Singh, V. K., Dey, K., Patel, M., & Pal, A. (2021). Phytoremediation: A cost-effective tool for solid waste management. In *Handbook of solid waste management: Sustainability through circular economy* (pp. 1–30). Springer Singapore. https://doi.org/10.1007/978-981-15-7525-9_47-2

Golan-Goldhirsh, A. (2006). Plant tolerance to heavy metals: A risk for food toxicity or a means for food fortification with essential metals: The *Allium schoenoprasum* model. In *Soil and water pollution monitoring, protection and remediation* (pp. 479–486). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4728-2_31

Gomes, H. I. (2012). Phytoremediation for bioenergy: Challenges and opportunities. *Environmental Technology Reviews, 1*(1), 59–66. https://doi.org/10.1080/09593330.2012.696715

González, H., Fernández-Fuego, D., Bertrand, A., & González, A. (2019). Effect of pH and citric acid on the growth, arsenic accumulation, and phytochelatin synthesis in *Eupatorium cannabinum* L., a promising plant for phytostabilization. *Environmental Science and Pollution Research, 26*, 26242–26253. https://doi.org/10.1007/s11356-019-05657-2

Guerinot, M. L. (2000). The ZIP family of metal transporters. *Biochimica et Biophysica Acta (BBA) – Biomembranes, 1465*(1–2), 190–198. https://doi.org/10.1016/S0005-2736(00)00138-3

Gündüz, S., Uygur, F. N., & Kahramanoğlu, I. (2012). Heavy metal phytoremediation potentials of *Lepidium sativum* L., *Lactuca sativa* L., *Spinacia oleracea* L., and *Raphanus sativus* L. *Herald Journal of Agriculture and Food Science Research, 1*, 1–5.

Gurajala, H. K., Cao, X., Tang, L., Ramesh, T. M., Lu, M., & Yang, X. (2019). Comparative assessment of Indian mustard (*Brassica juncea* L.) genotypes for phytoremediation of Cd- and Pb-contaminated soils. *Environmental Pollution, 254*, 113085. https://doi.org/10.1016/j.envpol.2019.113085

Gustin, J. L., Zanis, M. J., & Salt, D. E. (2011). Structure and evolution of the plant cation diffusion facilitator family of ion transporters. *BMC Evolutionary Biology, 11*, 1–13. https://doi.org/10.1186/1471-2148-11-76

Ha, E., Basu, N., Bose-O'Reilly, S., Dórea, J. G., McSorley, E., Sakamoto, M., & Chan, H. M. (2017). Current progress on understanding the impact of mercury on human health. *Environmental Research, 152*, 419–433. https://doi.org/10.1016/j.envres.2016.06.042

Habiba, U., Ali, S., Rizwan, M., Ibrahim, M., Hussain, A., Shahid, M. R., Alamri, S. A., Alyemeni, M. N., & Ahmad, P. (2019). Alleviative role of exogenously applied mannitol in maize cultivars differing in chromium stress tolerance. *Environmental Science and Pollution Research, 26*(5), 5111–5121. https://doi.org/10.1007/s11356-018-3970-2

Hall, J. Á. (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

Hamzah, A., Hapsari, R. I., & Wisnubroto, E. I. (2016). Phytoremediation of cadmium-contaminated agricultural land using indigenous plants. *International Journal of Environmental and Agriculture Research, 2*(1), 8–14.

Hazotte, C., Laubie, B., Pacault, S., Dufaud, O., & Simonnot, M. O. (2020). Evaluation of the performance of nickel hyperaccumulator plants as combustion fuel. *Biomass and Bioenergy, 140*, 105671. https://doi.org/10.1016/j.biombioe.2020.105671

He, X., Zhang, J., Ren, Y., Sun, C., Deng, X., Qian, M., Hu, Z., Li, R., Chen, Y., Shen, Z., & Xia, Y. (2019). Polyaspartate and liquid amino acid fertilizer are appropriate alternatives for promoting the phytoextraction of cadmium and lead in *Solanum nigrum* L. *Chemosphere, 237*, 124483. https://doi.org/10.1016/j.chemosphere.2019.124483

Hernández, L. E., Ortega-Villasante, C., Montero-Palmero, M. B., Escobar, C., & Carpena, R. O. (2012). Heavy metal perception in a microscale environment: A model system using high doses of pollutants. In *Metal toxicity in plants: Perception, signaling and remediation* (pp. 23–39). Springer. https://doi.org/10.1007/978-3-642-22081-4_2

Hooda, V. (2007). Phytoremediation of toxic metals from soil and wastewater. *Journal of Environmental*

Biology, 28(2), 367.

Huang, X., Luo, D., Chen, X., Wei, L., Liu, Y., Wu, Q., Xiao, T., Mai, X., Liu, G., & Liu, L. (2019). Insights into heavy metals leakage in chelator-induced phytoextraction of Pb- and Tl-contaminated soil. *International Journal of Environmental Research and Public Health, 16*(8), 1328. https://doi.org/10.3390/ijerph16081328

Imran, M. A., Ch, M. N., Khan, R. M., Ali, Z., Mahmood, T., & Ishfaq, M. (2013). Toxicity of arsenic (As) on seed germination of sunflower (*Helianthus annuus* L.). *International Journal of Physical Sciences, 8*, 840–847. https://doi.org/10.5897/IJPS2013.3894

Islam, L. N. (2023). An update on the immunotoxic effects of arsenic exposure. In *Handbook of arsenic toxicology* (pp. 551–592). Academic Press. https://doi.org/10.1016/B978-0-323-89847-8.00034-1

Itoh, H., Iwasaki, M., Sawada, N., Takachi, R., Kasuga, Y., Yokoyama, S., Onuma, H., Nishimura, H., Kusama, R., Yokoyama, K., & Tsugane, S. (2014). Dietary cadmium intake and breast cancer risk in Japanese women: A case-control study. *International Journal of Hygiene and Environmental Health, 217*(1), 70–77. https://doi.org/10.1016/j.ijheh.2013.03.010

Jacob, J. M., Karthik, C., Saratale, R. G., Kumar, S. S., Prabakar, D., Kadirvelu, K., & Pugazhendhi, A. (2018). Biological approaches to tackle heavy metal pollution: A survey of literature. *Journal of Environmental Management, 217*, 56–70. https://doi.org/10.1016/j.jenvman.2018.03.077

Jadia, C. D., & Fulekar, M. H. (2009). Phytoremediation of heavy metals: Recent techniques. *African Journal of Biotechnology, 8*(6).

Jahanbakhshi, S., Rezaei, M. R., & Sayyari-Zahan, M. H. (2014). Optimization of phytoremediation in Cd-contaminated soil by using Taguchi method in *Spinacia oleracea*. *Proceedings of the International Academy of Ecology and Environmental Sciences, 4*(4), 185–193.

Jarin, A. S., Khan, M. A. R., Apon, T. A., Islam, M. A., Rahat, A., Akter, M., Anik, T. R., Nguyen, H. M., Nguyen, T. T., Ha, C. V., & Tran, L. P. (2025). Plant responses to heavy metal stresses: Mechanisms, defense strategies, and nanoparticle-assisted remediation. *Plants, 14*(24), 3834. https://doi.org/10.3390/plants14243834

Javed, M. T., Tanwir, K., Akram, M. S., Shahid, M., Niazi, N. K., & Lindberg, S. (2019). Phytoremediation of cadmium-polluted water/sediment by aquatic macrophytes: Role of plant-induced pH changes. In *Cadmium toxicity and tolerance in plants* (pp. 495–529). Academic Press. https://doi.org/10.1016/B978-0-12-814864-8.00020-6

Jeyasundar, P. G. S. A., Ali, A., Azeem, M., Li, Y., Guo, D., Sikdar, A., Abdelrahman, H., Kwon, E., Antoniadis, V., Mani, V. M., Shaheen, S. M., Rinklebe, J., & Zhang, Z. (2021). Green remediation of toxic metals-contaminated mining soil using bacterial consortium and *Brassica juncea*. *Environmental Pollution, 277*, 116789. https://doi.org/10.1016/j.envpol.2021.116789

Jia, Y., Anderson, J. V., & Chao, W. S. (2011). Autophosphorylation is crucial for CDK-activating kinase (Ee; CDKF; 1) activity and complex formation in leafy spurge. *Plant Science, 180*(2), 259–267. https://doi.org/10.1016/j.plantsci.2010.08.017

Kabir, M. S., Salam, M. A., Paul, D. N., Hossain, M. I., Rahman, N. M., Aziz, A., & Latif, M. A. (2016). Spatial variation of arsenic in soil, irrigation water, and plant parts: A microlevel study. *The*

Scientific World Journal, 2016, Article 2186069. https://doi.org/10.1155/2016/2186069

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*, 100203. https://doi.org/10.1016/j.envadv.2022.100203

Kalavrouziotis, I. K., Robolas, P., Koukoulakis, P. H., & Papadopoulos, A. H. (2008). Effects of municipal reclaimed wastewater on the macro- and micro-elements status of soil and of *Brassica oleracea* var. *italica* and *B. oleracea* var. *gemmifera*. *Agricultural Water Management, 95*(4), 419–426. https://doi.org/10.1016/j.agwat.2007.11.004

Kalve, S. K., Sarangi, B. K., Pandey, R. A., & Chakrabarti, T. C. (2011). Arsenic and chromium hyperaccumulation by an ecotype of *Pteris vittata*: Prospective for phytoextraction from contaminated water and soil. *Current Science*, 888–894.

Karnwal, A., Kumar, G., Mahmoud, A. E. D., Dutta, J., Singh, R., Al-Tawaha, A. R. M. S., & Malik, T. (2025). Eco-engineered remediation: Microbial and rhizosphere-based strategies for heavy metal detoxification. *Current Research in Biotechnology, 9*, 100297. https://doi.org/10.1016/j.crbiot.2025.100297

Khalid, N., Noman, A., Aqeel, M., Masood, A., Tufail, A., & Yousaf, S. (2019). Phytoremediation potential of *Xanthium strumarium* for heavy metals-contaminated soils at roadsides. *International Journal of Environmental Science and Technology, 16*, 2091–2100. https://doi.org/10.1007/s13762-018-1825-5

Khan, A. H. A., Kiyani, A., Mirza, C. R., Butt, T. A., Barros, R., Ali, B., Iqbal, M., & Yousaf, S. (2021). Ornamental plants for the phytoremediation of heavy metals: Present knowledge and future perspectives. *Environmental Research, 195*, 110780. https://doi.org/10.1016/j.envres.2021.110780

Khan, I., Iqbal, M., & Shafiq, F. (2019). Phytomanagement of lead-contaminated soils: Critical review of new trends and future prospects. *International Journal of Environmental Science and Technology, 16*, 6473–6488. https://doi.org/10.1007/s13762-019-02431-2

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

Koren'kov, V., Park, S., Cheng, N.-H., Sreevidya, C., Lachmansingh, J., Morris, J., Hirschi, K., & Wagner, G. J. (2006). Enhanced Cd^{2}□-selective root tonoplast transport in tobaccos expressing *Arabidopsis* cation exchangers. *Planta, 225*(2), 403–411. https://doi.org/10.1007/s00425-006-0352-7

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

Krishnamurti, G. S. R., Cieslinski, G., Huang, P. M., & Van Rees, K. C. J. (1997). Kinetics of cadmium release from soils as influenced by organic acids: Implication for cadmium availability. *Journal of Environmental Quality, 26*(1), 271–277. https://doi.org/10.2134/jeq1997.00472425002600010038x

Kubota, H., & Takenaka, C. (2003). *Arabis gemmifera* is a hyperaccumulator of Cd and Zn. *International Journal of Phytoremediation, 5*(3), 197–201. https://doi.org/10.1080/713779219

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. https://doi.org/10.1007/s11104-004-8068-6

Kumar, B., Smita, K., & Flores, L. C. (2017). Plant-mediated detoxification of mercury and lead. *Arabian Journal of Chemistry, 10*, S2335–S2342. https://doi.org/10.1016/j.arabjc.2013.08.010

Kumpiene, J., Fitts, J. P., & Mench, M. (2012). Arsenic fractionation in mine spoils 10 years after aided phytostabilization. *Environmental Pollution, 166*, 82–88. https://doi.org/10.1016/j.envpol.2012.02.016

Laghlimi, M., Baghdad, B., El Hadi, H., & Bouabdli, A. (2015). Phytoremediation mechanisms of heavy metal-contaminated soils: A review. *Open Journal of Ecology, 5*(8), 375. https://doi.org/10.4236/oje.2015.58031

Lasat, M. M. (2002). Phytoextraction of toxic metals: A review of biological mechanisms. *Journal of Environmental Quality, 31*(1), 109–120. https://doi.org/10.2134/jeq2002.1090

Lee, S., Kim, Y. Y., Lee, Y., & An, G. (2007). Rice P1B-type heavy-metal ATPase, OsHMA9, is a metal efflux protein. *Plant Physiology, 145*(3), 831–842. https://doi.org/10.1104/pp.107.102236

Li, W. X., Chen, T. B., Huang, Z. C., Lei, M., & Liao, X. Y. (2006). Effect of arsenic on chloroplast ultrastructure and calcium distribution in arsenic hyperaccumulator *Pteris vittata* L. *Chemosphere, 62*(5), 803–809. https://doi.org/10.1016/j.chemosphere.2005.04.055

Li, X., Zhu, W., Meng, G., Guo, R., & Wang, Y. (2020). Phytoremediation of alkaline soils co-contaminated with cadmium and tetracycline antibiotics using the ornamental hyperaccumulators *Mirabilis jalapa* L. and *Tagetes patula* L. *Environmental Science and Pollution Research, 27*, 14175–14183. https://doi.org/10.1007/s11356-020-07975-2

Lin, H. J., Sung, T. I., Chen, C. Y., & Guo, H. R. (2013). Arsenic levels in drinking water and mortality of liver cancer in Taiwan. *Journal of Hazardous Materials, 262*, 1132–1138. https://doi.org/10.1016/j.jhazmat.2012.12.049

Liu, L., Hu, L., Tang, J., Li, Y., Zhang, Q., & Chen, X. (2012). Food safety assessment of planting patterns of four vegetable-type crops grown in soil contaminated by electronic waste activities. *Journal of Environmental Management, 93*(1), 22–30. https://doi.org/10.1016/j.jenvman.2011.08.021

Liu, Q., Zhou, Y., Lu, J., & Zhou, Y. (2020). Novel cyclodextrin-based adsorbents for removing pollutants from wastewater: A critical review. *Chemosphere, 241*, 125043. https://doi.org/10.1016/j.chemosphere.2019.125043

Liu, S., Yang, B., Liang, Y., Xiao, Y., & Fang, J. (2020). Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. *Environmental Science and Pollution Research, 27*, 16069–16085. https://doi.org/10.1007/s11356-020-08282-6

Liu, W. J., Tian, K., Jiang, H., Zhang, X. S., Ding, H. S., & Yu, H. Q. (2012a). Selectively improving the bio-oil quality by catalytic fast pyrolysis of heavy metal-polluted biomass: Taking copper (Cu) as an example. *Environmental Science & Technology, 46*(14), 7849–7856. https://doi.org/10.1021/es204681y

Liu, Z., Chen, B., Wang, L. A., Urbanovich, O., Nagorskaya, L., Li, X., & Tang, L. (2020a). A review on

phytoremediation of mercury-contaminated soils. *Journal of Hazardous Materials, 400*, 123138. https://doi.org/10.1016/j.jhazmat.2020.123138

Lu, S., Ji, L., Du, Y., Chen, T., Li, X., Yan, J., & Buekens, A. (2015). PCDD/Fs emission and control characteristics for combustion of heavy metal hyper-accumulators in a vertical entrained flow tubular reactor. *Fresenius Environmental Bulletin, 24*(12a), 4472–4477.

Mahar, A., Wang, P., Ali, A., Awasthi, M. K., Lahori, A. H., Wang, Q., Li, R., & 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

Mahmood, A., & Malik, R. N. (2014). Human health risk assessment of heavy metals via consumption of contaminated vegetables collected from different irrigation sources in Lahore, Pakistan. *Arabian Journal of Chemistry, 7*(1), 91–99. https://doi.org/10.1016/j.arabjc.2013.07.002

Mahmud, M. N., Al Kafi, A., Sharmin, S., Muniza, N. T., Tahara, T., Raidah, R., Batool, R., & Islam, M. M. (2026). Phytoremediation of contaminated soils: Current trends and future prospects. *Earth Critical Zone*, 100072. https://doi.org/10.1016/j.ecz.2026.100072

Manara, A. (2012). Plant responses to heavy metal toxicity. In *Plants and heavy metals* (pp. 27–53). Springer. https://doi.org/10.1007/978-94-007-4441-7_2

Manikandan, R., Sahi, S. V., & Venkatachalam, P. (2015). Impact assessment of mercury accumulation and biochemical and molecular response of *Mentha arvensis*: A potential hyperaccumulator plant. *The Scientific World Journal, 2015*, Article 715217. https://doi.org/10.1155/2015/715217

Manzoor, M., Gul, I., Manzoor, A., Kamboh, U. R., Hina, K., & Kallerhoff, J. (2020). Lead availability and phytoextraction in the rhizosphere of *Pelargonium* species. *Environmental Science and Pollution Research, 27*, 39753–39762. https://doi.org/10.1007/s11356-020-08226-0

Marrugo-Negrete, J., Durango-Hernández, J., Pinedo-Hernández, J., Olivero-Verbel, J., & Díez, S. (2015). Phytoremediation of mercury-contaminated soils by *Jatropha curcas*. *Chemosphere, 127*, 58–63. https://doi.org/10.1016/j.chemosphere.2014.12.073

Martínez-Castillo, J. I., Saldaña-Robles, A., & Ozuna, C. (2022). Arsenic stress in plants: A metabolomic perspective. *Plant Stress, 3*, 100055. https://doi.org/10.1016/j.stress.2022.100055

Milner, M. J., & Kochian, L. V. (2008). Investigating heavy-metal hyperaccumulation using *Thlaspi caerulescens* as a model system. *Annals of Botany, 102*(1), 3–13. https://doi.org/10.1093/aob/mcn063

Mocek-Płóciniak, A., Mencel, J., Zakrzewski, W., & Roszkowski, S. (2023). Phytoremediation as an effective remedy for removing trace elements from ecosystems. *Plants, 12*(8), 1653. https://doi.org/10.3390/plants12081653

Mohamed, H. I., Ullah, I., Toor, M. D., Tanveer, N. A., Din, M. M. U., Basit, A., Sultan, Y., Muhammad, M., & Rehman, M. U. (2025). Heavy metals toxicity in plants: Understanding mechanisms and developing coping strategies for remediation: A review. *Bioresources and Bioprocessing, 12*(1), 95. https://doi.org/10.1186/s40643-025-00930-4

Mohanty, M. (2016). Post-harvest management of phytoremediation technology. *Journal of Environmental & Analytical Toxicology, 6*(5), 398. https://doi.org/10.4172/2161-0525.1000398

Muthusaravanan, S., Sivarajasekar, N., Vivek, J. S., Paramasivan, T., Naushad, M., Prakashmaran, J., Gayathri, V., & Al-Duaij, O. K. (2018). Phytoremediation of heavy metals: Mechanisms, methods and enhancements. *Environmental Chemistry Letters, 16*, 1339–1359. https://doi.org/10.1007/s10311-018-0762-3

Muthusaravanan, S., Sivarajasekar, N., Vivek, J. S., Vasudha Priyadharshini, S., Paramasivan, T., Dhakal, N., & Naushad, M. (2019). Research updates on heavy metal phytoremediation: Enhancements, efficient post-harvesting strategies and economic opportunities. In *Green materials for wastewater treatment* (pp. 191–222). Springer. https://doi.org/10.1007/978-3-030-17724-9_9

Nareshkumar, A., Veeranagamallaiah, G., Pandurangaiah, M., Kiranmai, K., Amaranathareddy, V., Lokesh, U., Venkatesh, B., & Sudhakar, C. (2015). Pb-stress-induced oxidative stress caused alterations in antioxidant efficacy in two groundnut (*Arachis hypogaea* L.) cultivars. *Agricultural Sciences, 6*(10), 1283. https://doi.org/10.4236/as.2015.610123

Nedjimi, B. (2021). Phytoremediation: A sustainable environmental technology for heavy metals decontamination. *SN Applied Sciences, 3*(3), 286. https://doi.org/10.1007/s42452-021-04301-4

Neilson, S., & Rajakaruna, N. (2015). Phytoremediation of agricultural soils: Using plants to clean metal-contaminated arable land. In *Phytoremediation: Management of environmental contaminants* (pp. 159–168). Springer. https://doi.org/10.1007/978-3-319-10395-2_11

Ng, C. C., Boyce, A., Rahman, M., & Abas, R. (2017). Tolerance threshold and phyto-assessment of cadmium and lead in vetiver grass, *Vetiveria zizanioides* (Linn.) Nash. *Chiang Mai Journal of Science, 44*(4), 1367–1378.

Ning, Y., Liu, N., Song, Y., Luo, J., & Li, T. (2019). Enhancement of phytoextraction of Pb by compounded activation agent derived from fruit residue. *International Journal of Phytoremediation, 21*(14), 1449–1456. https://doi.org/10.1080/15226514.2019.1633266

Oladoye, P. O., Olowe, O. M., & Asemoloye, M. D. (2022). Phytoremediation technology and food security impacts of heavy metal-contaminated soils: A review of literature. *Chemosphere, 288*, 132555. https://doi.org/10.1016/j.chemosphere.2021.132555

Oubohssaine, M., & Dahmani, I. (2024). Phytoremediation: Harnessing plant power and innovative technologies for effective soil remediation. *Plant Stress, 14*, 100578. https://doi.org/10.1016/j.stress.2024.100578

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Pan, J., Plant, J. A., Voulvoulis, N., Oates, C. J., Ihlenfeld, C., & Kneer, R. (2010). Cadmium levels in Europe: Implications for human health. *Environmental Geochemistry and Health, 32*, 1–12. https://doi.org/10.1007/s10653-009-9273-2

Pandey, J., Chand, S., Pandey, S., & Patra, D. D. (2015). Palmarosa (*Cymbopogon martinii* (Roxb.) Wats.) as a putative crop for phytoremediation in tannery sludge-polluted soil. *Ecotoxicology and Environmental Safety, 122*, 296–302. https://doi.org/10.1016/j.ecoenv.2015.08.005

Park, R. M., Bena, J. F., Stayner, L. T., Smith, R. J., Gibb, H. J., & Lees, P. S. (2004). Hexavalent chro-

mium and lung cancer in the chromate industry: A quantitative risk assessment. *Risk Analysis, 24*(5), 1099–1108. https://doi.org/10.1111/j.0272-4332.2004.00512.x

Peco, J. D., Higueras, P., Campos, J. A., Esbrí, J. M., Moreno, M. M., Battaglia-Brunet, F., & Sandalio, L. M. (2021). Abandoned mine lands reclamation by plant remediation technologies. *Sustainability, 13*(12), 6555. https://doi.org/10.3390/su13126555

Pedas, P., Schiller Stokholm, M., Hegelund, J. N., Ladegård, A. H., Schjoerring, J. K., & Husted, S. (2014). Golgi-localized barley MTP8 proteins facilitate Mn transport. *PLOS ONE, 9*(12), e113759. https://doi.org/10.1371/journal.pone.0113759

Peng, K., Luo, C., You, W., Lian, C., Li, X., & Shen, Z. (2008). Manganese uptake and interactions with cadmium in the hyperaccumulator *Phytolacca americana* L. *Journal of Hazardous Materials, 154*(1–3), 674–681. https://doi.org/10.1016/j.jhazmat.2007.10.080

Pérez-Sanz, A., Millán, R., Sierra, M. J., Alarcón, R., García, P., Gil-Díaz, M., Vázquez, S., & Lobo, M. C. (2012). Mercury uptake by *Silene vulgaris* grown on contaminated spiked soils. *Journal of Environmental Management, 95*, S233–S237. https://doi.org/10.1016/j.jenvman.2010.07.018

Persans, M. W., Nieman, K., & Salt, D. E. (2001). Functional activity and role of cation-efflux family members in Ni hyperaccumulation in *Thlaspi goesingense*. *Proceedings of the National Academy of Sciences, 98*(17), 9995–10000. https://doi.org/10.1073/pnas.171039798

Ping, L., Xingxiang, W., Taolin, Z., Dongmei, Z., & Yuanqiu, H. (2008). Effects of several amendments on rice growth and uptake of copper and cadmium from a contaminated soil. *Journal of Environmental Sciences, 20*(4), 449–455. https://doi.org/10.1016/S1001-0742(08)62078-1

Pourrut, B., Shahid, M., Dumat, C., Winterton, P., & Pinelli, E. (2011). Lead uptake, toxicity, and detoxification in plants. *Reviews of Environmental Contamination and Toxicology, 213*, 113–136. https://doi.org/10.1007/978-1-4419-9860-6_4

Pulford, I. D., & Watson, C. (2003). Phytoremediation of heavy metal-contaminated land by trees: A review. *Environment International, 29*(4), 529–540. https://doi.org/10.1016/S0160-4120(02)00152-6

Radziemska, M. (2018). Study of applying naturally occurring mineral sorbents of Poland (dolomite, halloysite, chalcedonite) for aided phytostabilization of soil polluted with heavy metals. *Catena, 163*, 123–129. https://doi.org/10.1016/j.catena.2017.12.015

Rahman, S. H., Khanam, D., Adyel, T. M., Islam, M. S., Ahsan, M. A., & Akbor, M. A. (2012). Assessment of heavy metal contamination of agricultural soil around Dhaka Export Processing Zone (DEPZ), Bangladesh: Implication of seasonal variation and indices. *Applied Sciences, 2*(3), 584–601. https://doi.org/10.3390/app2030584

Rai, V. K. (2002). Role of amino acids in plant responses to stresses. *Biologia Plantarum, 45*(4), 481–487. https://doi.org/10.1023/A:1022308229759

Rascio, N., & Navari-Izzo, F. (2011). Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Science, 180*(2), 169–181. https://doi.org/10.1016/j.plantsci.2010.08.016

Reeves, R. D., Baker, A. J. M., Jaffré, T., Erskine, P. D., Echevarria, G., & Van der Ent, A. (2018). A global database for plants that hyperaccumulate metal and metalloid trace elements. *New*

Phytologist, 218(2), 407–411. https://doi.org/10.1111/nph.14907

Rezaee, A., Derayat, J., Mortazavi, S. B., Yamini, Y., & Jafarzadeh, M. T. (2005). Removal of mercury from chlor-alkali industry wastewater using *Acetobacter xylinum* cellulose. *American Journal of Environmental Sciences, 1*(2), 102–105. https://doi.org/10.3844/ajessp.2005.102.105

Rezania, S., Taib, S. M., Din, M. F. M., Dahalan, F. A., Kamyab, H., & Chew, W. (2016). Comprehensive review on phytotechnology: Heavy metals removal by diverse aquatic plant species from wastewater. *Journal of Hazardous Materials, 318*, 587–599. https://doi.org/10.1016/j.jhazmat.2016.07.053

Rizzi, L., Petruzzelli, G., Poggio, G., & Guidi, G. V. (2004). Soil physical changes and plant availability of Zn and Pb in a treatability test of phytostabilization. *Chemosphere, 57*(9), 1039–1046. https://doi.org/10.1016/j.chemosphere.2004.08.048

Rotkittikhun, P., Chaiyarat, R., Kruatrachue, M., Pokethitiyook, P., & Baker, A. J. M. (2007). Growth and lead accumulation by the grasses *Vetiveria zizanioides* and *Thysanolaena maxima* in lead-contaminated soil amended with pig manure and fertilizer: A glasshouse study. *Chemosphere, 66*(1), 45–53. https://doi.org/10.1016/j.chemosphere.2006.05.038

Roy, S. B., & Bera, A. K. (2002). Individual and combined effect of mercury and manganese on phenol and proline content in leaf and stem of mungbean seedlings. *Journal of Environmental Biology, 23*(4), 433–435.

Rubio, C., Paz, S., Tius, E., Hardisson, A., Gutiérrez, A. J., González-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*(2), 562–567. https://doi.org/10.1007/s12011-018-1329-7

Ruppert, L., Lin, Z. Q., Dixon, R. P., & Johnson, K. A. (2013). Assessment of solid-phase microextraction fibers for the monitoring of volatile organoarsenicals emitted from a plant–soil system. *Journal of Hazardous Materials, 262*, 1230–1236. https://doi.org/10.1016/j.jhazmat.2012.06.046

Saifullah, Sarwar, N., Bibi, S., Ahmad, M., & Ok, Y. S. (2014). Effectiveness of zinc application to minimize cadmium toxicity and accumulation in wheat (*Triticum aestivum* L.). *Environmental Earth Sciences, 71*, 1663–1672. https://doi.org/10.1007/s12665-013-2570-1

Salido, A. L., Hasty, K. L., Lim, J. M., & Butcher, D. J. (2003). Phytoremediation of arsenic and lead in contaminated soil using Chinese brake ferns (*Pteris vittata*) and Indian mustard (*Brassica juncea*). *International Journal of Phytoremediation, 5*(2), 89–103. https://doi.org/10.1080/713610173

Sarret, G., Saumitou-Laprade, P., Bert, V., Proux, O., Hazemann, J.-L., Traverse, A., Marcus, M. A., & Manceau, A. (2002). Forms of zinc accumulated in the hyperaccumulator *Arabidopsis halleri*. *Plant Physiology, 130*(4), 1815–1826. https://doi.org/10.1104/pp.007799

Sarwar, N., Imran, M., Shaheen, M. R., Ishaque, W., Kamran, M. A., Matloob, A., Rehim, A., & Hussain, S. (2017). Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. *Chemosphere, 171*, 710–721. https://doi.org/10.1016/j.chemosphere.2016.12.116

Sas-Nowosielska, A., Galimska-Stypa, R., Kucharski, R., Zielonka, U., Małkowski, E., & Gray, L. (2008). Remediation aspect of microbial changes of plant rhizosphere in mercury-contaminated soil. *Environmental Monitoring and Assessment, 137*, 101–109. https://doi.org/10.1007/s10661-

007-9732-0

Sharma, P., & Pandey, S. (2014). Status of phytoremediation in the world scenario. *International Journal of Environmental Bioremediation & Biodegradation, 2*(4), 178–191.

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. S., Dietz, K. J., & Mimura, T. (2016). Vacuolar compartmentalization as an indispensable component of heavy metal detoxification in plants. *Plant, Cell & Environment, 39*(5), 1112–1126. https://doi.org/10.1111/pce.12706

Sheoran, V., Sheoran, A. S., & Poonia, P. (2010). Role of hyperaccumulators in phytoextraction of metals from contaminated mining sites: A review. *Critical Reviews in Environmental Science and Technology, 41*(2), 168–214. https://doi.org/10.1080/10643380902718418

Singh, J., & Kalamdhad, A. S. (2011). Effects of heavy metals on soil, plants, human health and aquatic life. *International Journal of Research in Chemistry and Environment, 1*(2), 15–21.

Singh, N., Ma, L. Q., Vu, J. C., & Raj, A. (2009). Effects of arsenic on nitrate metabolism in arsenic hyperaccumulating and non-hyperaccumulating ferns. *Environmental Pollution, 157*(8–9), 2300–2305. https://doi.org/10.1016/j.envpol.2009.03.036

Song, U., & Park, H. (2017). Importance of biomass management acts and policies after phytoremediation. *Journal of Ecology and Environment, 41*, 1–6. https://doi.org/10.1186/s41610-017-0033-4

Srivastava, M., Ma, L. Q., & Santos, J. A. (2006). Three new arsenic hyperaccumulating ferns. *Science of the Total Environment, 364*(1–3), 24–31. https://doi.org/10.1016/j.scitotenv.2005.11.002

Sumiahadi, A., & Acar, R. (2018). A review of phytoremediation technology: Heavy metals uptake by plants. In *IOP Conference Series: Earth and Environmental Science* (Vol. 142, Article 012023). IOP Publishing. https://doi.org/10.1088/1755-1315/142/1/012023

Sun, R. L., Zhou, Q. X., & Jin, C. X. (2006). Cadmium accumulation in relation to organic acids in leaves of *Solanum nigrum* L. as a newly found cadmium hyperaccumulator. *Plant and Soil, 285*, 125–134. https://doi.org/10.1007/s11104-006-0064-6

Sun, Y., Lu, Q., Cao, Y., Wang, M., Cheng, X., & Yan, Q. (2019). Comparative transcriptome analysis of the molecular mechanism of the hairy roots of *Brassica campestris* L. in response to cadmium stress. *International Journal of Molecular Sciences, 21*(1), 180. https://doi.org/10.3390/ijms21010180

Takahashi, R., Ishimaru, Y., Senoura, T., Shimo, H., Ishikawa, S., Arao, T., Nakanishi, H., & Nishizawa, N. K. (2011). The OsNRAMP1 iron transporter is involved in Cd accumulation in rice. *Journal of Experimental Botany, 62*(14), 4843–4850. https://doi.org/10.1093/jxb/err136

Tamma, A. A., Lejcuś, K., Fiałkiewicz, W., & Marczak, D. (2025). Advancing phytoremediation: A review of soil amendments for heavy metal contamination management. *Sustainability, 17*(13), 5688. https://doi.org/10.3390/su17135688

Tamura, H., Honda, M., Sato, T., & Kamachi, H. (2005). Pb hyperaccumulation and tolerance in common buckwheat (*Fagopyrum esculentum* Moench). *Journal of Plant Research, 118*, 355–359. https://doi.org/10.1007/s10265-005-0229-z

Tangahu, B. V., Abdullah, S. R. S., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. A. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering, 2011*, Article 939161. https://doi.org/10.1155/2011/939161

Tayibi, S., Monlau, F., Bargaz, A., Jimenez, R., & Barakat, A. (2021). Synergy of anaerobic digestion and pyrolysis processes for sustainable waste management: A critical review and future perspectives. *Renewable and Sustainable Energy Reviews, 152*, 111603. https://doi.org/10.1016/j.rser.2021.111603

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In *Molecular, clinical and environmental toxicology* (pp. 133–164). Springer. https://doi.org/10.1007/978-3-7643-8340-4_6

Tekle-Haimanot, R., Melaku, Z., Kloos, H., Reimann, C., Fantaye, W., Zerihun, L., & Bjorvatn, K. (2006). The geographic distribution of fluoride in surface and groundwater in Ethiopia with an emphasis on the Rift Valley. *Science of the Total Environment, 367*(1), 182–190. https://doi.org/10.1016/j.scitotenv.2005.11.003

Thakur, S., Singh, L., Wahid, Z. A., Siddiqui, M. F., Atnaw, S. M., & Din, M. F. (2016). Plant-driven removal of heavy metals from soil: Uptake, translocation, tolerance mechanism, challenges, and future perspectives. *Environmental Monitoring and Assessment, 188*, 1–11. https://doi.org/10.1007/s10661-016-5211-9

Thangavel, P., & Subbhuraam, C. V. (2004). Phytoextraction: Role of hyperaccumulators in metal-contaminated soils. *Proceedings of the Indian National Science Academy Part B, 70*(1), 109–130.

Tlustoš, P., Száková, J., Hrubý, J., Najmanová, J., Nedělník, J., Pavlíková, D., & Batysta, M. (2006). Removal of As, Cd, Pb, and Zn from contaminated soil by high biomass-producing plants. *Plant, Soil and Environment, 52*(9), 413–423. https://doi.org/10.17221/3460-PSE

Tong, Y. P., Kneer, R., & Zhu, Y. G. (2004). Vacuolar compartmentalization: A second-generation approach to engineering plants for phytoremediation. *Trends in Plant Science, 9*(1), 7–9. https://doi.org/10.1016/j.tplants.2003.11.009

Udoka, O. C., Ekanem, E. O., Harami, M. A., & Tafawa, A. (2014). Phytoaccumulation potentials of *Tamarindus indica*. *International Journal of Innovation Science and Research, 11*, 72–78.

Usman, K., Al Jabri, H., Abu-Dieyeh, M. H., & Alsafran, M. H. (2020). Comparative assessment of toxic metals bioaccumulation and the mechanisms of chromium (Cr) tolerance and uptake in *Calotropis procera*. *Frontiers in Plant Science, 11*, 883. https://doi.org/10.3389/fpls.2020.00883

Usman, K., Al-Ghouti, M. A., & Abu-Dieyeh, M. H. (2018). Phytoremediation: Halophytes as promising heavy metal hyperaccumulators. In *Heavy metals* (pp. 27–38). IntechOpen. https://doi.org/10.5772/intechopen.73879

Vasilachi, I. C., Stoleru, V., & Gavrilescu, M. (2023). Analysis of heavy metal impacts on cereal crop growth and development in contaminated soils. *Agriculture, 13*(10), 1983. https://doi.org/10.3390/agriculture13101983

Verbruggen, N., Hermans, C., & Schat, H. (2009). Molecular mechanisms of metal hyperaccumulation in plants. *New Phytologist, 181*(4), 759–776. https://doi.org/10.1111/j.1469-8137.2008.02748.x

Verret, F., Gravot, A., Auroy, P., Leonhardt, N., David, P., Nussaume, L., Vavasseur, A., & Richaud, P. (2004). Overexpression of AtHMA4 enhances root-to-shoot translocation of zinc and cadmium and plant metal tolerance. *Plant Physiology, 136*(1), 1–10. *(DOI eksik/bozulmuş olduğu için eklenmedi — kontrol önerilir)*

Viaene, J., Van Lancker, J., Vandecasteele, B., Willekens, K., Bijttebier, J., Ruysschaert, G., De Neve, S., & Reubens, B. (2016). Opportunities and barriers to on-farm composting and compost application: A case study from northwestern Europe. *Waste Management, 48*, 181–192. https://doi.org/10.1016/j.wasman.2015.09.021

Vogel-Mikuš, K., Pongrac, P., Kump, P., Nečemer, M., & Regvar, M. (2006). Colonisation of a Zn-, Cd-, and Pb-hyperaccumulator *Thlaspi praecox* Wulfen with indigenous arbuscular mycorrhizal fungal mixture induces changes in heavy metal and nutrient uptake. *Environmental Pollution, 139*(2), 362–371. https://doi.org/10.1016/j.envpol.2005.05.005

Wan, Y., Liu, J., Zhuang, Z., Wang, Q., & Li, H. (2024). Heavy metals in agricultural soils: Sources, influencing factors, and remediation strategies. *Toxics, 12*(1), 63. https://doi.org/10.3390/toxics12010063

Wang, D., Liu, H., Ma, Y., Qu, J., Guan, J., Lu, N., Lu, Y., & Yuan, X. (2016). Recycling of hyperaccumulator biomass: Synthesis of ZnO nanoparticles and photocatalytic degradation for dichlorophenol. *Journal of Alloys and Compounds, 680*, 500–505. https://doi.org/10.1016/j.jallcom.2016.04.100

Wang, F., Zhang, S., Cheng, P., Zhang, S., & Sun, Y. (2020). Effects of soil amendments on heavy metal immobilization and accumulation by maize grown in a multiple-metal-contaminated soil and their potential for safe crop production. *Toxics, 8*(4), 102. https://doi.org/10.3390/toxics8040102

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*, 1–18. https://doi.org/10.1016/j.jhazmat.2012.04.035

Wang, K., Liu, Y., Song, Z., Wang, D., & Qiu, W. (2019). Chelator complexes enhanced *Amaranthus hypochondriacus* L. phytoremediation efficiency in Cd-contaminated soils. *Chemosphere, 237*, 124480. https://doi.org/10.1016/j.chemosphere.2019.124480

Wang, Z., Tian, Q., Guo, J., Wu, R., Zhu, H., & Zhang, H. (2021). Co-pyrolysis of sewage sludge and cotton stalks with K□CO□ for biochar production: Improved biochar porosity and reduced heavy metal leaching. *Waste Management, 135*, 199–207. https://doi.org/10.1016/j.wasman.2021.08.042

Wei, H., Tucker, M. P., Baker, J. O., Harris, M., Luo, Y., Xu, Q., Himmel, M. E., & Ding, S.-Y. (2012). Tracking dynamics of plant biomass composting by changes in substrate structure, microbial community, and enzyme activity. *Biotechnology for Biofuels, 5*(1), 20. https://doi.org/10.1186/1754-6834-5-20

Wei, Z., Le, Q. V., Peng, W., Yang, Y., Yang, H., Gu, H., Lam, S. S., & Sonne, C. (2021). A review on phytoremediation of contaminants in air, water, and soil. *Journal of Hazardous Materials, 403*, 123658. https://doi.org/10.1016/j.jhazmat.2020.123658

White, P. J. (2016). Selenium accumulation by plants. *Annals of Botany, 117*(2), 217–235.

World Health Organization. (1996). *Guidelines for drinking-water quality* (2nd ed., Vol. 2).

Williams, L. E., & Mills, R. F. (2005). P1B-ATPases: An ancient family of transition metal pumps with diverse functions in plants. *Trends in Plant Science, 10*(10), 491–502. https://doi.org/10.1016/j.tplants.2005.08.008

Wu, X., Wei, Z., Liu, J., Chen, Z., Evrendilek, F., & Huang, W. (2021). Oxy-fuel and air combustion performances and gas-to-ash products of aboveground and belowground biomass of *Sedum alfredii* Hance. *Chemical Engineering Journal, 422*, 130312. https://doi.org/10.1016/j.cej.2021.130312

Wuana, R. A., & Okieimen, F. E. (2010). Phytoremediation potential of maize (*Zea mays* L.): A review. *African Journal of General Agriculture, 6*(4), 275–287.

Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks, and best available strategies for remediation. *International Scholarly Research Notices, 2011*, Article 402647. https://doi.org/10.5402/2011/402647

Wysocki, R., Bobrowicz, P., & Ułaszewski, S. (1997). The *Saccharomyces cerevisiae* ACR3 gene encodes a putative membrane protein involved in arsenite transport. *Journal of Biological Chemistry, 272*(48), 30061–30066. https://doi.org/10.1074/jbc.272.48.30061

Xiong, Y. H., Yang, X. E., Ye, Z. Q., & He, Z. L. (2004). Characteristics of cadmium uptake and accumulation by two contrasting ecotypes of *Sedum alfredii* Hance. *Journal of Environmental Science and Health, Part A, 39*(11–12), 2925–2940. https://doi.org/10.1081/LESA-200034269

Xu, L., Wang, Y. Y., Huang, J., Chen, C. Y., Wang, Z. X., & Xie, H. (2020). Silver nanoparticles: Synthesis, medical applications, and biosafety. *Theranostics, 10*(20), 8996. https://doi.org/10.7150/thno.45413

Xu, W., Jin, Y., & Zeng, G. (2024). Introduction of heavy metals contamination in water and soil: A review on sources, toxicity, and remediation methods. *Green Chemistry Letters and Reviews, 17*(1). https://doi.org/10.1080/17518253.2024.2404235

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*, 359. https://doi.org/10.3389/fpls.2020.00359

Yap, C. K., Yaacob, A., Tan, W. S., Al-Mutairi, K. A., Cheng, W. H., Wong, K. W., Edward, F. B., Ismail, M. S., You, C.-F., Chew, W., Nulit, R., Ibrahim, M. H., Amin, B., & Sharifinia, M. (2022). Potentially toxic metals in the high-biomass non-hyperaccumulating plant *Amaranthus viridis*: Human health risks and phytoremediation potentials. *Biology, 11*(3), 389. https://doi.org/10.3390/biology11030389

Yeşilyurt, S. (2023). Phytoremediation method and Brassica family: Removal of chromium, cadmium, and lead accumulation with broccoli (*Brassica oleracea* var. *italica*). *Results in Chemistry*, 101005. https://doi.org/10.1016/j.rechem.2023.101005

Ying, S., Guan, Z., Ofoegbu, P. C., Clubb, P., Rico, C., He, F., & Hong, J. (2022). Green synthesis of nanoparticles: Current developments and limitations. *Environmental Technology & Innovation, 26*, 102336. https://doi.org/10.1016/j.eti.2022.102336

Yuan, M., He, H., Xiao, L., Zhong, T., Liu, H., Li, S., Deng, P., Ye, Z., & Jing, Y. (2014). Enhancement of Cd phytoextraction by two *Amaranthus* species with endophytic *Rahnella* sp. JN27. *Chemosphere, 103*, 99–104. https://doi.org/10.1016/j.chemosphere.2013.11.040

Zeng, H., Xu, L., Singh, A., Wang, H., Du, L., & Poovaiah, B. W. (2015). Involvement of calmodulin and calmodulin-like proteins in plant responses to abiotic stresses. *Frontiers in Plant Science, 6*, 600. https://doi.org/10.3389/fpls.2015.00600

Zeremski, T., Ranđelović, D., Jakovljević, K., Marjanović Jeromela, A., & Milić, S. (2021). Brassica species in phytoextractions: Real potentials and challenges. *Plants, 10*(11), 2340. https://doi.org/10.3390/plants10112340

Zhakypbek, Y., Kossalbayev, B. D., Belkozhayev, A. M., Murat, T., Tursbekov, S., Abdalimov, E., Pashkovskiy, P., Kreslavski, V., Kuznetsov, V., & Allakhverdiev, S. I. (2024). Reducing heavy metal contamination in soil and water using phytoremediation. *Plants, 13*(11), 1534. https://doi.org/10.3390/plants13111534

Zhang, B., Zhang, J., Zhong, Z., Wang, W., & Zhu, M. (2019). Syngas production and trace element emissions from microwave-assisted chemical looping gasification of heavy metal hyperaccumulators. *Science of the Total Environment, 659*, 612–620. https://doi.org/10.1016/j.scitotenv.2018.12.176

Zhang, J., Wu, S., Xu, J., Liang, P., Wang, M., Naidu, R., Liu, Y., Man, Y. B., Wong, M. H., & Wu, S. (2021). Comparison of ashing and pyrolysis treatment on cadmium/zinc hyperaccumulator plant: Effects on bioavailability, metal speciation in solid residues, and risk assessment. *Environmental Pollution, 272*, 116039. https://doi.org/10.1016/j.envpol.2020.116039

Zhang, M., Wang, J., Bai, S. H., Zhang, Y., Teng, Y., & Xu, Z. (2019a). Assisted phytoremediation of a co-contaminated soil with biochar amendment: Contaminant removal and bacterial community properties. *Geoderma, 348*, 115–123. https://doi.org/10.1016/j.geoderma.2019.04.031

Zhang, X., Xia, H., Li, Z., Zhuang, P., & Gao, B. (2010). Potential of four forage grasses in remediation of Cd- and Zn-contaminated soils. *Bioresource Technology, 101*(6), 2063–2066. https://doi.org/10.1016/j.biortech.2009.11.065

Zhang, Z.-W., Dong, Y.-Y., Feng, L.-Y., Deng, Z.-L., Xu, Q., Tao, Q., Wang, C.-Q., Chen, Y.-E., Yuan, M., & Yuan, S. (2020). Selenium enhances cadmium accumulation capability in two mustard family species—*Brassica napus* and *B. juncea*. *Plants, 9*(7), 904. https://doi.org/10.3390/plants9070904

Zhao, A., Gao, L., Chen, B., & Feng, L. (2019). Phytoremediation potential of *Miscanthus sinensis* for mercury-polluted sites and its impacts on soil microbial community. *Environmental Science and Pollution Research, 26*, 34818–34829. https://doi.org/10.1007/s11356-019-06563-3

Zhao, F. J., Dunham, S. J., & McGrath, S. P. (2002). Arsenic hyperaccumulation by different fern species. *New Phytologist, 156*(1), 27–31. https://doi.org/10.1046/j.1469-8137.2002.00493.x

Zhao, F. J., McGrath, S. P., & Meharg, A. A. (2010). Arsenic as a food chain contaminant: Mechanisms of plant uptake and metabolism and mitigation strategies. *Annual Review of Plant Biology, 61*, 535–559. https://doi.org/10.1146/annurev-arplant-042809-112152

Zhao, L., Li, T., Zhang, X., Chen, G., Zheng, Z., & Yu, H. (2016). Pb uptake and phytostabilization potential of the mining ecotype of *Athyrium wardii* (Hook.) grown in Pb-contaminated soil. *Clean—Soil, Air, Water, 44*(9), 1184–1190. https://doi.org/10.1002/clen.201400870

Zhou, W., & Qiu, B. (2005). Effects of cadmium hyperaccumulation on physiological characteristics of *Sedum alfredii* Hance (Crassulaceae). *Plant Science, 169*(4), 737–745. https://doi.org/10.1016/j.

plantsci.2005.05.030

Zhu, Z., Huang, Y., Zha, J., Yu, M., Liu, X., Li, H., & Zhu, X. (2019). Emission and retention of cadmium during the combustion of contaminated biomass with mineral additives. *Energy & Fuels, 33*(12), 12508–12517. https://doi.org/10.1021/acs.energyfuels.9b03266

Zohdi, H., Emami, M., & Shahverdi, H. R. (2012). Galvanic corrosion behavior of dental alloys. In *Environmental and industrial corrosion: Practical and theoretical aspects* (pp. 157–168). IntechOpen. https://doi.org/10.5772/52319

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. https://doi.org/10.1016/j.jenvman.2019.109557