

11. Heavy Metal Bioavailability and Phytoremediation Strategies in Contaminated Soils

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1. Introduction

Industrialization, agricultural activities, and urbanization have led to the widespread contamination of soils with heavy metals. HMs such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), and mercury (Hg) are non-essential elements for plants and, even at low concentrations, can be highly toxic. Their persistence in the environment, coupled with their ability to enter the food chain, makes HM-contaminated soils a serious concern for ecosystem health and human well-being.

The term "bioavailability" is central to understanding the ecological risk of HMs. It refers to the fraction of a total chemical in the environment that is available for uptake by organisms. A high total concentration of an HM in soil does not necessarily translate to a high risk if its bioavailability is low due to various soil-metal interactions. Therefore, effective remediation strategies must consider not only the total HM

concentration but also the factors influencing their availability to plants.

2. Factors Influencing Heavy Metal Bioavailability

The bioavailability of heavy metals in soil is a complex phenomenon influenced by a multitude of physicochemical and biological factors. These interactions dictate the speciation, mobility, and ultimately, the uptake of HMs by plants.

2.1. Soil pH

Soil pH is arguably the most critical factor influencing HM solubility and bioavailability.

a. Acidic Conditions (Low pH):

Generally, a decrease in soil pH increases the solubility and mobility of most cationic HMs (e.g., Cd, Pb, Zn, Ni, Cu). This is because hydrogen ions compete with metal cations for binding sites on soil particles, leading to the desorption of metals into the soil solution.

b. Alkaline Conditions (High pH):

Conversely, an increase in pH

typically reduces the solubility and bioavailability of cationic HMs by promoting their precipitation as hydroxides, carbonates, or metal-oxide complexes, and increasing adsorption to soil colloids. However, the bioavailability of certain oxoanionic HMs like arsenic (As) and molybdenum (Mo) can increase under alkaline conditions.

2.2. Organic Matter Content

Soil organic matter (SOM) plays a dual role in HM bioavailability.

- a. **Complexation:** SOM contains various functional groups (carboxyl, hydroxyl, phenolic) that can complex with HMs, forming stable organometallic complexes. This complexation can either decrease HM bioavailability by reducing their free ionic form or, in some cases, increase their mobility if the complexes are water-soluble.
- b. **Adsorption:** SOM provides numerous adsorption sites, thereby reducing the concentration of HMs in the soil solution. The strength of these interactions varies with the type of organic matter and the specific heavy metal.

2.3. Clay Content and Mineralogy

Clay minerals, with their high specific surface area and cation exchange capacity

(CEC), significantly influence HM adsorption and desorption.

- a. **Adsorption:** Clay particles, particularly 2:1 clay minerals (e.g., montmorillonite, illite), possess negatively charged surfaces that can adsorb metal cations, reducing their bioavailability.
- b. **Surface Precipitation:** HMs can also precipitate on the surface of clay minerals as hydroxides or carbonates.

2.4. Redox Potential (Eh)

Redox potential primarily affects the speciation and mobility of HMs that exist in multiple oxidation states (e.g., Cr, As, Fe, Mn).

- a. **Reducing Conditions (Low Eh):** Under anaerobic conditions, HMs like Cr (VI) can be reduced to less mobile Cr (III), and arsenate (As(V)) can be reduced to more mobile arsenite (As (III)). The solubility of certain metals (e.g., Fe, Mn) also increases under reducing conditions due to the dissolution of iron and manganese oxides, which often co-precipitate HMs.
- b. **Oxidizing Conditions (High Eh):** Conversely, oxidizing conditions favor the formation of less mobile species for certain metals.

2.4. Root Exudates

Plant roots release a variety of organic compounds, known as root exudates, into the rhizosphere. These exudates can significantly modify HM bioavailability in the immediate vicinity of the root.

- a. **Chelation:** Organic acids (e.g., citric acid, oxalic acid) and phytosiderophores released by roots can chelate HMs, making them more soluble and available for plant uptake.
- b. **pH Modification:** Root exudates can locally alter rhizosphere pH, further influencing HM solubility.

Soil microorganisms play a crucial role in the biogeochemical cycling of HMs.

a. Methylation/Demethylation:

Microbes can transform HMs into more volatile or less toxic forms (e.g., mercury methylation).

- b. **Oxidation/Reduction:** Microbial activity can alter the redox state of HMs, influencing their mobility and toxicity.

c. Bioadsorption/Bioaccumulation:

Microbes can adsorb or accumulate HMs, thereby altering their bioavailability.

2.5. Microbial Activity

Table 1 Summary of Factors Influencing Heavy Metal Bioavailability in Soil

Factor	Effect on Cationic HM Bioavailability (e.g., Pb, Cd, Zn)	Effect on Anionic HM Bioavailability (e.g., As, Mo)	Primary Mechanism
Decreasing pH	Increased	Decreased or increased for some	Desorption, proton competition, dissolution
Increasing pH	Decreased	Increased	Precipitation, adsorption, complexation
Increasing SOM	Depending on complex stability	Variable	Complexation, adsorption
Increasing Clay	Decreased	Decreased	Adsorption, surface precipitation
Decreasing Eh	Variable (e.g., Increased for Fe, Mn; Decreased for Cr (VI))	Variable (e.g., Increased for As (III))	Redox transformations, dissolution of Fe/Mn oxides
Root Exudates	Increased	Variable	Chelation, pH alteration

Microbial Activity	Variable	Variable	Biotransformation, bioadsorption, redox changes
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3. Phytoremediation Strategies

Phytoremediation is a cost-effective, aesthetically pleasing, and environmentally friendly approach that uses plants and associated microorganisms to remove, immobilize, or degrade environmental contaminants. It leverages the natural ability of plants to absorb, translocate, accumulate, and transform HMs. The choice of phytoremediation strategy depends on the type and concentration of contaminants, soil characteristics, and desired outcome.

3.1. Phytoextraction

(Phytoaccumulation)

Phytoextraction involves the uptake of HMs by plant roots and their translocation and accumulation in harvestable plant shoots. The contaminated biomass is then harvested and disposed of, leading to the removal of HMs from the soil. This strategy is suitable for soils with moderate levels of contamination and is particularly effective for cadmium (Cd), zinc (Zn), nickel (Ni), and copper (Cu).

- a. Hyperaccumulators:** These are rare plant species (e.g., *Thlaspi caerulescens* for Zn/Cd, *Pteris vittata* for As) that can accumulate

exceptionally high concentrations of HMs (at least 100 times more than common plants) in their shoots without exhibiting toxicity symptoms.

b. Induced Phytoextraction (Chelate-Assisted

Phytoextraction): Involves the application of chelating agents (e.g., EDTA, EDDS, citric acid) to the soil to increase HM solubility and mobility, thereby enhancing their uptake by non-hyperaccumulating, high-biomass plants (e.g., Indian mustard, sunflower). This approach can be controversial due to the potential for chelating agents to leach HMs into groundwater.

3.2. Phytostabilization

Phytostabilization (or phytoimmobilization) aims to reduce the mobility and bioavailability of HMs in soil, thereby preventing their leaching into groundwater, runoff to surface waters, and entry into the food chain. This strategy does not remove HMs from the soil but rather contains them. It is suitable for heavily contaminated sites where complete removal is impractical.

a. Mechanisms:

- **Root uptake and accumulation:** HMs are absorbed by roots and accumulated, but not translocated to shoots.
- **Rhizosphere immobilization:** Plant roots release exudates that can precipitate or complex HMs in the rhizosphere.
- **Reduced erosion:** A dense plant cover reduces soil erosion by wind and water, preventing the spread of contaminants.
- **Evapotranspiration:** Plants reduce water percolation through the soil profile, minimizing HM leaching.

b. Suitable Plants: Metal-tolerant plants with extensive root systems and high biomass (e.g., grasses like *Vetiveria zizanioides*, certain legumes) are preferred.

c. Soil Amendments: Often combined with soil amendments (e.g., lime, phosphates, organic matter) to further reduce HM mobility.

Rhizofiltration involves the use of plant roots (terrestrial or aquatic) to absorb or adsorb HMs from contaminated water (e.g., wastewater, industrial effluent, groundwater). The plants are grown hydroponically or in ponds, and their roots are submerged in the contaminated water. Once the roots are saturated with HMs, the plants are harvested and disposed of.

a. Suitable Plants: Plants with high biomass and fibrous root systems (e.g., sunflower, Indian mustard, rye, various aquatic plants).

b. Applications: Particularly useful for remediating large volumes of water with low HM concentrations.

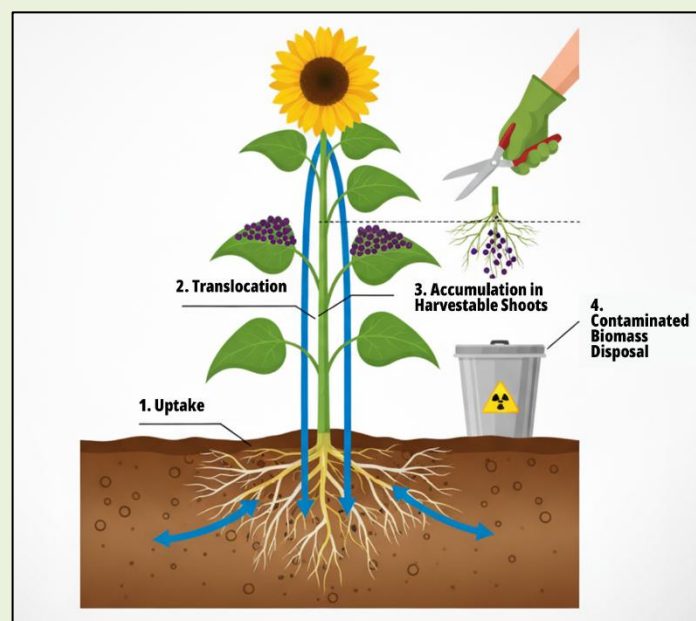


Figure 1 Schematic Representation of Phytoextraction

3.3. Rhizofiltration

3.4. Phytovolatilization

Phytovolatilization involves the uptake of HMs by plants and their subsequent transformation into volatile forms, which are then released into the atmosphere through transpiration. This strategy is limited to a few HMs that can be transformed into volatile organic or inorganic compounds.

- a. Mercury (Hg):** Plants can absorb ionic mercury (Hg^{2+}), convert it into

elemental mercury (Hg^0), and release it as a vapor. Genetically modified plants have shown enhanced capabilities for phytovolatilization of Hg.

- b. Selenium (Se):** Plants can take up inorganic selenium and convert it into volatile organic selenium compounds (e.g., dimethyl selenide).

Table 2 Comparison of Phytoremediation Strategies for Heavy Metals

Strategy	Mechanism	Target Contaminants	Advantages	Disadvantages	Application
Phytoextraction	Uptake, translocation, and accumulation in shoots; harvest and disposal.	Cd, Zn, Ni, Cu, Pb	Actual removal of HMs; aesthetically pleasing.	Slow process; suitable for shallow, moderately contaminated soils; biomass disposal issues.	Moderately contaminated agricultural land, mining sites.
Phytostabilization	Immobilization of HMs in soil/roots; reduced leaching and runoff.	Pb, Cr, Cd, Zn	Prevents spread of HMs; relatively inexpensive.	HMs remain in situ; long-term monitoring required.	Highly contaminated industrial sites, mine tailings.
Rhizofiltration	Adsorption/absorption of HMs by	Cd, Pb, Cr, As, Ni	Effective for large	Plants require	Wastewater

	roots from contaminated water.		volumes of dilute contaminants.	harvesting and disposal; root saturation limits effectiveness.	treatment, contaminated groundwater.
Phytovolatilization	Uptake and conversion to volatile form; release to the atmosphere.	Hg, Se	Actual removal from soil; no biomass disposal.	Contaminants released to the atmosphere; limited to specific HMs; atmospheric modeling needed.	Hg and Se contaminated sites.

4. Challenges and Future Perspectives

Despite its significant environmental and economic advantages, the widespread application of phytoremediation is constrained by several scientific and logistical challenges. Addressing these limitations through cutting-edge research is paramount to scaling the technology.

4.1. Scientific and Operational Challenges

The primary hurdles for commercial-scale phytoremediation include:

a. Prolonged Remediation

Duration: Phytoextraction, in particular, is an intrinsically **slow process**, often requiring multiple growing seasons (years to decades) to achieve regulatory cleanup targets, especially for heavily contaminated sites.

b. Contaminant Bioavailability

Limit: Even in highly contaminated soils, the majority of the heavy metal (HM) fraction may be chemically bound and unavailable for plant uptake, which limits the

efficiency of phytoextraction. The application of chemical chelants (e.g., EDTA) to increase bioavailability risks **secondary pollution** via the leaching of mobile metal-chelate complexes into groundwater.

- c. **Shallow Root Depth:** Most plants can only remediate the topsoil layer (typically <0.5 meters). Effective remediation of deeper soil profiles or contaminated groundwater remains a significant challenge for plant-based systems.
- d. **Biomass Management:** The large volume of **contaminated plant biomass** generated by phytoextraction requires safe and cost-effective disposal, which can be an operational and regulatory bottleneck. Options like **phytomining** (agromining) for metal recovery or safe incineration with energy recovery are complex and site-specific.
- e. **Phytotoxicity and Edibility Risk:** High HM concentrations can induce severe stress, inhibit plant growth, and ultimately reduce biomass yield, lowering overall remediation efficiency. For agricultural lands, the risk of HM translocation into the

edible parts of non-target crops must be strictly managed.

4.2. Future Perspectives: Technological Integration and Advanced Modeling

Future success hinges on integrating plant biology with advanced monitoring and computational technologies.

4.2.1. Enhanced Biological Systems

- a. **Genetic and Metabolic Engineering:** Developing "super-accumulators" through gene modification for increased metal uptake, transport, and sequestration, resulting in high biomass and hyperaccumulation capabilities in plants.
- b. **Microbe-Assisted Phytoremediation (MAP):** Employing Plant Growth-Promoting Rhizobacteria (PGPR) and mycorrhizal fungi to enhance plant tolerance to heavy metal (HM) stress and improve nutrient uptake, thereby influencing HM bioavailability.
- c. **Nanophytoremediation:** Utilizing nanomaterials (e.g., nano-biochar, iron oxides) in soil amendments to either enhance plant tolerance and absorption or immobilize metals, based on remediation goals.

4.2.2. Spectroscopic Monitoring and Remote Sensing

The need for large-scale, non-destructive, and continuous monitoring of remediation sites drives the integration of spectral technologies:

- a. **High-Throughput Phenotyping and Spectroscopy:** Using Visible-Near Infrared (Vis-NIR) and Shortwave Infrared (SWIR) spectroscopy as rapid methods for assessing soil health and plant stress, detecting changes in reflectance spectra.
- b. **Upscaling with Remote Sensing:** Employing drone and satellite spectral data to assess plant vigor and stress across large areas, facilitating timely interventions.
- c. **Challenge of Spectral Data Application:** Developing robust calibration models for predicting soil HM concentrations and plant uptake remains critical. This

requires sophisticated machine learning models due to the complex relationships influenced by soil properties.

4.2.3. Machine Learning and Modeling

- a. **Optimization and Prediction:** Leveraging Machine Learning (ML) techniques (e.g., Random Forest, Gradient Boosting Machines, Artificial Neural Networks) to optimize remediation strategies by analyzing various dataset parameters for improved predictions of cleanup time.
- b. **Model-Assisted Design:** Combining Reactive Transport Models (RTMs) with ML to simulate contaminant transport and calculate cost-effectiveness before field deployment, reducing trial-and-error in remediation efforts.

Table 3 Interdisciplinary Research Areas for Advancing Phytoremediation

Research Area	Focus	Current Challenges Addressed	Key Future Tools/Technologies
Plant Biology		Low biomass, poor metal tolerance.	Genetic Engineering, CRISPR/Cas9, Hyperaccumulator-to-Biomass Plant Crosses.
Soil Chemistry		Low bioavailability, high leaching risk.	Nanophytoremediation (e.g., nano-amendments), Microbial-Assisted strategies.
Monitoring & Management		Slow progress, high monitoring cost, spatial variability.	Proximal & Remote Sensing, Vis-NIR/SWIR Spectroscopy, Drone/Satellite Imagery.
Optimization & Strategy		Uncertainty in cleanup time, non-optimal parameter selection.	Machine Learning (RF, ANN, GBM), Reactive Transport Modeling.

5. Conclusion

Heavy metal contamination in soils poses a significant environmental and human health risk. Understanding the complex interplay of soil physicochemical properties, organic matter, microbial activity, and plant exudates is critical for predicting and managing HM bioavailability. Phytoremediation offers a sustainable, cost-effective, and aesthetically pleasing alternative or complement to conventional remediation technologies. While challenges remain, advancements in plant science, microbial ecology, and genetic engineering hold significant promise for enhancing the efficiency and applicability of phytoremediation strategies in tackling the global problem of heavy metal-contaminated soils. Continued research and field-scale implementation are essential to fully harness the potential of these green technologies.

References

- Abbasi, S. R., & Mirbaha, A. (2025). Modeling phytoremediation of heavy metal contaminated soils through machine learning. *Request PDF - ResearchGate*.
- Ali, H., Khan, E., & Sajad, M. A. (2025). Phytoremediation of heavy metals: Techniques, challenges, and prospects. *EcoEvoRxiv*.
- Burin, D., Kilteni, K., Rabuffetti, M., Slater, M., & Pia, L. (2019). Body ownership increases the interference between observed and executed movements. *PLOS ONE*, 14(1), Article e0209899. <https://doi.org/10.1371/journal.pone.0209899>
- Das, D., & Maiti, S. K. (2025). Advanced phytoremediation strategies: Tackling heavy metal contamination in agricultural soils. *International Journal of Research in Agronomy*, 7(7), 47-499.
- Kaur, J., & Kaur, S. (2025). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science*, 11. <https://doi.org/10.3389/fpls.2020.00359>
- Memon, S. S., Khan, J. U. S., & Kumar, B. (2025). Benefits and limitations of phytoremediation: Heavy metal remediation review. *ResearchGate*. https://www.researchgate.net/publication/355312310_Benefits_and_limitations_of_phytoremediation_Heavy_metal_remediation_review
- Raza, A. (2025). Advancing phytoremediation: A review of soil amendments for heavy metal contamination management.

- Sustainability*, 17(13), 5688.
<https://doi.org/10.3390/su17135688>
- Saha, A., & Saha, R. (2025). Application of phytoremediation for heavy metal contaminated sites in the South Pacific. *Applied Spectroscopy Reviews*.
<https://doi.org/10.1080/05704928.2021.1904410>
- Shukla, S., & Upadhyay, K. (2025). Machine learning-driven optimization of arsenic phytoextraction using amendments. *Request PDF - ResearchGate*.
https://www.researchgate.net/publication/393871459_Machine_learning-driven_optimization_of_arsenic_phytoextraction_using_amendments
- Singh, J., & Singh, P. (2025). Screening and optimization of soil remediation strategies assisted by machine learning. *Applied Sciences*, 12(6), 1157.
<https://doi.org/10.3390/app12061157>
- Wang, X., & Xu, H. (2025). Reducing heavy metal contamination in soil and water using phytoremediation. *Horticulturae*, 13(11), 1534.
<https://doi.org/10.3390/horticulturae13111534>
- Xie, X., & Zhang, Y. (2025). Phytoremediation as a green and sustainable prospective method for heavy metal contamination: A review. *RSC Publishing*.
<https://pubs.rsc.org/en/content/articlehtml/2024/su/d3su00440f>
- Zhong, X. (2025). Modelling phytoremediation: Concepts, methods, challenges, and perspectives. *ResearchGate*.
https://www.researchgate.net/publication/377735187_Modelling_phytoremediation_Concepts_methods_challenges_and_perspectives