

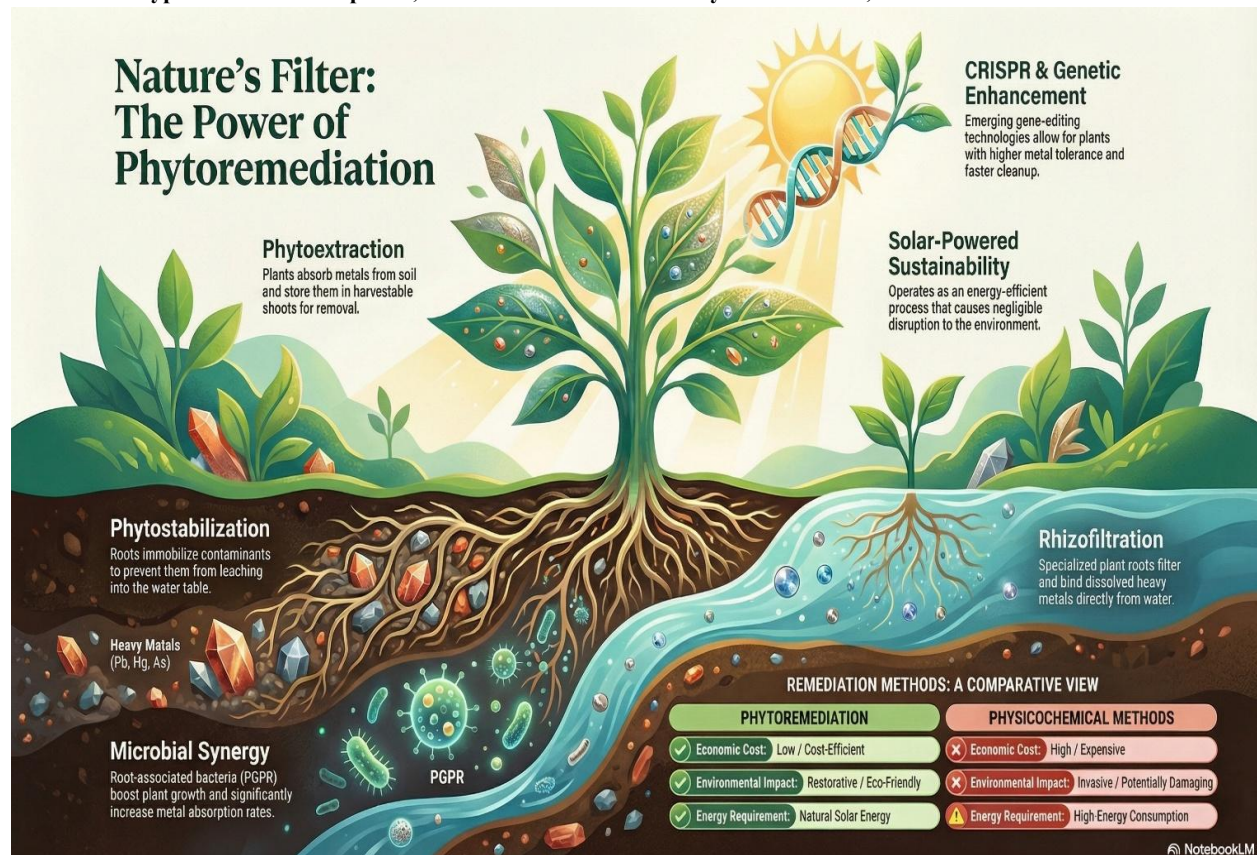
Phytoremediation of Heavy Metals in Soil and Water: Mechanisms, Plant Materials, and Field Applications

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Abstract—Phytoremediation is a solar-powered technology that harnesses plants and microorganisms of their rhizospheres to clean up HM pollution in soils and water systems. In contrast to expensive physiochemical treatment methods that are usually invasive to the environment, plants can act as a sustainable solution for the treatment of non-decomposable HMs, such as Cd, Pb, Hg, and As. The present paper aims to summarize the existing literature concerning the principal pathways of phytoremediation, such as phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization, and discusses the choice of plant material, including terrestrial hyperaccumulator plants, like *Nocca*

caerulescens; high biomass production plants and aquatic macrophytes, such as *Eichhornia crassipes* and *Lemna minor*. Although the practical implementation of phytoremediation may face several limitations, such as low rates of cleanup and toxic effect of metals on plants, recent advances in studies of the interaction between plants and microorganisms, gene editing using CRISPR, and application of soil amendments, such as biochar and chelators, make phytoremediation a promising technique.

Index Terms—Aquatic Macrophytes, Bioavailability, Phytoremediation, -



Source NotebookLM

I. INTRODUCTION

Due to rapid industrialization, urbanization, mining operations, and agricultural practices, there is a noticeable level of HM pollution in both soil and aquatic ecosystems, causing environmental and health hazards (Ali et al., 2013; Ashraf et al., 2019; Bhat et al., 2022; Sharma et al., 2023; Yan et al., 2020). The non-biodegradable and persistent HMs like Cd, Pb, Hg, As, among others, are highly hazardous even at trace amounts. These contaminants do not break down as organic substances, get accumulated in soil and aquatic systems, and then reach humans by entering the food chain (Kanwar et al., 2020; Madhav et al., 2023; Oladoye et al., 2021).

The effects of contamination by heavy metals are quite significant. In the case of plants, they interfere with physiological functions like photosynthesis, respiration, and mineral absorption, causing limited growth (Rai et al., 2021; Sharma et al., 2023). For human health, there are cancer-causing effects, as well as being harmful to brain function and kidney health, while endocrine disruption occurs as a result of chronic exposure (Awa & Hadibarata, 2020; Yaashikaa et al., 2022; Priya et al., 2023). Heavy metals are also harmful to soil microbial activity, which affects fertility and nutrient cycling (Ashraf et al., 2019; Shen et al., 2021).

Traditional physicochemical remediation approaches like soil removal, cleaning, and electrokinetics prove to be costly and energy consuming as well as environmentally detrimental (Liu et al., 2024; Gavrilesco, 2021). In this regard, phytoremediation is seen as an eco-friendly solution. Phytoremediation employs plants along with soil microbes to decontaminate soils by removing, stabilizing, and converting contaminants (Muthusaravanan et al., 2018; Raklami et al., 2022).

Phytoremediation mechanisms comprise phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization and depend on soil conditions, metal form, and interactions between plants and soil microbiota (Pang et al., 2023; Priya et al., 2023; Yaashikaa et al., 2022). The range of remediation-effective plant species varies widely from hyperaccumulators to aquatic macrophytes (Ali et al., 2020; Liang et al., 2024). Despite the problems of slow remediation process and biomass disposal, biotechnological developments and innovations

contribute to improvement of this technique (Deng et al., 2024; Zhakypbek et al.,

II. SOURCES AND EFFECTS OF HEAVY METAL POLLUTION

2.1 Sources

Industrial wastewaters (from mining, smelting, and electroplating activities)

Inputs from agriculture (fertilizers and pesticides)

Domestic wastewaters and sludges

Air pollution (Madhav et al., 2023; Kanwar et al., 2020; Priya et al., 2023)

2.2 Environmental and Health Consequences

Degradation of soil quality and lower soil fertility

Plant toxicity (inhibition of photosynthesis and oxidative damage)

Human health hazards (cancer and neurological effects)

Microbial population reduction (Rai et al., 2021; Ashraf et al., 2019; Yaashikaa et al., 2022)

III. METHODS OF PHYTOREMEDIATION

Phytoremediation is a group of methods aimed at the removal of pollutants from the environment, depending on their chemical composition and ecological compartment. Main methods of phytoremediation include the following:

3.1 Phytoextraction (phytoaccumulation): the process of metal uptake by the plants and their migration to the shoots for harvest in order to remove heavy metals from the soil.

3.2 Phytostabilization: stabilization of metals in soil rhizosphere using roots, limiting their mobility and preventing leaching to the water table.

3.3 Rhizofiltration (phytofiltration): binding of dissolved metals from the solution by plant roots.

3.4 Phytovolatilization: biotransformation of certain elements (selenium, mercury) into gaseous forms and their release into the atmosphere.

3.5 Rhizodegradation: stimulation of microflora inhabiting soil rhizosphere due to the secretions

released by the roots, resulting in degradation of co-contaminants in organic-metal mixture.

IV. PLANT MATERIALS SELECTION

The success of the entire process depends greatly on proper selection of plant materials based on specific requirements of the site.

4.1 Terrestrial Plants Hyperaccumulators: These specialized plants are capable of tolerating and accumulating extraordinarily high amounts of metals in their tissues without being affected by the metals themselves (for e.g. *Prosopis juliflora* (Gando Baval It has demonstrated a considerable potential for absorbing heavy metal pollutants such as Lead (Pb), Cadmium (Cd), and Zinc (Zn) from polluted soils, especially those found in proximity to industrial sites.). Hyperaccumulators are used in phytomining projects to extract metals from the plants themselves.

4.2 High-Biomass Species: They have lower metal accumulation capacities compared to hyperaccumulators, but fast-growing trees, grasses and crops are important for stabilization of the area and biomass production for energy purposes.

4.3 Aquatic Plants: For water-based systems, floating and emergent aquatic macrophytes are used as biological filters. Here are some specific examples with respect to the Kachchh and Gujarat region:

- *Typha angustata* (Gha-Bajariyu / Indian Reedmace)

This is arguably the most dominant emergent macrophyte of Kachchh. They grow rampantly in the marsh areas as well as along the banks of Narmada canals and local dams.

Role: It acts as an excellent bioremediation agent against heavy metal contaminants such as iron (Fe), Manganese (Mn) and zinc (Zn). The roots and underground rhizomes of this plant provide an enormous surface area for the formation of microbial biofilms which aid in the degradation of organic pollutants.

- *Ipomoea aquatica* (Nari ni Bhaji / Water Spinach)
The water spinach is an extremely hardy species often found floating or hanging from the margins of freshwaters in the region.

Role: Known for its ability to uptake cadmium (Cd) and chromium (Cr) compounds, it plays a pivotal role in the purification of graywater (from domestic waste).

- *Hydrilla verticillata* (Jal-Sargasso)
A submersed macrophyte often found in clear standing water bodies.

Role: These plants efficiently accumulate mercury (Hg) and arsenic (As). Being completely submersed in water, these plants not only help in aeration of the water body but also trap the particulate matter as well as dissolve metals within their tissues.

Large-scale application for phytoremediation process (Liang et al., 2024; Kafle et al., 2022)

V. THE ROLE OF MICROBES IN PHYTOREMEDIATION

PGPRs increase metal absorption and plant growth through mechanisms such as siderophores and phytohormones. (Raklami et al., 2022; Ren et al., 2023)

VI. INFLUENCING FACTORS FOR PHYTOREMEDIATION EFFECTIVENESS

- Soil pH and organic content
- Metal form and availability
- Type of plants and root system
- Microbe interactions

VII. APPLICATIONS IN THE FIELD

The field applications of phytoremediation have been found in:

- Polluted agricultural soils
- Mine sites and tailing areas
- Industrial water purification

Advantages

- Economic efficiency
- Environmental friendliness
- Ecological restoration

Disadvantages

- Time-consuming
- Depth-limited
- Waste biomass management problems (Ashraf et al., 2019; Zhakypbek et al., 2024)

VIII. ENHANCEMENT TECHNIQUES

Although it has some advantages, implementation at the field scale is hindered by issues such as low remediation efficiency, shallow roots, and the toxic effect of metals. Recent studies have been directed at "phytocombination" techniques, which aim to solve these problems as follows:

- **Microbial Inoculation:** Through the inoculation of PGPRs and mycorrhiza to increase metal solubility and stress resistance through siderophore and organic acid secretion
- **Amendment:** Using biochar, chelators, and nanoparticles to adjust metal bioavailability.
- **Gene Editing:** With CRISPR and OMICS technologies to increase metal uptake and translocation.
- **Bioeconomy:** By coupling metal remediation with biomass utilization, in which plants are used to produce biofuel or other biomass.

IX. CHALLENGES AND PERSPECTIVES FOR THE FUTURE

- Scale of operation challenges
- Dependency on climate
- Biomass management requirement
- Multidisciplinary approach required

The following areas require future research:

- Biotechnology advancements
- Plant adaptation to specific sites
- Circular economy application (Sharma et al., 2023; Liang et al., 2024)

X. CONCLUSION

Phytoremediation technology has proved to be very effective and sustainable for tackling heavy metals (Pb, Cd, Zn, Hg, As, Fe, Cr etc.) pollution issues. It is because of being environmentally friendly, inexpensive, and causing negligible disruption to the surrounding environment that it proves to be an excellent option for remediation purposes compared with conventional techniques of physicochemical treatments. By taking advantage of the natural process and by incorporating rhizospheric microbial interactions, phytoremediation technology ensures

environmental sustainability in a sustainable manner and becomes a socially acceptable method.

Another important strength of the technique of phytoremediation is its wide applicability. This is because this technique can be implemented through different mechanisms like phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization according to site conditions and types of contaminants. Moreover, use of hyperaccumulating plants, high biomass species, and aquatic macrophytes makes this technology more flexible in remediation of soil and water. Another way to improve performance of phytoremediation is through incorporation of plant growth-promoting rhizobacteria.

Nevertheless, there are several constraints that impede its large-scale deployment. Slower speed of removal of contaminants, shallowness of roots, and possible toxicity effects on plants are some of the most significant barriers. Also, the problem of safe disposal or valorization of plant tissues contaminated with metal residues deserves particular attention to prevent secondary contamination.

Moving forward, advances in the field of biotechnology, such as genetic engineering, omics, and application of CRISPR technology, will certainly allow increasing efficiency and resistance of plants. Additionally, it is possible to consider an innovative approach of combining different techniques like biochar and nanomaterial amendment, use of microbial consortia, and others. Finally, implementation of circular economy methods like transformation of metal-laden plants into biomass will make the process more economically feasible.

In summary, further investigation, technological progress, and practical applications will enable phytoremediation to play a significant role in the sustainable management and rehabilitation of ecosystems in the future.

ACKNOWLEDGEMENT

The author wishes to extend his sincerest appreciation to the Department of Chemistry, Krantiguru Shyamji Krishna Verma Kachchh University, Bhuji-Kachchh for their unrelenting assistance in the writing of this review article..

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