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RHIZOREMEDIATION OF HEAVY METALS IN THE SOIL

A Anto Rashwin[1*], R Sunitha[2], T Shangameshwaran[1] & A Muthamizh Selvan[1]

[1]Postgraduate Scholar, Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore - 641003, Tamil Nadu

[2]Assistant Professor (Environmental Science), The Controllerate of Examination, Tamil Nadu Agricultural University, Coimbatore - 641003, Tamil Nadu

**Corresponding Author Mail ID: antorashwin@gmail.com*

Abstract

Although heavy metals are generally immobile in soil, they can still interact with various living organisms and get translocated to different parts of plants, including leaves, roots, fruits, seeds, and vegetables. As a result, these toxic metals can enter the human and animal food chain, primarily through the consumption of contaminated crops, accounting for nearly 98% of heavy metal intake, with only about 1% coming from drinking water and aquatic sources. Conventional remediation techniques like landfilling, incineration, leaching, and chemical treatments, while commonly used, are often costly, inefficient, environmentally disruptive, and labour-intensive. These approaches mainly focus on transferring pollutants from soil into other material forms, which frequently leads to the degradation of soil properties and ecological imbalance, making the land unsuitable for agriculture or other purposes. In contrast, rhizoremediation is a process that uses plant roots and their associated microbial communities to detoxify heavy metal-contaminated sites. It has been shown to achieve greater degradation rates than using plants or microbes independently, making it a promising solution for environmental remediation.

Keywords: *Rhizoremediation, rhizosphere, microorganisms, heavy metals, environmental sustainability, and pollutants*

1. Introduction

Heavy metal contamination is a growing environmental problem around the world. Unlike organic pollutants that can break down naturally, heavy metals do not degrade and tend to stay in the environment for a long time. They build up in the soil and water and eventually enter the food chain through crops and animals, posing serious health risks to both humans and wildlife. Even small amounts of metals like cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As) can cause damage to the nervous system, kidneys, and other organs.

Many food crops are capable of taking up heavy metals from the soil and storing them in their roots, stems, leaves, fruits, and seeds. This process is called bioaccumulation. This hidden contamination can go unnoticed and lead to long-term exposure when people eat the affected food. Studies have shown that vegetables like spinach and potatoes, and grains like rice, often absorb high levels of cadmium and lead from polluted soils.

Traditional methods to remove heavy metals from soil, like landfilling, incineration, soil washing, or chemical treatment, are expensive, time-consuming, and harmful to the environment. They often damage soil health and fertility, making the land unfit for farming. These methods usually move the contamination from one place to another, instead of removing it completely.

Rhizoremediation offers a better and greener solution. It is a method that uses plant roots and the microbes (bacteria and fungi) living around them to clean up heavy metal pollution. The area around the root, known as the rhizosphere, is filled with beneficial microorganisms that collaborate with the plant. These microbes can make the metals less toxic, reduce their movement in the soil, or help the plant absorb and store them safely. In return, the plant provides nutrients and energy to the microbes through its root exudates.

2. Heavy Metal Pollution

Heavy metals are broadly defined as elements with a density greater than 5 g/cm³, encompassing transition metals, metalloids, lanthanides, and actinides. Key examples include mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), zinc (Zn), copper (Cu), and nickel (Ni). These elements are persistent, non-degradable, and exhibit properties such as toxicity, biomagnification (increasing concentration up the food chain), and bioaccumulation (gradual buildup in organisms). Biologically, heavy metals are categorized into essential elements (e.g., Cu, Zn, Mo, Ni, Co, Se), vital for metabolic processes in small amounts, and non-essential elements (e.g., As, Ag, U, Cd, Hg, Pb), which are toxic even at low concentrations due to their biomagnification potential.

2.1. Sources and Global Impact

Heavy metal contamination stems from both natural processes and anthropogenic activities. Natural sources include volcanic eruptions, forest fires, and the weathering and erosion of parent rocks, which can leach heavy metals into water bodies and soil. However, human activities are the predominant contributors, including mining, industrial processes (e.g., smelting, electroplating, chemical production), solid waste disposal, use of synthetic fertilizers and pesticides, and wastewater irrigation. For instance, Vellore District in Tamil Nadu, India, is significantly contaminated with heavy metals such as Cr, Co, Cu, Cd, and Fe (Dange *et al.,* 2024). Industrial smelters and tanneries are major contributors, discharging large quantities of heavy metals into the environment.

The ecological and health consequences of heavy metal pollution are severe. In soil, heavy metals can alter soil characteristics, disrupt microbial communities, and hinder plant growth by interfering with nutrient uptake, photosynthesis, and various metabolic pathways. For humans, exposure to these contaminants, often through the food chain, can lead to a range of health issues, including cardiovascular disorders, neurological damage, and various cancers (Guo *et al*., 2018).

3. Rhizoremediation: A Green and Cost-Effective Technology

Rhizoremediation is an environmentally sustainable and economically viable strategy that harnesses the symbiotic relationship between plants and their root-associated microorganisms (Saravanan *et al.,* 2019). This approach exploits the unique environment of the rhizosphere, the narrow zone of soil directly influenced by root exudates, where microbial activity is significantly enhanced.

3.1. Plant-Microbe Interaction in the Rhizosphere

Plant roots actively secrete various organic compounds, including organic acids, sugars, amino acids, and sterols, into the rhizosphere. These "root exudates" act as a vital food source, stimulating the growth, activity, and diversity of microbial communities in the surrounding soil. In turn, these plant growth-promoting rhizobacteria (PGPR) and fungi provide numerous benefits to the plant, such as nutrient cycling, nitrogen fixation, protection against pathogens, and modulation of soil chemistry. Crucially, in the context of heavy metal remediation, these microbes play a direct role in transforming, immobilizing, or degrading contaminants.

3.2. Enhancing Remediation Efficiency

To optimize rhizoremediation, several techniques are employed:

- **Biostimulation:** This involves enhancing the activity of indigenous rhizosphere microorganisms by adding nutrients (fertilizers), minerals, or biosurfactants to the contaminated soil.
- **Bioaugmentation:** Specific microorganisms with known heavy metal-transforming capabilities are introduced into the rhizosphere. This can be achieved through soil drenching, root dipping, or seed coating.
- **Rhizoengineering:** This advanced approach involves genetically modifying plants to produce altered or increased quantities of root exudates, thereby enhancing the plant-microbe interaction and leading to more effective contaminant removal.

4. Mechanisms of Heavy Metal Removal

The removal of heavy metals through rhizoremediation is a multi-faceted process involving a complex interplay of physical, chemical, and biological mechanisms occurring within the rhizosphere. The primary mechanisms include:

- **Biosurfactant Production:** Microbes secrete biosurfactants, amphiphilic extracellular compounds that can increase the bioavailability and mobility of hydrophobic contaminants, facilitating their uptake or degradation.
- **Biofilm Formation:** Microorganisms form structured communities encased in an extracellular polymeric substance around plant roots. These biofilms can immobilise heavy metals through adsorption, complexation, and precipitation, preventing their uptake by plants or reducing their mobility in the soil.
- **Organic Acid Secretion:** Plant roots and rhizosphere microbes release various organic acids (e.g., oxalic, citric, malic, lactic, succinic acids). These acids act as chelating agents, forming soluble complexes with heavy metals, which can either enhance their mobility for plant uptake (phytoextraction) or immobilise them by precipitating insoluble compounds.
- **Adsorption and Complexation:** Microbial cell walls and extracellular polymeric substances can directly adsorb heavy metal ions.
- **Redox Reactions:** Certain microorganisms can change the oxidation state of heavy metals, transforming them into less toxic or

less mobile forms. For example, some bacterial species, such as Bacillus spp., Acinetobacter spp., and Pseudomonas spp., can reduce hexavalent chromium (Cr(VI)) to the less toxic trivalent chromium (Cr(III)) (Ramli et al., 2023).

- **Precipitation:** Microbes can induce the precipitation of heavy metals as insoluble compounds (e.g., carbonates, sulfides, phosphates) by altering the rhizosphere pH or producing specific enzymes.
- **Immobilization:** Through various mechanisms like biosorption, complexation, and precipitation, heavy metals can be sequestered within the microbial biomass or converted into immobile forms, preventing their movement into plants or groundwater.

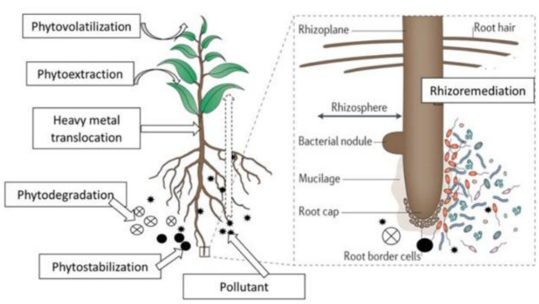

Figure 1: Phytoremediation techniques and rhizoremediation of heavy metals (El-Tahlawy & Ali, 2021)

5. Key Factors Influencing Rhizoremediation Efficiency

The effectiveness of rhizoremediation is highly dependent on a variety of interacting factors, including:

- **Microbial Population and Activity:** A diverse and abundant microbial community in the rhizosphere is crucial for efficient degradation and immobilization processes.
- **Plant Root Exudates:** The quantity, composition, and quality of root exudates, which vary with plant species, developmental stage, and environmental conditions, directly influence the microbial community and its ability to interact with contaminants.
- **Nature and Concentration of Contaminants:** The type of heavy metal (e.g., its valence state, solubility), its concentration, and its bioavailability in the soil significantly impact remediation success.
- **Soil Properties:** Soil characteristics such as pH, texture, organic matter content, and humidity play a critical role. For instance, optimum soil pH is essential for microbial activity, and organic matter can influence sorption processes.
- **Nutrient Availability:** Adequate nutrient levels in the rhizosphere are necessary to support robust microbial growth and metabolic activity, which are essential for remediation.

6. Promising Plant-Microbe Partnerships in Rhizoremediation

Research has identified numerous effective plant-microbe combinations for heavy metal rhizoremediation:

Table 1: Key factors influencing rhizoremediation of heavy metals in soil, highlighting the complex plant-microbe interactions (Adopted and modified from Singh *et al*. (2024))

Heavy Metal	Rhizo-microbes	Plant	Efficiency
Cd^{2+}	*Pseudomonas aeruginosa* MKRh3	*Vigna mungo* (Mung bean)	Seed coating prevents Cd toxicity and accumulation, allowing plant growth in contaminated soil.
Cr	*Bacillus* sp. PSB10	*Cicer arietinum* (Chickpea)	Reduces chromium toxicity in contaminated soils.
Cu & Cd	*Serratia* sp. SY5	*Echinochloa crus-galli* (Barnyard grass)	Increases remediation efficiency in soils contaminated with both Cu and Cd.
Zn, Cu, Pb, Cd	*Glomus macrocarpum*, *Paraglomus occultum*, *Glomus* sp. (AMF)	*Urochloa brizantha, Sorghum bicolor, Acacia mangium*	Arbuscular mycorrhizal fungi (AMF) can improve plant growth and assist in phytoremediation of contaminated soils.
Cd	*Bacillus paramycoides* & *Bacillus subtilis*	*Pennisetum purpureum*	Co-culture bioaccumulates Cd without hindering plant growth.
Cd^{2+}, Pb^{2+}, Zn^{2+}	*Trichoderma harzianum* & *Bacillus subtilis* (biofilm)	*Solanum tuberosum* (Potato)	Biofilm reduces the soil availability of Pb^{2+}, Cd^{2+}, and Zn^{2+}.
As	*Kocuria flava* AB402 & *Bacillus vietnamensis* AB403	*Oryza sativa* (Rice)	Arsenic-resistant halophilic strains decrease As uptake/accumulation through biofilm formation.

7. Prospects and Challenges

Rhizoremediation holds immense potential as a sustainable and effective solution for heavy metal contamination. Prospects include the continued discovery and engineering of superior plant-microbe consortia. Advances in genomics and synthetic biology can facilitate the development of "rhizoengineered" plants and microbes with enhanced exudate production and pollutant degradation capabilities. For example, engineering rhizobacteria to express specific enzymes or chelators could significantly boost remediation.

However, several challenges need to be addressed for broader implementation. The complexity of the rhizosphere environment, with its numerous interacting factors, makes it difficult to predict and control remediation outcomes.

8. Conclusion

The rapid pace of industrialization has led to a critical increase in heavy metal contamination in soils and water bodies worldwide. Given the persistent, non-biodegradable, and toxic nature of these pollutants, innovative and sustainable remediation strategies are imperative.

Rhizoremediation stands out as a promising green technology that harnesses the powerful synergistic relationship between plants and their rhizosphere microorganisms (Dange *et al*., 2024).

While various factors such as microbial population, plant root exudates, contaminant characteristics, and soil properties significantly influence its efficiency, ongoing research continues to identify and optimise effective plant-microbe partnerships. Overcoming the existing challenges, particularly in scaling up and understanding complex environmental interactions, will be key to establishing rhizoremediation as a widespread and reliable solution for heavy metal contamination issues globally.

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