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Review Article

# Plant-Microbes' Interactions for Heavy Metals Pollution Remediation

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**Abstract:** Heavy metal pollution presents a serious risk to the environment and human health, making effective remediation strategies essential. Conventional methods are frequently ineffective and unsustainable. This study investigates the effects of soil-borne heavy metal pollution on the biodiversity of plants and microorganisms, emphasizing the potential of these interactions for phytoremediation. Industrialization, mining, and agricultural activities have significantly degraded soil quality, introducing hazardous metal (loid)s that poses risks to both ecosystems and human health. This review delves into the multifaceted mechanisms of plant-associated microorganism in reducing metal uptake, enhancing plant stress tolerance, and facilitating metal remediation. This eco-friendly approach utilizes natural processes, which is recognized as a promising strategy for environmental pollution mitigation. This study also examines the impact of floods, which intensify environmental challenges by causing oxygen deprivation and activating anaerobic microorganisms, thereby complicating plant and microbial survival. The complex relationships between plants, their microbiomes, and the environment are explored, highlighting their crucial role in shaping microbial communities and driving the remediation of metal (loid) pollutants. Moreover, it also covers current challenges and future prospects in refining plant-microbe-based remediation strategies for sustainable environmental management.

**Keywords:** Bioremediation, Plant Microbe Interaction, Heavy Metals Pollution, Phytoremediation, Plant Growth Promoting Rhizobacteria (PGPR), Environmental Contamination.

## Introduction

A notable decline in industrial production and human activity over the past few decades has resulted in the leakage of numerous hazardous chemicals into water sources. A greater concern for aquatic ecosystems and the environment results from this [1]. These anthropogenic activities are extremely poisonous and are a major cause of water contamination. Human health is imperilled by very toxic heavy metal ions, such as mercury (II), lead (II), and cadmium (II), which must be eradicated from water sources by effective methods. The hexavalent nature of chromium is most dangerous among them [2].

In addition, they can stay in nature, act as persistent toxins, and produce biomagnification in the food chain. They affect aquatic environments directly or indirectly. Heavy metal ions generate problems even in soil ecosystems because plants absorb them and, ultimately animals and humans also swallow them. As a result, it is tough to examine, control, or execute preventative actions at the regional level due to heavy metal ion (HMI) pollution. HMI can be perceived by, electrochemical, optical, and spectroscopic tools [3].

Investigating plant-microbe interactions has drawn more attention in recent years as a potential method of reducing heavy metal pollution. Studies indicate that few fungi and bacteria can release organic acids, which serves as organic HM chelating agents. Arbuscular mycorrhizal fungi, or AMF, aid immunity to plants for climate change and this relationship facilitates a crucial process called phytoremediation [4].

The phytoremediation phenomenon during biosorption includes entrapment, ion-exchange, micro-precipitation, coordination, chelation, and complexation. The composition of the microbial cell wall and different functional groups, such as -OH, -COOH, and -SH, have a great affinity for HMs [5].

Phytoremediation is less costly, easier to use, and less deleterious than physicochemical methods. The interaction between the plant root and rhizospheric microbe enhance the ability of phytoremediation. Rhizospheric microbes such as bacteria and fungi play pivotal role in amplifying plant growth, bio-availability of metals and metal uptake. It also aids in sequestration and detoxification of metals in plant tissues [6].

Furthermore, recent research relied on plant-microbe interactions in soil with high level heavy metals. A lot of drugs discharged by plants captivate and restore microbial population in soil. Therefore, plant growth-promoting bacteria (PGPR) secrete phytohormones that aid in the absorption of nutrients by the plant, and lessen biotic and abiotic stress. This allows plants to thrive in high levels of heavy metals. This highlights the convoluted and entangled nature of the interactions throughout the bioremediation process [7].

## Phytoremediation

Plant-based phytoremediation, which has been in use for years, is a very promising alternative method that relies on solar power and is low-cost, efficient, effective, and nature affable. The concept of phytoremediation was first introduced in 1983. A plant-based process for treating soil, water, and air is called phytoremediation. Using microbes to stimulate plant growth, phytoremediation assembles a lot of peculiarity in recent years by cleaning soil from toxic metals. Rhizosphere bacteria, endophytic bacteria, and bacteria that aid phytoremediation by multiple routes [8].

There are five sub-classes, which defines the phytoremediation method used for HM-contaminated soils: Phytoextraction (refers to the use of hyperaccumulating plants, which have the ability to absorb metals from the soil by their roots and accumulate them in their aerial portions), Phyto-stabilization (refers to the process by which plants immobilize impurities through their roots, adsorb them, or condense in the root zone due to organic compound binding), Phytovolatilization (refers the way precarious molecules are taken up by plants from the soil, modified into volatile substances, and then released into the atmosphere), Phyto-transformation (uses enzymes found in plants to break down organic impurities), and Phyto-filtration (refers to use plant biomass to remove HMs and other particles) [9].

Plant roots perform as a dynamic micro-environment that promote intricate relation between microbes, soil particles, and plants in the rhizosphere [10]. Through processes like metal solubilization, chelation, and immobilization, microbes living in the rhizosphere play a major role in the remediation of heavy metal. Moreover, the rhizo-degradation of organic pollutants by microbes may impact the fate and mobility of heavy metals in the environment by indirectly affecting their mobility and bioavailability in the rhizosphere [11]. Table 1 provides a comprehensive overview of various metals and the microbes involved in their remediation and their mechanism of action.

**Table 1:** Microbial Mechanisms for Heavy Metal Remediation.

| Metal | Microbes | Mechanism of Action | Citation |
|---|---|---|---|
| Arsenic | *Bacillius spp., Alcaligenes, Shewanella spp., P. aeruginosa* | Reduction, oxidation, biomethylation, biosurfactant production | [30] |
| Iron | *Geobacter, Bacillus spp., Shewanella spp., R. rhodochrous* | Reduction, precipitation, oxidation, siderophores, adsorption in exopolysaccharides | [31] |
| Copper | *Desulfovibrio, Thiobacillis spp., Bacillus spp.* | Potassium and phosphorus solubilization, biosorption, extracellular precipitation, oxidation-reduction | [32] |
| Chromium | *Bacillus spp., Pseudomonas spp., Arthrobacter spp.* | Reduction bioaccumulation, biosorption | [33] |

| Metal | Microbes | Mechanism of Action | Citation |
|---|---|---|---|
| Nickel | *Pseudomonas spp., Bacillus spp., Rhodococcus spp.* | Biosorption, extracellular precipitation, enzymatic reduction | [34] |
| Manganese | *Bacillus spp., Pseudomonas spp., Rhizobium spp.* | Reduction, biosorption, oxidation, hydrolytic enzymes | [35] |
| Lead | *Pseudomonas spp., Bacillus spp., Rhizobium spp.* | Bioaccumulation, biosorption, hydrolytic & ligninolytic enzymatic reduction | [36] |
| Cadmium | *Saccharomyces spp., Bacillus spp., Pseudomonas spp., Penicillium chrysosporium, Aspergillus niger* | Phytoextraction, biosorption, metal precipitation, Gibberellins, siderophores | [37] |
| Zinc | *Pseudomanas spp, Bacillus spp., Klebsiella spp., E. meliloti, Glomus spp., Sclerocystic spp.* | Indole-3-acetic acid, Biosorption, extracellular precipitation, enzymatic reduction | [38] |

## Microbial Assisted Plant Growth Promotion

The ability of microbial communities to modify HMs into less vicious form and this is pivotal for the microbial remediation of HMs. Studies on the interactions of plant and microbe provide clarity for sustainable agriculture. To improve metal bioavailability, Heavy Metal Tolerant - Plant Growth Promoting (HMT-PGP) bacteria and microorganisms alter soil physicochemical properties and plant growth. Hence, HM is removed from the soil. To alter the metal bioavailability in the soil, HMT-PGP microorganisms use precipitation, redox reactions, complexation, chelation, and acidification [12].

Mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR) form symbiotic relation with plants, invigorating growth, and resilience to biotic stressors. These beneficial microbes are vital for lessen metal toxicity, promoting root growth, and fostering the efficiency of nutrient intake in heavy metals-polluted soils. PGPR and mycorrhizal fungi help plants adapt to stressful environmental conditions through processes such as metal detoxification, sequestration, and modification of plant stress responses. This increases the strength of bio-remediation [13].

## Mycorrhizal Fungi and Heavy Metal Tolerance

Heavy metals like copper, lead, and zinc are common and non-degradable in the contaminated soils. Arbuscular mycorrhizal fungi are there in soils polluted with HMs. AMF and most plants have a symbiotic relation and this increases the surface area for more nutrient uptake [14]. It helps in nutrient uptake, like phosphorus (P) in return for carbohydrates from the host plant, the AMF hyphae serve as the intermediary between plants and fungi. Heavy metals are extensively slurped by vesicles, spores, and extra and intraradical AMF mycelia. Because AMF raises the uptake of P, it strengthens the growth of plant and weaken the stress posed by excess metals in the soil indirectly [15].

Although the studies on plant-microbe interactions in heavy metal remediation shows promising results in the lab, yet, field applications are less usual and comes with additional bar. It is important to tackle challenges including soil heterogeneity, environmental unreliability, and the risk of secondary pollution. Large-scale field trials should be the major focus of future research to allow verify laboratory results and create long-term bioremediation plans. Testing in the field is needed to ensure the long-term success of bioremediation initiatives by bridging the gap between lab research and real-world applications [16].

## Microbial Biosorption and Bioaccumulation

By the method of microbial biosorption, heavy metals are retrieved from soils and water by adhering to proteins and polysaccharides present in cell walls.

 

Although when the rate of pollutant absorption surpasses the rate of pollutant removal, bioaccumulation occurs. As a result, the impurity is trapped inside the organism and accumulates. Since metals cannot be digested, bioaccumulation of metals is a valuable as an indication of exposure. Some microbes such as Bacillus, Saccharomyces, and Pseudomonas, shows the great effect in biosorbing metals like lead and cadmium [17].

**Rhizosphere Microbiome**

The dynamic zone called as the rhizosphere, in which plant roots involves with an array of microbial communities, is key for ameliorate metal absorption and stress tolerance. Organic materials secreted by plants stimulate microbial activity, which in turn makes more metals accessible for plant absorption. Because the rhizosphere microbiome heightened metal bioavailability and plant uptake, it is crucial to the bioremediation of heavy metal-contaminated soils [18].

**Utilization of Microbial Consortia**

The growing need for adequate remediation solutions lead to the rise of microbial consortiums as a suitable bioremediation method. Many microbial species combine to foster actions such as oxidation-reduction, methylation-demethylation, volatilization, immobilization, and arsenic mobilization to fight Heavy metal poisoning in soil. Microbial consortia's overall performance is affected by a number of factors like diversity, activity, community structure, and environmental events. However, the optimization of these consortia for field-based, real-world applications is a difficult task [19].

**Microbial Enzymatic Reduction and Precipitation**

It is significant to use biological agents and phytoremediation methods like enzymes due to their great potential for altering and detoxifying harmful chemicals. They are useful in cleaning up contaminated areas as they have capacity to change pollutants at a high rate. It has been shown that soils polluted with heavy metals, fungicides, herbicides, and hydrocarbons may be bio-remediated by bacteria immobilized on biochar [20]. For example, they can convert Cr (VI) to Cr (III) by certain bacterial species which are needed for the detoxification and immobilization of chromium in soils. Microbial enzymatic reduction of chromium is an efficient method for immobilization and detoxification of the molecules in polluted soils. Microorganisms assist in the process of microbial-induced precipitation by production of insoluble metal compounds [21].

**Phytoextraction with Hyperaccumulators**

Heavy metals from polluted soils can be absorbed and sequestered by plants, primarily by hyperaccumulators. Rhizosphere microbes that boost metal bioavailability greatly improve this process. For example, when linked to microbial communities, hyperaccumulators like Thlaspi caerulescens and Alyssum murale possess high efficiency in metal absorption. Rhizosphere microbes are vital to boosting plants' capacity for phytoextraction because they solubilize heavy metals and promote plant development [22].

**Genetic Engineering and Synthetic Biology**

The use of microorganisms in engineering appears as a cheaper and environmentally friendly remedy to the HM contamination. Physicochemical remediation technologies are costly, tough to use, and have an adverse impact on soil fertility, secondary pollution, and the agricultural environment. This is the best option as this pose serious risk to the sustainability of the ecosystem and creates risk to human health and the environment due to their high toxicity, complex break down, and buildup of biological molecule. Bio-augmentation is now a viable solution to the problem of waste and pollution degradation that is ineffective and steady due to the use of engineered microbial strains [23].

Researchers are studying to introduce genes that aid in metal absorption, transport, and detoxification to discover more efficient bioremediation agents. Advances in science and technology uses DNA molecule fragments made by one or more nucleotides may be precisely inserted, deleted, or swapped into an organism's genome's, allowing rational genetic engineering at the global (genome) or local (gene) level [24].

**Role of PGPR in Heavy Metal Removal**

The use of PGPR in phytoremediation has drawn a lot of attention lately. In the case of plants, PGPR often refers to beneficial, free-living soil bacteria that are present in plant roots. PGPR employs different methods such as efflux systems, siderophores and chelation, biotransformation, biosorption, bioaccumulation, precipitation, ACC deaminase activity, biodegradation, and biomineralization, to clean up the heavy metal-contaminated environment.

Through increased nutrient availability in the soil, modified heavy metal routes, and production of certain chemical compounds like siderophores and chelating ions, these PGPRs have been proven to be successful in bio-remediating the heavy metal-contaminated soil [25].

**Microbial Siderophores and Organic Acids**

Organic acids and microbial siderophores play a crucial part in unleashing heavy metals for plant intake. While organic acids can solubilize heavy metals and aid in their uptake by plant roots, siderophores bind to heavy metals and promote their bioavailability to plants. The efficacy of phytoremediation methods is stimulated by this mutual interaction [26].

**Biosurfactants and Microbial Redox Processes**

Improving microbial bioremediation, biosurfactants enhance the solubility and bioavailability of heavy metals. To immobilize heavy metals and limit their bioavailability, biosurfactants help in the synthesis of metal-mineral complexes. The detoxification and durability of heavy metals in soil are further promoted by microbial redox actions, which require the reduction of metal ions to less damaging forms. Many factors, like redox potential, moisture, pH, temperature, and the chemical nature of heavy metals, dictate how effective bioremediation is [27].

**Synergy in Symbiotic Systems**

Microalgae and bacteria conjunction system biological adsorption is a suitable method for cleaning wastewater with a large volume and low content of heavy metals. As a result, its application capacity is very promising. There are many sources from which species can be obtained and screened, especially places contaminated with heavy metals. As a result, such characteristics strengthen their wield as bio sorbents [28].

The valuable metals that have been recovered with high commercial value, enough development potential and positive social impacts. By photosynthesis, microalgae take carbon dioxide and convert inorganic molecules into organic while releasing oxygen. Carbon dioxide is produced when oxygen-consuming bacteria degrade organic matter and oxygen. For making a consortium, these two needs symbiosis to develop. The positive effect of treatment of heavy metals with microalgae and bacteria includes high removal, rapid reaction rates, simple regeneration, no secondary pollution, and simple operation [29].

## Conclusion

Significant amounts of heavy metals damage soil microbes and plants. Soil microbes are stimulated by various substances released by plants. Many microbes increase resistance to heavy metals and lessen their harmful effects, which all helps, plant thrive in the soil by providing the necessary nutrients. Thus, the interaction of organisms and plants can significantly improve the success of phytoremediation. Research on the relation amongst plants and microbes in cases of high heavy metal levels in the soil is equally crucial from an ecological and scientific view. To fully hire plant-microbe-based remediation methods for squabble over heavy metal pollution, joint research efforts and progress in technology are required.

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