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# Soil Heavy Metal Toxicity Origins, Remediation Strategies, and Challenges

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## ABSTRACT

Agricultural soils carry a considerable load of pollutants from various sources, presenting significant challenges to environmental and human health. The concern arises from the contamination of these soils with heavy metals, potentially causing functional disorders in the soil, hindering plant growth, and posing health risks to humans through the contamination of the food chain. Compounding the issue is the resistance of these heavy metals or metalloids to microbial and chemical degradation, leading to their prolonged persistence in the soil. This review highlights the crucial analysis of heavy metal sources in soil and emphasizes the essential role of remediation technologies in alleviating their impact on agricultural ecosystems. Efforts to comprehend and address heavy metal contamination involve an in-depth exploration of the divers sources contributing to soil pollution, ranging from industrial discharges to agricultural practices. Additionally, the review delves into the various remediation technologies that play a pivotal role in the removal of heavy metals from the soil, emphasizing the importance of sustainable and effective strategies to safeguard the health of agricultural ecosystems and the well-being of communities dependent on these environments.

**Keywords:** Human-induced sources, Metallic Elements, Metalloids, Remediation Strategies, Soil contamination.

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## Introduction

Soil pollution with heavy metals poses a significant threat to living organisms due to their harmful effects. The persistent nature of these non-biodegradable metals allows them to accumulate in the environment. Various sources, such as rapid urbanization, industrialization, and improper agricultural practices, heavily contribute to the contamination of agricultural soils with metal contaminants. This contamination can result in functional disorders, hinder plant growth, and pose risks to human health through the food chain, as heavy metals bioaccumulate, increasing in concentration up the trophic levels. Babula et al. [2] define heavy metals as elements with a higher molecular weight, including transition metals, some metalloids, lanthanides, and actinides, with a specific density greater than water (i. e., 5g cm-3). They are categorized as essential like Zinc (Zn), Nickel (Ni), Manganese (Mn), Iron (Fe) or non-essential heavy metals like Lead (Pb), Arsenic (As), Cadmium (Cd), Chromium (Cr), Mercury (Hg) based on their function in living organisms. Beyond critical limits, non-essential heavy metals pose hazards to human health, disrupting normal physiological functions. ASTDR (1) listed As, Pb, Hg, and Cd at first, second, third and seventh position given according to their frequency, toxicity, and potency for human exposure. The production of livestock and poultry products generates significant waste released into the soil from industries. Proper treatment of this waste is crucial, considering environmental measures in land treatment. Elevated levels of heavy metals in agricultural soils depend on soil characteristics and the application rate by suppliers with its elemental concentration. These metals or metalloids resist microbial and chemical degradation, persisting in the soil for extended periods. As public awareness grows about the harmful effects of these contaminants on human health, scientific communities are actively developing new technologies to remove these metals from contaminated soils. This review delves into the sources of heavy metals in soil, the strategies or technologies for their removal, and the challenges associated with using various amendments for soil remediation.

## What are the sources of heavy metals in soil

The distribution of heavy metals in soils results from a combination of natural and anthropogenic influences. Geological processes, such as the breakdown of parent rock materials and volcanic eruptions, constitute natural sources. Anthropogenic inputs, stemming from the widespread use of agrochemicals (both inorganic and organic fertilizers), pesticides, wastewater irrigation, sewage

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sludge supplementation, and increased atmospheric depositions due to industrial activities and fossil fuel combustion, collectively contribute to elevated levels of inorganic pollutants in the soils [3]. Fungicides, phosphate fertilizers, and inorganic fertilizers demonstrate varying concentrations of Pb, Cd, Cr, Ni, Zn, etc., contingent upon their respective sources. The repetitive application of phosphate fertilizers serves to continually enrich agricultural soils with heavy metals. Figure 1 provides an illustration depicting both natural and anthropogenic sources of heavy metals in the environment.

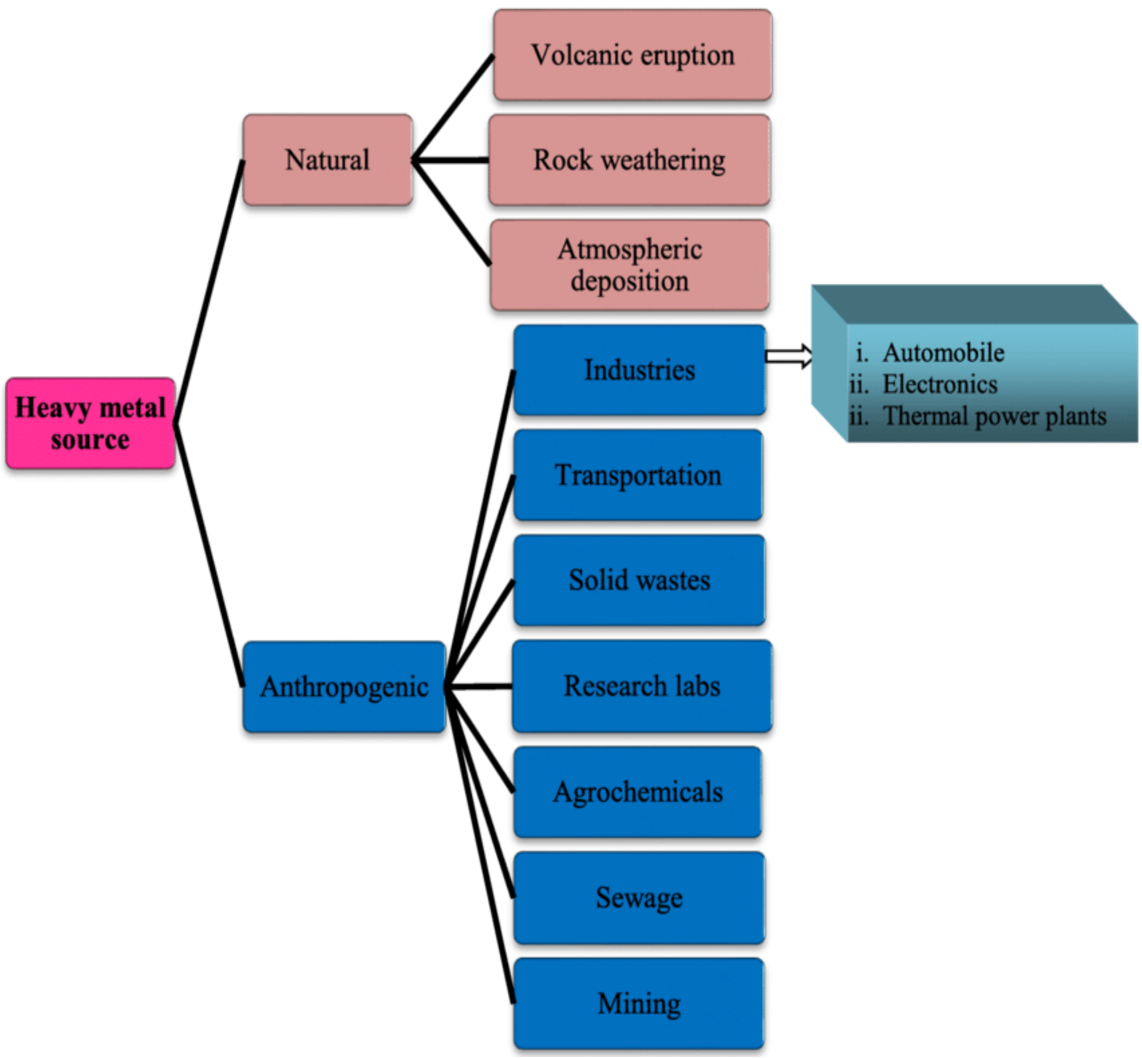


**Figure 1: Sources of heavy metals**

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**Technologies for remediating heavy metal contamination in soil**

Numerous measures have been developed to address the remediation of heavy metals in contaminated sites. The USEPA [4] has categorized these remediation measures for contaminated soils into two types: in-situ and ex-situ treatment. In in-situ treatment, the soil is treated in its original location, while in ex-situ treatment, the contaminated soil is excavated and removed from the site. Additionally, remediation technologies can be further classified into physical remediation, chemical remediation, and biological remediation. These approaches offer a range of strategies for effectively mitigating the impact of heavy metal contamination in diverse environmental settings.

**Physical remediation methods**

Physical remediation of soil involves primarily two methods: soil replacement and thermal desorption. In the soil replacement method, contaminated soil undergoes partial substitution with clean soil to reduce the concentrations of contaminants [6]. Despite its effectiveness, this approach is financially demanding and suitable only for relatively small areas due to its high cost. On the other hand, thermal desorption relies on heating contaminated soil to vaporize pollutants. Volatile metals are then collected through vacuum pressure, effectively removing them from the soil [6]. Despite its efficacy, the labor-intensive and expensive nature of thermal desorption restricts its application in larger-scale soil remediation projects. The economic constraints and practical limitations make soil replacement and thermal desorption less feasible for widespread soil remediation efforts, necessitating the exploration of alternative and more cost-effective remediation technologies.

**Chemical remediation methods**

Chemical remediation encompasses various techniques, including chemical leaching, chemical fixation, electrokinetic remediation, and vitrification. In the chemical leaching process, contaminated soils undergo washing with water, reagents, fluids, and gases, facilitating the leaching of pollutants from the soil. Metals extracted through this method are subsequently recovered from the leachate using chelating agents and surfactants [5]. Chemical fixation involves the addition of reagents to contaminated soils, forming insoluble bonds with heavy metals and reducing their mobility in the soil [8]. Electrokinetic remediation is a process wherein the application of high voltage to the soil aids in the removal of metals [7]. Additionally, vitrification involves heating the soil to extremely high temperatures (1400-2000°C) to volatilize or decompose pollutants. Despite its effectiveness, vitrification is limited in its application due to its high cost, labor-intensive nature, and complexity [5]. While chemical remediation techniques offer viable solutions, the choice of method depends on the specific characteristics of the contaminated site, the types of pollutants involved, and considerations related to cost and feasibility.

**Biological remediation methods**

Biological remediation techniques provide environmentally friendly solutions for the removal of heavy metals from soils, utilizing both phytoremediation and microbial remediation strategies. Phytoremediation employs a versatile array of strategies, including phytoextraction, phytostabilization, rhizofiltration, phytovolatilization, and phytodegradation [9]. Phytoextraction facilitates the transfer of metals from the soil to above-ground plant parts, effectively reducing metal concentrations in contaminated soils. Phytostabilization relies on plants to diminish the mobility and bioavailability of metals in the soil, contributing to stabilization. Rhizofiltration capitalizes on plant roots to extract toxic materials from contaminated water, presenting an effective approach for water remediation. Phytovolatilization entails plants absorbing contaminants from the soil, transporting them upward, and releasing them from aerial parts. Phytodegradation involves the collaboration of plant roots and associated microbes to degrade pollutants in the soil, offering a comprehensive solution for organic contaminants [10]. Within the realm of phytoremediation, phytoextraction and phytovolatilization emerge as pivotal strategies for the removal of heavy metals, each addressing specific contamination scenarios. Phytostabilization and phytodegradation, on the other hand, find greater utility in addressing organic contaminants [11]. Microbial remediation, another facet of biological intervention, employs microorganisms to efficiently eliminate heavy metals. These microbes induce changes in the physical and chemical properties of pollutants, influencing the mobility and transformation of heavy metals within soils. Both phytoremediation and microbial remediation present sustainable approaches to combat soil contamination, with unique advantages and considerations tailored to specific environmental contexts.

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### Challenges in the Application of Remediation Technologies

The previously mentioned remediation technologies pose significant challenges due to their high costs, time-intensive nature, and labor requirements. To address these challenges, attempts are made to enhance the solubility of metals in the soil, making them more accessible for removal. However, the incorporation of chelating agents and surfactants in remediation technologies introduces serious issues. These include the potential leaching of contaminants into groundwater and the remobilization of metals in the soil due to the highly stable nature of these agents. These challenges highlight the need for continuous research and innovation in remediation strategies to develop more efficient and environmentally friendly approaches.

### Conclusion

The toxicity of heavy metals in soil stands as a significant global issue. Various in-situ and ex-situ technologies have been developed and employed to address contaminated soils, aiming to reduce, remove, and degrade heavy metals. However, challenges arise with the use of chelating agents or surfactants in these technologies, as they may leach into groundwater, posing a threat to the water table. Additionally, the amendments used to immobilize contaminants may lack specificity for particular metals, potentially resulting in the release of toxic metals into the soil. Consequently, further studies are imperative to explore and develop new methods that can effectively and specifically lead to the removal of heavy metals from contaminated soil. This underscores the ongoing need for research and innovation to advance environmentally sustainable solutions for soil remediation.

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