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Phytoremediation of Soil Contaminated with Lead and Cadmium Metals

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Annotation: Soil contamination with heavy metals such as lead (Pb) and cadmium (Cd) poses severe risks to human health, agriculture, and ecosystems. Phytoremediation, an eco-friendly and cost-effective technology, has emerged as a sustainable solution for decontaminating such polluted soils. This study explores the mechanisms and effectiveness of phytoremediation in reducing Pb and Cd concentrations in soil using hyperaccumulator plant species. Key processes, including phytoextraction, phytostabilization, and rhizofiltration, are discussed. The study also highlights factors affecting the efficiency of phytoremediation, such as plant species selection, soil properties, and the bioavailability of metals. Results indicate that certain plants significantly reduce Pb and Cd levels in soil, offering a practical approach to mitigate heavy metal pollution and restore soil health.

Keywords: Phytoremediation, heavy metals, lead contamination, cadmium contamination, soil remediation, hyperaccumulator plants, phytoextraction, environmental sustainability.

Introduction

Over the past decade, there has been a noticeable increase in the constant anthropogenic impact on the environment. As a result, soils are increasingly contaminated with chemically toxic substances. Among the most hazardous pollutants of soil are "heavy metals." The primary sources of these pollutants include industrial waste, energy production complexes, transportation, and agricultural activities, among others[1].

Heavy metals, such as lead (Pb) and cadmium (Cd), cause significant harm to living organisms. Currently, the concentration of these metals in soil is steadily rising, leading to technogenic desertification. The removal of heavy metals from soil is one of the most urgent tasks of today. Solving this problem requires modern technologies, including the phytoremediation system, where plants are used for soil detoxification by accumulating metals[2].

This technology is highly efficient and enhances natural material cycles by employing plants to accumulate metals. It also improves soil properties and prevents erosion without introducing harmful chemical factors into the soil. Economically, the "phytoremediation" method is more effective compared to chemical and mechanical methods, as it requires minimal financial investment and no excessive emissions or other environmental costs.

The primary aim of this scientific research is to study the patterns of removing heavy metals, particularly Pb and Cd, from contaminated soils within the "soil-plant" system[3-11].

To achieve the research objectives, the following tasks are prioritized:

1. Investigating the physical and mechanical properties of the soil and their impact on the migration processes of Pb and Cd within the "soil-plant" system.
2. Identifying highly efficient plants capable of accumulating Pb and Cd and using these plants to remediate contaminated soils.
3. Studying the mechanism by which the activator (succinic acid) influences the exchange process of Pb and Cd removal from the soil.

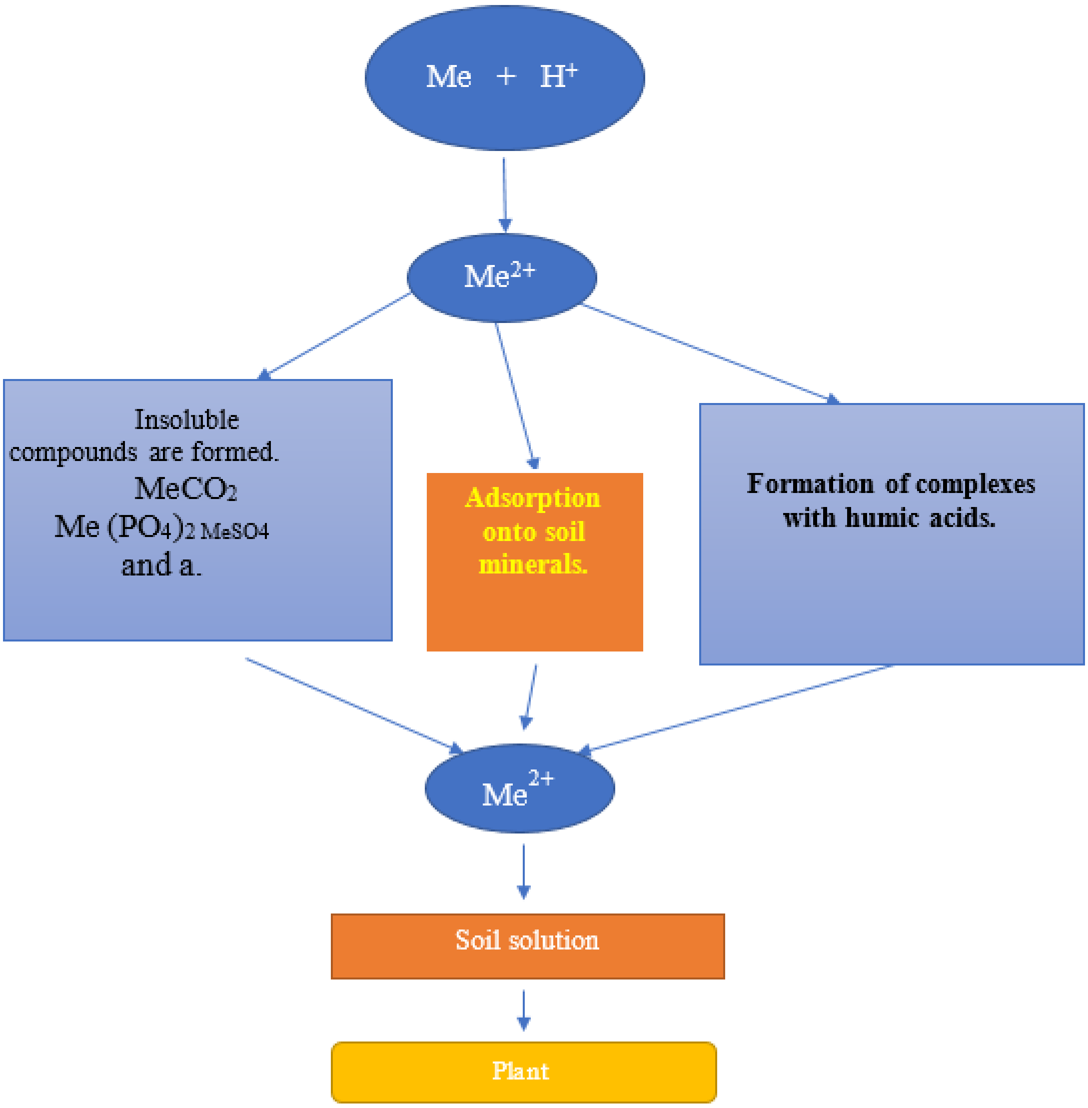
Method and results

The analysis of the obtained results indicates that lead (Pb) and cadmium (Cd) metals primarily accumulate in the above-ground parts of plants rather than in their roots. Approximately 60-80% of lead is concentrated in the aerial parts of plants, while cadmium is evenly distributed in the aerial parts at a level of 60-65%.

Based on the preliminary results, it was concluded that certain wild-growing plants, such as stinging nettle (*Urtica dioica*), wild mustard (*Sinapis arvensis*), and pigweed (*Chenopodium album*), as well as cultivated plants like barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and mustard (*Brassica juncea*), are highly effective in removing heavy metals from soils contaminated with Pb and Cd.

Treating the soil with succinic acid was also found to be a highly efficient method for removing Pb and Cd from the soil. If both Pb and Cd are present simultaneously in the soil, the optimal molar concentration ratio of heavy metal (HM) to succinic acid (SA) is 1:1. For Pb alone, the ratio should be 1:2, while for Cd, the ratio remains 1:1. Thus, the addition of succinic acid as an activator accelerates the phytoextraction process of Pb and Cd.

The mechanism of Pb and Cd uptake by plants can be illustrated in the following schematic:



Lead and cadmium form the following strong complexes with succinic acid. $\{(Me(H_2O)_4(OOC(CH_2)_2COO)\}n$

Six-coordinate Me^{2+} cations form oligomer chain structures with water (H_2O) molecules and the diamine of succinic acid. Under laboratory conditions, barley and mustard plants were continuously exposed to heavy metals in the soil, with varying amounts of succinic acid added. Experiments were conducted at different ratios of heavy metals to succinic acid (HM: SA) (1:0.5, 1:1, 1:2, 1.5).

When studying the changes in the biomass weight of the plants, it was found that the addition of succinic acid to the soil increased the resistance of the soil to heavy metals (HM). This is due to the formation of large, less mobile complexes of lead and cadmium in the soil. The formation of complexes between HM and succinic acid occurs based on the biostimulatory properties of succinic acid. Succinic acid enhances the plant's reaction to the toxic poisoning effects of heavy metals. The mechanism of the stimulating effect of succinic acid (SA) on the phytoextraction process of heavy metals and the changes in plant phytotoxicity are presented in Figures 1 and 2.

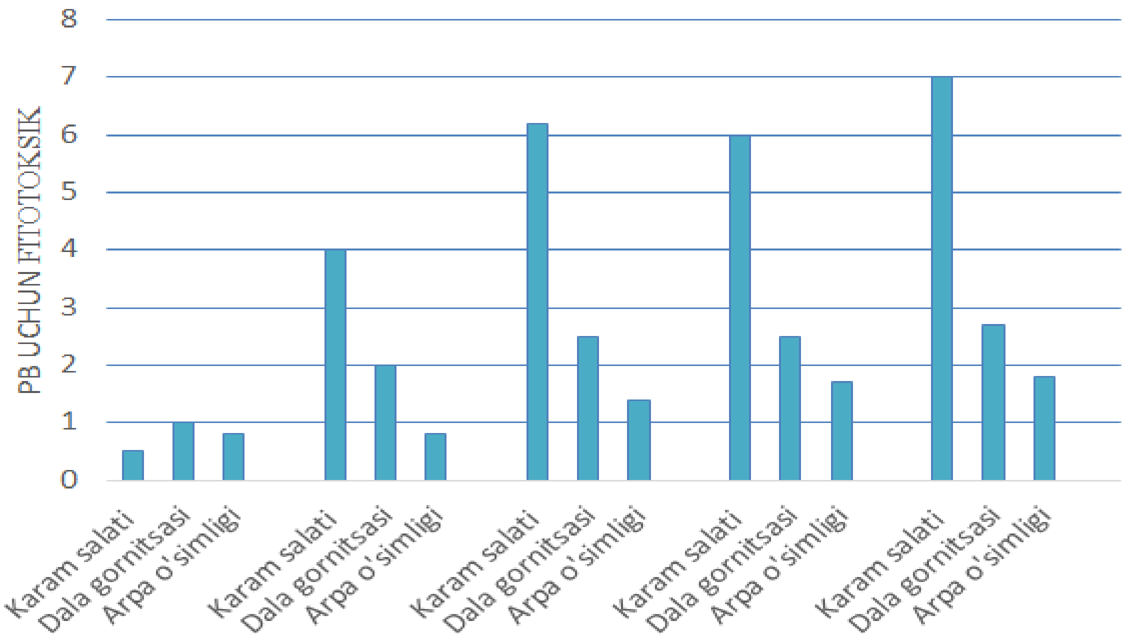


Figure 1. Effect of humic acid on the phyto-toxic state of lead in the absence of heavy metals.1 – Lead, 2 - Lead + Humic acid (1:0.5 ratio), 3 - Lead + Humic acid (1:1 ratio), 4 - Lead + Humic acid (1:2 ratio), 5 - Lead + Humic acid (1:5 ratio)

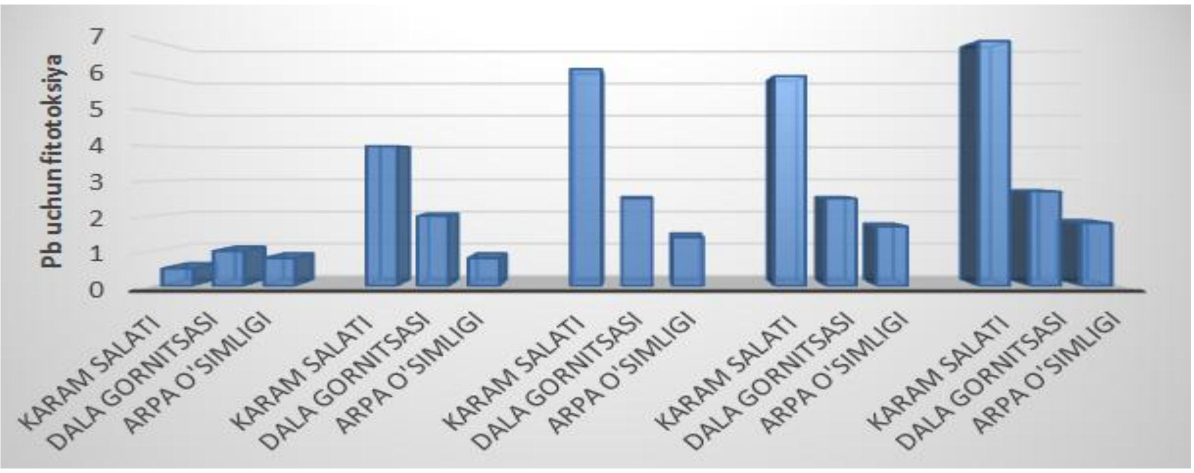


Figure 2. Effect of humic acid on the phyto-toxic state of cadmium (Cd) in the absence of heavy metals. Cadmium (Cd), Cd + Humic acid (1:0.5 ratio), Cd + Humic acid (1:1 ratio), Cd + Humic acid (1:2 ratio), Cd + Humic acid (1:5 ratio)

Analysis of the experimental results showed that the concentration of Pb and Cd in plants was significantly higher in soils with the addition of humic acid (HA) compared to soils without HA.

Conclusion

The phytoremediation of soil contaminated with lead (Pb) and cadmium (Cd) metals using various plant species and humic acid (HA) has demonstrated promising results. The study revealed that both Pb and Cd predominantly accumulate in the aerial parts of plants, with Pb showing a higher concentration in the upper plant tissues. The addition of humic acid (HA) significantly enhanced the phytoextraction process, improving the plants' ability to absorb and accumulate these heavy metals. The combination of HA and certain plant species, including wild and cultivated plants, showed improved effectiveness in removing Pb and Cd from contaminated soils.

Wild plants such as wild nettle, field mustard, and hemp, as well as cultivated plants like barley, wheat, and mustard, were identified as key species for effective phytoremediation. Furthermore, the addition of HA to soil was found to enhance the formation of complex molecules, increasing the bioavailability of metals and accelerating their uptake by plants.

The results suggest that using a combination of HA and appropriate plant species can offer an efficient, environmentally friendly method for remediating soils contaminated with heavy metals like Pb and Cd. This approach not only contributes to cleaning up polluted environments but also promotes sustainable agricultural practices. However, further research is needed to optimize the application of HA and explore the long-term impacts of such remediation techniques.

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