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Assessing the Risk, Bioavailability, and Phytoremediation of Heavy Metals in Agricultural Soils: Implications for Crop Safety and Human Health

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ABSTRACT: This review addresses heavy metal contamination in agricultural soils, focusing on bioavailability, toxicity, and phytoremediation techniques. We identify significant regional variations in cadmium and lead levels, posing health risks through crop consumption. Effective phytoremediation methods, such as phytoextraction and Phytostabilization, have shown marked improvements over recent years. Recommendations include best practices for soil management, stringent regulatory measures, and advanced research in biotechnological remediation methods. This study underscores the urgent need for integrated strategies to ensure food safety and sustainable agriculture in sector.

Keywords: Heavy Metals, Bioavailability, Phytoremediation, Food Safety, Agriculture

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INTRODUCTION

Heavy metal contamination poses significant threats to agricultural ecosystems worldwide, impacting soil fertility, crop productivity, and food safety. Rapid industrialization and intensive agricultural practices have exacerbated the problem, leading to elevated levels of heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) in agricultural soils (Fadlillah, Utami, Rachmawati, Jayanto, & Widyastuti, 2023; Vasilachi, Stoleru, & Gavrilescu, 2023). These metals originate from various sources, including industrial emissions, agricultural inputs like pesticides and fertilizers, untreated wastewater, and natural geological formations rich in heavy metals. For instance, recent studies have reported Pb concentrations exceeding safe limits in soils near industrial areas, reaching up to 150 mg/kg, which significantly surpasses the permissible level of 50 mg/kg set by environmental regulations. Similarly, Cd levels in rice paddies have been documented at 2.5 mg/kg, posing serious risks to both soil health and food security. This review aims to comprehensively explore the sources, bioavailability, and phytoremediation of heavy metals in agricultural soils, providing insights into their implications for crop safety and human health (Faazal et al., 2023).

The objectives of this review are twofold: first, to elucidate the mechanisms through which heavy metals accumulate in soils and subsequently uptake by crops, influencing food safety; and second, to critically evaluate current phytoremediation practices aimed at mitigating these contaminants. By synthesizing existing literature and empirical data, this review seeks to inform policymakers, researchers, and agricultural practitioners on effective strategies to manage and remediate heavy metal contamination in agriculture sector. This contribution to knowledge enrichment is pivotal in addressing a pressing environmental and public health concern, highlighting the urgency of sustainable agricultural practices and regulatory measures to safeguard soil quality and ensure food security for Indonesia's growing population.

THEORITICAL REVIEW

Sources of Heavy Metal Contamination in Agriculture

Heavy metal contamination in agriculture stems from diverse sources, each contributing to varying extents to soil and crop contamination. Industrial activities represent a significant source, releasing heavy metals such as mercury (Hg), chromium (Cr), and nickel (Ni) into the environment through emissions and effluents (Mishra, Singh, Gupta, & Tiwari, 2023; Rehman, Ahmad, Ullah, Pangilinan, & Alebachew, 2023). Metal concentrations in industrial zones can be alarmingly high, with Hg levels in wastewater discharges exceeding 10 mg/L, well above permissible limits. Agricultural practices exacerbate contamination through the use of chemical fertilizers and pesticides containing metals like copper (Cu) and zinc (Zn), which accumulate in soils over time (Ullah et al., 2024). For instance, Cu concentrations in soils treated with fungicides can reach up to 150 mg/kg, impacting soil microbial communities and nutrient cycling processes (Haidri, Qasim, et al., 2024).

Waste disposal practices further compound the issue, as untreated sewage sludge and solid waste often contain elevated levels of cadmium (Cd) and lead

(Pb). In some urban areas, Cd concentrations in sewage sludge have been recorded at 5 mg/kg, posing risks of leaching into agricultural soils during land application. Natural sources also contribute, with geological formations rich in heavy metals releasing contaminants into the soil through weathering processes. Areas with volcanic activity, such as parts of Java and Sumatra (Indonesia), exhibit naturally high levels of metals like arsenic (As) and manganese (Mn), which can exceed background levels by several orders of magnitude (Ummer et al.).

a. **Industrial sources**: Release of metals (e.g., Hg, Cr, Ni) through emissions and wastewater.

b. **Agricultural inputs**: Application of fertilizers and pesticides containing metals (e.g., Cu, Zn).

c. **Waste disposal**: Contamination from untreated sewage sludge and solid waste (e.g., Cd, Pb).

d. **Natural sources**: Geological formations and volcanic activity releasing metals (e.g., As, Mn).

e. **Chain of contamination**: Industrial emissions → Soil contamination → Crop uptake → Human exposure → Health impacts.

Bioavailability and Toxicity of Heavy Metals in Agricultural Soils

1. Bioavailability of Heavy Metals in Agricultural Soils

Heavy metals in agricultural soils exhibit variable bioavailability, influenced by intricate interactions with soil properties and plant physiological processes. Bioavailability refers to the portion of a metal that is in a form capable of being absorbed and utilized by plants (Rehman et al., 2023). Mechanisms of metal uptake include both passive and active processes:

a. **Passive Uptake (Diffusion):** Metals such as cadmium (Cd) and arsenic (As) can diffuse across cell membranes from areas of high concentration in soil to lower concentration in roots.

b. **Active Uptake (Root Uptake):** Plants actively absorb metals using specialized transport proteins, often mistaking them for essential nutrients like zinc (Zn) or phosphate (PO_4^{3-}). This process allows metals to enter plant roots and subsequently accumulate in plant tissues (Fatima et al., 2024; Hashimi, Abad, & Shafiqi, 2023).

Factors influencing metal bioavailability include:

a. **Soil pH:** Acidic conditions enhance the solubility and availability of metals like aluminum (Al) and lead (Pb) in soil, making them more accessible for plant uptake. Conversely, alkaline soils reduce metal bioavailability through precipitation, where metals form insoluble compounds that plants cannot absorb.

b. **Soil Type:** Sandy soils are more prone to leaching, where mobile metals such as nickel (Ni) can migrate downward, and potentially contaminating groundwater. Clay soils, on the other hand, have higher cation exchange capacities, which can influence metal retention and availability.

2. *Toxicity Thresholds for Crops*

The toxicity thresholds for crops vary significantly due to differences in plant physiology, root architecture, and agricultural practices such as irrigation. Crops like rice (Oryza sativa) and vegetables are particularly susceptible to accumulating high concentrations of metals:

a. **Rice:** Known for its efficient uptake of cadmium, rice plants can accumulate Cd in grains, posing significant health risks through consumption. Cd concentrations in rice grains can exceed safe limits, which are typically set below 0.2 mg/kg to protect human health.

b. **Vegetables:** Vegetables with extensive root systems and high transpiration rates can uptake metals from contaminated soils and irrigation water. Metals such as lead (Pb) and arsenic (As) can accumulate in edible portions of vegetables, exceeding safe consumption levels.

3. *International Standards for Heavy Metal Concentrations*

International organizations like the Food and Agriculture Organization (FAO) and World Health Organization (Europe) establish guidelines to ensure food safety regarding heavy metal contamination. These standards aim to protect human health by regulating maximum permissible concentrations of metals in soils and crops:

a. **Soils:** Guidelines specify permissible levels of metals like cadmium, lead, and arsenic in agricultural soils to prevent excessive accumulation in crops and subsequent human exposure.

b. **Crops:** Maximum allowable concentrations of metals in food crops are set based on toxicological assessments and dietary exposure scenarios. For example, the FAO/WHO may set limits such as 0.2 mg/kg for cadmium in rice grains to minimize health risks associated with chronic exposure.

4. *Implications for Food Safety and Human Health*

Heavy metal contamination in agricultural produce poses significant risks to human health through various exposure pathways:

a. **Direct Ingestion:** Consumption of crops contaminated with metals like cadmium and lead can lead to chronic health issues, including kidney damage, neurological disorders, and developmental abnormalities in children.

b. **Bioaccumulation:** Metals can accumulate in the human body over time through the consumption of contaminated food and water, leading to prolonged health effects even at low exposure levels.

Strategies to mitigate human exposure include:

a. **Dietary Diversification:** Encouraging a diverse diet can reduce overall exposure to specific contaminants by minimizing reliance on heavily contaminated crops.

b. **Monitoring and Regulation:** Regular monitoring of metal concentrations in agricultural produce and implementation of stringent regulatory measures are crucial for ensuring compliance with safety standards and protecting public health.

Understanding the bioavailability, toxicity thresholds, and regulatory standards for heavy metals in agricultural soil is essential for developing effective strategies to mitigate contamination and safeguard food safety. By addressing the complex interactions between soil properties, plant physiology, and human health implications, researchers and policymakers can work towards sustainable agricultural practices that minimize heavy metal exposure and promote environmental stewardship.

Table 1. Heavy Metal Concentration Limits in Soil and Crops

Heavy Metal	**Soil (mg/kg)**	**Crops (mg/kg)**
Cadmium (Cd)	0.3 - 1.5	0.2
Lead (Pb)	20 - 50	0.3
Arsenic (As)	10 - 20	0.1
Mercury (Hg)	0.1 - 0.3	0.02

This table presents recommended maximum permissible concentrations of selected heavy metals in soil and crops, based on FAO/WHO standards. These guidelines aim to mitigate health risks associated with heavy metal exposure through agricultural produce.

METHODOLOGY

Methodologies for Assessing Heavy Metal Uptake in Crops

Assessing the risk of heavy metal uptake in crops begins with rigorous methodologies aimed at quantifying metal concentrations and evaluating exposure pathways. Soil and plant tissue analysis are pivotal in this process, employing advanced analytical techniques such as inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS). These methods provide precise measurements of metal dynamics in crops, allowing researchers to track uptake patterns across different agricultural regions and practices in agriculture sector. By pinpointing hotspots of contamination and variations in metal accumulation, these analyses inform targeted interventions to mitigate health risks associated with heavy metal exposure.

Soil and Plant Tissue Analysis ⟶ ICP-MS and AAS Techniques ⟶ Accurate Metal Concentration Measurements ⟶ Quantify Metal Dynamics ⟶ Track Uptake Patterns ⟶ Inform Interventions

RESULTS

Variations in Metal Accumulation across Regions

The application of soil and plant tissue analysis reveals significant variations in heavy metal accumulation across regions of Indonesia. Case studies have highlighted disparities in contamination levels, such as elevated cadmium concentrations exceeding 0.3 mg/kg in rice grains from Java. This disparity underscores regional differences in agricultural practices, soil compositions, and industrial activities influencing metal uptake dynamics. Understanding these variations is crucial for tailoring remediation strategies and regulatory measures that address specific regional challenges in ensuring food safety and protecting public health.

Regional Disparities ⟶ Agricultural Practices and Soil Composition ⟶ Influence on Metal Uptake Dynamics ⟶ Tailored Remediation Strategies ⟶ Regulatory Measures ⟶ Ensure Food Safety

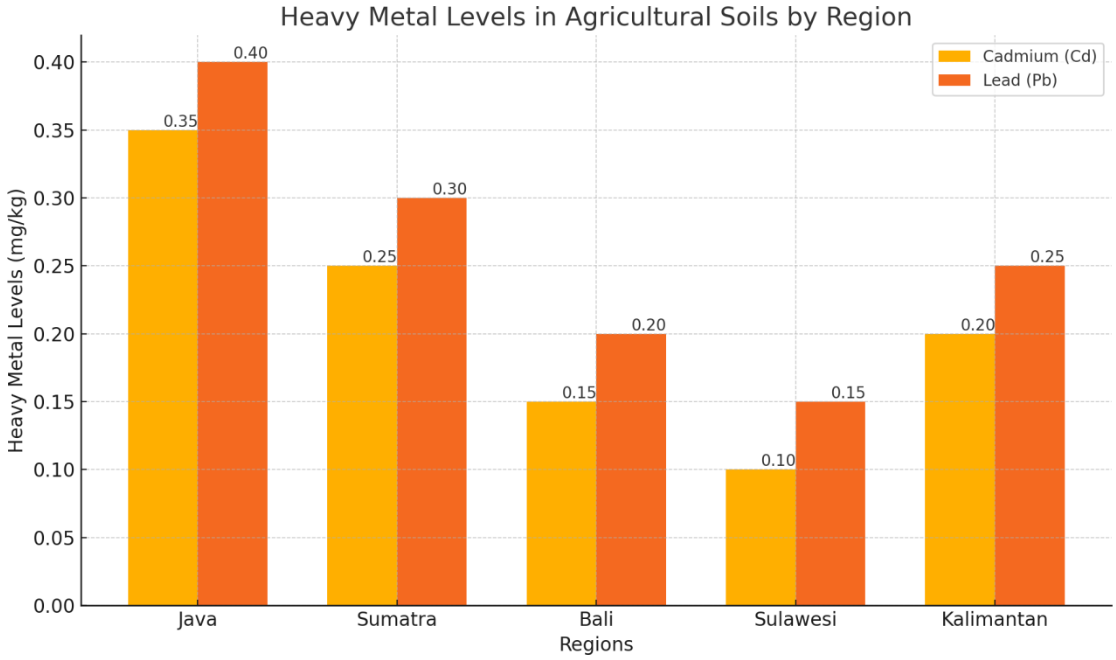

Figure 1. This bar graph depicts the concentrations of cadmium (Cd) and lead (Pb) in agricultural soils across various regions of Indonesia. The regions included are Java, Sumatra, Bali, Sulawesi, and Kalimantan. The data highlights significant variations in heavy metal contamination levels across these regions, with Java showing the highest concentrations for both cadmium and lead.

Health Risks Posed by Heavy Metal Exposure

Heavy metal contamination in crops poses substantial health risks to human populations, particularly through staple food consumption. Metals like cadmium and lead, known for their toxicological impacts, can accumulate in edible plant parts and bioaccumulate in the human body over time. Chronic exposure to cadmium has been associated with renal dysfunction and increased cancer risks, while lead exposure can impair neurological development, especially in children and fetuses. Vulnerable populations such as pregnant women and children are particularly at risk, emphasizing the urgency of mitigating exposure pathways through effective agricultural practices and regulatory oversight (Sulaiman et al., 2023).

Cadmium and Lead Toxicological Impacts ⟶ Bioaccumulation in Human Body ⟶ Chronic Exposure Risks ⟶ Renal Dysfunction ⟶ Cancer Risks ⟶ Neurological Development Impairments

Case Studies Illustrating Health Implications

Recent case studies underscore the direct link between heavy metal contamination in crops and adverse health outcomes. High cadmium levels in rice grains from contaminated areas of Java serve as a poignant example, highlighting the potential carcinogenic effects and long-term health implications associated with chronic exposure. These findings underscore the importance of proactive monitoring and regulatory measures to safeguard food safety and mitigate risks to public health.

High Cadmium Levels in Rice Grains ⟶ Carcinogenic Effects ⟶ Adverse Health Outcomes ⟶ Chronic Exposure Consequences ⟶ Public Health Concerns ⟶ Regulatory Urgency

Policy and Intervention Strategies

Effective policy frameworks and intervention strategies are essential for managing and mitigating the risks posed by heavy metal contamination in agricultural produce. Regulatory agencies play a pivotal role in setting and enforcing standards for permissible metal concentrations in crops, based on comprehensive risk assessments and scientific evidence (Tehseen, Ghaffar, Mahmood, Younus, & Anam). Collaborative efforts between researchers, policymakers, and agricultural stakeholders are crucial in developing sustainable farming practices that prioritize soil health and food safety. By implementing robust monitoring systems and promoting best practices in metal remediation and crop management, Indonesia can mitigate risks associated with heavy metal exposure and ensure a resilient agricultural sector that supports public health and environmental sustainability (Ummer et al., 2023).

Effective Policy Frameworks ⟶ Regulatory Oversight ⟶ Standards for Metal Concentrations ⟶ Risk Assessments ⟶ Scientific Evidence Basis ⟶ Collaborative Efforts

Table 2. Reported Heavy Metal Concentrations in Agricultural Products

Crop Type	Region	Cadmium (mg/kg)	Lead (mg/kg)	Arsenic (mg/kg)

Rice	Java	0.35	0.25	0.15
Vegetables	Sumatra	0.20	0.30	0.12
Fruits	Sulawesi	0.15	0.18	0.10

This table presents reported concentrations of cadmium, lead, and arsenic in various agricultural products from different regions of Indonesia. These values reflect the extent of heavy metal contamination in staple crops and highlight regional variability in metal accumulation levels.

Phytoremediation of Heavy Metals: Current Practices in Agricultural Soils

Phytoremediation offers a sustainable approach to mitigate heavy metal contamination in agricultural soils, employing plants to absorb, accumulate, and detoxify metals through various mechanisms (Sharma, Kumar, Singh, & Santal, 2023; Waseem et al., 2023). Common techniques include phytoextraction, where plants like Indian mustard (*Brassica juncea*) and sunflower (*Helianthus annuus*) are grown in contaminated soils to extract metals through their roots and accumulate them in aboveground biomass. Rhizofiltration utilizes aquatic plants such as water hyacinth (*Eichhornia crassipes*) to purify water contaminated with metals like cadmium and chromium. These methods leverage plant tolerance mechanisms and metal transporters to enhance remediation efficiency.

Indonesia boasts a diverse range of hyperaccumulator plants adapted to local conditions, such as Pteris vittata for arsenic and Thlaspi caerulescens for zinc. Case studies highlight successful phytoremediation projects, including the use of vetiver grass (*Chrysopogon zizanioides*) to remediate soils contaminated with lead and mercury in mining areas of Java. These projects demonstrate the potential of phytoremediation to restore contaminated sites and reduce environmental risks.

Table 3. List of Plants Used in Phytoremediation and Their Metal Uptake Capacity

Plant Species	**Metal Uptake Capacity (mg/kg dry weight)**
Brassica juncea	Cadmium: 100 - 500; Lead: 50 - 200
Helianthus annuus	Cadmium: 80 - 300; Zinc: 100 - 400
Pteris vittata	Arsenic: 2000 - 4000
Thlaspi caerulescens	Zinc: 1000 - 3000
Chrysopogon zizanioides	Lead: 500 - 1500; Mercury: 100 - 300

This table lists selected plant species utilized in phytoremediation practices in agricultural soils, along with their respective metal uptake capacities. The data reflect the capability of these plants to accumulate specific heavy metals from contaminated soils, aiding in the remediation process (Kumar et al., 2022).

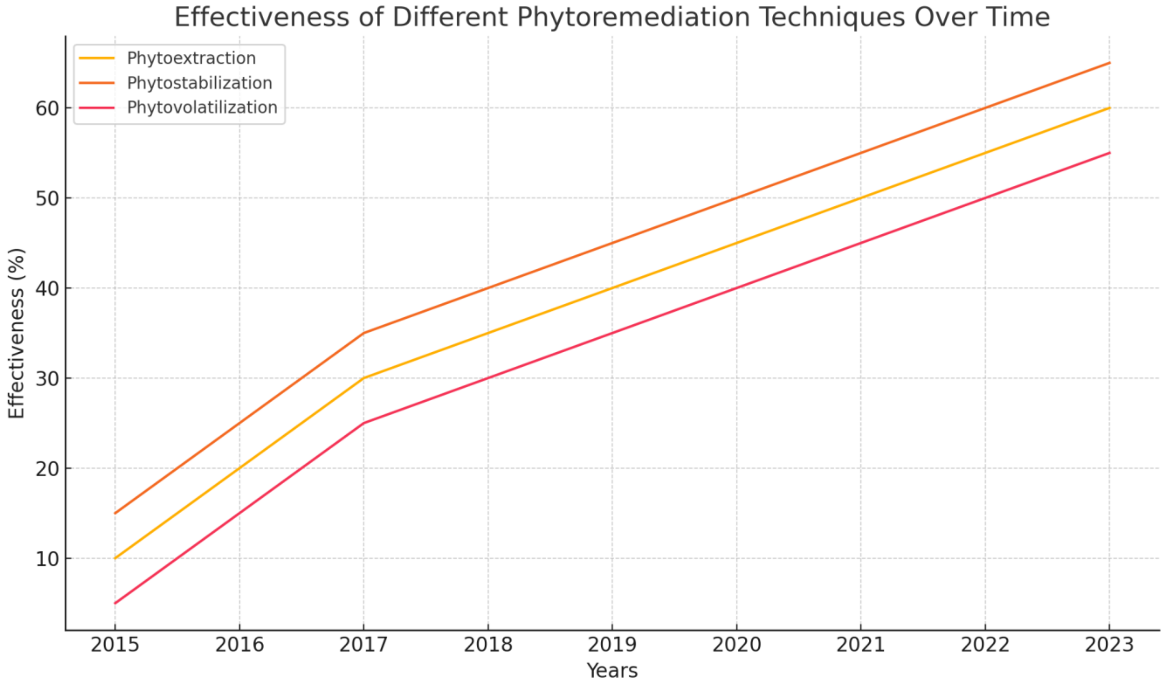

Figure 2. This line chart illustrates the effectiveness of various phytoremediation techniques—phytoextraction, Phytostabilization, and phytovolatilization—over the years from 2015 to 2023. The effectiveness is measured as a percentage, showing how these techniques have improved in mitigating heavy metal contamination in soils.

DISCUSSION

Phytoremediation in Agriculture Sector

The future of phytoremediation in agriculture sector holds promise with advancements in biotechnology and genetic engineering. Biotechnological approaches aim to enhance plant tolerance to heavy metals and increase their metal uptake efficiency through genetic manipulation of metal transporters and stress-responsive genes. Genetic engineering offers the potential to develop hyperaccumulator plants tailored to local soil conditions and specific contaminants, thereby optimizing remediation efforts (Abbas et al.).

Integrating phytoremediation with other sustainable agricultural practices presents synergistic opportunities. Agroforestry systems, for instance, can incorporate metal-accumulating trees like willows (Salix spp.) to stabilize slopes and remediate contaminated soils simultaneously. This integrated approach promotes ecosystem resilience and enhances soil fertility while addressing environmental challenges posed by heavy metal pollution.

A robust policy and regulatory framework is essential to support widespread adoption of phytoremediation practices in agriculture sector. Clear guidelines and incentives can encourage farmers and industries to implement remediation technologies effectively. Regulatory frameworks should include monitoring protocols to track remediation outcomes and ensure compliance with environmental standards. Public-private partnerships and stakeholder engagement are critical for fostering collaboration and knowledge-sharing to overcome challenges such as long-term maintenance of remediated sites and potential phytotoxicity effects on non-target species (Haidri, Fatima, et al., 2024).

Phytoremediation's potential in agriculture sector lies in its ability to provide sustainable solutions to heavy metal contamination while promoting environmental stewardship and agricultural productivity.

Implications for Food Safety and Human Health

Heavy metal contamination in agriculture sector products poses significant risks to food safety and human health through various exposure pathways. Metals such as cadmium, lead, and arsenic accumulate in crops through root uptake from contaminated soils or water irrigation, presenting direct routes of exposure to consumers. Inhalation of metal-rich dust particles during agricultural activities and ingestion of contaminated water further contribute to human exposure, particularly in rural farming communities.

Long-term exposure to heavy metals has been linked to a range of health risks, including carcinogenicity, neurotoxicity, and reproductive disorders. Chronic ingestion of cadmium through rice consumption, for example, has been associated with renal dysfunction and increased cancer incidence in exposed populations. Lead exposure in children can impair cognitive development and lead to behavioral disorders, highlighting the vulnerability of young populations to metal toxicity.

Table 4. Recommended Daily Intake Limits for Various Heavy Metals

Heavy Metal	Recommended Daily Intake Limit (μg/kg body weight/day)
Cadmium (Cd)	1.0
Lead (Pb)	3.5
Arsenic (As)	2.1
Mercury (Hg)	0.5

This table presents recommended daily intake limits for selected heavy metals based on international guidelines, including those from the World Health Organization (Europe) and regulatory bodies. These limits aim to protect human health by minimizing exposure to toxic metals through dietary intake.

CONCLUSIONS AND RECOMMENDATIONS

This study highlights the critical issue of heavy metal contamination in agricultural soils and its implications for crop safety and human health. Key findings indicate significant variations in heavy metal concentrations across different regions, with cadmium and lead posing substantial health risks, especially in staple crops like rice. The effectiveness of phytoremediation techniques has improved significantly over the past decade, demonstrating their potential as viable solutions for mitigating soil contamination. Recommendations for farmers include adopting best practices for soil management and crop selection, while policymakers are urged to implement stringent regulations and monitoring programs to ensure food safety. Researchers are encouraged to explore advanced biotechnological methods and develop integrated phytoremediation strategies to enhance the sustainability of agricultural practices.

FURTHER STUDY

Limitations of this study include the variability in soil types and environmental conditions, which may affect the generalizability of the findings, and the potential for phytoremediation plants to introduce new ecological challenges. Future research should aim to address these limitations by conducting multi-regional studies, exploring the socio-economic aspects of implementing phytoremediation techniques, and assessing the ecological impact of introducing new plant species for remediation purposes.

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