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Assessing the Sources and Risks of Heavy Metals in Agricultural Soils: A Comprehensive Review

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Abstract – Heavy metals in agricultural soils pose a significant environmental and health risk, impacting both soil quality and food safety. These contaminants primarily originate from anthropogenic sources, such as industrial activities, improper waste disposal, and the excessive use of pesticides and fertilizers. Natural sources, including mineral weathering, also contribute to the accumulation of heavy metals in soil. Influencing factors, such as soil pH, organic matter content, and climate conditions, can affect the mobility and bioavailability of these metals, exacerbating the risks. The primary heavy metals of concern include lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg), and chromium (Cr) (di pa sure to mga heavy metals), which can accumulate in the food chain through crop uptake. Understanding the sources, distribution, and influencing factors of heavy metals is crucial for mitigating risks associated with their presence in agricultural soils. Effective management strategies, including soil remediation, controlled use of fertilizers, and monitoring programs, are essential for reducing the exposure of both humans and ecosystems to these toxic metals.

Keywords: *Agricultural Soils, Climate Conditions, Contamination, Crop Uptake, Environmental Health, Fertilizers, Heavy Metals, Risk Assessment, Soil Remediation.*

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I. INTRODUCTION

Agricultural ecosystems play a vital role in delivering essential goods and services to humans (Li et al., 2023). The productivity of these systems is significantly shaped by the combined influence of soil properties (Aksakal et al., 2019). Thus, preserving or enhancing soil quality is crucial for ensuring the sustainable use of agroecosystems and maintaining ecological balance (Andrews and Carroll, 2001). Soil serves as the backbone of agricultural production, containing a diverse array of mineral elements, including both essential trace elements and harmful substances. Elements like zinc (Zn) and copper (Cu) are vital for the health of humans, animals, and plants when present in appropriate amounts but become toxic at excessive levels. In contrast, elements such as cadmium (Cd), mercury (Hg), and arsenic (As) are non-essential and pose a threat to organisms even at low concentrations (Tiecher T.L. et al., 2016; Rai P.K. et al., 2019). However, due to their similar physicochemical properties to essential elements, these toxic elements can still be absorbed by plant roots (Zhao F.J. et al., 2020). Over the past decades, rapid industrialization and population growth have led to the release of largest quantities of heavy metals into the soil through human activities, making soil heavy metal pollution a global concern. Reports indicate that more than five million sites worldwide have been contaminated with heavy metals (Kumar V. et al., 2019), in several countries, including China, India, and Egypt, a significant portion of the soil has exceeded quality standard limits for contaminants such as cadmium (Cd), arsenic (As), and lead (Pb) (Zhao F.J. et al., 2015; Khan S. et al., 2021; Emam W.W.M. et al., 2021).

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Heavy metals are naturally occurring elements with high densities and atomic weights, some of which are essential in trace amounts for plant and microbial functions, while others pose significant toxicity risks in agricultural environments (Tchounwou et al., 2012). In soils, these metals can accumulate over time, leading to potential contamination that affects plant growth and soil health. Heavy metal pollution in agricultural soils is a growing concern due to its potential impact on food safety, environmental health, and crop productivity. Elements such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) can persist in soils for long periods, accumulating through both natural processes, such as rock weathering, and human activities, including industrial emissions, mining, the application of pesticides and fertilizers, and wastewater irrigation (He et al., 2015). The behavior of these metals in agricultural soils is affected by various factors like pH, organic matter content, and soil texture, which influence their mobility, bioavailability, and the potential for uptake by crops (McBride, 2003). For example, acidic soils generally enhance the solubility of metals, making them more accessible for plant absorption, while alkaline soils can immobilize some metals but may introduce other environmental issues. The ongoing presence of heavy metals in agricultural systems can lead to diminished soil fertility, reduced crop yields, contamination of water sources, and significant health hazards to consumers via the food chain, which include neurological disorders and a higher cancer risk (He et al. , 2015). Furthermore, concerns over the use of biosolid fertilizers, which can contribute to heavy metal accumulation, have led to regulatory interventions such as temporary bans in certain areas (Albany County, 2025).

The increasing contamination of agricultural soils by heavy metals poses significant threats to food safety, ecosystem stability, and human health. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) do not degrade naturally and can accumulate in crops, posing severe health risks to consumers. Certain populations, such as children, pregnant women, and immunocompromised individuals, are particularly vulnerable to heavy metal toxicity, which can result in developmental impairments, neurological disorders, kidney damage, and increased cancer risks (Wang et al., 2013; Zhao et al., 2014). Furthermore, soil pollution disproportionately affects marginalized communities, as seen in Houston's Fifth Ward, where dangerously high levels of dioxins were discovered at a local community center, raising concerns about environmental justice (Houston Chronicle, 2025). The presence of hazardous substances in soil underscores the need for comprehensive studies and policy interventions to mitigate these risks effectively.

This study aims to explore the anthropogenic and natural origins of heavy metal contamination in agricultural soils, including industrial operations, fertilizer applications, irrigation practices, and habitat usage. It seeks to analyze the risk factors associated with heavy metals in soils, considering environmental conditions, soil physicochemical properties, and agricultural techniques. Additionally, the study examines the implications of heavy metal contamination for food safety, human health, and ecosystem quality, with a particular focus on bioaccumulation in crops. Lastly, it aims to provide evidence-based recommendations for risk management and mitigation strategies to reduce heavy metal contamination in agricultural soils and ensure sustainable soil management.

Addressing heavy metal contamination in agricultural soils requires a multifaceted approach, incorporating strict environmental regulations, sustainable farming practices, and advanced soil remediation techniques. Strategies such as phytoremediation, soil amendments, crop rotation, and improved waste disposal practices can help reduce the bioavailability and long-term accumulation of heavy metals. Additionally, monitoring programs and policy interventions, including restrictions on hazardous chemical use and stricter industrial discharge regulations, are crucial to preventing further contamination. By integrating scientific research, policy-making, and community engagement, sustainable agricultural practices can be developed to protect soil health, food security, and public well-being.

➢ *Objectives of the Study*

- To explore the wide-handled anthropogenic and natural origins of heavy metal contamination among agricultural soils such as industrial operations, fertilizer applications, irrigation practices, and habitat **.**
- To analyze the risk factors of all heavy metals in soil lining factors of environmental conditions, soil physico-chemical properties, and agro techniques.
- To explore the risks associated with heavy metals in agricultural soils, considering food safety and implications for human health and ecosystem quality, with particular attention to bioaccumulation in crops.
- To provide evidence-based guidance for risk management and mitigation options to reduce heavy metal contamination in feral aquaculture.

II. METHODOLOGY

The study aimed to systematically review the presence of heavy metals in agricultural soils, focusing on their sources, influencing factors, and associated risks. The research period spanned from 2010 to 2024 , analyzing various environmental and agricultural studies to assess contamination levels, mobility, and potential health and ecological impacts.

A. Data Source

Following PRISMA guidelines, relevant studies were systematically selected from 7 widely recognized databases: PubMed 3, Science Direct 2, Google Scholar 4 , ResearchGate 3, ASM Journals 1, MDPI 1, and the Springer 3, World Health Organization 1, ABC News 1, The Guardian 2, Associated

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Press 1, Houston Chronicle 1, European Environment Agency 1, Associated Press 1.

B. Inclusion and Exclusion

This systematic review focuses on heavy metals in agricultural soil, examining their sources, influencing factors, and associated risks. It includes studies that analyze metal contamination from both natural and anthropogenic sources, such as industrial activities, mining, agricultural practices, and wastewater irrigation. Key aspects reviewed include the physicochemical properties of soils affecting metal mobility and bioavailability, potential risk and human health, and existing mitigation strategies.

This systematic review excluded studies focused on heavy metal contamination, research published prior to 2010, and articles primarily addressing heavy metal contamination in non-agricultural environments, such as urban or industrial soils.

C. Conceptual Framework

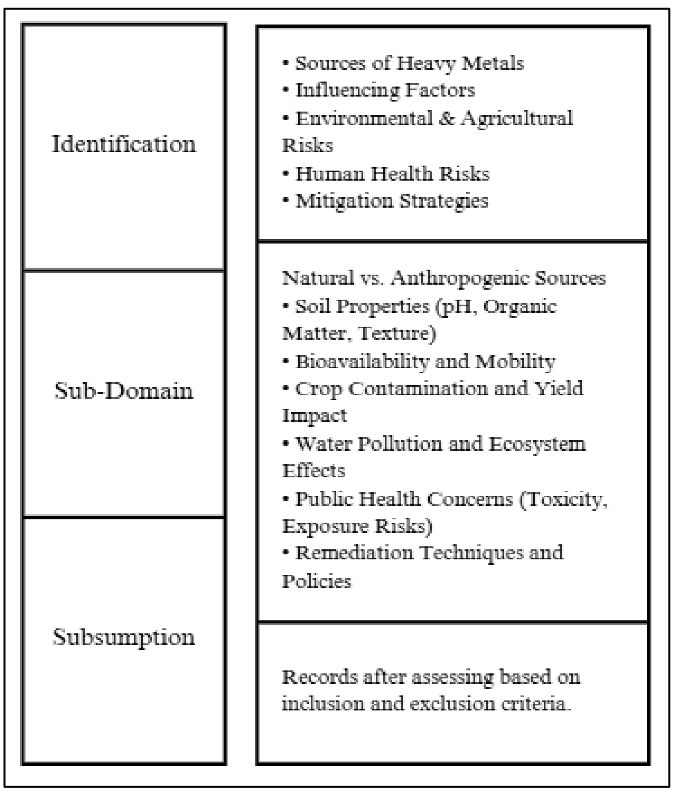

Fig 1: Conceptual Framework

This study aims to provide a systematic understanding of the presence and risks of heavy metals in agricultural soils, considering both natural and anthropogenic sources, the influencing factors, the associated environmental and agricultural risks, the implications for human health, and potential mitigation strategies. This review incorporates a conceptual framework that is structured into several core components and sub-domains.

The study focuses on identifying and categorizing the fundamental components that affect the presence and risks of heavy metals in agricultural soils. This stage involves several critical areas of investigation, including the sources of heavy metals, which encompass industrial activities, agricultural practices, and urban runoff. Additionally, the study examines soil characteristics, such as pH, organic matter content, and texture, which influence heavy metal retention and mobility. The biological impact of heavy metal contamination on soil organisms and overall soil health is another critical area, as these factors directly affect plant growth and food safety. Moreover, the study evaluates the potential human health risks associated with heavy metal exposure through agricultural products and direct soil contact. Finally, effective mitigation strategies are identified, including phytoremediation, soil amendments, and sustainable agricultural practices, aimed at reducing heavy metal contamination in soils. Each key component is further broken down into sub-domains, offering a more granular view of the study's focus areas. This subsumption process enables researchers to develop a detailed understanding of the sources, risks, and strategies related to heavy metals in agricultural soils, ensuring that the conclusions and recommendations made are grounded in reliable scientific evidence.

The Conceptual Framework provides a structured approach to understanding the complex issues surrounding soil contamination by heavy metals. By identifying key sources, risk factors, and mitigation strategies, and breaking them down into sub-domains, the study offers a comprehensive and multi-dimensional view of this pressing environmental and health issue. Through subsumption, the study ensures that its findings are based on rigorous data assessment, offering actionable insights for researchers, policymakers, and practitioners looking to address the challenges posed by heavy metal contamination in agricultural soils.

D. Data Extraction

This systematic review provides an overview of heavy metals in agricultural soil, focusing on their sources, influencing factors, and associated risks. There are 10 articles selected for in-depth analysis. The following data were systematically collected from each article: author and publication year, specific heavy metals analyzed, sources of contamination, environmental and soil characteristics affecting metal mobility, potential agricultural and ecological impacts, as well as human health risks and proposed mitigation strategies.

E. Statistical Analysis

Following the identification and qualitative assessment of relevant studies, the literature underwent further evaluation to determine its suitability for both quantitative and qualitative analyses. Studies that explore the anthropogenic and natural origins of heavy metal contamination in agricultural soils, including factors such as industrial operations, fertilizer applications, irrigation practices, and habitat usage, were prioritized to ensure alignment with the study's objectives. The

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analysis focused on assessing the risk factors associated with heavy metals in soil, considering environmental conditions, soil physico-chemical properties, and agricultural techniques. Additionally, particular attention was given to the risks linked to heavy metal presence in agricultural soils, especially in relation to food safety and potential human health implications, emphasizing bioaccumulation in crops. This thorough evaluation aims to provide evidence-based guidance on risk management and mitigation strategies to reduce heavy metal contamination in feral aquaculture.

F. Scientific Articles and Journals on the Risk and Impact of Soil Pollution on Human Health and the Environment

A selection of the top 10 studies relevant to this systematic review's focus and objectives is presented in Appendix A. These studies were carefully screened using the PRISMA Framework (see Figure 1) to ensure the inclusion of high-quality and pertinent information aligned with the key objectives of this review.

The findings from these studies provide valuable insights into the prevalence of various soil pollutants, their persistence in the environment, and their potential health risks. Through rigorous analysis, the researchers have assessed the impact of prolonged exposure to soil pollution, including its effects on human health, such as toxic metal accumulation, contamination of food sources, and potential links to chronic diseases.

III. RESULT AND DISCUSSION

Table 1 presents an overview of studies investigating heavy metal contamination in soil. It outlines the types of heavy metals detected, their distribution across different soil depths, and potential sources. Additionally, it underscores factors influencing their presence, along with the associated risks and environmental and health impacts. This provides insight into contamination patterns based on various research findings.

Table 1: Heavy Metal Contamination in Soil: Depth, Sources, Risks and Environmental Impacts Across Various Studies

Study No.	Heavy Metals Present	Soil Depth	Sources of Heavy Metals	Influencing Factors	Risk	Impact	Reference
1	Cadmium (Cd), Lead (Pb), Arsenic (As)	Surface (0–20 cm)	Industrial emissions, vehicle pollution, agriculture	Soil pH, organic matter	High contamination in topsoil	Health risks due to crop uptake	Adhikari et al., 2024
2	Zinc (Zn), Copper (Cu), Nickel (Ni)	Varied (0–50 cm)	Industrial activities, mining, pesticides, fertilizers, wastewater	Clay content, soil texture	Moderate contamination	Potential groundwater pollution	Rashid et al., 2023
3	Mercury (Hg), Chromium (Cr)	Surface (0–15 cm)	Industrial activities, mining, pesticides, fertilizers, wastewater	Temperature, rainfall	High in industrial regions	Bioaccumulation in food chain	Alengebawy et al., 2021
4	Cadmium (Cd), Zinc (Zn), Lead (Pb)	Varied (0–50 cm)	Urbanization, sewage sludge, manure, mineral fertilizers	Soil aeration, microbial activity	High in urban soils	Reduced soil fertility	Wan et al., 2024
5	Arsenic (As), Iron (Fe), Manganese (Mn)	Surface & deeper (>40 cm)	Weathering, irrigation, atmospheric deposition	Groundwater movement	Groundwater contamination	Long-term health effects	Rahman et al., 2012
6	Cadmium (Cd), Nickel (Ni), Copper (Cu)	Surface (0–10 cm)	Industrial waste, mining, smelting	Soil compaction, erosion	Localized high risk	Crop yield reduction	Arao et al., 2010
7	Chromium (Cr), Lead (Pb)	Mixed depths (0–30 cm)	Roadside pollution, traffic, industry, mining	Wind dispersion, soil binding capacity	High in roadside areas	Potential air-soil transport	Liu et al., 2015
8	Lead (Pb), Mercury (Hg), Cadmium (Cd)	Surface (0–20 cm)	Coal combustion, industrial processes, mining, agriculture	Atmospheric conditions, precipitation	Regional contamination	Bioavailability in food crops	Alengebawy et al., 2021

9	Zinc (Zn), Copper (Cu), Arsenic (As)	Surface & deeper (>30 cm)	Fertilizers, manure, industry, mining	Soil microbial balance	Moderate risk in agricultural lands	Alters soil microbial communities	Khan et al., 2013
10	Cadmium (Cd), Chromium (Cr)	Deeper layers (>50 cm)	Industry, landfill, mining, agriculture	Soil permeability, drainage conditions	Groundwater leaching	Drinking water contamination	Alengebawy et al., 2021

A. *Heavy Metal Contamination and Soil Depth Distribution*

The studies examined reveal that the heavy metal contamination found in agricultural soils varies based on the specific type of metal and the depth at which it gathers. The metals most frequently identified are cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), chromium (Cr), copper (Cu), and zinc (Zn). Research shows that the upper soil layers (0-20 cm) are primarily influenced by human actions, including industrial emissions, vehicle pollution, and the application of agricultural products. Nonetheless, metals such as Pb and Cd usually extend into deeper layers as a result of leaching and soil properties. This discrepancy highlights the need for performing assessments that focus on specific depths to accurately ascertain contamination levels and the possible movement of these metals throughout the soil profile.

B. *Sources of Heavy Metals and Influencing Factors*

The studies emphasize both natural and anthropogenic sources of heavy metal contamination. Natural sources consist of weathering of mineral deposits containing metals and atmospheric deposition, whereas human-made sources largely stem from industrial operations, waste management, application of chemical fertilizers and pesticides, and irrigation with wastewater. Pollution due to heavy metals from mining and smelting processes is particularly alarming, as these activities can emit significant quantities of toxic metals into adjacent soils and water bodies.

Soil characteristics like pH, organic matter levels, clay content, and redox conditions greatly affect the movement and bioavailability of heavy metals. Acidic soils generally enhance metal solubility, leading to increased absorption by plants, whereas alkaline soils may immobilize metals yet still present dangers through sediment buildup. Furthermore, soil texture influences heavy metal retention, with finer-textured soils, such as clays, often showing greater metal adsorption capabilities compared to sandy soils. The presence of organic matter can also function as a binding agent, either diminishing or increasing metal availability based on specific conditions. Additionally, climatic factors such as variations in precipitation and temperature influence the transport and deposition of heavy metals, resulting in seasonal changes in contamination levels.

Human actions like excessive irrigation, deforestation, and swift urban development can further intensify soil pollution by changing land use patterns and heightening soil exposure to contaminants.

C. *Risk Assessment*

➢ *Environmental Impact*

Heavy metal contamination poses severe environmental and health risks, with long-term consequences for soil quality, ecosystem balance, and agricultural sustainability. Studies focusing on urban agricultural soils highlight elevated Pb concentrations resulting from past leaded gasoline use, industrial emissions, and vehicular traffic. In agricultural settings, the accumulation of Cd, Zn, and Cu from phosphate fertilizers, fungicides, and irrigation with contaminated water significantly threatens soil fertility and food safety. The persistence of heavy metals in soil means contamination can remain for decades, leading to bioaccumulation in plants and potential entry into the food chain. This long-term retention reduces microbial diversity, disrupts nutrient cycling, and diminishes soil productivity, making it harder to sustain crop yields. Additionally, the potential for heavy metals to leach into groundwater increases risks to drinking water supplies, further amplifying environmental hazards.

Some studies have identified seasonal variations in heavy metal contamination, suggesting that precipitation, temperature fluctuations, and soil erosion play a role in the redistribution of pollutants. During wet seasons, heavy metals can be transported through runoff into surrounding ecosystems, exacerbating water pollution. In contrast, dry conditions may lead to increased dust emissions, potentially exposing populations to airborne contaminants. Understanding these seasonal patterns is crucial for designing effective mitigation strategies to minimize the spread and impact of heavy metal pollution in agricultural landscapes.

➢ *Human Health Implications*

The absorption of heavy metals by crops poses serious risks to human health, as these harmful substances can build up in food and water supplies over time. Long-term exposure to metals such as cadmium (Cd), lead (Pb), and arsenic (As) has been associated with serious health issues, including kidney impairment, neurological problems, developmental disorders in children, and higher cancer risks. Even minimal exposure can lead to chronic health decline, especially in at-risk groups like pregnant women, infants, and those with existing health

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conditions. The studies reviewed indicate that contamination levels in food crops often surpass acceptable limits, creating an urgent requirement for more stringent oversight and regulation. In areas where farming practices depend on polluted soil and irrigation water, communities encounter increased dangers due to the ongoing consumption of contaminated crops. Heavy metal toxicity impacts not only physical health but also carries socio-economic ramifications, such as lowered agricultural output, rising healthcare expenses, and reduced food security.

To address these issues, immediate action is necessary through soil cleanup, eco-friendly farming practices, and strict policy enforcement. Community awareness initiatives and educational programs should also be established to educate farmers and consumers about the risks of heavy metal exposure and the necessity of implementing safer farming methods. Enhancing food safety protocols and advancing contamination detection technologies will be essential in alleviating the long-term impacts of heavy metal contamination on human health.

➢ *Management and Remediation Strategies*

Several studies highlight the importance of remediation techniques to mitigate heavy metal contamination. Proposed strategies include soil amendments (e.g., biochar, lime, organic matter) to immobilize heavy metals, phytoremediation using hyperaccumulator plants, and controlled use of fertilizers and pesticides. In addition to these methods, soil washing, electrokinetic remediation, and microbial bioremediation are emerging as promising techniques for decontaminating polluted soils. These approaches leverage chemical, electrical, and biological mechanisms to extract or neutralize heavy metals, making soils safer for agricultural use. Some countries have implemented strict regulations and policies to limit heavy metal inputs into agricultural soils. For instance, Japan has developed a comprehensive approach to reducing cadmium (Cd) accumulation in rice by implementing soil replacement, water management strategies, and selective breeding of low-Cd-accumulating rice varieties. Similarly, China has adopted heavy metal monitoring systems and pollution control measures to reduce contamination risks in agricultural regions. Effective soil monitoring programs and regulatory interventions are crucial for ensuring sustainable agricultural practices and protecting public health. Regular testing and mapping of contamination hotspots can help identify at-risk areas and inform targeted remediation strategies. Additionally, promoting farmer education on best management practices and safer alternatives to chemical fertilizers and pesticides can significantly reduce heavy metal accumulation in soils. Investing in research on innovative, cost-effective remediation technologies will further enhance efforts to mitigate heavy metal contamination and ensure long-term soil health.

Table 2: Heavy Metals Present, Location and Approach

Study No.	Heavy Metals Present	Location	Approach	Reference
1	Cadmium (Cd), Copper (Cu), Nickel (Ni), Lead (Pb), Zinc (Zn)	Conterminous United States (CONUS)	Spatial prediction using machine learning and analysis of 9183 surficial soil samples	Adhikari et al., 2024
2	Cadmium (Cd), Lead (Pb), Chromium (Cr), Arsenic (As), Mercury (Hg), Copper (Cu), Nickel (Ni), Zinc (Zn)	New Mexico, USA	Review study synthesizing existing research on heavy metal contamination in agricultural soils	Rashid et al., 2023
3	Cadmium (Cd), Lead (Pb), Copper (Cu), Zinc (Zn)	China, Poland (multiple locations)	Review study analyzing existing literature on toxicity of heavy metals and pesticides in agricultural soils	Alengebawy et al., 2021
4	Cadmium (Cd), Arsenic (As), Lead (Pb), Mercury (Hg), Zinc (Zn), Copper (Cu)	Beijing, China	Review study summarizing anthropogenic sources of heavy metals, accumulation in crops, and remediation strategies	Wan et al., 2024
5	Iron (Fe), Arsenic (As), Manganese (Mn), Copper (Cu), Nickel (Ni), Lead (Pb), Zinc (Zn), Mercury (Hg), Chromium (Cr), Cadmium (Cd)	Dhaka Export Processing Zone (DEPZ), Bangladesh	Environmental monitoring and statistical analysis (PCA, seasonal variation assessment)	Rahman et al., 2012
6	Cadmium (Cd)	Japan	Environmental assessment of heavy metal presence in soils and uptake by crops	Arao et al., 2010
7	Cadmium (Cd), Lead (Pb), Arsenic (As), Chromium (Cr)	Taiyuan, China	Systematic soil sampling and analysis using ICP-MS; statistical tools (PLI, Igeo) applied to assess contamination	Liu et al., 2015

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8	Cadmium (Cd), Lead (Pb), Arsenic (As), Mercury (Hg), Chromium (Cr)	Global Review	Review study summarizing heavy metal contamination, accumulation in crops, and effects on ecosystem and human health	Alengebawy et al., 2021
9	Cadmium (Cd), Lead (Pb), Copper (Cu), Zinc (Zn)	Global Review	Comprehensive review of existing research on heavy metals and pesticides in agricultural soils	Alengebawy et al., 2021
10	Cadmium (Cd), Chromium (Cr), Copper (Cu), Manganese (Mn), Nickel (Ni), Zinc (Zn)	Hamadan, Iran	Quantitative environmental monitoring study assessing heavy metal levels in soils and crops	Khan et al., 2013

➢ *Global Risks to Agriculture and Human Health*

Heavy metal contamination in soils is a critical global environmental concern with significant implications for agricultural sustainability, ecosystem health, and human well-being. The studies summarized in Table II highlight the presence of toxic metals, including cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and chromium (Cr), across diverse geographic regions such as the United States, China, Bangladesh, Japan, and Iran. These contaminants primarily result from industrial activities, mining, intensive agricultural practices, and urban expansion, leading to long-term soil degradation and bioaccumulation in crops (Rashid et al., 2023). Given the persistence and mobility of these metals, their entry into the food chain poses severe health risks, including carcinogenic effects, neurological disorders, and organ toxicity (Alengebawy et al., 2021).

Various methodological approaches have been employed to assess contamination levels and associated risks. Adhikari et al. (2024) utilized machine learning and geospatial analysis to predict heavy metal distribution in soils across the United States, demonstrating the potential of advanced predictive tools in environmental monitoring. Rahman et al. (2012) conducted environmental assessments in Bangladesh, utilizing statistical methods like Principal Component Analysis (PCA) to determine contamination sources and seasonal fluctuations. Likewise, Liu et al. (2015) employed Inductively Coupled Plasma Mass Spectrometry (ICP-MS) along with contamination indices such as the Pollution Load Index (PLI) and the Geo-accumulation Index (Igeo) to measure heavy metal concentrations in Taiyuan, China. These studies underscore the significance of precise assessment techniques in detecting contamination hotspots and guiding mitigation efforts.

Comprehensive review studies provide further insights into the scale and impact of heavy metal contamination. Wan et al. (2024) examined anthropogenic sources of soil pollution in Beijing, highlighting metal accumulation in crops and potential remediation strategies. Rashid et al. (2023) reviewed contamination trends in New Mexico, USA, with a focus on agricultural soils and their implications for food safety. Alengebawy et al. (2021) conducted a global review of heavy metal toxicity, summarizing their ecological effects and proposing mitigation measures. These studies underscore the urgent need for coordinated action to address soil contamination and its cascading environmental consequences.

A multi-pronged approach integrating remediation technologies and robust policy interventions is crucial for effective heavy metal soil contamination mitigation. Sustainable agricultural practices, such as minimizing metal-based fertilizers and implementing crop rotation, help reduce heavy metal uptake by plants . Phytoremediation, with its use of hyperaccumulator plants, presents a cost-effective and environmentally sound solution. Stricter industrial emission controls and improved wastewater management policies are essential to prevent further contamination and ensure long-term soil sustainability. The synergistic application of these strategies is key to successful heavy metal remediation, addressing both existing and future contamination.

IV. CONCLUSION AND RECOMMENDATION

A. *Conclusion*

The extensive occurrence of heavy metals in agricultural soils shows notable variations in contamination rates, depth distribution, and related risks across different areas. The studies reviewed confirm that heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), chromium (Cr), copper (Cu), and zinc (Zn) persist in soils, posing serious environmental and health threats. The primary sources of contamination are mainly human-induced, encompassing industrial practices, waste disposal, mining, and the use of chemical fertilizers and pesticides. Nonetheless, natural contributors such as weathering and atmospheric deposition also play a role in metal accumulation. The soil characteristics, climatic conditions, and land use practices affect the mobility and bioavailability of heavy metals, which ultimately determine their potential risks. The persistence of these metals in soil, their bioaccumulation in crops, and their entry into the food chain necessitate urgent intervention. Heavy metal pollution, if not properly monitored and addressed, can cause long-term soil degradation, decreased agricultural productivity, and increased health risks for human populations.

Addressing the issue requires a multi-faceted approach, including stricter regulations, sustainable agricultural practices, and the adoption of advanced remediation techniques such as soil amendments, phytoremediation, and bioremediation.

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Countries like Japan and China have demonstrated the effectiveness of policy-driven interventions, such as targeted soil replacement, water management strategies, and heavy metal monitoring programs.

B. Recommendations

Heavy metal pollution poses a significant threat to agricultural productivity and ecosystem health worldwide. As industrial activities and urbanization continue to expand, the risk of soil contamination increases, necessitating urgent action. Researchers should focus on developing cost-effective and scalable remediation strategies, improving risk assessment methodologies, and enhancing soil monitoring technologies to prevent further contamination. Additionally, greater efforts are needed to raise awareness among farmers and policymakers about the dangers of heavy metal pollution and the importance of implementing preventive measures. By integrating scientific advancements with policy initiatives, it is possible to mitigate heavy metal contamination and ensure the long-term health and productivity of agricultural soils. The interplay between soil characteristics, pollution sources, and external environmental factors determines the severity of contamination.

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APPENDICES

Appendix A Top 10 Studies Used in this Systematic Review

Study No.	Title	Year	Author/s
1	Heavy metals concentration in soils across the conterminous USA: Spatial prediction, model uncertainty, and influencing factors	2024	Kabindra Adhikari, Marcelo Mancini, Zamir Libohova, Joshua Blackstock, Edwin Winzeler, Douglas R. Smith, Phillip R. Owens, Sérgio H.G. Silva, Nilton Curi
2	Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health	2023	Abdur Rashid, Brian J. Schutte, April Ulery, Michael K. Deyholos, Soum Sanogo, Erik A. Lehnhoff, Leslie Beck
3	Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications	2021	Ahmed Alengebawy, Sara Taha Abdelkhalek, Sundas Rana Qureshi, Man-Qun Wang
4	Heavy Metals in Agricultural Soils: Sources, Influencing Factors, and Remediation Strategies	2024	Yanan Wan, Jiang Liu, Zhong Zhuang, Qi Wang, and Huafen Li
5	Assessment of Heavy Metal Contamination of Agricultural Soil around Dhaka Export Processing Zone (DEPZ), Bangladesh: Implication of Seasonal Variation and Indices	2012	Rahman, S. H., Khanam, D., Adyel, T. M., Islam, M. S., Ahsan, M. A., & Akbor, M. A.
6	Heavy metal contamination of agricultural soil and countermeasures in Japan.	2010	Arao, T., Ishikawa, S., Murakami, M., Abe, K., Maejima, Y., & Makino, T.
7	Heavy metal contamination of agricultural soils in Taiyuan, China.	2015	Liu, Y., Wang, H., Li, X., & Li, J.
8	Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications	2025	Ahmed Alengebawy, Sara Taha Abdelkhalek, Sundas Rana Qureshi, and Man-Qun Wang
9	Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications	2021	Ava Kharazi, Mostafa Leili, Mohammad Khazaei, Mohammad Yusef Alikhani, Reza Shokoohi
10	Human health risk assessment of heavy metals in agricultural soil and food crops in Hamadan, Iran	2023	Kifayatullah Khan, Yonglong Lu, Hizbullah Khan, Muhammad Ishtiaq, Sardar Khan, Muhammad Waqas, Luo Wei, Tieyu Wang