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Review Article

Review of Heavy Metal Removal from Soil: Methods and Technologies

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Abstract: Soil health is vital for ecosystem functioning, agriculture, and human well-being, yet heavy metal contamination poses significant risks to environmental and public health. This review examines various methods for removing heavy metals from contaminated soils, focusing on physical, chemical, and biological remediation techniques. Sources of contamination, including industrial activities, mining, and improper waste disposal, are discussed, alongside the environmental and health impacts of heavy metals like lead, cadmium, and mercury. Physical techniques such as soil washing and excavation effectively reduce contamination but generate secondary waste and incur high costs. Chemical methods, including soil stabilization and chemical leaching, immobilize or extract metals but may risk recontamination. Biological approaches like phytoremediation and bioremediation leverage natural processes for eco-friendly remediation, though they often require longer timescales for significant results. Emerging technologies, such as nanotechnology and biochar application, show promise for enhancing remediation efficacy. However, challenges remain, including economic constraints, regulatory inconsistencies, and the need for sustainable, long-term solutions. Future directions include integrating various remediation techniques, developing eco-friendly technologies, and emphasizing long-term monitoring to ensure the effectiveness of remediation efforts. This comprehensive overview aims to inform future research and policy development to address heavy metal contamination sustainably.

Keywords: Heavy Metal Contamination, Remediation Techniques, Physical Methods, Chemical Methods, Biological Methods, Nanotechnology, Sustainability.

1. INTRODUCTION

Soil health is critical for ecosystem function, agriculture, and human well-being. Healthy soils support plant growth, regulate water, and sustain biodiversity, while providing a buffer against pollution. However, contamination by heavy metals threatens soil quality, posing serious risks to both the environment and human health. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr), and zinc (Zn) are particularly harmful due to their toxicity, persistence, and ability to bioaccumulate in organisms (Järup, 2003; Hassan and Umer, 2022).

The objective of this review is to provide a comprehensive overview of the various methods and approaches for the removal of heavy metals from contaminated soils. By analyzing physical, chemical, and biological remediation techniques, this paper seeks to outline their advantages, limitations, and

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potential future developments. Emphasis is placed on the need for sustainable, cost-effective methods that address both short-term and long-term contamination challenges (Mulligan, Yong & Gibbs, 2001).

1.1 Sources of Contamination

The primary sources of heavy metal contamination in soils include:

Industrial Activities:

Metal smelting, manufacturing, and fossil fuel combustion release significant amounts of metals into the environment (Alloway, 2012; Hassana and Umerb, 2022).

Mining:

Mining operations for metals and minerals often lead to the leaching of heavy metals into nearby soils and water bodies (Tchounwou *et al*., 2012).

Wastewater Irrigation:

The use of untreated or poorly treated wastewater for irrigation introduces metals like lead, mercury, and cadmium into agricultural soils (Hassan and Al-Barware, 2016; Chaoua *et al*., 2019).

Agricultural Runoff:

Fertilizers, pesticides, and herbicides can contain heavy metals, which leach into soils during agricultural activities (Li *et al.,* 2019).

Improper Disposal of Hazardous Waste:

Inadequate disposal methods for industrial waste, e-waste, and other hazardous materials contribute to the accumulation of heavy metals in soils (Kiddee, Naidu & Wong, 2013).

1.2 Environmental and Health Impacts

Heavy metals are non-biodegradable and can persist in the soil for long periods, leading to adverse effects. Contaminated soils affect plant growth and microbial communities, reducing soil fertility. These metals enter food chains through plant uptake, posing health risks to animals and humans. Health issues associated with heavy metal exposure include neurotoxicity, cancer, organ damage, and developmental disorders (Wuana & Okieimen, 2011). For instance, lead exposure can lead to cognitive impairment and developmental delays in children, while cadmium is linked to kidney damage and osteoporosis (Godt *et al*., 2006).

2. MECHANISMS OF HEAVY METAL CONTAMINATION AND IMPACT

2.1 Sources of Contamination: Natural vs. Anthropogenic

Heavy metal contamination in soils can arise from both natural and anthropogenic sources. Natural sources include volcanic activity, weathering of metal-containing rocks, and forest fires, which release metals like arsenic (As), lead (Pb), and mercury (Hg) into the environment (Alloway, 2012). Anthropogenic sources are predominantly linked to human activities such as industrial emissions, mining, smelting, agricultural practices, and waste disposal (Nagajyoti *et al*., 2010). Industrial processes, including fossil fuel combustion and metal processing, are among the major contributors to anthropogenic heavy metal pollution, releasing elements such as cadmium (Cd), chromium (Cr), and zinc (Zn) into surrounding ecosystems (Wuana & Okieimen, 2011).

2.2 Mobility and Bioavailability

The mobility and bioavailability of heavy metals in soil are influenced by several factors, including pH, cation exchange capacity, organic matter content, and soil texture. Metals tend to become more mobile and bioavailable under acidic conditions, as lower pH levels increase metal solubility, enhancing their uptake by plants and leaching into groundwater (Tchounwou *et al*., 2012). Conversely, soils rich in organic matter or with a high cation exchange capacity can immobilize heavy metals by forming stable complexes, reducing their availability for plant uptake (Alloway, 2013). Soil texture also plays a role, with clay soils generally retaining metals more effectively than sandy soils due to their greater surface area and binding capacity (Li *et al*., 2019).

2.3 Toxicological Effects

Heavy metal toxicity affects various organisms differently, but its adverse impacts on plants, microorganisms, and humans are well-documented.

Plants:

Heavy metal exposure can disrupt essential processes such as photosynthesis, nutrient uptake, and water balance, leading to stunted growth, chlorosis, and even plant death (Nagajyoti *et al*., 2010). Metals like lead (Pb) and cadmium (Cd) can interfere with the production of chlorophyll, reducing photosynthetic efficiency and overall plant vitality (Rizwan *et al*., 2016).

Microorganisms:

Soil microorganisms are essential for nutrient cycling and organic matter decomposition. However, heavy metals can reduce microbial diversity and activity by inhibiting enzymatic processes and metabolic functions (Wuana & Okieimen, 2011). This disruption compromises soil fertility and ecosystem functioning.

Humans:

The consumption of crops grown in contaminated soils can result in the accumulation of heavy metals in the human body, leading to severe health problems. Exposure to metals like lead and mercury can cause neurological damage, cognitive impairments, and developmental delays, especially in children (Khan *et al*., 2008). Long-term exposure to cadmium is associated with kidney dysfunction and osteoporosis, while arsenic and chromium are known carcinogens (Järup, 2003).

3. PHYSICAL REMEDIATION TECHNIQUES

3.1 Soil Washing

Soil washing is a widely used physical remediation technique that employs aqueous solutions, often combined with surfactants or chelating agents, to leach out heavy metals from contaminated soils (Mulligan, Yong & Gibbs, 2001). The process is effective for extracting metals by dissolving them into the liquid phase, which can then be separated from the soil particles. Efficiency of soil washing largely depends on the soil properties (such as particle size, organic matter content, and pH) and the type of contaminant present (Wuana & Okieimen, 2011). For example, sandy soils are easier to treat than clay soils because of their larger particle size and lower adsorption capacity for metals (Alloway, 2013).

Advantages of soil washing include its effectiveness in reducing contamination at highly polluted sites, particularly where heavy metals are present in soluble or exchangeable forms (Mulligan *et al*., 2001). However, one significant limitation is that the process generates secondary waste, in the form of contaminated wash water and residual soil slurries, which require further treatment or disposal (Wuana & Okieimen, 2011).

3.2 Soil Excavation and Disposal

Soil excavation and disposal is a traditional method that involves physically removing contaminated soil from the site and replacing it with clean soil. This technique is often employed for areas with severe contamination where immediate risk reduction is needed (Nagajyoti *et al*., 2010). It is considered a straightforward method because it eliminates the source of contamination entirely, ensuring that the site is safe for reuse.

However, soil excavation is an expensive and non-sustainable option, as it requires transporting large volumes of soil to designated landfills, which can be costly and pose logistical challenges (Wuana & Okieimen, 2011). Moreover, landfill disposal raises concerns about the long-term environmental impact, as the contaminants are not neutralized but simply relocated (Tchounwou *et al*., 2012).

3.3 Vitrification

Vitrification involves heating the contaminated soil to high temperatures (typically between 1,200°C and 2,000°C) to immobilize heavy metals by incorporating them into a glass-like structure (Mulligan *et al*., 2001). The high temperature alters the chemical state of the metals, reducing their mobility and bioavailability. This technique is suitable for small areas with high levels of contamination, such as industrial sites or hazardous waste dumps (Wuana & Okieimen, 2011).

While vitrification effectively immobilizes metals and reduces long-term environmental risks, it is an energy-intensive and costly process (Nagajyoti *et al*., 2010). Additionally, it is typically applied to localized contamination rather than large-scale areas due to the high costs associated with the technology (Alloway, 2013).

4. CHEMICAL REMEDIATION TECHNIQUES

4.1 Soil Stabilization and Solidification

Soil stabilization and solidification (S/S) is a widely used chemical remediation technique that involves the addition of stabilizing agents such as lime, cement, or other binding materials to contaminated soil. The purpose of this method is to immobilize heavy metals by converting them into less soluble and less mobile forms, thus preventing their leaching into groundwater or being taken up by plants (Mulligan, Yong & Gibbs, 2001). Although S/S effectively reduces the mobility of contaminants, it does not remove the metals from the soil, meaning that the contamination remains on site (Wuana & Okieimen, 2011). The technique is particularly advantageous for treating sites with heavy metal contamination, as it is relatively cost-effective and can be applied to a wide range of contaminants (Alloway, 2013).

However, one limitation is that stabilization and solidification only address the mobility of contaminants and do not offer a permanent solution, as the metals remain in the soil and may become mobile again if environmental conditions change (e.g., pH shifts) (Tchounwou *et al*., 2012). Additionally, large volumes of stabilizing materials may be required, which can increase costs and alter the physical properties of the soil.

4.2 Chemical Leaching

Chemical leaching is a remediation technique that involves applying chemicals to contaminated soil to solubilize heavy metals, allowing them to be removed through extraction (Wuana & Okieimen, 2011). Chelating agents such as EDTA (ethylenediaminetetraacetic acid) are commonly used because they form strong bonds with metal ions, enhancing their mobility and facilitating their removal from the soil matrix (Nagajyoti *et al*., 2010). The use of EDTA is particularly effective for metals like lead (Pb), cadmium (Cd), and zinc (Zn), as it binds with these metals and makes them available for extraction (Mulligan *et al*., 2001).

One of the primary advantages of chemical leaching is that it offers a removal mechanism for heavy metals, unlike stabilization, which only immobilizes them. However, chemical leaching also has limitations, including the risk of introducing secondary pollution from the leaching agents themselves and the potential for remobilizing other contaminants (Alloway, 2013). The method is also highly dependent on soil properties such as pH and organic matter content, which can affect the efficiency of metal removal (Wuana & Okieimen, 2011).

4.3 Electrokinetic Remediation

Electrokinetic remediation uses an applied electric field to mobilize metal ions in the soil, allowing them to migrate toward electrodes where they can be extracted (Tchounwou *et al*., 2012). This technique is particularly suitable for soils with low permeability, such as clay or silt, where conventional methods like soil washing are less effective (Wuana & Okieimen, 2011). The electric field induces the movement of charged metal ions (like lead, cadmium, and arsenic) toward electrodes, where they are collected and removed from the soil.

Despite its effectiveness, electrokinetic remediation has some drawbacks, primarily related to cost and energy requirements. The process can be expensive due to the need for specialized equipment and the high energy consumption required to maintain the electric field (Mulligan *et al*., 2001). Moreover, electrokinetic methods may be less effective in soils with high organic matter content, which can interfere with the movement of ions (Nagajyoti *et al*., 2010).

5. BIOLOGICAL REMEDIATION TECHNIQUES

5.1 Phytoremediation

Phytoremediation involves using plants to remediate contaminated soils by either extracting or stabilizing heavy metals (Wuana & Okieimen, 2011). This method is eco-friendly and cost-effective as it relies on natural plant processes to either uptake (phytoextraction), immobilize (phytostabilization), or transform (phytovolatilization) heavy metals (Ali, Khan & Sajad, 2013). Phytoextraction focuses on the removal of metals from the soil through plant uptake, while phytostabilization involves using plants to stabilize contaminants in the soil and prevent their spread. Phytovolatilization transforms metals, such as mercury (Hg), into a gaseous state, which plants release into the atmosphere (Salt, Smith & Raskin, 1998).

While phytoremediation is promising due to its low cost and environmentally benign nature, its limitations include being a slow process that may take several growing seasons to achieve significant metal removal. Moreover, the effectiveness of this method depends on the bioavailability of metals in the soil, which varies with soil pH, organic matter, and the presence of competing ions (Wuana & Okieimen, 2011).

5.2 Bioremediation

Bioremediation utilizes microorganisms, such as bacteria and fungi, to either degrade or transform heavy metals into less toxic or immobile forms (Tchounwou *et al*., 2012). Bioleaching involves using microbes to leach out metals from soil, while biosorption relies on the adsorption of metals onto the cell walls of microorganisms. Additionally, microbial reduction of metals, like the conversion of hexavalent chromium (Cr6+) to the less toxic trivalent form (Cr3+), is a common bioremediation strategy (Mulligan, Yong & Gibbs, 2001).

Bioremediation offers a sustainable approach to dealing with heavy metal contamination, but the success of microbial processes depends on environmental conditions such as oxygen levels, temperature, and nutrient availability (Wuana & Okieimen, 2011). This method is also more suitable for organic pollutants, and for metals, the rate of degradation or transformation can be slower compared to chemical or physical techniques (Tchounwou *et al*., 2012).

5.3 Rhizoremediation

Rhizoremediation is a synergistic approach that combines the use of plants and associated soil microbes to remediate contaminated soils (Thijs and Vangronsveld, 2015). In this method, plant roots exude organic compounds that stimulate microbial activity in the rhizosphere, enhancing the efficiency of metal uptake and transformation (Salt *et al*., 1998). This method not only enhances metal accumulation in plants but also facilitates the breakdown of organic pollutants through microbial processes.

The main advantage of rhizoremediation is its ability to target both metals and organic contaminants simultaneously. However, the method is dependent on maintaining optimal interactions between plants and microbes, which can be influenced by soil conditions and microbial communities (Wuana & Okieimen, 2011).

6. EMERGING TECHNOLOGIES AND INNOVATIONS

6.1 Nanotechnology

The application of nanotechnology has shown great potential in enhancing the removal of heavy metals from contaminated soils. Nanoparticles, such as zero-valent iron (nZVI) and carbon-based nanomaterials, are increasingly used due to their high surface area, reactivity, and adsorption capacity (Qu *et al*., 2013). The small size of nanoparticles allows them to penetrate soil matrices more effectively than larger particles, thereby increasing the contact between contaminants and the reactive surface of the nanoparticles (Zhang, 2003).

Nanoparticles like nZVI can reduce and immobilize metals such as arsenic (As) and chromium (Cr) by converting them into less toxic or immobile forms. However, concerns about the long-term stability of nanoparticles and their potential environmental risks are still being evaluated (Nowack & Bucheli, 2007).

6.2 Biochar

Biochar is a carbon-rich, porous material produced through the pyrolysis of biomass. It has been widely studied for its ability to adsorb and immobilize heavy metals in soils (Beesley *et al*., 2015). The porous structure and surface functional groups of biochar enable it to effectively bind metals like lead (Pb), cadmium (Cd), and zinc (Zn), reducing their mobility and bioavailability (Cao *et al*., 2009).

One of the key advantages of biochar is that it can also improve soil properties such as pH, organic matter content, and microbial activity, making it a sustainable option for soil remediation (Beesley *et al*., 2011). However, the effectiveness of biochar can vary depending on the feedstock used and the pyrolysis conditions (Cao *et al*., 2009).

6.3 Hyperaccumulators

Hyperaccumulators are plants that have the natural or engineered ability to take up high concentrations of heavy metals from contaminated soils (Rascio & Navari-Izzo, 2011). Genetic engineering has been employed to enhance the metal uptake capabilities of certain plants, making them more efficient in accumulating metals like nickel (Ni), cadmium (Cd), and arsenic (As) (Kotrba *et al*., 2012).

While natural hyperaccumulators such as *Thlaspi caerulescens* and *Pteris vittata* are commonly used, genetically modified plants have the potential to further improve the efficiency and speed of metal uptake (Rascio & Navari-Izzo, 2011). However, the limitations include the slow growth rate of these plants and the challenge of harvesting large amounts of biomass for processing.

7. CHALLENGES IN HEAVY METAL REMEDIATION

7.1 Economic and Technical Constraints

One of the major challenges in heavy metal remediation is the high cost associated with treatment methods such as vitrification and soil washing. These techniques require specialized equipment, significant energy inputs, and trained personnel, making them economically prohibitive, especially for large-scale or low-income regions (Mulligan *et al*., 2001). Vitrification, for example, is energy-intensive, as it requires heating soil to extremely high temperatures to immobilize heavy metals, while soil washing requires large volumes of water and chemicals to leach metals out of soils (Mulligan *et al*., 2001).

Furthermore, energy and infrastructure requirements are significant barriers to the widespread implementation of these methods, particularly in developing regions where the necessary technologies and resources may not be readily available (Wuana & Okieimen, 2011).

7.2 Effectiveness and Longevity

Many current remediation methods lack long-term effectiveness, particularly in preventing recontamination. Techniques such as soil stabilization or solidification generally work by immobilizing metals in the soil, but do not remove them. This creates a risk of releasing contaminants back into the environment if the soil is disturbed through natural processes like erosion or human activities (Mulligan *et al*., 2001). For example, stabilized metals may leach into water bodies during extreme weather events, posing ongoing environmental and health risks (Tchounwou *et al*., 2012).

Additionally, the longevity of remediation efforts is often uncertain, as many techniques focus on immediate stabilization rather than complete removal. This can lead to issues where contaminants remain present, albeit immobilized, and can still pose risks to ecosystems and human health if disturbed or if conditions change, such as a shift in soil pH or moisture content (Mulligan *et al*., 2001).

7.3 Regulatory and Policy Issues

Regulatory frameworks for soil contamination vary widely between countries, leading to inconsistent approaches to remediation. In some regions, there are strict environmental standards and remediation goals, while in others, regulations are weak or absent (Alloway, 2013). This inconsistency makes it difficult to manage contaminated sites effectively on a global scale. Countries with less stringent regulations may allow for higher levels of contamination, creating health and environmental risks that could spread beyond borders (Wuana & Okieimen, 2011).

The need for global regulatory frameworks to address soil contamination has become more apparent, as heavy metal pollution can affect ecosystems and human populations worldwide. International cooperation and harmonized regulations are necessary to ensure that remediation efforts are both effective and sustainable in the long term (Alloway, 2013).

8. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

8.1 Integration of Different Techniques

One promising future direction in heavy metal remediation is the integration of different techniques. Combining approaches, such as phytoremediation with chemical leaching, could enhance overall effectiveness by leveraging the strengths of each method. For instance, plants can help extract heavy metals, while chemical agents can enhance bioavailability and solubility, facilitating easier removal (Rascio & Navari-Izzo, 2011). This integrated approach may lead to more efficient and sustainable remediation strategies that minimize environmental impact.

8.2 Development of Eco-friendly and Cost-effective Technologies

There is a growing need for the development of eco-friendly and cost-effective technologies for heavy metal remediation. Approaches based on green chemistry principles, such as using biodegradable and non-toxic materials for remediation, hold significant promise (Wang *et al*., 2021). These technologies can reduce the environmental footprint of remediation efforts while still effectively addressing contamination issues. Research into bioremediation methods utilizing naturally occurring organisms or engineered microorganisms is also expected to provide sustainable solutions that are both effective and economical (Tchounwou *et al*., 2012).

8.3 Advancing Understanding of Heavy Metal Behavior in Soils

Improving our understanding of heavy metal behavior in soils is crucial for developing better remediation strategies. Research efforts should focus on the bioavailability, mobility, and speciation of heavy metals under varying soil conditions (Alloway, 2013). Enhanced knowledge in these areas can inform the design of more effective remediation technologies and strategies. Furthermore, the development of better risk assessment models that take into account the dynamic interactions between contaminants, soil properties, and biotic factors will be vital for managing contaminated sites (Li *et al*., 2019).

8.4 Focus on Long-term Monitoring of Remediated Sites

Finally, there should be a greater emphasis on the long-term monitoring of remediated sites to assess the effectiveness and sustainability of various remediation techniques (Mulligan *et al*., 2001). Continuous monitoring can help identify potential risks of recontamination and provide valuable data for improving future remediation efforts. Developing standardized protocols for monitoring heavy metal levels and the ecological health of remediated areas will support ongoing research and regulatory compliance.

CONCLUSIONS

The review of heavy metal removal from soil highlights the pressing issue of soil contamination, driven by both natural and anthropogenic activities. Heavy metals pose significant risks to ecosystems and human health, necessitating effective remediation strategies. This review examined various methodologies (physical, chemical, biological, and emerging technologies), while also acknowledging the challenges associated with each.

Various methods exist for addressing heavy metal contamination, each with distinct advantages and limitations. Physical techniques, such as soil washing and excavation, are effective but often generate secondary waste or require significant resources. Chemical methods like stabilization and leaching provide removal options but may not offer long-term solutions. Biological methods, including phytoremediation and bioremediation, are more sustainable but can be slow and dependent on specific environmental conditions.

Innovations such as nanotechnology, biochar, and hyperaccumulators show promise for enhancing remediation effectiveness. These technologies could improve metal immobilization and bioavailability, making them valuable tools in addressing soil contamination.

Economic constraints, regulatory inconsistencies, and the long-term effectiveness of remediation efforts remain significant barriers. Many current methods focus on immobilization rather than removal, risking future recontamination. The need for global regulatory frameworks is crucial to ensure consistent management of contaminated sites.

Future research should focus on integrating different remediation techniques to leverage their strengths, developing eco-friendly solutions, and advancing our understanding of heavy metal behavior in soils. Long-term monitoring of remediated sites is essential for assessing effectiveness and preventing recontamination.

In summary, while significant progress has been made in heavy metal remediation, ongoing research and innovation are necessary to develop sustainable, cost-effective strategies that address the complexities of soil contamination and protect environmental and human health.

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