MSI Journal of Sustainable
Agriculture and Food Systems

Recent Advances in the Remediation of Heavy Metal-Contaminated Soils

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ABSTRACT: Heavy metal contamination of soils has become a significant environmental concern due to its persistence, toxicity, and potential risks to ecosystems, agriculture, and human health. Rapid industrialization, urbanization, mining activities, wastewater irrigation, and intensive agricultural practices have contributed substantially to the accumulation of heavy metals in soils. These contaminants can adversely affect soil quality, plant growth, microbial activity, and food safety through bioaccumulation and biomagnification. This review discusses the major sources of heavy metals in soils, their environmental and health impacts, and the remediation technologies used for their management. Physical, chemical, and biological remediation approaches are examined, highlighting their mechanisms, advantages, and limitations. The review also addresses the challenges associated with current remediation methods and emphasizes the need for sustainable, cost-effective, and environmentally friendly strategies for the restoration of contaminated soils.

Keywords: *Soil contamination; Phytoremediation; Chemical remediation; Biological remediation; Soil restoration.*

Received: 10-May-2026
Accepted: 19-June-2026
Published: 21-June-2026

This article is published in the **MSI Journal of Sustainable Agriculture and Food Systems**

ISSN 3139-2458 (Online)

Volume 2, Issue 1 Jan-Jun, 2026

Introduction

Heavy metal contamination of soil is a major environmental concern due to its persistence, toxicity, and adverse effects on ecosystems, agricultural productivity, and human health. Unlike organic pollutants, heavy metals are non-biodegradable and can accumulate in soils, water bodies, plants, animals, and humans over long periods. Rapid industrialization, urbanization, intensive agriculture, mining activities, wastewater irrigation, and the excessive use of fertilizers and pesticides have significantly increased heavy metal concentrations in agricultural soils [1]. The behavior and mobility of heavy metals in soil are influenced by factors such as pH, organic matter content, soil texture, and microbial activity. Elevated metal concentrations can impair soil fertility, disrupt microbial communities, inhibit plant growth, and reduce crop yield and quality. Moreover, heavy metals can enter the food chain through plant uptake, leading to bioaccumulation and biomagnification, which pose serious risks to human and animal health. Heavy metals are generally classified as essential and non-essential elements. Essential metals, including zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and nickel (Ni), are required in small amounts for normal biological functions but become toxic at high concentrations. In contrast, non-essential metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) are highly toxic and can cause various health disorders [3].

Due to the growing threat of heavy metal pollution, considerable attention has been directed toward the development of effective remediation technologies. Physical, chemical, and biological remediation approaches have been widely investigated to reduce metal concentrations and restore soil health. Therefore, this review discusses the major sources of heavy metals in soils, their environmental and health impacts, available remediation technologies, and the challenges associated with sustainable soil restoration.

Sources of Heavy Metals in Soil

Heavy metals enter soil ecosystems through a combination of natural processes and human-induced activities. The distribution, concentration, and mobility of these metals in soils are influenced by both geogenic (natural) and anthropogenic (human-related) sources. While natural processes have contributed to the presence of heavy metals in soils for millions of years, rapid industrialization, urbanization, and intensive agricultural practices have significantly accelerated their accumulation in recent decades. As a result, heavy metal contamination has become a major environmental concern worldwide, particularly in agricultural regions where soil quality directly affects crop productivity and food safety [4].

Natural sources (Figure 1) of heavy metals primarily originate from the weathering and decomposition of parent rock materials. Rocks and minerals naturally contain various metallic elements, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), cadmium (Cd), lead (Pb), and arsenic (As). Through physical, chemical, and biological weathering processes, these elements are gradually released into the soil environment. Geological activities such as volcanic eruptions, geothermal emissions, forest fires, and natural erosion also contribute to the introduction of heavy metals into soils. The concentration of naturally occurring metals varies depending on the mineralogical composition of the parent materials, climatic conditions, topography, and soil-forming processes. Although these natural inputs are generally slow and balanced within ecosystems, certain geological formations may contain exceptionally high concentrations of toxic metals, creating naturally contaminated soils [5].

In contrast, anthropogenic activities are currently recognized as the dominant source of heavy metal accumulation in many agricultural and urban soils. Human activities often introduce metals at rates far exceeding natural background levels, resulting in significant environmental degradation. Agricultural practices represent one of the most important pathways for heavy metal entry into soils. The continuous and excessive application of chemical fertilizers, organic manures, pesticides, herbicides, and fungicides can substantially increase the concentration of potentially toxic metals in agricultural lands. Many commercial fertilizers contain trace amounts of cadmium, lead, chromium, nickel, copper, and zinc as impurities originating from their raw materials. Among these, phosphate fertilizers are considered a particularly important source of cadmium contamination because phosphate rock deposits frequently contain elevated concentrations of this metal. Repeated fertilizer application over many years can therefore result in gradual accumulation of heavy metals in cultivated soils [6].

Pesticides and fungicides also contribute significantly to soil contamination. Historically, several pesticide formulations contained metal-based compounds such as arsenic, copper, mercury, and lead. Although the use of many of these products has been restricted in numerous countries, residues from past applications may persist in soils for decades. Copper-based fungicides, for example, are still widely used in horticultural and agricultural systems and can lead to elevated copper concentrations in treated soils. Continuous use of such agrochemicals may adversely affect soil microorganisms, reduce soil fertility, and increase the risk of metal uptake by crops. Wastewater irrigation is another major source of heavy metal contamination in agricultural soils, particularly in developing countries where freshwater resources are limited. Industrial and municipal wastewater often contains substantial concentrations of cadmium, chromium, lead, mercury, nickel, copper, and zinc. Long-term irrigation with untreated or partially treated wastewater can cause significant accumulation of these metals in surface and subsurface soil layers. Although wastewater may provide valuable nutrients and organic matter for crop growth, its prolonged use poses serious environmental and health risks due to heavy metal enrichment and subsequent transfer into the food chain. The application of sewage sludge and biosolids to agricultural lands has also become a notable source of heavy metal input. Sewage sludge is commonly used as a soil amendment because it contains high levels of organic matter and plant nutrients. However, sludge may simultaneously contain considerable amounts of toxic metals derived from domestic sewage, industrial discharges, pharmaceuticals, and urban runoff. Repeated land application of sludge can increase soil concentrations of cadmium, lead, mercury, chromium, copper, and zinc beyond permissible limits, potentially affecting soil health and crop safety. Industrial activities are among the most significant contributors to heavy metal pollution worldwide. Mining operations, smelting industries, metal processing plants, electroplating facilities, battery manufacturing units, textile industries, tanneries, and chemical factories release substantial quantities of heavy metals into the environment. These contaminants may reach agricultural soils through direct discharge, accidental spills, atmospheric transport, or deposition of industrial dust. Areas located near industrial zones often exhibit significantly higher concentrations of toxic metals compared with uncontaminated regions. Atmospheric deposition represents another important pathway through which heavy metals are transferred to soils. Industrial emissions, thermal power plants, waste incineration, and vehicular exhaust release metal-containing particulates into the atmosphere. These particles can be transported over long distances before settling onto soil surfaces through dry deposition or precipitation. Fossil fuel combustion, particularly coal and petroleum products, contributes significantly to atmospheric emissions of mercury, lead, cadmium, arsenic, and other potentially toxic elements. Consequently, even remote agricultural areas may receive measurable quantities of heavy metals through atmospheric deposition. Urbanization and increasing human population densities have further intensified heavy metal contamination in soils. Construction activities, municipal solid waste disposal, electronic waste accumulation, traffic emissions, and urban runoff introduce various metallic contaminants into the surrounding environment. Improper management of these wastes can result in the gradual migration of heavy metals into nearby agricultural lands and water bodies [7].

Overall, the accumulation of heavy metals in soils results from the combined influence of natural geological processes and anthropogenic activities. While natural sources establish the baseline concentrations of metals in soils, human activities have substantially increased their levels beyond natural background values in many regions. Understanding the various sources of heavy metals is essential for developing effective monitoring, management, and remediation strategies aimed at protecting soil quality, agricultural productivity, ecosystem health, and food safety.

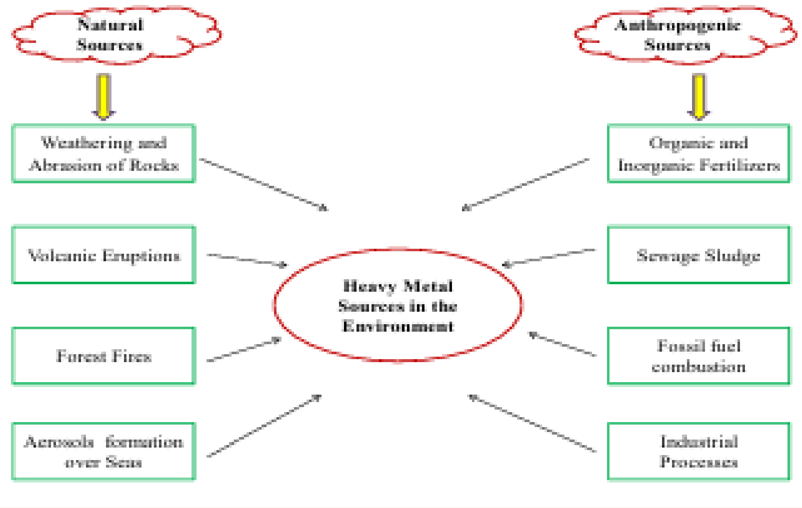

Figure 1: Sources of heavy metals in the environment.

Remediation Technologies Involved In Removal of Heavy Metals From Soil

The increasing accumulation of heavy metals in agricultural and industrial soils has necessitated the development of effective remediation strategies to restore soil quality and minimize environmental and human health risks. Because heavy metals are persistent, non-biodegradable, and capable of bioaccumulating within living organisms, their removal or stabilization in contaminated soils presents a significant challenge. Over the years, various remediation technologies have been developed and implemented to address heavy metal pollution. These technologies aim to reduce metal concentrations, decrease their bioavailability, prevent their migration into surrounding environments, and ultimately restore the ecological functions of contaminated soils. According to the classification proposed by the United States

Environmental Protection Agency (USEPA), remediation approaches for contaminated soils can be broadly categorized into in-situ and ex-situ treatment methods. In in-situ remediation, treatment is performed directly at the contaminated site without excavating or transporting the soil. This approach minimizes disturbance to the environment and is generally more cost-effective for large contaminated areas. In contrast, ex-situ remediation involves the excavation, removal, and transportation of contaminated soil to another location where treatment is carried out. Although ex-situ methods often provide faster and more controlled remediation, they are generally associated with higher operational costs and greater environmental disturbance. Based on the mechanisms employed for contaminant removal or stabilization, remediation technologies can further be classified into physical, chemical, and biological remediation methods. Each category offers unique advantages and limitations depending on the nature and extent of contamination, soil characteristics, economic feasibility, and environmental considerations [8-9].

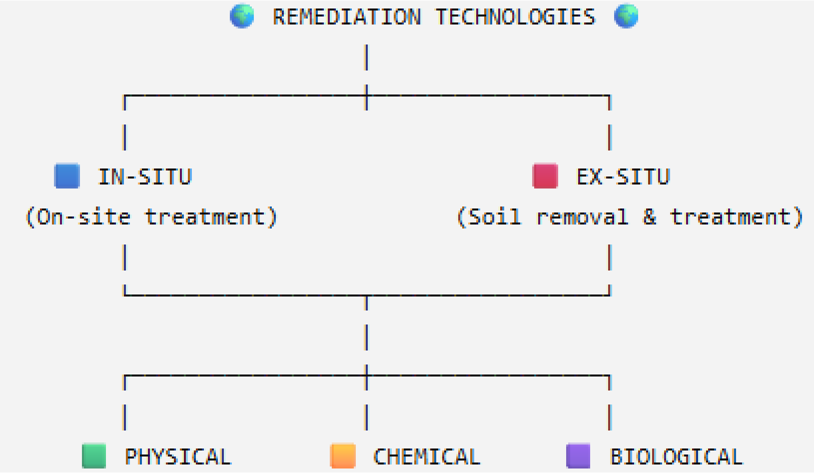

Figure 2. Types of remediation technologies

Physical Remediation

Physical remediation techniques focus on the direct removal, isolation, or containment of heavy metals from contaminated soils. These methods generally do not alter the chemical nature of the contaminants but aim to physically separate or immobilize them. Common physical remediation approaches include soil excavation, soil washing, thermal treatment, vitrification, and containment technologies. Soil excavation and landfilling involve the removal of contaminated soil and its disposal in specially engineered landfills. Although effective in reducing contamination at the original site, this method merely transfers pollutants from one location to another and requires substantial financial investment. Soil washing is another widely used technique in which contaminated soil is treated with water or chemical solutions to dissolve and separate heavy metals from soil particles. This method is particularly effective for sandy soils and contaminants with high mobility. Advanced physical technologies such as electrokinetic remediation utilize electric fields to mobilize and transport metal ions toward collection electrodes, facilitating their removal from the soil matrix. Similarly, thermal desorption and vitrification employ high temperatures to immobilize or concentrate contaminants, thereby reducing their environmental risk. While physical methods can provide rapid remediation, they are often energy-intensive and costly, limiting their application in large-scale agricultural settings. Physical remediation represents one of the earliest and most direct approaches for the management of heavy metal-contaminated soils. These techniques primarily focus on the removal, isolation, dilution, or containment of contaminants through physical means rather than altering their chemical composition. Physical remediation methods are generally effective in reducing pollutant concentrations within a relatively short period; however, their practical application is often limited by high operational costs, intensive labor requirements, and environmental disturbances associated with soil handling. Among the various physical remediation techniques, soil replacement and thermal desorption are two commonly employed methods for the treatment of contaminated soils [9].

1. Soil Replacement

Soil replacement, also known as soil substitution, involves the removal of contaminated soil from the affected site and its replacement with uncontaminated or less contaminated soil. This technique aims to reduce the concentration of heavy metals and other pollutants in the root zone by physically diluting or eliminating the contaminated material. In some cases, only the upper contaminated layer is removed and replaced, whereas in severely polluted sites a larger volume of soil may require excavation and substitution. The primary advantage of soil replacement is its ability to provide immediate improvement in soil quality and reduce the exposure of plants, animals, and humans to hazardous contaminants. The method is particularly suitable for areas where contamination is localized and confined to a relatively small surface area. It can also be effectively used in residential zones, playgrounds, agricultural plots, and industrial sites where rapid risk reduction is required. Despite its effectiveness, soil replacement possesses several limitations. The excavation, transportation, disposal, and replacement of contaminated soil require substantial financial resources and specialized equipment. Furthermore, identifying suitable disposal sites for contaminated soil and obtaining large quantities of clean replacement soil can be challenging. The process may also disrupt soil structure, microbial communities, and ecological balance. Consequently, soil replacement is generally considered practical only for small-scale contamination scenarios and is often economically unfeasible for large agricultural landscapes [9].

2. Thermal Desorption

Thermal desorption is another important physical remediation technology used for the treatment of contaminated soils. This method involves heating contaminated soil to elevated temperatures in order to volatilize and separate pollutants from the soil matrix. During the heating process, contaminants are converted into gaseous forms and subsequently extracted, collected, and treated using specialized recovery systems. Vacuum pressure or gas collection systems are often employed to capture volatilized contaminants and prevent their release into the environment. The effectiveness of thermal desorption depends on the physicochemical properties of the contaminants, treatment temperature, soil characteristics, and duration of heating. The process is particularly suitable for contaminants that exhibit relatively high volatility. In certain cases, thermal treatment may also alter the chemical forms of heavy metals, thereby reducing their mobility and toxicity. One of the major advantages of thermal desorption is its ability to achieve rapid and significant reductions in contaminant concentrations. The technology can be applied either on-site or off-site, depending on the level and extent of contamination. Additionally, thermal treatment may reduce the volume of hazardous waste requiring final disposal. However, thermal desorption is associated with several drawbacks. The technology requires sophisticated equipment, substantial energy inputs, and skilled personnel for operation and maintenance. High treatment temperatures increase operational costs and may adversely affect soil properties, including organic matter content, microbial populations, nutrient availability, and overall soil fertility. Furthermore, not all heavy metals can be effectively volatilized under economically feasible temperature conditions. As a result, thermal desorption is often considered a costly and labor-intensive remediation technique with limited applicability, particularly for large-scale agricultural soils [9].

Advantages and Limitations of Physical Remediation Approaches

Physical remediation methods are among the most direct and effective techniques for managing heavy metal-contaminated soils. A major advantage of these approaches is their ability to achieve rapid and immediate reductions in contaminant concentrations, making them particularly useful in situations where urgent remediation is required. Techniques such as soil replacement and thermal desorption can effectively remove or isolate contaminants within a relatively short period compared to many biological methods. Physical remediation also offers a high degree of control over the treatment process, allowing remediation objectives to be achieved with predictable outcomes. Furthermore, these methods can be applied to a wide range of contaminants and are often effective even in highly polluted soils where biological remediation may not be feasible. In certain cases, physical techniques can significantly reduce environmental and human health risks by preventing the spread of contaminants to groundwater, crops, and surrounding ecosystems [10].

Despite these advantages, physical remediation approaches possess several important limitations. Although they can rapidly decrease contaminant concentrations, they are often considered temporary or site-specific solutions rather than comprehensive long-term remediation strategies. Many physical methods do not completely destroy or detoxify contaminants; instead, they simply transfer pollutants from one location to another. For example, contaminated soil removed during excavation must still be transported, treated, or disposed of elsewhere, creating additional environmental and logistical challenges. Similarly, thermal desorption may require further treatment of the volatilized contaminants after collection. Another significant drawback is the high economic cost associated with physical remediation technologies. Excavation, transportation, treatment, specialized equipment, energy requirements, and waste disposal contribute substantially to overall project expenses. These methods are also labor-intensive and may require skilled personnel for implementation and monitoring. In addition, certain physical treatments, particularly thermal processes, consume large amounts of energy and may increase the environmental footprint of remediation activities. Physical remediation can also disturb the natural characteristics of soil. Excavation and soil replacement may alter soil structure, disrupt microbial communities, reduce soil fertility, and negatively affect ecosystem functions. High-temperature treatments such as thermal desorption can destroy beneficial soil microorganisms and organic matter, thereby reducing soil productivity and necessitating further rehabilitation measures before agricultural use can resume. Because of these limitations, physical remediation methods are increasingly being combined with chemical and biological remediation technologies to enhance treatment effectiveness and sustainability. Integrated remediation approaches can simultaneously reduce contaminant concentrations, improve soil quality, restore ecological functions, and minimize environmental impacts. Such combinations often provide more sustainable and cost-effective solutions for long-term management of contaminated sites [11].

Chemical Remediation

Chemical remediation is one of the most widely applied approaches for the management of heavy metal-contaminated soils. These techniques utilize chemical reactions and processes to remove, immobilize, transform, or reduce the toxicity of contaminants present in the soil environment. Compared with many physical remediation methods, chemical remediation often provides higher efficiency in reducing metal mobility and bioavailability. However, the effectiveness of these techniques depends on soil properties, contaminant characteristics, treatment conditions, and economic feasibility. Common chemical remediation methods include chemical leaching**,** chemical fixation (stabilization)**,** electrokinetic remediation, and vitrification [12].

1. Chemical Leaching

Chemical leaching, often referred to as soil washing, is a remediation technique designed to extract heavy metals from contaminated soils through the use of water, chemical reagents, extracting solutions, surfactants, or gaseous agents. The fundamental principle of this method involves transferring contaminants from the solid soil phase into a liquid phase where they can be collected and treated separately. During the leaching process, contaminated soil is brought into contact with washing solutions that dissolve or mobilize heavy metals attached to soil particles. Various extracting agents, including acids, chelating compounds, surfactants, and organic solvents, may be used to enhance the removal efficiency. Chelating agents such as EDTA are particularly effective because they form stable complexes with metal ions, increasing their solubility and facilitating extraction. After extraction, the resulting leachate containing dissolved metals undergoes further treatment to recover or remove contaminants. Metal recovery may be achieved through precipitation, adsorption, ion exchange, membrane filtration, or chemical treatment processes. Chemical leaching is generally effective for soils contaminated with cadmium, lead, zinc, copper, nickel, and other potentially toxic elements. Despite its effectiveness, the technique has certain limitations. Large quantities of chemical reagents may be required, generating secondary wastewater that must be carefully treated before disposal. Excessive use of extracting agents can also alter soil properties and potentially increase the risk of contaminant migration if not properly managed [12].

2. Chemical Fixation or Stabilization

Chemical fixation, also known as chemical stabilization or immobilization, is another important remediation strategy for heavy metal-contaminated soils. Rather than removing contaminants from the soil, this method aims to reduce their mobility, bioavailability, and environmental risk by converting them into chemically stable forms. In this process, various amendments or reagents are added to contaminated soils to promote adsorption, precipitation, complexation, or ion-exchange reactions. These reactions result in the formation of insoluble compounds that are less available for plant uptake and less likely to leach into groundwater. Common stabilizing agents include lime, phosphates, biochar, zeolites, clay minerals, iron oxides, compost, and industrial by-products. Chemical fixation offers several advantages. It is generally less expensive than excavation and disposal, can be implemented directly at contaminated sites, and effectively reduces the ecological risks associated with heavy metal contamination. Furthermore, stabilization techniques often improve soil structure and fertility when organic amendments are incorporated. However, one major limitation is that contaminants remain in the soil rather than being permanently removed. Therefore, long-term monitoring is necessary to ensure that environmental changes such as pH fluctuations or redox variations do not remobilize the stabilized metals in the future [12].

3. Electrokinetic Remediation

Electrokinetic remediation is an innovative chemical–physical treatment technology used for the removal of heavy metals from contaminated soils, particularly those with low permeability such as clay-rich soils. The process involves the application of a direct electric current across contaminated soil using electrodes placed at opposite ends of the treatment area. When an electric field is applied, several electrochemical processes occur simultaneously, including electromigration, electroosmosis, and electrophoresis. These mechanisms facilitate the movement of dissolved metal ions toward oppositely charged electrodes, where they can be concentrated, collected, and subsequently removed from the system. Electrokinetic remediation is especially useful for extracting contaminants such as cadmium, lead, chromium, copper, zinc, and nickel from fine-textured soils where conventional extraction methods may be less effective. The technology can be implemented in situ, reducing the need for excavation and transportation of contaminated soil. The major advantages of electrokinetic remediation include its high efficiency, ability to treat low-permeability soils, and relatively low disturbance to the environment. However, its effectiveness may be influenced by soil conductivity, moisture content, pH, and contaminant speciation. Moreover, the requirement for electrical energy and specialized equipment can increase operational costs, limiting its widespread application in large agricultural areas [13].

4. Vitrification

Vitrification is a high-temperature remediation technology that involves heating contaminated soil to extremely elevated temperatures, typically ranging from approximately 1400°C to 2000°C. At such temperatures, soil minerals melt and subsequently cool to form a glass-like, chemically stable material known as a vitrified matrix. During the vitrification process, certain contaminants are volatilized and captured through emission control systems, while many heavy metals become encapsulated within the glass structure. This immobilization significantly reduces the mobility and bioavailability of contaminants, thereby minimizing environmental risks. The vitrified product is highly resistant to weathering, leaching, and chemical degradation, making vitrification one of the most effective long-term stabilization technologies available. In addition, the process can destroy organic contaminants that may coexist with heavy metals in polluted soils. Despite its effectiveness, vitrification is associated with several significant disadvantages. The technology requires extremely high energy inputs, sophisticated equipment, and careful operational control. Installation and maintenance costs are substantial, and the process may not be economically feasible for large-scale agricultural applications. Furthermore, high temperatures can completely alter soil characteristics, rendering the treated material unsuitable for agricultural use without further rehabilitation. Consequently, vitrification is generally reserved for highly contaminated industrial or hazardous waste sites where other remediation methods are inadequate [14].

Advantages and Limitations of Chemical Remediation

Chemical remediation technologies offer several important advantages, including relatively rapid treatment, high removal efficiency, and the ability to reduce contaminant mobility and toxicity. These methods can be applied either in situ or ex situ and are often effective for a wide range of heavy metals and soil conditions. However, chemical remediation also presents several challenges. Many techniques require expensive reagents, specialized equipment, and skilled operators. Some methods generate secondary waste streams that require additional treatment, while others merely immobilize contaminants without removing them completely from the environment. Economic constraints, environmental concerns, and site-specific factors often limit their large-scale implementation. Overall, chemical remediation remains a critical component of modern soil restoration programs. Techniques such as chemical leaching, chemical fixation, electrokinetic remediation, and vitrification have demonstrated considerable potential for managing heavy metal-contaminated soils. Nevertheless, their successful application requires careful evaluation of contamination characteristics, soil properties, treatment objectives, and long-term environmental sustainability. For this reason, chemical remediation is increasingly being integrated with physical and biological approaches to achieve more effective and sustainable restoration of contaminated soils [15].

Biological Remediation

Biological remediation, commonly known as bioremediation, utilizes living organisms such as plants, microorganisms, fungi, and algae to remove, stabilize, transform, or detoxify heavy metals in contaminated soils. Biological approaches have gained increasing attention because they are environmentally friendly, sustainable, and often more economical than conventional physical and chemical methods. Among biological techniques, phytoremediation is one of the most widely studied and applied methods. This approach employs plants capable of accumulating, stabilizing, or transforming heavy metals. Different forms of phytoremediation include phytoextraction, where plants absorb metals and store them in harvestable tissues; phytostabilization, where plants immobilize contaminants in the root zone; and phytovolatilization, where certain metals are transformed into volatile forms and released into the atmosphere. Hyperaccumulator plant species are particularly valuable because they can accumulate exceptionally high concentrations of metals without exhibiting toxicity symptoms. Microbial remediation involves the use of bacteria, fungi, and other microorganisms that can adsorb, precipitate, transform, or immobilize heavy metals. Soil microorganisms influence metal mobility through various mechanisms such as biosorption, bioaccumulation, biomineralization, and redox reactions. Certain plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi have demonstrated remarkable potential in enhancing phytoremediation efficiency while simultaneously improving plant growth under metal stress conditions. Recent advances have also highlighted the potential of integrated biological approaches involving biochar, compost, beneficial microbes, and metal-tolerant plants. These combined strategies can significantly enhance remediation efficiency while promoting soil fertility and ecosystem restoration [12].

1. Phytoremediation

Phytoremediation is a plant-based remediation technology that utilizes specific plant species to extract, stabilize, degrade, or transform contaminants from soil, water, and sediments. This technique has emerged as a promising alternative to conventional remediation methods because it is environmentally benign, aesthetically pleasing, and relatively inexpensive. In addition, phytoremediation can improve soil structure, enhance biodiversity, and contribute to carbon sequestration while remediating contaminated sites. The effectiveness of phytoremediation depends on several factors, including plant species, contaminant type, soil characteristics, climatic conditions, and contaminant concentration. Hyperaccumulator plants, which can accumulate exceptionally high concentrations of heavy metals in their tissues without suffering toxicity symptoms, are particularly valuable for phytoremediation applications.

Phytoremediation generally encompasses five major strategies:

1.1. Phytoextraction

Phytoextraction is one of the most extensively studied and widely applied phytoremediation techniques for heavy metal removal. In this process, plants absorb heavy metals from contaminated soils through their root systems and subsequently transport them to aboveground tissues such as stems, leaves, and shoots. As the plants grow, substantial quantities of metals accumulate in their harvestable biomass. The contaminated plant material is then harvested and removed from the site, thereby reducing the concentration of heavy metals in the soil over time. Repeated cultivation and harvesting cycles can significantly decrease soil contamination levels. Phytoextraction is particularly effective for metals such as cadmium (Cd), zinc (Zn), nickel

(Ni), copper (Cu), and lead (Pb). Hyperaccumulator species belonging to genera such as *Brassica*, *Thlaspi*, and *Sedum* have demonstrated remarkable metal uptake capacities. The major advantages of phytoextraction include low operational costs, minimal site disturbance, and the potential recovery of valuable metals through phytomining. However, the process is relatively slow and may require several growing seasons to achieve desired remediation targets, especially in highly contaminated soils.

1.2. Phytostabilization

Phytostabilization involves the use of plants to immobilize heavy metals within the soil and root zone rather than removing them from the site. Through various physical, chemical, and biological mechanisms, plants reduce the mobility and bioavailability of contaminants, thereby minimizing their movement into groundwater, surface water, and the food chain. Plant roots stabilize contaminated soils by preventing erosion, reducing dust generation, and promoting the adsorption or precipitation of metals around the rhizosphere. In some cases, root exudates facilitate the formation of insoluble metal compounds that remain bound within the soil matrix. Phytostabilization is particularly useful in areas where contaminant concentrations are too high for efficient phytoextraction or where complete removal is impractical. Although the contaminants remain in the soil, their environmental risks are substantially reduced.

1.3. Rhizofiltration

Rhizofiltration is a remediation technique that utilizes plant roots to remove contaminants from polluted water rather than directly from soil. In this process, plant root systems absorb, adsorb, or precipitate heavy metals present in contaminated groundwater, wastewater, or surface water bodies. The extensive root network acts as a natural filtration system capable of trapping and accumulating toxic metals. Species such as sunflower (*Helianthus annuus*), water hyacinth (*Eichhornia crassipes*), and Indian mustard (*Brassica juncea*) have demonstrated considerable effectiveness in rhizofiltration applications. This method is particularly suitable for treating industrial effluents, mining wastewater, and contaminated groundwater containing dissolved heavy metals.

1.4. Phytovolatilization

Phytovolatilization involves the uptake of contaminants by plant roots, followed by their transformation into volatile forms and subsequent release into the atmosphere through plant transpiration processes. Certain plant species possess metabolic pathways capable of converting absorbed contaminants into less toxic gaseous compounds. These transformed substances are then released from aerial plant parts such as leaves and stems. This strategy has been particularly investigated for contaminants such as mercury (Hg), selenium (Se), and arsenic (As). Although phytovolatilization effectively removes contaminants from soil, concerns remain regarding the environmental implications of transferring pollutants from soil to the atmosphere. Consequently, careful assessment is required before large-scale implementation.

1.5. Phytodegradation

Phytodegradation, also known as phytotransformation, refers to the breakdown of contaminants through the metabolic activities of plants and their associated rhizosphere microorganisms. Plant enzymes and root-associated microbial communities work together to degrade, transform, or detoxify pollutants into less harmful compounds. This approach is particularly effective for the remediation of organic contaminants such as pesticides, herbicides, petroleum hydrocarbons, and industrial chemicals. Although phytodegradation plays a limited role in the direct removal of heavy metals, it contributes significantly to the remediation of mixed contamination sites where metals coexist with organic pollutants [12-15].

2. Microbial Remediation

Microbial remediation represents another important biological approach for the management of heavy metal-contaminated soils. This technique utilizes bacteria, fungi, actinomycetes, algae, and other microorganisms to transform, immobilize, accumulate, or detoxify heavy metals through natural metabolic processes.

Microorganisms interact with heavy metals through several mechanisms, including:

- Biosorption
- Bioaccumulation
- Biomineralization
- Biotransformation
- Bioleaching
- Redox reactions
- Precipitation and complexation

Through these processes, microbes alter the physical and chemical properties of contaminants, thereby affecting their mobility, bioavailability, toxicity, and environmental fate. Certain bacterial species can convert highly toxic metal forms into less toxic and less mobile species. For example, some microorganisms can reduce toxic hexavalent chromium [Cr(VI)] to the less toxic trivalent chromium [Cr(III)]. Similarly, sulfate-reducing bacteria can precipitate metals as insoluble sulfides, thereby decreasing their bioavailability. Fungi also play an important role in heavy metal remediation. Their extensive mycelial networks provide large surface areas for metal adsorption and accumulation. Mycorrhizal fungi establish symbiotic relationships with plant roots and can significantly enhance plant tolerance to metal stress while improving nutrient uptake and phytoremediation efficiency [12].

Advantages and Limitations of Biological Remediation

Biological remediation has gained considerable attention as an environmentally sustainable and cost-effective approach for the management of heavy metal-contaminated soils. One of its major advantages is its eco-friendly nature, as it utilizes natural biological processes involving plants and microorganisms to remove, stabilize, or transform contaminants without causing significant secondary pollution. Compared with conventional physical and chemical remediation methods, biological remediation generally requires lower operational and maintenance costs, making it economically feasible for large-scale applications. Furthermore, it causes minimal disturbance to soil structure, preserves ecological balance, and often enhances soil fertility by improving organic matter content, nutrient cycling, and microbial diversity. The approach is particularly suitable for the remediation of extensive contaminated areas where excavation or intensive chemical treatment may be impractical. In addition, biological remediation is generally well accepted by the public because it is visually appealing, environmentally benign, and contributes to the restoration of vegetation cover and ecosystem functions [15].

Despite these advantages, biological remediation also has several limitations. The remediation process is typically slower than physical or chemical methods because contaminant removal depends on biological growth and metabolic activities. Its effectiveness is strongly influenced by environmental factors such as soil pH, temperature, moisture content, nutrient availability, and contaminant concentration. As a result, remediation efficiency may vary considerably across different sites and environmental conditions. Moreover, biological methods often have limited effectiveness in soils containing extremely high concentrations of heavy metals, where toxic conditions may inhibit plant growth and microbial activity. Seasonal variations and climatic fluctuations can further affect the performance of biological remediation systems, particularly in field conditions. Additionally, since contaminants are not always completely removed within a short period, long-term monitoring and management are often necessary to evaluate remediation progress and ensure the sustainability of the treatment process. Therefore, while biological remediation offers a promising and environmentally sound solution for contaminated soil restoration, its successful implementation requires careful site assessment, appropriate species selection, and continuous monitoring [16].

Integrated and Sustainable Approaches

In practice, no single remediation technology is universally suitable for all contaminated sites. The effectiveness of a remediation strategy depends on factors such as contamination level, metal species, soil properties, climatic conditions, land use objectives, and economic considerations. Therefore, integrated approaches that combine physical, chemical, and biological techniques are increasingly being adopted to achieve more efficient and sustainable remediation outcomes. Modern remediation research focuses not only on contaminant removal but also on restoring soil health, maintaining agricultural productivity, and ensuring environmental sustainability. The development of cost-effective, eco-friendly, and long-term remediation technologies remains a major priority for scientists, policymakers, and environmental managers worldwide. Consequently, the successful remediation of heavy metal-contaminated soils requires a comprehensive understanding of contaminant behavior, site characteristics, and the advantages and limitations of available remediation technologies. Such knowledge is essential for selecting the most appropriate strategy to protect ecosystem integrity, food safety, and human health [16].

Challenges Related to Remediation Technologies

Despite significant advancements in remediation technologies for heavy metal-contaminated soils, several technical, economic, and environmental challenges continue to limit their large-scale implementation and long-term effectiveness. Physical, chemical, and biological remediation methods have demonstrated considerable potential for reducing heavy metal concentrations and mitigating associated environmental risks. However, many of these technologies remain expensive, labor-intensive, and time-consuming, particularly when applied to extensive contaminated areas. The selection of an appropriate remediation strategy often depends on contamination level, soil characteristics, climatic conditions, land use objectives, and economic feasibility, making site-specific assessments essential for successful implementation. One of the major challenges associated with heavy metal remediation is the inherently low mobility and bioavailability of many metals in soil. Since remediation efficiency often depends on the ability to mobilize contaminants, various amendments such as chelating agents, surfactants, organic acids, and synthetic extractants are frequently applied to increase metal solubility and facilitate their removal. Although these substances can significantly improve the extraction and uptake of heavy metals during remediation processes, they may also generate unintended environmental consequences. Chelating agents, particularly synthetic compounds such as EDTA and DTPA, form highly stable complexes with metal ions, enhancing their mobility within the soil profile. While this characteristic improves metal extraction efficiency, it simultaneously increases the risk of contaminant migration beyond the treatment zone. Mobilized metal-chelate complexes can leach into deeper soil layers and eventually reach groundwater resources, posing serious threats to water quality and public health. Furthermore, the persistence of some synthetic chelating agents in the environment may prolong contaminant mobility and create secondary pollution problems [17-18].

Surfactants used in soil washing and extraction technologies can improve contaminant desorption from soil particles but may also contribute to the remobilization of previously immobilized metals. This process can increase the likelihood of contaminant transport through runoff, leaching, or groundwater infiltration. Consequently, remediation activities intended to reduce pollution may inadvertently facilitate the spread of contaminants if not carefully managed. Another challenge relates to the use of immobilizing amendments in stabilization and fixation technologies. Materials such as phosphates, lime, biochar, clay minerals, and industrial by-products are commonly applied to reduce metal mobility by promoting adsorption, precipitation, or complexation reactions. Although these amendments can effectively decrease the bioavailability of contaminants, they are not always selective toward specific heavy metals. Changes in soil conditions, including fluctuations in pH, redox potential, moisture content, and microbial activity, may alter the stability of immobilized contaminants and potentially lead to their re-release into the soil environment. In some cases, an amendment designed to immobilize one metal may inadvertently increase the mobility of another toxic element, thereby creating additional environmental concerns. Economic considerations also present significant obstacles to remediation efforts. Many advanced technologies require specialized equipment, skilled personnel, substantial energy inputs, and long-term monitoring programs. These requirements can substantially increase remediation costs, limiting their adoption in developing countries and resource-constrained regions where heavy metal contamination is often most severe. Moreover, biological remediation methods, although environmentally friendly and relatively inexpensive, generally require extended treatment periods and may be influenced by seasonal variations, climatic factors, and site-specific ecological conditions. Another important limitation is the lack of universal remediation technologies capable of addressing all types of heavy metal contamination. Different metals exhibit distinct chemical behaviors, toxicity levels, and interactions with soil components. Consequently, a remediation strategy effective for one contaminant may not perform equally well for another. This complexity often necessitates the integration of multiple remediation approaches to achieve satisfactory treatment outcomes [19].

Limitations of the Review

This review provides a comprehensive overview of heavy metal contamination in soils and the major remediation technologies available for their management. However, several limitations should be acknowledged. First, the review primarily focuses on general sources, impacts, and remediation approaches and does not provide site-specific assessments for particular regions or contaminated locations. Second, the effectiveness of remediation technologies may vary considerably depending on soil properties, contaminant type, climatic conditions, and management practices, which are not discussed in detail for all environmental settings. Third, recent advances in nanotechnology-assisted remediation, genetic engineering, and emerging hybrid remediation techniques are only briefly addressed due to limited coverage within the scope of this review. Finally, economic feasibility and long-term field-scale performance data for many remediation technologies remain limited, highlighting the need for further research and practical validation under diverse environmental conditions.

Conclusion

Heavy metal contamination of soils is a major environmental concern due to its persistence, toxicity, and potential risks to ecosystems, crop production, and human health. Various physical, chemical, and biological remediation technologies have been developed to reduce or remove heavy metals from contaminated soils. Although these methods can be effective, many are costly, time-consuming, and may cause secondary environmental problems such as metal remobilization or groundwater contamination. Therefore, further research is needed to develop sustainable, cost-effective, and environmentally friendly remediation strategies that ensure the long-term restoration of contaminated soils and protection of environmental health.

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