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Phytomanagement of Heavy Metals Contaminated Soil: Potentials and Challenges

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ABSTRACT: Phytomanagement of heavy metal-contaminated soil has appeared as a sustainable and promising method for soil remediation. This article explores the potentials and challenges associated with phytomanagement techniques and their application in addressing heavy metal contamination. Phytomanagement encompasses a range of strategies, including phytoremediation approaches such as rhizofiltration, phytoextraction, phytovolatilization, and phytostabilization. These techniques utilize the unique abilities of plants to uptake, accumulate, and stop heavy metals, thereby reducing their bioavailability and potential risks to the environment and human health. The review discusses the principles and advantages of phytomanagement and the several challenges and limitations were identified, such as the slow growth and limited metal accumulation in some plant species, constraints in using hyperaccumulator plants, and the potential transfer of metals to the food chain. To overcome these challenges, the review highlights the importance of careful plant selection based on metal tolerance and accumulation characteristics, consideration of soil properties and environmental factors, and

the exploration of emerging technologies such as nanotechnology applications and genetic engineering. Phytomanagement offers a promising pathway for the remediation of heavy metal-contaminateJd soil. By understanding its potentials and addressing the associated challenges, phytomanagement can be effectively utilized to restore contaminated sites and promote sustainable environmental management.

Keywords: *Phytomanagement, Phytoremediation, contaminated soil, heavy metals, environmental pollution.*

1.0 Introduction

The presence of heavy metals in soil represents a significant global environmental issue, with serious consequences for both public health and ecological stability (Ogundele et al., 2023). A range of human-driven activities, including industrial operations, mining processes, and agricultural interventions, are responsible for introducing and accumulating heavy metals within soil systems. Among these, industrial operations remain a key contributor to soil contamination by heavy metals (Liu et al., 2005). Industries involved in mining, metal smelting, manufacturing, and waste disposal release considerable amounts of hazardous metals into the environment. Metals such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) typically reach soils through mechanisms like atmospheric fallout, improper effluent discharge, and inadequate waste management practices (Ogundele & Anaun, 2022; Ali et al., 2020).

Mining processes are particularly well known for depositing heavy metals into soils (Mendez & Maier, 2008). The extraction and refining of mineral resources often generate substantial quantities of toxic metals, including arsenic (As), cadmium, and lead, which can pollute surrounding soils through tailings, leachate, and runoff into adjacent areas and water bodies (Azizullah et al., 2015). Agricultural operations also contribute to soil contamination via the use of chemical fertilizers, pesticides, and animal manure (Khan et al., 2018). These agrochemicals frequently contain trace amounts of metals such as cadmium, copper (Cu), and zinc (Zn), which can build up in soils over prolonged use. Furthermore, improper handling and disposal of animal manure, particularly when animals are exposed to contaminated feeds or veterinary drugs, can further increase soil heavy metal levels (Kabata-Pendias & Mukherjee, 2007).

From a public health perspective, heavy metal contamination in soil poses numerous hazards. Humans may encounter these contaminants through direct soil contact, inhalation of dust, or ingestion of contaminated materials (Mukhopadhyay et al., 2019). Lead and cadmium are especially concerning due to their high toxicity and ability to accumulate within biological systems (Tchounwou et al., 2012). Continuous, low-level exposure to these metals has been associated with a range of health complications, including kidney damage, neurological dysfunction, respiratory illnesses, and elevated cancer risk (Kordas et al., 2016). Moreover, heavy metals can infiltrate the food chain by being absorbed by crops cultivated on contaminated land. Plants tend to accumulate these metals in their edible portions, potentially endangering consumers (Rizwan et al., 2017). An example is rice grown in cadmium-rich soils, which can significantly increase dietary cadmium intake in populations relying heavily on this staple (Zhao et al., 2015). The extent of metal uptake and bioavailability to plants is influenced by factors like soil pH, organic matter, and the chemical form of the metals present (Shahid et al., 2019).

Environmental consequences of heavy metal-laden soils are equally severe. Such metals tend to persist within the soil matrix for extended durations, negatively affecting flora, fauna, and microbial life (Whipps, 2001). Elevated metal concentrations can hinder plant development, diminish biodiversity, and alter soil microbial diversity and activity (Zhang et al., 2016). Additionally, heavy metal contamination disrupts vital soil processes such as nutrient cycling, soil structure maintenance, and overall fertility, thereby leading to ecosystem degradation (Hiroki, 1992). Beyond terrestrial impacts, leaching and runoff of these metals from soils can introduce contaminants into surface and groundwater systems, posing risks to drinking water quality and aquatic ecosystems (Kumar et al., 2018). In aquatic environments, heavy metals accumulate in sediments, threatening aquatic species diversity and ecological health (Liu et al., 2016).

Soil contamination by heavy metals from industrial, mining, and agricultural sources carries extensive repercussions for both human health and the natural environment.

These metals present risks through direct exposure and through contamination of food crops. Simultaneously, their persistence in soils can destabilize ecosystems, impacting plant, animal, and microbial populations. Addressing soil contamination through effective mitigation and remediation strategies remains essential for protecting public health and ensuring ecological balance

2.0 Phytomanagement as a Sustainable Approach

Phytomanagement has emerged as an eco-friendly and sustainable strategy for addressing heavy metal contamination in soils, attracting growing interest in recent years. This approach harnesses the innate capabilities of plants to manage and remediate heavy metal pollutants, presenting notable advantages when compared to conventional remediation practices. Essentially, phytomanagement integrates the deliberate use of plant species to rehabilitate contaminated soils while offering concurrent ecological, economic, and social benefits (Raskin et al., 2002). Its fundamental concepts include phytoremediation, phytostabilization, phytoextraction, and phytodegradation.

Phytoremediation operates through the uptake and accumulation of heavy metals by plants, effectively reducing metal concentrations in the soil (Mishra, 2021). This mechanism capitalizes on the natural properties of certain plant species, known as hyperaccumulators, which can selectively absorb and concentrate substantial quantities of heavy metals within their tissues. Phytostabilization, in contrast, employs plants to immobilize or contain heavy metals within the soil matrix, thereby limiting their movement and reducing bioavailability (Mench et al., 2009).

Another integral concept is phytoextraction, which focuses on removing heavy metals from contaminated soils by facilitating plant uptake, followed by harvesting and properly managing the metal-laden plant biomass (Mishra, 2021). Phytodegradation, meanwhile, emphasizes the capacity of plants and their associated microbial communities to metabolically break down or transform toxic substances, including certain heavy metals, through biochemical interactions (Van Aken, 2009).

The appeal of phytomanagement lies in its multiple advantages over traditional remediation options, positioning it as a sustainable and economically viable alternative. One major benefit is the reduction in reliance on energy-demanding and intrusive practices like excavation and off-site disposal (Meers et al., 2005). Conventional remediation techniques typically involve physically removing contaminated soil, which can be both financially burdensome and ecologically disruptive. In contrast, phytomanagement allows for remediation to occur in place, preserving the integrity of the soil and its surrounding environment.

Moreover, phytomanagement is often more financially feasible than conventional approaches. Its lower operational costs stem from minimal energy inputs, reduced labor requirements, and the regenerative nature of plant systems that can adapt to environmental fluctuations (Kumar et al., 2018). This cost-effectiveness makes phytomanagement particularly suitable for large contaminated areas where the financial demands of excavation and disposal would otherwise be prohibitive. In addition, this strategy opens opportunities for economic returns through the use of harvested plant material. Biomass collected from remediation projects can be repurposed for bioenergy generation, biofuel production, or even metal recovery (Chaney et al., 2005). Such applications support renewable energy initiatives while generating economic opportunities at the community level, fostering local economic development.

Phytomanagement also contributes to improved soil health and ecological restoration. As plants accumulate and stabilize heavy metals, they simultaneously aid in the remediation of other soil pollutants, enhancing overall soil conditions (Ma et al., 2015). Vegetative growth improves soil texture and stability, supports nutrient cycling, and encourages biodiversity, collectively restoring essential ecosystem services (Wu et al., 2020). The approach’s long-term viability and adaptability to different contamination contexts further underscore its value. Phytomanagement enables ongoing land use and remediation, as plants continue to regulate and reduce heavy metal concentrations over extended periods (Bolan et al., 2018). Furthermore, this strategy can be customized to suit specific contaminants and site characteristics, offering versatility and effectiveness across a variety of polluted soil environments.

3.0 Industrial Activities and Soil Pollution

Industrial operations are known to introduce a variety of heavy metals into the environment through activities such as mining, manufacturing, and waste disposal (Alloway, 2013). Facilities involved in metal extraction, smelting, and processing including mining sites, metallurgical operations, and battery production are among the major contributors to heavy metal pollution (Morton-Bermea et al., 2002). For instance, mining activities discharge significant quantities of metals like lead, zinc, copper, and cadmium into the environment via tailings, wastewater, and airborne emissions (Mendez & Maier, 2008). Similarly, emissions from metal smelting often contain hazardous metals such as mercury, arsenic, and cadmium (Satarug et al., 2017).

Heavy metal entry into soils from industrial operations occurs through several pathways. A major route is atmospheric deposition, where metal-laden emissions from industrial sources settle onto soil surfaces through both wet and dry deposition processes (Chen et al., 2019). Additionally, industrial wastewater and effluent discharges serve as important contributors to soil contamination. When wastewater containing heavy metals is improperly managed, it can contaminate soil through surface runoff, leaching, or infiltration (Alloway, 2013). Moreover, the disposal of industrial solid wastes such as sludge and by-products also adds to soil metal loads when not adequately controlled (Wang et al., 2016).

After heavy metals enter soil systems, they undergo several processes that influence their movement and availability. Some metals attach to soil particles or associate with organic matter, thereby limiting their mobility (Kabata-Pendias & Mukherjee, 2007). However, certain metals like cadmium and lead are less strongly bound and can easily leach into groundwater, posing potential threats to potable water resources (Liu et al., 2013). The extent of heavy metal accumulation in soils is governed by factors such as metal solubility, soil characteristics, and waste management practices. Notably, metals like cadmium and zinc have a tendency to persist and build up in soils, especially in areas subject to prolonged industrial exposure or poor waste handling (Kabata-Pendias & Mukherjee, 2007). The continued presence and build-up of these metals in soils present considerable risks to both human health and environmental stability.

4.0 Natural Sources of Heavy Metals in Soil

Heavy metals are naturally occurring elements that can be found in soil through various geological processes and natural phenomena. Understanding the natural sources of heavy metals is essential for differentiating between natural background levels and contamination resulting from human activities.ref

4.1 Geological Processes and Weathering of Rocks

Natural geological processes significantly influence how heavy metals are distributed within soil environments. One of the main ways these metals enter the environment is through the gradual weathering of rocks. Continuous exposure to elements like water, temperature variations, and wind over extended periods leads to the disintegration of rocks and minerals, releasing trace elements, including heavy metals, into surrounding soils (Kabata-Pendias & Mukherjee, 2007).

The mineralogical makeup of the original or parent rock is a key factor in determining both the type and quantity of heavy metals eventually present in the soil. Rocks that contain minerals rich in heavy metals such as sulfides and oxides tend to release larger amounts of these elements when subjected to weathering processes (Alloway, 2013). Once released, these metals become incorporated into the soil matrix, forming part of the soil's inherent background metal content.

4.2 Volcanic Activity and Geothermal Emissions

Volcanic activity is another natural source of heavy metals in soil. Volcanoes emit gases, aerosols, and ash particles containing various elements, including heavy metals. During volcanic eruptions, these emissions are released into the atmosphere and can settle onto nearby soils through dry and wet deposition (Mandaliev *et al.,* 2015).

The volcanic ash, which consists of fragmented rock material, can contain elevated concentrations of heavy metals due to their presence in the parent rocks (Nriagu, 1996). As the volcanic ash deposits onto the soil surface, it contributes to the enrichment of heavy metals in the soil.

Geothermal emissions, often associated with volcanic activity, can also release heavy metals into the surrounding environment. Geothermal systems involve the circulation of hot water or steam through underground reservoirs. During this process, the water can dissolve trace elements, including heavy metals, from the rocks, subsequently releasing them into the surface environment through geothermal vents and springs (Einaudi *et al.,* 2003).

4.3 Impacts on Soil Quality

The existence of heavy metals in soil due to natural processes does not automatically indicate contamination. Nevertheless, the concentration levels and bioavailability of these metals can significantly affect soil functionality and the health of ecosystems. Elevated concentrations of specific heavy metals, even from geological sources, may negatively impact soil organisms, plants, and animals (Alloway, 2013).

For example, consistent exposure to high levels of heavy metals in soil environments can result in phytotoxic effects, impairing plant growth, physiology, and productivity (Kabata-Pendias & Mukherjee, 2007). Furthermore, these metals can accumulate within plant tissues, creating a pathway into the food chain and potentially threatening human health through dietary exposure (Mandaliev et al., 2015). As a result, it becomes essential to determine natural baseline concentrations and regularly track heavy metal levels in soils to evaluate possible ecological hazards and health-related concerns.

5.0 Common Heavy Metals Found in Contaminated Soil: Lead, Cadmium, Arsenic, Mercury, and Chromium

Heavy metal contamination in soil is a significant environmental concern due to its potential adverse effects on human health and ecosystem integrity. Some of the heavy metals commonly found in soil include, lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr). Ref

5.1 Lead (Pb)

Soil contamination by lead is largely attributed to human activities such as mining operations, metal smelting, industrial production, and the historic application of leaded gasoline and lead-based paints (Brännvall et al., 1999). Lead is environmentally persistent and tends to accumulate in soils over extended periods. Its toxic effects are well-documented, targeting critical human systems including the nervous, blood-forming, and renal systems (Flora et al., 2012).

5.2 Cadmium (Cd)

The release of cadmium into soil environments typically occurs through industrial processes like metal refining, the manufacture of phosphate fertilizers, and the incineration of waste materials (Alloway, 2013). This element has a prolonged biological half-life and has the potential to bioaccumulate in plants, making its way into the human food chain. Long-term cadmium exposure is linked to serious health concerns, including kidney dysfunction, bone-related abnormalities, and harmful effects on both the cardiovascular and respiratory systems (Järup, 2003).

5.3 Arsenic (As)

Soil contamination by arsenic can originate from both natural geological sources and various human-induced activities such as mining, pesticide application, and industrial waste disposal (Mandal et al., 2017). Arsenic appears in multiple chemical forms, though its inorganic species are considered the most hazardous. Persistent exposure to arsenic, especially through contaminated soil and water, is associated with several health conditions, including skin diseases, cancer development, and cardiovascular complications (Naujokas et al., 2013).

5.4 Mercury (Hg)

Mercury contamination in soils is predominantly linked to industrial sources such as artisanal gold mining, the burning of fossil fuels like coal, and the disposal of products containing mercury (Bose-O'Reilly et al., 2018). In environmental settings, mercury can convert to methylmercury, an especially harmful organic form.

Extended exposure to methylmercury poses serious neurological risks and can impair the development of the nervous system (Clarkson et al., 2003).

5.5 Chromium (Cr)

Chromium presence in soil is often due to various industrial applications, including chrome plating, leather processing, and stainless steel production (Alloway, 2013). The element occurs in several oxidation states, with hexavalent chromium (Cr(VI)) identified as the most dangerous variant. Prolonged contact with Cr(VI) has been associated with respiratory ailments, dermal irritation, and an elevated likelihood of developing lung cancer (Abadin et al., 2012).

6.0 Phytoremediation

Phytoremediation represents a sustainable and eco-friendly strategy that relies on plants to address pollution in soil, water, and air environments. This technique makes use of plants alongside their symbiotic microbial communities to extract, stabilize, or break down harmful substances present in contaminated ecosystems (Salt et al., 1998). It harnesses the natural capacity of plants to absorb pollutants via their root systems, transfer them to other plant parts, and either detoxify or confine them within plant tissues. The approach has been widely implemented in diverse polluted settings. Notably, it has been effective in remediating soils contaminated with heavy metals in areas surrounding mining activities and industrial operations (Wuana and Okieimen, 2011). Specific plant species like sunflowers, Indian mustard, and willows have shown considerable efficiency in accumulating and extracting metal pollutants from soil.

Similarly, aquatic environments have benefited from phytoremediation through the application of water-tolerant plants such as duckweeds and water hyacinths, which have demonstrated their ability to absorb, degrade, and remove a range of pollutants, including both organic substances and heavy metals (Mendez and Maier, 2008). Beyond soil and water, this green technology has also proven valuable for improving air quality. Vegetation, particularly in urban spaces, contributes to filtering and capturing airborne pollutants, thereby mitigating the adverse effects of air contamination (Escobedo et al., 2010).

6.1 Phytoextraction

Phytoextraction is an effective phytoremediation strategy that involves the use of hyperaccumulator plant species to eliminate heavy metals from polluted soils. These plants rely on various mechanisms to absorb and retain heavy metals within their tissues. The primary route for metal acquisition is through root uptake, where metals dissolved in soil water enter plant roots via passive or active transport processes (Luo et al., 2016). This uptake is facilitated by specialized metal transport proteins and ion channels located in the membranes of root cells.

Once heavy metals are absorbed, they can be compartmentalized within the vacuoles of root cells by forming stable chelates or complexes (Ali et al., 2013). Chelating molecules like phytochelatins and organic acids bind to metal ions, thereby reducing their toxicity and aiding in their sequestration. Another important aspect of phytoextraction is the movement of these metals from the roots to the aerial parts of the plant through xylem transport (Clemens et al., 2002). This process enables the accumulation of metals in above-ground tissues such as leaves and stems, allowing for the eventual harvest and disposal of the metal-laden biomass.

Hyperaccumulators possess distinctive physiological and biochemical traits that enable them to survive and prosper in metal-rich environments. Notable species include Thlaspi caerulescens, Sedum alfredii, and Arabidopsis halleri (Ma et al., 2015). These plants are characterized by their superior metal absorption and translocation capacities, highly effective detoxification mechanisms, and elevated tolerance to metal toxicity (Ali et al., 2013). Key adaptations involve enhanced expression of metal transporters, secretion of chelating compounds by roots, and robust intracellular detoxification systems. Additionally, hyperaccumulators often exhibit fast growth rates and quick reproductive cycles, supporting their utility in phytoextraction applications.

Several environmental and biological factors govern the effectiveness of phytoextraction. Soil pH is a critical determinant, as it influences the solubility and availability of metals for plant uptake. Generally, soils with slightly acidic to neutral pH levels are more conducive to metal absorption by plants (Luo et al., 2016). The chemical form or speciation of metals in the soil also affects their uptake efficiency. Metals existing as free ions or soluble complexes are more accessible to plant roots than those bound to soil particles or present in insoluble forms (Ali et al., 2013).

Additionally, plant-specific factors such as root architecture, symbiotic relationships with mycorrhizal fungi, and developmental stage significantly influence phytoextraction performance. Plants with extensive, branched root systems can explore larger soil volumes, thereby increasing metal acquisition. Mycorrhizal associations enhance nutrient and water uptake, indirectly improving metal absorption. Furthermore, metal uptake often varies with plant age, with younger plants generally displaying higher absorption rates (Luo et al., 2016).

6.2 Phytostabilization

Phytostabilization is an effective phytoremediation technique that utilizes plants to immobilize metals in the soil, reducing their bioavailability and mobility. Plants play a vital role in phytostabilization by facilitating the immobilization of metals in the soil matrix. They release various compounds, including organic acids, exopolysaccharides, and enzymes, which promote metal binding and precipitation (Shackira & Puthur, 2019). These compounds create complexation reactions, forming stable metal complexes or precipitates, thus reducing metal mobility and bioavailability. Furthermore, plants enhance the soil's physical properties, such as aggregation and water holding capacity, through their root system and rhizosphere interactions (Cunningham *et al.,* 1997). This helps in stabilizing metals in the soil by reducing erosion and leaching.

The selection of suitable plant species is crucial for the success of phytostabilization. Metal-tolerant plant species capable of establishing and thriving in contaminated environments are preferred (Kidd *et al.,* 2015). These species should exhibit deep and extensive root systems that can effectively penetrate the soil, promoting metal immobilization.

Some plant species, such as grasses (e.g., *Festuca spp., Agrostis spp*.) and legumes (e.g., *Trifolium spp., Medicago spp*.), have shown promising results in phytostabilization due to their ability to form extensive root systems and secrete metal-binding compounds (Bolan *et al.,* 2011). Additionally, native plant species that are well-adapted to the specific site conditions should be considered for successful phytostabilization.

Several factors influence the success of phytostabilization as a remediation technique. Soil properties, including pH, organic matter content, and texture, play a significant role in metal immobilization (Cunningham *et al.,* 1997). Optimal soil pH conditions, typically slightly acidic to neutral, favor metal immobilization by promoting metal complexation and precipitation reactions.

Plant-associated factors, such as root morphology and exudation, influence metal immobilization. Deep and fibrous root systems improve soil structure and enhance metal binding and retention (Pérez-Esteban *et al.,* 2014). The exudation of metal-binding compounds, such as organic acids and phytochelatins, by plant roots enhances metal immobilization in the rhizosphere.

Furthermore, environmental factors, including climate and site-specific conditions, impact the success of phytostabilization. Adequate moisture availability and temperature regimes that support plant growth and metal immobilization are essential (Alkorta *et al.,* 2010). Additionally, the presence of competing elements, such as calcium or iron, may affect metal complexation and precipitation reactions.

6.3 Phytovolatilization

Phytovolatilization is a phytoremediation technique that utilizes plants to release volatile metal compounds into the atmosphere. Phytovolatilization involves the release of volatile metal compounds from plant tissues into the atmosphere. Certain plants have the ability to uptake metals from the soil and subsequently convert them into volatile forms. Common volatile metal compounds include methylmercury (MeHg), dimethylarsenate (DMA), and dimethylnickel (DMNi) (Ali *et al.,* 2017). These compounds can be emitted into the air through the leaves or other plant organs.

Several plant species have demonstrated phytovolatilization potential for different metals. For example, certain ferns, such as *Pteris vittata*, are known to volatilize arsenic (As) in the form of DMA (Mench *et al.,* 2010). In the case of mercury (Hg), aquatic and wetland plants like *Typha spp.* and *Phragmites spp*. can volatilize methylmercury (MeHg) through their leaves (Ali *et al.,* 2017). Similarly, nickel (Ni) can be volatilized by hyperaccumulator plants like *Alyssum spp*. (Lombi *et al.,* 2002).

Several factors influence the phytovolatilization process, including plant physiology, soil properties, and environmental conditions. Plant-specific factors, such as plant species, growth stage, and metal uptake capacity, affect the extent of phytovolatilization (Ali *et al.,* 2017). Additionally, soil characteristics like pH, organic matter content, and microbial activity can influence metal availability and transformation.

Environmental factors such as temperature, light intensity, and atmospheric conditions also play a role in phytovolatilization. Higher temperatures generally enhance volatilization rates, while light can stimulate plant metabolic processes involved in the release of volatile compounds (Khalid *et al.,* 2017). However, extreme environmental conditions can limit plant growth and phytovolatilization efficiency.

Optimization of phytovolatilization processes involves considering various strategies. Soil amendments like sulfur and organic matter can enhance metal availability and facilitate volatilization (Ali *et al.,* 2017). Selecting appropriate plant species with high metal uptake and volatilization capacities is essential. Modifying environmental conditions, such as adjusting temperature and light regimes, can further optimize phytovolatilization processes.

6.4 Rhizofiltration

Rhizofiltration is a phytoremediation technique that utilizes the roots of plants to capture and accumulate metals from contaminated water sources. Plant roots play a crucial role in rhizofiltration by serving as a barrier that captures and accumulates metals from water. The roots act as filters, physically trapping metal particles and ions through processes such as adsorption, ion exchange, and entrapment in the root matrix (Ali *et al.,* 2014). Additionally, roots release chemical compounds, including organic acids and enzymes, that enhance metal binding and immobilization.

The selection of suitable plant species is vital for the success of rhizofiltration. Some plant species have demonstrated a high affinity for metal uptake and accumulation. For example, aquatic plants like water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) have shown efficient metal uptake capabilities (Yadav *et al.,* 2021). Terrestrial plants such as Indian mustard (*Brassica juncea*) and sunflower (*Helianthus annuus*) are also commonly used in rhizofiltration due to their metal hyperaccumulation traits (Ali *et al.,* 2014).

Several factors need to be considered to optimize and effectively apply rhizofiltration as a remediation technique. The choice of plant species should be based on the metal(s) of concern, their uptake capacity, and tolerance to environmental conditions (Ali *et al.,* 2014). Proper hydraulic design and flow management are essential to ensure contact between the contaminated water and plant roots. Optimizing the rhizofiltration process involves enhancing root development and metal uptake. Strategies such as manipulating root architecture through hydroponic culture or optimizing nutrient availability can improve metal capture efficiency (Chen *et al.,* 2018). Additionally, optimizing environmental conditions, such as pH and temperature, can influence metal solubility and root activity.

Application considerations include the scale of implementation and site-specific factors. Large-scale rhizofiltration systems may require proper engineering design and maintenance. The characteristics of the contaminated water, including metal concentrations and the presence of other contaminants, must be evaluated to determine the suitability of rhizofiltration as a remediation option (Saha *et al.,* 2017).

7.0 Factors Affecting Phytomanagement

Choosing the right plant species is fundamental for the success of phytoremediation at sites contaminated with heavy metals. Identifying metal-tolerant plants involves evaluating their capacity to survive and perform optimally in polluted soils. Common parameters used in selection include tolerance to specific metals, the ability to produce substantial biomass, root system architecture, metal absorption efficiency, and the capacity to translocate metals within the plant structure (Ali et al., 2013). Plant tolerance is typically assessed through experimental trials exposing various species to different metal concentrations to observe which can sustain growth and physiological functions under stress.

Genetic differences among plant species greatly influence their potential to endure and accumulate heavy metals. Certain species possess unique genetic features that allow them to survive in metal-laden environments without adverse effects. These adaptations involve specialized metal transport proteins, chelation processes, and detoxifying enzymes that manage internal metal concentrations (Cobbett & Goldsbrough, 2002). Such genetic factors largely explain the differing capacities for metal uptake and storage observed between plant varieties.

Some species, identified as hyperaccumulators, have evolved specific traits enabling them to amass unusually high metal concentrations in their tissues. These plants typically carry genes responsible for regulating processes such as metal absorption, internal distribution, and secure storage. For instance, the gene HMA4 has been associated with *Arabidopsis halleri's* ability to accumulate cadmium (Cd) at elevated levels without showing toxicity symptoms (Hanikenne et al., 2008). These genetic traits allow hyperaccumulators to tolerate and immobilize heavy metals effectively.

Selecting species suited to phytoremediation efforts is pivotal in maximizing metal extraction from polluted soils. Plants capable of tolerating high metal levels while producing significant biomass contribute to improving overall remediation efficiency. Furthermore, selecting species that combine strong metal absorption and translocation capacities enhances the process by enabling effective removal and containment of metals.

The choice of plant species should also be guided by the type of heavy metal targeted for cleanup. Different plants display varied affinities for specific metals. For example, Indian mustard (*Brassica juncea*) is noted for its effectiveness in cadmium (Cd) uptake, while species like *Pteris vittata* are particularly efficient in accumulating arsenic (As) (Ali et al., 2013). Utilizing species with known accumulation capabilities can help tailor phytoremediation to the contamination profile of each site.

Soil properties are another critical factor influencing both plant growth and metal absorption during phytoremediation. Soil pH directly impacts nutrient availability and metal mobility. Acidic soils tend to increase the solubility and bioavailability of metals like manganese (Mn) and aluminum (Al), which can be harmful to plant health (Kabata-Pendias, 2011). Conversely, alkaline soils may restrict the availability of essential elements such as iron (Fe), copper (Cu), and zinc (Zn) due to reduced solubility.

For most plants, an optimal pH range lies between 6 and 7, supporting balanced nutrient uptake and robust root system development (Ali et al., 2013). However, some species thrive in more extreme pH conditions. For example, blueberries perform better in acidic soils (pH 4-5), while other plants like cacti prefer alkaline environments (pH 7-8) (Kabata-Pendias, 2011). Soil amendments can be used to modify pH and enhance the success of phytoremediation efforts.

Soil organic matter plays an important role in both plant nutrition and metal behavior in the soil. It improves soil texture, water retention, and nutrient exchange, which promotes healthy plant growth. Organic matter acts as a nutrient reservoir and helps stabilize metals by forming complexes, thereby limiting their mobility and potential toxicity (Kabata-Pendias, 2011). Applying organic amendments, including compost and animal manure, can raise organic matter levels, enhancing both plant vigor and metal absorption efficiency (Ali et al., 2013; Babaniyi et al., 2023).

Soil texture, defined by the proportions of sand, silt, and clay, also affects metal availability and plant performance. Sandy soils, with large particle sizes, tend to drain quickly and hold less water and nutrients, reducing both plant growth potential and metal bioavailability. In contrast, clay-rich soils have finer particles and larger surface areas, increasing their capacity to retain metals and nutrients (Kabata-Pendias, 2011). While this can make metals more accessible to plants, excessive clay content may cause waterlogging, hindering plant health.

Environmental factors, such as temperature and precipitation patterns, substantially influence plant growth rates and metal uptake during phytomanagement. Plant species vary in their tolerance to different climate conditions, which affects their physiological processes and contaminant absorption capacity (Ali et al., 2013). Temperature modulates key plant functions like nutrient uptake and photosynthesis, directly impacting their remediation performance.

Rainfall distribution is equally important, as adequate moisture is essential for sustaining plant growth and facilitating metal translocation. Drought can impede these processes by causing water stress, while excessive rainfall may lead to poor aeration and root damage (Mendez & Maier, 2008). Managing water availability through irrigation or drainage systems can improve the efficiency of phytomanagement projects.

Light is another essential factor since it drives photosynthesis and influences plant biomass accumulation and energy allocation towards contaminant absorption (Numan et al., 2018). Low light levels or shading from neighboring plants and structures can reduce photosynthetic rates, slowing plant growth and reducing metal uptake capacity.

Finally, air pollution itself can impact the performance of phytomanagement systems. Atmospheric deposition of heavy metals onto plant surfaces and soil contributes additional contamination burdens. Metals present in air pollutants may be absorbed by plants or alter soil chemistry and microbial activity, indirectly affecting plant health and metal uptake potential (Baker et al., 2000). Furthermore, gases such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) can acidify soils and disrupt nutrient cycling, thereby influencing the overall effectiveness of phytomanagement (Ali et al., 2013). It is therefore important to consider air quality and environmental conditions when designing and implementing phytoremediation strategies, especially in urban or industrial regions.

8.0 Challenges and Limitations of Phytomanagement

Phytomanagement is a promising approach for the remediation of heavy metal-contaminated soil. However, several challenges and limitations can hinder its effectiveness.

8.1 Constraints of Slow Growth and Limited Metal Accumulation

One of the challenges in phytomanagement is the slow growth and limited metal accumulation in some plant species. The natural growth rate of some plants may be insufficient to achieve significant metal removal within practical time frames (Pilon-Smits, 2005). Additionally, some plant species may have limited metal uptake capacity, restricting their effectiveness in remediation efforts.

8.2 Constraints in Using Hyperaccumulator Plants

Hyperaccumulator plants, which possess the ability to accumulate exceptionally high levels of heavy metals, are often considered ideal candidates for phytomanagement. However, their use is not without constraints. Some hyperaccumulator species may have slow growth rates or limited biomass production, which can hinder the overall efficiency of metal removal (Baker *et al.,* 2000). Furthermore, hyperaccumulators are often site-specific and may not be suitable for all contaminated areas.

8.3 Potential Risks of Metal Transfer to the Food Chain through Phytomanagement

Edible crops cultivated in soils contaminated with heavy metals have the capacity to absorb these elements through their root systems. Certain metals, including lead (Pb), cadmium (Cd), and arsenic (As), tend to be taken up more easily by plants and can subsequently be transported to different tissues, including the consumable parts (Kachenko & Singh, 2006; Adewumi & Ogundele). This raises public health concerns about the potential intake of toxic metals through the consumption of affected food crops. The accumulation of heavy metals in edible plants carries significant health implications for humans. Continuous exposure to elevated concentrations of these metals, particularly through dietary sources, can negatively impact physiological functions and contribute to various health complications (Xue et al., 2010; Ogundele et al., 2024). Prolonged ingestion of lead and cadmium, for instance, has been linked to neurological impairments, kidney dysfunction, and developmental challenges, especially among vulnerable groups such as children (Agency for Toxic Substances and Disease Registry, 2007).

9.0 Emerging Technologies and Future Perspectives

Phytomanagement, as a sustainable approach for remediating heavy metal-contaminated soil, continues to evolve with the development of emerging technologies. This session explores the potential of genetic engineering and plant breeding in enhancing metal tolerance and accumulation in plants. It also discusses various approaches used to improve metal uptake and tolerance in plants, along with the potential implications of genetic modifications.

9.1 Genetic Engineering and Plant Breeding for Enhanced Metal Tolerance

Genetic engineering and plant breeding offer promising avenues for developing plants with enhanced metal tolerance. Genetic engineering techniques, such as gene overexpression or gene silencing, can introduce specific genes involved in metal transport, sequestration, or detoxification pathways into plants (Rascio & Navari-Izzo, 2011). This approach enables the targeted manipulation of metal-related genes to improve plant metal tolerance and accumulation.

Plant breeding, on the other hand, employs traditional breeding techniques to select and cross plants with desirable traits, including metal tolerance. Breeding programs focus on identifying and combining favorable traits from different plant varieties to develop new cultivars with enhanced metal tolerance and accumulation capacities (Wójcik *et al.,* 2012). This approach utilizes natural genetic variation within plant populations to select for desired traits.

9.2 Approaches for Enhancing Metal Accumulation and Tolerance in Plants

Various approaches are employed to enhance metal accumulation and tolerance in plants. One approach involves the identification and selection of naturally occurring metal hyperaccumulator plants. These plants possess unique mechanisms for efficient metal uptake, translocation, and sequestration, allowing them to accumulate high levels of metals in their tissues (Chaney *et al.,* 2012). By understanding and harnessing these mechanisms, researchers can develop strategies to improve metal accumulation in non-hyperaccumulator plants.

Another approach involves the use of microbial symbionts, such as arbuscular mycorrhizal fungi and rhizobacteria, to enhance plant metal uptake and tolerance. These beneficial microbes form associations with plant roots, facilitating nutrient and water uptake and improving plant health (Cicatelli *et al.,* 2020). Some microbial species have been found to enhance metal mobilization and uptake by plants, contributing to improved phytomanagement outcomes.

9.3 Alternative Plant Selection Strategies

To overcome the limitations of slow growth and limited metal accumulation, alternative plant selection strategies can be employed in phytomanagement. One approach is to focus on fast-growing plant species that can establish and proliferate quickly, thereby maximizing biomass production (Meers *et al.,* 2005). These plants may have moderate metal accumulation capacity but compensate for it through rapid growth, allowing for effective metal uptake over time. Another strategy involves the use of mixed plant communities or polycultures, combining multiple plant species with complementary characteristics (Van der Lelie *et al.,* 2004). This approach leverages the different metal uptake capacities and growth rates of various plants, creating a synergistic effect that enhances overall metal removal efficiency. By selecting a combination of plants with varying metal accumulation abilities, the limitations of individual species can be mitigated.

9.4 Strategies to Mitigate Metal Transfer and Ensure Food Safety

To mitigate the potential transfer of metals to the food chain and ensure food safety, several strategies can be employed in phytomanagement practices. The addition of soil amendments, such as organic matter and liming agents, can help reduce metal bioavailability and uptake by plants (Wang *et al.,* 2016). These amendments can alter soil properties, including pH and metal binding capacity, thus reducing the uptake of metals by plant roots.

Careful selection of plant species and cultivars that have lower metal accumulation potential can minimize the risk of metal transfer to the food chain (Ullah *et al.,* 2021). By choosing low-accumulating plant varieties for cultivation in contaminated areas, the likelihood of metal uptake by edible parts can be reduced. Implementing proper soil management practices, such as soil coverings and erosion control measures, can minimize metal input into the food chain (Kidd *et al.,* 2015). Controlling soil erosion helps prevent the dispersal of contaminated soil particles and reduces the potential contamination of crops.

Regular monitoring and testing of soil and crop samples for metal concentrations are crucial for ensuring food safety (Clemens *et al.,* 2013). This allows for early detection of potential metal contamination and facilitates appropriate actions to be taken, such as adjusting cultivation practices or implementing additional remediation measures.

9.5 Nanotechnology Applications in Phytomanagement

Nanotechnology offers promising solutions for improving phytomanagement strategies in heavy metal-contaminated soil. Nanoparticles have unique properties that make them effective in metal immobilization. Engineered nanoparticles, such as zero-valent iron nanoparticles (nZVI) and nanoscale metal oxides, can effectively adsorb and bind heavy metals, reducing their mobility and bioavailability in soil (Sasidharan *et al.,* 2014). These nanoparticles can create stable complexes with metals, preventing their leaching into groundwater and further contamination (Gogos *et al.,* 2016). Nanoparticles can also be used to enhance plant uptake of heavy metals in phytomanagement. Functionalized nanoparticles, such as those coated with organic molecules or chelating agents, can increase metal solubility in soil and facilitate their uptake by plant roots (Rico *et al.,* 2013). The nanoparticles act as carriers, delivering metals to plant roots and improving their bioavailability for uptake and subsequent accumulation in plant tissues (Cifuentes *et al.,* 2010).

10. Conclusion

Despite the several challenges and limitations need to be considered when implementing phytomanagement strategies. Overall, phytomanagement offers a promising pathway for addressing heavy metal contamination in soil. With continued research, innovation, and the integration of multiple approaches, the potentials of phytomanagement can be maximized, and the challenges can be effectively mitigated. By adopting a holistic and multidisciplinary approach, we can leverage the power of plants to restore contaminated sites and create a more sustainable and healthier environment for future generations.

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