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REMEDIATING HEAVY METAL POLLUTION THROUGH PLANTS AN OVERVIEW OF PHYTOREMEDIATION TECHNIQUES AND IMPACT

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ABSTRACT

Traditional techniques for the remediation of heavy metals from polluted soil and water are frequently expensive, time-consuming, and detrimental to the environment. In contrast to organic contaminants, heavy metals do not undergo natural degradation, necessitating immobilization or extraction to mitigate their harmful impacts. In light of these constraints, recent advancements have concentrated on environmentally sustainable and economically viable methods utilizing microbes, biomass, or living flora to remediate contaminated ecosystems. Phytoremediation has developed as a promising eco-friendly method that utilizes the inherent powers of plants to absorb, stabilize, or change pollutants from soil, water, or sediments. This approach is particularly appropriate for locations with superficial contamination by metals, fertilizers, or organic contaminants. Phytoremediation techniques encompass phytostabilization, phytoextraction, and rhizofiltration, phytovolatilization. These processes depend on biological, chemical, and physical interactions within the plant system and its surroundings. This paper delineates the function of phytoremediation in mitigating heavy metal contamination and examines its effects on plant physiology and growth, emphasizing its potential for extensive application.
Keywords **:** Heavy metals, phytoremediation, metal uptake, metal toxicity, phytoextraction, rhizofiltration, phytostabilization, phytovolatilization.

Introduction

Science, industry, and technology have advanced remarkably as a result of human civilization's evolution. The modern world has seen significant change, from agricultural mechanization to fast urbanization. However, the increasing degradation of our natural environment is a hidden cost of this progress. The well-being of the environment is frequently neglected or sacrificed in the name of industrial and economic expansion. Heavy metal poisoning of soil is one of the most concerning effects of uncontrolled development (Khatun *et al.*, 2022). Toxic compounds emitted into the air, water, and land have reached harmful levels due to the expansion of industry and mining activities (Okereafor *et al.*, 2020). The situation is only made worse by the use of artificial fertilizers, pesticides, and inappropriate waste disposal techniques. Nowadays, soils in both urban and rural areas frequently include metals including lead, cadmium, chromium, arsenic, mercury, and nickel, which are frequently byproducts of mining and industrial processes (Alloway, 2013). Heavy metals do not deteriorate with time, in contrast to organic contaminants. They silently make their way into the food chain through crops and groundwater, where they stay ingrained for decades. When ingested by people, animals, or plants, these metals gradually build up in bodily tissues. Numerous health problems, such as cancer, kidney failure, developmental delays in children, and neurological damage, can result from this bioaccumulation and biomagnification (Agbugui & Abe, 2022). Heavy metal concentrations in soil samples have been found to be well over permissible levels in areas with substantial industrial activity, including sections of China, India, and Africa (Yang *et al.*, 2018) . For instance, chromium levels in soil have been found to be up to ten times higher than the allowable limit in certain locations close to tanneries and mining zones (Oruko *et al*., 2021). In a similar vein, lead concentrations close to battery recycling facilities and smelting facilities have rendered the area unusable for farming, endangering public health and food security (Riani *et al*., 2024). Areas that are industrial and coastal are more at risk, frequently, improperly treated wastewater is dumped straight into rivers and oceans, damaging the water and eventually harming the soil around (Tariq & Mushtaq, 2023). Fertile land is deteriorated over time by these harmful substances, which also upset the delicate equilibrium of nearby ecosystems. Once-productive agricultural areas have become dangerous and desolate in some locations. Even though the problem is serious, conventional techniques for cleaning up heavy metal-contaminated soil are not only costly but also harmful to the environment. Numerous traditional cleanup techniques include chemical agents, cremation, or excavation, all of which might worsen the biodiversity in the area. Scientists and environmentalists are looking for sustainable solutions as awareness rises. Phytoremediation, which involves using particular plants that are known to absorb, store, or neutralize dangerous metals in the soil, is one potential strategy. The potential of plants like vetiver grass, sunflowers, and Indian mustard to clean up contaminated land without upsetting the ecology is drawing more and more attention (Prasad, 2015; Singh & Pandey, 2020). These natural technologies provide an affordable and environmentally responsible substitute for traditional techniques. A change in perspective is necessary for the long-term well-being of our planet, one that places equal importance on environmental sustainability and economic expansion. Industries, legislators, and residents must collaborate to embrace cleaner practices, impose more stringent environmental rules, and invest in green technology that promote healing rather than harm in order to secure a safe and equitable future. Economic development and environmental preservation will need to coexist.

The Global Scale and Impact of Heavy Metal Contamination

Heavy metals constitute a significant environmental threat worldwide. Their toxicity, persistence, and bioaccumulation in living beings have rendered them a significant public health and environmental issue. It is estimated that more than millions of individuals globally are directly impacted by heavy metal contamination in their surrounding environment, notably in regions adjacent to industrial, mining, and waste disposal sites (Chowdhury & Rahman, 2024). In numerous areas, industrial pollution has attained concerning levels. In certain contaminated areas, soil has been detected with lead concentrations of 1,000 mg/kg, far exceeding the advisable threshold of 400 mg/kg (Chaney & Ryan, 1994). In these regions, children frequently encounter lead concentrations that can significantly impair brain development and result in enduring cognitive and behavioral problems. Former mining and smelting communities sometimes exhibit air and water pollution levels that exceed safe guidelines by several hundred times (Zhang *et al*., 2012). In certain municipalities adjacent to defunct battery recycling facilities or chemical plants, cadmium levels in groundwater have been documented above 0.1 mg/L, a concentration tenfold greater than the acceptable threshold for potable water (Adeleke *et al*., 2023). Liver and kidney problems, along with bone fragility, are prevalent in these regions. Worldwide, heavy industry and mining activities emit around 22 million metric tons of heavy metals into the atmosphere annually. These encompass metals like lead, mercury, cadmium, arsenic, chromium, copper, and zinc (Cimboláková *et al*., 2019) . Upon release, these metals permeate the atmosphere, soil, and aquatic environments, potentially enduring for over a century inside ecosystems. The food chain is a highly perilous route of exposure. Fish in contaminated rivers and lakes have been detected with mercury levels reaching 1.5 ppm, when safe eating thresholds are generally below 0.5 ppm (Newberne & Stillings, 1974). Vegetables cultivated in contaminated soils have exhibited chromium and arsenic concentrations that surpass safety limits by 5 to 10 times, presenting considerable health hazards to consumers. Developing nations constitute a substantial share of global mining production, however they disproportionately endure environmental degradation. Countries such as China, Brazil, and India jointly account for approximately 45% of global iron ore production and 30% of copper production, frequently employing methods that significantly contribute to environmental pollution due to lenient legislation and insufficient waste management (Holmes *et al*., 2022). The health impact is immense. In numerous industrial regions, as much as 30% of the population is afflicted by ailments directly or indirectly associated with metal pollution, including malignancies, renal failure, and developmental problems in children. In several instances, complete water systems serving more than 3 million individuals have been deemed dangerous due to contamination from industrial effluents, such as dyes, solvents, and heavy metals (Alsukaibi, 2022; Chowdhary *et al*., 2020; Rathi *et al*., 2021). Environmental degradation is not confined to human activities. Contaminated rivers experience a decline of over 60% in indigenous aquatic biodiversity, as numerous fish species are incapable of reproduction or survival due to heavy metal toxicity (Rathi *et al.*, 2021). Soil quality deteriorates swiftly, with contaminated farms exhibiting up to a 70% decrease in agricultural productivity and microbiological diversity (Lal, 2015). The magnitude of the issue necessitates synchronized intervention. In the absence of appropriate intervention, these metals will persist in accumulating inside our environment and our bodies, insidiously exacerbating the burden of sickness and ecological degradation. Remediation techniques remain costly and frequently ineffective, becoming prevention and regulation far more essential.

Sources of Heavy Metal Pollution

Table 1: Sources of Heavy Metal Pollution

Source Type	Specific Activities or Materials Contributing to Pollution	References
Geological	Natural mineral deposits and rock weathering	(Carroll, 2012)
Industrial	Industrial effluents, fuel production, smelting, metal products, cable coating industries	(Stringer, 1998; Tünay *et al.*, 2004)
Mining Operations	Mining, metal extraction, and refining activities	(Igogo *et al.*, 2021)
Military	Weapons testing, explosive residues, and military waste	(Letzel *et al.*, 2003; Lima *et al.*, 2011)
Agricultural	Use of pesticides, fungicides, and chemical fertilizers (including banned or excessive use)	(N. Sharma & Singhvi, 2017)
Municipal Waste	Roadside dumping, landfill usage, and sewage-based irrigation contributing toxic metals and carcinogens	(N. Sharma & Singhvi, 2017)
Small-scale Industries	Battery production, brick kilns, metal smelting, informal recycling	(Michikazu & Amit, 2008; I. D. Williams, 2016)
Combustion Sources	Coal burning and fuel combustion releasing airborne metal particulates	(Morawska & Zhang, 2002)
Contaminated Water	Irrigation with sewage or effluent-contaminated water, leading to polluted soil and crops	(Dheri *et al.*, 2007; Kisku *et al.*, 2000)

Impact of Heavy Metal Toxicity on Plant Physiology

Plants possess the inherent capacity to assimilate vital metals, including calcium, cobalt, copper, iron, potassium, magnesium, manganese, molybdenum, sodium, nickel, selenium, vanadium, and zinc from the soil, which are needed for their growth and development (Bhatla & Lal, 2023). This uptake system enables the absorption of non-essential metals such as aluminum, arsenic, cadmium, chromium, mercury, lead, platinum, and uranium, which lack any known biological function. Due to the non-biodegradable nature of metals, their excessive accumulation in plant cells can induce toxicity, either directly by inducing oxidative stress and destroying cellular structures or indirectly by displacing essential nutrients at exchange points (Kumar *et al.*, 2022). To adapt to metal-rich environments, certain plants have evolved strategies including exclusion, which restricts metal absorption and sustains stable concentrations in the shoot; inclusion, where shoot concentrations mirror those in the soil; and bioconcentration, where metals accumulate in the roots and upper plant structures irrespective of soil levels (Clemens, 2006). Elevated metal concentrations in soil impede plant metabolic functions and growth, perhaps resulting in mortality (Nagajyoti *et al.*, 2010). The ingestion of metal-contaminated crops by people can result in significant health complications, encompassing both acute and chronic ailments. Zinc is essential for enzyme activity and DNA function; nevertheless, excessive amounts can induce chlorosis in leaves (Bonnet *et al.*, 2000). Copper, a vital micronutrient, facilitates processes such as photosynthesis and respiration; yet, in excessive amounts, it can impede root development and cause foliar chlorosis (Morya *et al.*, 2023). Cadmium, while non-essential, is very harmful to plants, impairing enzyme activity, disrupting DNA activities, and heightening vulnerability to infections (Genchi *et al.*, 2020). Nickel, previously deemed non-essential, is now recognized for its role in iron metabolism and enzymatic processes; yet, its toxicity becomes evident at elevated amounts (Bhalerao *et al.*, 2015). Lead is completely non-essential and hazardous, even in trace doses, causing symptoms such as chlorosis, necrosis, stunted development, and diminished plant biomass (Jagota *et al.*, 2024).

Advancements in Soil Remediation Techniques from Conventional to Green Approaches

Soil remediation is the process of recovering polluted soil to a stable and healthy ecological condition, allowing it to once again sustain plant and microbial life as it did before pollution or deterioration

(Scullion, 2006). Historically, remediation methods entailed the actual extraction of contaminated soil and its subsequent conveyance to laboratories for treatment (Sims, 1990). These methods often involved chemical washing to eliminate dangerous metals, followed by either restoring the treated soil to its original site or disposing of it as hazardous waste. Although these traditional methods effectively diminish contamination, they are ex situ, necessitating soil removal from the site, and entail substantial financial expenses, considerable energy consumption, and detrimental effects on soil structure and long-term fertility. Additionally, techniques such as solidification, stabilization, thermal desorption, vitrification, and encapsulation may be effective for smaller, heavily polluted sites; but they are frequently unfeasible for large-scale implementations because to their expense and environmental impact (Conner & Hoeffner, 1998). To tackle these issues, other solutions have been created, including the application of soil amendments like lime, phosphate, and calcium carbonate to immobilize heavy metals in situ. Although these chemical techniques can diminish the mobility and bioavailability of metals and mitigate immediate environmental hazards, they frequently serve as temporary remedies, as the pollutants persist in the soil and may be reactivated under specific environmental conditions. The increasing recognition of environmental sustainability has prompted the investigation of biologically-based and eco-friendly methods for soil restoration. A viable approach is bioremediation, which utilizes the inherent detoxifying ability of microorganisms to decompose organic contaminants in contaminated settings (V. Kumar *et al.*, 2018; Megharaj *et al.*, 2011). Nonetheless, bioremediation has restricted efficacy for heavy metals, as these inorganic compounds are not subject to microbial degradation. This constraint has prompted the advancement of phytoremediation, a botanical method that leverages the inherent capacity of some plants to absorb, collect, and occasionally convert heavy metals and other contaminants from soil and water. In phytoremediation, plant roots absorb metal pollutants and translocate them to the shoots, where they accumulate (Nouri *et al.*, 2009). Eventually, these plants are harvested, thereby extracting the metals from the location. In certain sophisticated systems, the incineration of gathered biomass can diminish volume, while valuable metals may be extracted from the ash, offering a possible economic benefit that could mitigate remediation expenses (Vocciante *et al.*, 2019). This procedure eliminates toxins permanently while causing minimum disruption to the soil ecology. Phytoremediation is a multidisciplinary method that encompasses plant physiology, soil chemistry, and microbiology, and has been utilized for various contaminants such as heavy metals, petroleum hydrocarbons, radionuclides, pesticides, and other industrial pollutants (Priya *et al.*, 2023). Some plant species, termed hyperaccumulators, have developed systems to withstand and accumulate elevated levels of metals without experiencing toxicity. Families including Brassicaceae, Fabaceae, Asteraceae, and Lamiaceae have plants that are very efficacious for this objective (Anjum *et al.*, 2012; Vara Prasad & de Oliveira Freitas, 2003a). *Brassica juncea* (Indian mustard) is a rapidly growing plant characterized by substantial biomass production and demonstrated efficacy in the accumulation of metals such as lead, nickel, and cadmium in its shoots (Rathore *et al.*, 2019). Aquatic plants such as *Eichhornia crassipes* (water hyacinth), *Lemna minor* (duckweed), and *Pistia* have been examined for their efficacy in eliminating impurities from water via a process termed rhizofiltration (Banerjee & Roychoudhury, 2022). Recent research has identified several species, including *Pteris vittata*, a fern that can accumulate significant arsenic levels in its fronds without exhibiting toxicity, as well as crops such as corn, sunflower, and sorghum, which are effective for phytoremediation due to their rapid growth and high biomass yield (Niazi *et al.*, 2016). Plants such as alfalfa have been investigated as biosorbents for heavy metals, providing an additional natural and economical resource in the cleanup arsenal (Jócsák *et al.*, 2022). Phytoremediation is a viable alternative to traditional remediation techniques, notable for its cost-effectiveness, minimum ecological disturbance, and capacity for extensive implementation. Ongoing research in plant selection, genetic modification, and agronomic methods is anticipated to enhance the efficacy and usability of phytoremediation for the restoration of contaminated soils, positioning it as a crucial element in sustainable environmental management.

Phytoremediation in Practice

Phytoextraction

Phytoextraction is a type of phytoremediation that entails the absorption of metal pollutants by plant roots, followed by their buildup in aerial structures, including shoots and leaves (Asgari Lajayer *et al.*, 2019). The plants are subsequently harvested, so eliminating the pollutants from the soil in an eco-friendly and sustainable way. In comparison to traditional soil remediation techniques, phytoextraction is markedly more economical and less intrusive to the environment (Bhat *et al.*, 2022). It additionally offers benefits, including soil stabilization, as vegetative cover during restoration diminishes the likelihood of erosion and leaching. Through successive cycles of cultivation and harvest, the concentration of soil pollutants can be progressively diminished to acceptable levels. A notable instance is the Chinese brake fern (*Pteris vittata*), which demonstrates a remarkable capacity to hyperaccumulate arsenic from polluted soil (Bondada & Ma, 2003; Wei *et al*., 2020). Field research at a wood-preserving site demonstrated that these ferns could remove substantial quantities of arsenic from soil with exceedingly high concentrations. A further effective instance is to the utilization of sunflower plants (*Helianthus annuus*) for the remediation of radioactive elements, specifically cesium-137 and strontium-90 (Shaikh *et al*., 2024). These plants were utilized in a demonstration adjacent to the Chernobyl nuclear catastrophe site, where they were cultivated in a contaminated pond. In a few two weeks, the concentration of radionuclides in the water fell by about 90%. The plant roots absorbed radionuclides at concentrations thousands of times greater than those present in the surrounding water. In a separate project under a government program, sunflower plants were utilized to remediate soil contaminated with uranium. Within 24 hours, these plants diminished the uranium concentration in the impacted area by 95%, underscoring their swift and efficacious repair capability (Dudhe *et al*., 2025). These empirical case studies illustrate the effective and scalable implementation of phytoextraction, positioning it as a viable alternative for the remediation of habitats contaminated with heavy metals and radionuclides.

Phytostabilization

Phytostabilization, or in-situ inactivation, is a remediation method predominantly utilized for soils, sediments, and sludge (Xu *et al*., 2022). It entails utilizing plant roots to diminish the mobility and bioavailability of pollutants in the soil. The plants fulfill several essential roles: they restrict water infiltration through the soil, thereby mitigating the formation of hazardous leachate; they function as a physical barrier to prevent direct contact with contaminated soil by humans or animals; and they diminish soil erosion and the dissemination of toxic metals to adjacent areas (Gavrilescu, 2021). The process operates via mechanisms including sorption, precipitation, complexation, and alterations in metal oxidation states (Shi *et al*., 2021). This method is especially efficacious for immobilizing pollutants such as lead, arsenic, cadmium, chromium, copper, and zinc (Giergiczny & Król, 2008). A notable advantage is that it eliminates the need for hazardous biomass disposal, rendering it both economically viable and environmentally sustainable. It is particularly beneficial in scenarios necessitating rapid confinement to safeguard surface and groundwater sources, while concurrently reducing erosion and water availability within the system. Phytostabilization has been employed in numerous contaminated areas, including those impacted by mining and industrial operations (Alkorta *et al*., 2010). In a greenhouse experiment, sorghum a plant characterized by fibrous roots was employed to remediate soil contaminated with heavy metals. Vermicompost was incorporated as a natural soil enhancer. Results indicated that elevated concentrations of heavy metals (40–50 ppm) suppressed plant growth, whereas lower concentrations (5–20 ppm) enhanced shoot development and augmented biomass. The metals were predominantly absorbed by the roots in the following order: zinc > copper > cadmium > nickel > lead (Kutrowska *et al*., 2017). The extensive root system of sorghum, characterized by its substantial surface area and deep penetration, mitigated leaching and efficiently stabilized metals in the root zone (Vasilachi *et al*., 2023).

Rhizofiltration

Rhizofiltration is a technique primarily employed to remediate groundwater, surface water, and wastewater with minimal pollutant concentrations. This procedure employs terrestrial and aquatic plants to absorb, concentrate, and eliminate toxic compounds from contaminated water via their root systems (S. Sharma *et al*., 2015). Rhizofiltration specifically targets heavy metals such as lead, cadmium, copper, nickel, zinc, and chromium. These metals are predominantly sequestered in the roots rather than translocating to the aerial portions of the plants. Numerous plants have demonstrated the capacity to extract metals from water. Sunflowers, Indian mustard, tobacco, rye, spinach, and corn have been evaluated for their capacity to absorb lead, with sunflowers demonstrating the greatest efficacy (Samal *et al*., 2023). Indian mustard (*Brassica juncea (L.) Czern*) possesses a significant capacity to sequester lead and can extract lead from various quantities in water (Yang *et al*., 2021). A significant advantage of rhizofiltration is its adaptability. It permits the utilization of both terrestrial and aquatic flora and can be implemented either directly at the contamination location or in a regulated environment where contaminated water is processed. In contrast to several other plant-based remediation techniques, rhizofiltration does not necessitate the translocation of contaminants to the aerial parts of the plants (Woraharn *et al.*, 2021). This indicates that non-specialized accumulator plants can still be efficacious. Terrestrial plants are frequently favored due to their fibrous root systems, which expand significantly, hence enhancing the root surface area for pollutant absorption. Sunflowers have effectively remediated uranium contamination in regions impacted by nuclear incidents. Research involving aquatic cultivation of plants, including Indian mustard and sunflowers, has demonstrated their capacity to extract hazardous metals from contaminated water (Rahman *et al.*, 2013; Raj *et al.*, 2020; Vara Prasad & de Oliveira Freitas, 2003b). Further investigation into aquatic flora such as Pistia, duckweed, and water hyacinth has revealed their capacity for purifying water tainted with heavy metals from coal ash (Mishra & Shukla, 2016). These plants exhibit differing capacities for metal absorption, with pistia demonstrating the highest capability, succeeded by duckweed. Water hyacinth also sequesters metals, but to a smaller degree. These findings indicate that these aquatic plants may serve as effective agents for the removal of heavy metals from polluted water sources.

Phytovolatilization

Phytovolatilization is a botanical process wherein plants absorb pollutants from soil or water, convert them into volatile forms, and subsequently release them into the atmosphere via transpiration (Arya *et al.*, 2017). This method has been predominantly investigated for the remediation of metals like mercury, wherein plants absorb mercuric ions and transform them into elemental mercury, a less hazardous form that is subsequently released into the atmosphere. A primary advantage of this approach is the conversion of specific poisonous chemicals into less deleterious ones. Ionic mercury can be transformed into elemental mercury, hence diminishing its toxicity in the soil (Raj & Maiti, 2019). Nonetheless, a possible disadvantage is that once emitted, mercury in its gaseous state might re-enter the environment via atmospheric mechanisms like precipitation and ultimately re-circulate into aquatic ecosystems. This recycling could facilitate the creation of more dangerous chemicals, such as methylmercury, in anaerobic environment Laboratory research has shown that genetically engineered plants, including *Nicotiana tabacum* (tobacco) and *Arabidopsis thaliana*, can perform this procedure efficiently (Gorinova *et al.*, 2007; Ozyigit *et al.*, 2021). These plants, when endowed with genes that encode mercury-reducing enzymes, demonstrated an improved capacity to transform ionic mercury into its volatile metallic state. Likewise, *Liriodendron tulipifera* (yellow poplar) plantlets genetically manipulated for mercury resistance demonstrated enhanced survival and development rates in mercury-polluted settings and emitted substantially higher quantities of elemental mercury than their unmodified counterparts (Rugh *et al.*, 1998). Besides mercury, phytovolatilization has demonstrated potential in remediating selenium-contaminated settings. Plants such as *Brassica juncea* (Indian mustard) and *Brassica napus* (canola) can absorb selenium from the soil, release it in a volatile form, and store a part within their tissues (Bluskov, 2005). This technology provides a novel and low-impact strategy for managing certain metal contaminants, particularly in regions where conventional cleanup techniques may be less successful or more environmentally disruptive.

Uptake and Mobilization of Metals in Plants

Plants can extract and accumulate metals from the soil solution. Prior to a metal entering the plant system, it must traverse the outer surface of the root. This can occur either via a passive mechanism, wherein metal ions traverse the porous cell walls of root cells freely, or through an active mechanism, when metal ions enter the root cells through the symplastic pathway (S. S. Kumar *et al.*, 2017; Puschenreiter *et al.*, 2017). The active process necessitates the translocation of ions across the plasma membrane, which functions as a selective barrier encasing each cell. Plants possess distinct membrane proteins that identify the chemical composition of vital metal ions. These proteins associate with metals, promoting their absorption and translocation inside the plant. Plants possess a diverse array of metal transporters. *Arabidopsis thaliana* contains many cation transporters, several of which can identify and transport analogous metal ions (L. E. Williams *et al.*, 2000). Due to the molecular similarity between certain harmful or nonessential metals and essential metals, the former may be erroneously absorbed by identical transport proteins. Arsenate can infiltrate plant roots via the identical pathways utilized for phosphate transport. Metals like copper and zinc or nickel and cadmium may compete for same transporters owing to structural resemblance. Upon absorption, the metals are conveyed from the root to the shoot via the vascular system. The shoot, representing the aerial portion of the plant, accumulates these metals. Subsequent to harvesting, the metal-enriched biomass may be burnt to diminish its volume, disposed of securely, or processed to extract valuable metals through a method termed phytomining (Sheoran *et al.*, 2009). The transport of metal ions through the xylem of the plant is facilitated by natural chelating agents, including organic acids. Compounds such as malate, citrate, histidine, and nicotianamine chelate metal ions, facilitating their upward transit through the xylem without adsorption (Jan *et al*., 2016). These chelators facilitate the mobility of metals within the plant system and mitigate the danger of obstruction or loss during transport.

Conclusion

Soil and water contamination by heavy metals has emerged as a significant environmental issue. Metals and other inorganic pollutants are prevalent contaminants at waste sites, and their extraction from soils and sediments is a particularly formidable challenge. The substantial costs linked to traditional cleanup methods have prompted the exploration of new solutions that are economically viable, minimally invasive, aesthetically unobtrusive, and environmentally sustainable. Phytoremediation is a promising method that employs plants to remediate or stabilize polluted settings. Phytoremediation provides an effective approach for the extraction of inorganic contaminants from soil. As an economical and eco-friendly option, it presents significant potential for developing nations. This solar-powered in situ technique utilizes vascular plants to absorb and translocate metals from the roots to the shoots. The metals can subsequently be removed by harvesting the aerial portions of the plant. In contrast to forceful conventional techniques such as acid extraction and soil washing, phytoremediation preserves soil fertility and structure. This method is particularly effective for addressing shallow soil strata, as well as polluted groundwater and surface water bodies. Consequently, phytoremediation is progressively acknowledged as an environmentally friendly and pragmatic substitute for more aggressive and intrusive remediation techniques.

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