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Heavy metals' effect on human health and phytoremediation approaches-A Comprehensive Review

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Abstract

Heavy metal contamination has emerged as a critical environmental and public health concern due to its persistence, bioaccumulation, and toxicity. Unlike organic pollutants, heavy metals cannot be degraded and therefore accumulate in various environmental compartments such as soil, water, and air, ultimately entering the food chain. Conventional remediation strategies, including physical and chemical methods, have been widely employed but face significant limitations in terms of cost-effectiveness, technical feasibility, and secondary environmental impacts. In recent years, phytoremediation has emerged as a sustainable, eco-friendly alternative, exploiting the natural ability of certain plants to uptake, stabilize, or detoxify heavy metals from contaminated environments. Certain hyperaccumulator plants, such as Brassica juncea, Pteris vittata, and Thlaspi caerulescens have shown remarkable ability to uptake and stabilize metals including Cd, Pb, As, and Zn. This comprehensive review provides an in-depth analysis of the sources, distribution, and health impacts of major heavy metals, while critically evaluating the mechanisms, advantages, and challenges of phytoremediation approaches. The findings underscore that phytoremediation offers a cost-effective, eco-friendly alternative to conventional remediation, with potential to mitigate human exposure risks and restore ecological balance.

Introduction

Heavy metal contamination has emerged as one of the most pressing global environmental and public health challenges of the twenty-first century. Unlike organic pollutants, heavy metals are non-biodegradable, highly persistent, and capable of accumulating in living organisms through soil, water, and food chain pathways [1]. Industrialisation, urbanization, mining, smelting, and the extensive use of agrochemicals have significantly elevated the levels of toxic metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) in various environmental compartments [2, 3]. Once introduced into ecosystems, these metals readily interact with biological systems, posing serious risks to both ecological integrity and human well-being [4]. Heavy metals are naturally occurring elements with high atomic weights and densities greater than 4 g/cm^3. Some heavy metals, such as zinc (Zn), copper (Cu), manganese (Mn), and cobalt (Co), are essential micronutrients for plant and microbial life (**Table 1**) [5].

According to the United States Environmental Protection Agency (USEPA), heavy metals are categorised as priority pollutants due to their non-biodegradable nature, toxicity, and ability to bioaccumulate in ecosystems and living organisms [6]. Heavy metals are linked with severe physiological disorders, genetic mutations, and increased cancer risk in humans [7]. These elements persist indefinitely in the environment due to their non-degradable nature, transitioning between geochemical and biological cycles. Their mobility depends on factors like soil pH, organic matter content, and redox potential, with acidic conditions often increasing bioavailability [8]. Industrialisation has dramatically altered natural heavy metal distributions, with anthropogenic emissions now exceeding natural weathering processes by 10- to 100-fold [9].

These elements enter the environment through a variety of natural and anthropogenic sources. While weathering of metal-bearing rocks and volcanic activity are natural contributors, the largest influx results from human activities such as mining, smelting, industrial discharges, fossil fuel combustion, improper waste disposal, and extensive use of agrochemicals [10]. Industrial effluents, especially from textile, leather, electroplating, and pharmaceutical industries, often contain high concentrations of hazardous metals. When these effluents are discharged directly into agricultural lands or water bodies without treatment, they lead to long-term contamination of soil and groundwater systems [11].

Table 1: Heavy metals classification [6]

Classification A	Classification B	Examples
Non-essential metals	Extremely toxic heavy metals	As, Cd, Pb, Hg
Essential metals	Micronutrient metals	Zn, Cu, Mn, Ni
	Macronutrient metals	Ca, K, Mg
	Precious metals	Au, Ag, Pt
	Radionuclide metals	U, Th, Ra

Chronic exposure to Cd, even at 0.2 mg/kg in soil, can cause renal dysfunction and osteomalacia, while inorganic As is a Class I carcinogen associated with skin, lung, and bladder cancers [12]. The bioaccumulation factor (BAF) for these metals often exceeds 1 in crops like rice and leafy vegetables, posing direct dietary risks. For instance, 57% of global rice samples exceed safe As limits, highlighting the urgency for remediation. Notably, heavy metals exhibit synergistic toxicity, such as Pb and Cd co-exposure shows 30% greater genotoxicity than individual metals [13].

Despite extensive studies on heavy metal contamination and remediation strategies, several gaps remain. Many existing reviews either focus narrowly on specific metals or address phytoremediation without integrating its implications for human health. The paper aims to provide a comprehensive overview of the effects of heavy metals on humans and critically evaluate phytoremediation approaches as a sustainable solution. By synthesising current knowledge, articles highlight the potential and challenges of phytoremediation for heavy metal pollution to safeguard the environment and human.

Sources of heavy metal contamination

Heavy metal contamination in the environment originates from a combination of natural processes and anthropogenic (human-induced) activities (**Table 2**). While natural sources contribute to the geochemical background levels of metals in soils and water bodies, human activities have significantly accelerated their concentration, bioavailability, and ecological impact over the last century [14].

Table 2: Sources of major heavy metals with their dominant environmental compartments

Heavy Metal	Major Sources	Dominant Environmental Compartments
Cadmium (Cd)	Mining, smelting of zinc/lead ores, phosphate fertilizers, batteries, pigments	Soil, crops, sediments, groundwater
Lead (Pb)	Mining, smelting, leaded gasoline (historical), batteries, paints, plumbing materials	Soil, dust, sediments, surface water, atmosphere
Mercury (Hg)	Coal combustion, gold mining, industrial effluents, chlor-alkali plants, and medical waste	Atmosphere, sediments, aquatic systems (bioaccumulation in fish)
Arsenic (As)	Mining, pesticide/herbicide use, smelting, coal combustion, wood preservatives	Groundwater, soil, sediments, drinking water
Chromium (Cr)	Leather tanning, electroplating, stainless steel production, dyes, pigments	Soil, sediments, industrial effluents, groundwater
Nickel (Ni)	Mining, electroplating, stainless steel production, and combustion of fossil fuels	Soil, sediments, atmosphere, and industrial wastewater
Zinc (Zn)	Mining, galvanization, fertilizers, rubber and tire wear, smelting	Soil, sediments, wastewater, agricultural lands
Copper (Cu)	Mining, electroplating, pesticides, plumbing, and industrial effluents	Soil, sediments, wastewater, aquatic ecosystems
Manganese (Mn)	Mining, steel production, fertilizers, battery industry	Soil, sediments, groundwater, air (particulates)
Iron (Fe)	Mining, steel industry, natural weathering, fertilizers	Soil, sediments, surface water

Natural sources

Natural weathering of metal-rich geological formations, such as sulfide and laterite deposits, releases heavy metals into soil and water systems. Volcanic eruptions and forest fires also emit particulate-bound metals like mercury (Hg) and arsenic (As) into the atmosphere, which later settle through wet or dry deposition [15]. While these processes occur over geological timescales, they establish baseline metal concentrations in ecosystems.

Industrial activities

Industrial operations are the dominant anthropogenic source of heavy metal pollution (**Fig. 1**):

Mining and smelting: Extraction and processing of ores generate waste tailings rich in lead (Pb), cadmium (Cd), and chromium (Cr). For example, Pb concentrations near smelters can exceed 10,000 mg/kg, compared to the global average of 20 mg/kg in uncontaminated soils.

Manufacturing: Electroplating, battery production, and alloy manufacturing discharge nickel (Ni), zinc (Zn), and copper (Cu) into wastewater.

Coal Combustion: Coal-fired power plants emit Hg, As, and selenium (Se) in fly ash, contaminating air and water.

Agricultural practices

Agricultural practices also contribute significantly to heavy metal buildup in soils. The application of phosphate fertilizers, which often contain cadmium as a contaminant, introduces metals into the soil profile. Additionally, the prolonged use of pesticides, herbicides, and fungicides that include metallic compounds (e.g., arsenic-based pesticides) exacerbates contamination. The use of wastewater and sewage sludge as irrigation water and soil conditioner, especially in urban and peri-urban agriculture, is another widespread practice in developing countries like Pakistan. Such materials frequently contain trace metals, pharmaceutical residues, and synthetic compounds that accumulate in the soil over time.

Phosphate fertilizers contain Cd (up to 300 mg/kg) due to phosphate rock impurities, and long-term use increases soil Cd by 0.2% annually (Loganathan et al., 2008). Historic use of arsenical pesticides and sewage sludge (biosolids) adds As, Cu, and Pb to farmland.

Urban and domestic sources

Vehicle Emissions: Especially from vehicles running on leaded fuels and those with worn brake pads and tires, release fine particles containing heavy metals like lead, zinc, and copper into the atmosphere. These particles eventually settle onto nearby soils, especially along roadsides and highways.

Electronic waste (E-waste): Improper recycling releases Pb (from solder), Hg (switches), and Cd (batteries).

Wastewater and landfills

Municipal solid waste landfills are another major source of contamination. Leachate generated from waste decomposition often contains a variety of toxic metals, which, if not properly managed, infiltrate into the soil and groundwater. Inadequate waste segregation and the disposal of e-waste (electronic waste) further contribute to the release of hazardous substances, including lead, cadmium, and mercury.
Understanding the diverse sources of heavy metal contamination is essential for designing site-specific remediation strategies. Identifying whether contamination is from point sources (like a factory outlet) or diffuse sources (like agricultural runoff) helps in planning effective mitigation approaches, including phytoremediation, soil amendments, or regulatory interventions.

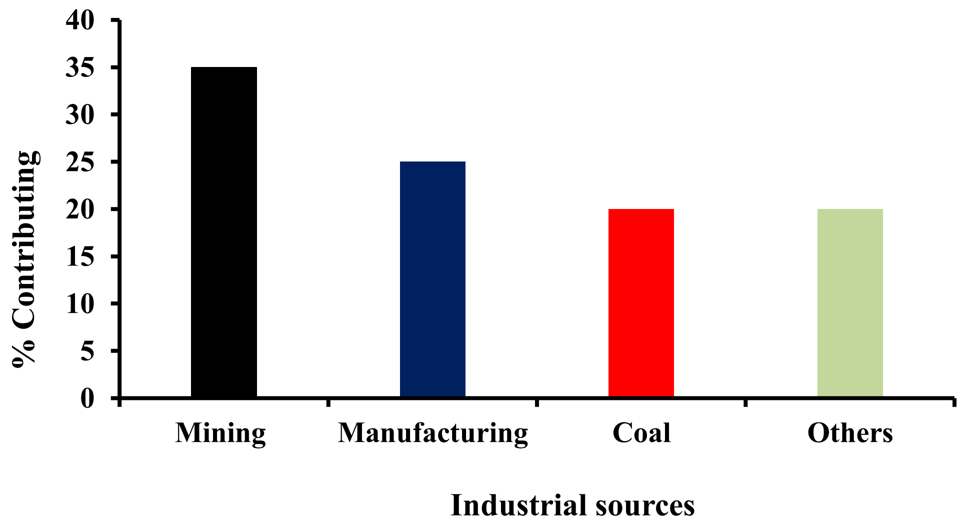

Fig. 1: Anthropogenic source of heavy metal pollution

Pathways of heavy metals into the food chain

The bioaccumulation and biomagnification result in elevated metal concentrations in animals and humans consuming contaminated food, leading to chronic exposure even when environmental concentrations appear low.

Soil-to-crop transfer

The journey of heavy metals into human diets often begins in agricultural soils, where contaminants bind to organic matter and clay particles. Certain crops exhibit a high bioaccumulation factor (BAF > 1), preferentially absorbing metals even when soil concentrations appear low:

Rice (Oryza sativa): A global staple that accumulates 10× more arsenic than other cereals due to anaerobic paddy conditions that mobilise As (III). In Bangladesh, rice contributes to 60% of daily arsenic intake, linking it to skin lesions and cancers [16].

Leafy vegetables (Spinacia oleracea, Lactuca sativa): Rapidly uptake cadmium and lead. A study in China found Cd levels in spinach exceeding safety limits by 8-fold near smelting sites [17].

Wheat (Triticum aestivum): Absorbs chromium and nickel from contaminated soils. In Punjab, India, wheat flour showed Pb concentrations 4 mg/kg—40× the FAO/WHO limit [18].

Aquatic bioaccumulation

Marine and freshwater ecosystems face parallel threats:

Methylmercury (MeHg) in fish: Formed by bacterial methylation of inorganic Hg in sediments, MeHg biomagnifies up aquatic food webs. Predatory fish like tuna and swordfish contain MeHg concentrations 1–10 million times higher than the surrounding water. The Minamata disaster in Japan demonstrated how chronic MeHg exposure causes ataxia, paralysis, and congenital deformities.

Arsenic in shellfish: Bivalves (e.g., mussels, clams) filter large water volumes, concentrating As. In Vietnam, clam consumption accounts for 50% of dietary arsenic exposure.

Livestock and dairy contamination

Animals grazing on polluted pastures or fed contaminated feed introduce metals into meat, milk, and eggs:

Cattle: Accumulate Cd in the kidneys and liver. A EU study found 12% of bovine kidneys exceeded Cd limits.

Poultry: Fed with arsenic-laced growth promoters (e.g., roxarsone) retain As in muscle tissue.

Toxicity of heavy metals in the ecosystem

Heavy metals pose a significant threat to ecosystems due to their toxicity, persistence, and ability to bioaccumulate and biomagnify through food chains. Once introduced into the environment, these metals interact with water, soil, and air, often leading to detrimental effects on living organisms and ecological processes. Their toxicity arises because heavy metals can interfere with essential biochemical and physiological functions at cellular, organismal, and population levels (**Table 3**). At the cellular level, heavy metals disrupt enzyme activities by binding to sulfhydryl groups or displacing essential metal cofactors, which impair metabolic pathways and cellular respiration [19].

The health implications of chronic exposure to heavy metals through the food chain are profound and multi-dimensional. Cadmium, commonly found in leafy vegetables and rice irrigated with wastewater, accumulates in the human kidneys and liver, impairing their function over time and causing bone demineralisation, a condition known as Itai-Itai disease. Lead exposure, especially harmful to children, results in cognitive impairment, behavioural changes, and reduced IQ. In adults, it is linked to hypertension, kidney damage, and reproductive issues. Arsenic, often present in drinking water and rice from contaminated fields, is a known carcinogen and is associated with skin lesions, bladder cancer, and cardiovascular diseases.

Mercury, particularly in its methylated form, affects the central nervous system, leading to tremors, memory loss, and developmental deficits in fetuses and infants. Chromium VI, although used industrially in small amounts, has been detected in certain grains and vegetables and is associated with respiratory disorders and genotoxic effects. The insidious nature of heavy metal toxicity lies in the latency of symptoms; health effects often appear after prolonged exposure, making diagnosis and treatment difficult.

At the molecular level, heavy metals exert toxicity through several interconnected mechanisms. Cadmium and lead interfere with essential enzyme systems by binding to sulfhydryl groups, disrupting protein structure and function [3]. Mercury readily binds to thiol-containing molecules, impairing antioxidant defenses and inducing oxidative stress. Arsenic generates reactive oxygen species (ROS), leading to DNA damage, chromosomal instability, and altered gene expression associated with carcinogenesis [20]. Chromium (VI) can penetrate cell membranes, undergo intracellular reduction, and cause oxidative DNA lesions and strand breaks. Collectively, these molecular mechanisms explain the wide spectrum of systemic health effects observed in humans following chronic metal exposure.

In plants, heavy metals interfere with nutrient uptake, enzyme activity, and cellular metabolism. Metal ions like Cd and Pb can displace essential elements such as calcium, magnesium, and zinc from vital biomolecules, leading to oxidative stress, disruption of photosynthesis, inhibition of root elongation, and overall stunted growth. Chlorosis, necrosis, and leaf deformation are common visual symptoms of heavy metal stress in vegetation. Furthermore, some heavy metals alter the hormonal balance of plants, affect transpiration rates, and damage DNA, ultimately reducing productivity and increasing vulnerability to pathogens and abiotic stressors [21].

Aquatic ecosystems are equally, if not more, vulnerable to heavy metal pollution. When industrial or agricultural runoff containing metals enters rivers, lakes, or estuaries, it leads to the accumulation of these toxicants in water, sediments, and aquatic biota. Benthic organisms that dwell in sediment-rich zones are often the first to be affected, resulting in reduced biodiversity and changes in community structure. Fish, molluscs, and crustaceans can absorb metals directly through their gills or via ingestion of contaminated food or sediment. Bioaccumulation of metals in aquatic organisms poses a serious threat to higher trophic levels, including birds and mammals that consume them, and ultimately to humans.

Table 3: Heavy metals and their toxic effects in humans

Heavy metal	Major sources of exposure	Target organs/systems	Key health effects
Lead (Pb)	Industrial emissions, batteries, paints, contaminated water/soil, traffic emissions	Nervous system, kidneys, blood	Neurotoxicity, cognitive impairment in children, anemia, kidney damage, and hypertension
Cadmium (Cd)	Mining, smelting, phosphate fertilizers, tobacco smoke, and industrial effluents	Kidneys, bones, lungs	Renal dysfunction, osteoporosis, lung cancer, reproductive toxicity ("Itai-Itai disease")
Mercury (Hg)	Coal combustion, gold mining, industrial discharges, contaminated fish (methylmercury)	Central nervous system, kidneys, liver	Tremors, vision/hearing impairment, developmental delays, memory loss, and immune suppression
Arsenic (As)	Contaminated groundwater, pesticides, mining, smelting	Skin, liver, cardiovascular system, lungs, bladder	Skin lesions, hyperpigmentation, cardiovascular disease, cancers (skin, lung, bladder)
Chromium (Cr, esp. Cr VI)	Electroplating, leather tanning, stainless steel production, and industrial effluents	Respiratory system, skin, liver, kidneys	Respiratory irritation, dermatitis, liver/kidney toxicity, carcinogenicity
Nickel (Ni)	Mining, electroplating, alloy production, and fossil fuel combustion	Skin, respiratory tract	Allergic dermatitis, asthma, lung and nasal cancers
Copper (Cu)	Plumbing pipes, industrial effluents, and excessive supplements	Liver, gastrointestinal tract	Abdominal pain, liver damage, Wilson's disease (genetic accumulation)
Zinc (Zn)	Galvanization, metal smelting, dietary supplements, fertilizers	Gastrointestinal tract, immune system	Nausea, vomiting, abdominal cramps, interference with Cu/Fe metabolism

Phytoremediation: An Overview

Phytoremediation is an emerging and environmentally friendly technology that uses plants and their associated microorganisms to remove, degrade, stabilize, or transform hazardous contaminants from soil, water, and air. It encompasses several mechanisms, including phytoextraction, phytostabilisation, phytodegradation, rhizofiltration, and phytovolatilization [22]. Among these, *phytoextraction* is the most widely studied approach for heavy metal-contaminated soils. It involves the uptake of metals from soil into plant tissues, particularly shoots and leaves, which can then be harvested and properly disposed of [23]

Mechanisms of phytoremediation

Phytoremediation encompasses several mechanisms through which plants interact with contaminants (**Fig. 2**).

Phytoextraction (Phytoaccumulation): Plants absorb contaminants, particularly heavy metals, from the soil through their roots and translocate them to above-ground tissues such as stems and leaves. These plant parts can then be harvested and safely disposed of or processed to recover valuable metals. This method is especially useful for removing metals like cadmium, lead, and nickel from contaminated soils.

Phytostabilisation: Plants immobilise contaminants in the soil by adsorption onto roots, precipitation, or complexation, reducing their bioavailability and preventing leaching or erosion. This mechanism helps contain pollutants on-site and reduces their spread to groundwater or the food chain.

Phytodegradation (Phytotransformation): Plants metabolise organic pollutants by enzymatic degradation within their tissues, breaking down harmful compounds into less toxic or inert forms. This process is effective for contaminants such as pesticides, petroleum hydrocarbons, and chlorinated solvents.

Phytovolatilization: Some plants take up volatile contaminants and release them into the atmosphere in a modified, less harmful form. For example, certain species can convert mercury or selenium compounds into volatile forms that evaporate from leaves.

Rhizodegradation: Plant roots release exudates that stimulate microbial communities in the rhizosphere (root zone), enhancing microbial degradation of organic pollutants in the soil.

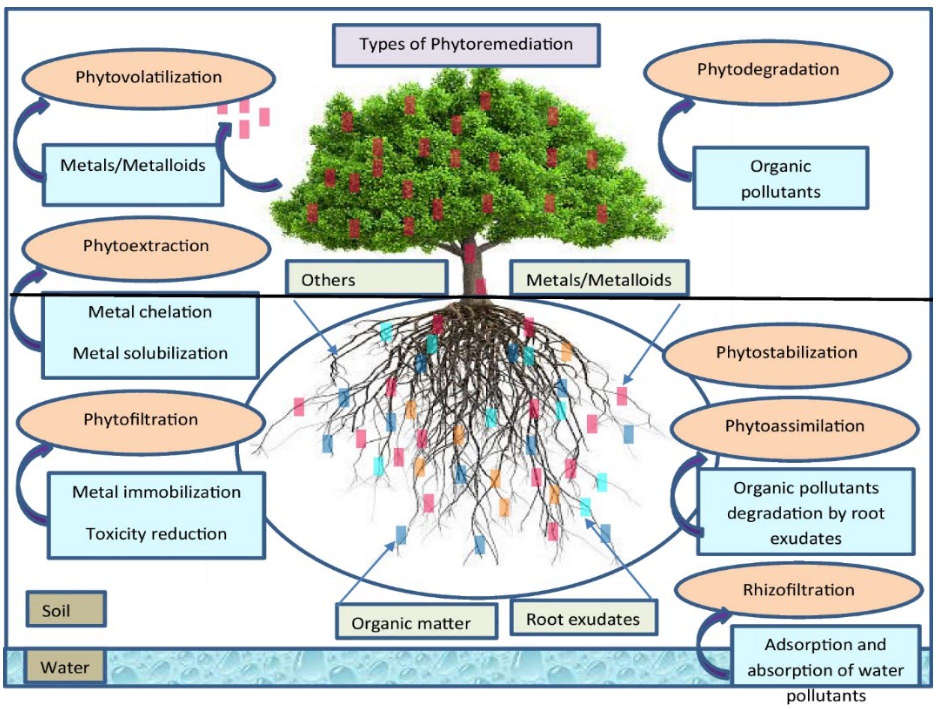

Fig. 2: Phytoremediation processes for metal-contaminated soils and water [24]

Advantages

Phytoremediation is advantageous due to its cost-effectiveness, aesthetic appeal, and minimal environmental disruption. However, its efficiency depends on various factors such as plant species, pollutant type, soil characteristics, and climate conditions [25]. Hyperaccumulator plants can accumulate extraordinarily high levels of metals in their biomass without displaying phytotoxic effects, making them ideal candidates for this technique.

Cost-effectiveness: It requires less capital investment and operational costs, as it utilises natural plant growth and solar energy.

Environmental friendliness: The process is non-invasive, preserves soil structure, and improves soil health by enhancing microbial activity and organic matter content.

Aesthetic and ecological benefits: Vegetative cover reduces erosion, improves landscape aesthetics, and provides habitat for wildlife.

Sustainability: It promotes long-term site restoration and can be integrated with agricultural or bioenergy production.

Limitations

Despite its advantages, phytoremediation has limitations that must be considered:

Time-consuming: Phytoremediation often requires several growing seasons to achieve significant contaminant reduction, making it unsuitable for urgent cleanups.

Depth limitation: Plant roots typically penetrate only the topsoil layers (up to 1–2 meters), limiting remediation of deeper contamination.

Bioavailability: The effectiveness depends on the bioavailability of contaminants; metals tightly bound to soil particles may not be readily taken up.

Contaminant toxicity: High pollutant concentrations can inhibit plant growth and reduce remediation efficiency.

Disposal of biomass: Harvested plant material containing concentrated contaminants must be managed carefully to avoid secondary pollution.

Key plant species used in phytoremediation

The success of phytoremediation relies heavily on the selection of suitable plant species. Ideal phytoremediator plants should possess high biomass productivity, rapid growth rates, extensive root systems, and tolerance to high levels of pollutants. Several plant species have been identified for their phytoremediation potential, particularly for heavy metal-contaminated soils:

Indian mustard (Brassica juncea): Known for its fast growth, high biomass, and exceptional ability to accumulate metals such as cadmium, lead, chromium, and nickel, Indian mustard is widely studied and used in phytoextraction.

Sunflower (Helianthus annuus): Effective in accumulating lead, uranium, and arsenic, sunflowers have been used in contaminated sites, including Chernobyl.

Poplar (Populus spp.) and Willow (Salix spp.): These trees have deep root systems and are used for phytostabilisation and degradation of organic pollutants.

Vetiver Grass (Chrysopogon zizanioides): Known for its extensive root system, vetiver is used for phytostabilisation and erosion control in contaminated soils.

Pteris vittata (Chinese brake fern): A hyperaccumulator of arsenic, useful in arsenic-contaminated soils.

Enhancing phytoremediation efficiency

To overcome some limitations, various strategies have been developed to enhance phytoremediation:

Use of chelating agents: Application of synthetic or natural chelators (e.g., EDTA, citric acid) increases metal bioavailability, promoting uptake by plants. However, care must be taken to prevent leaching of mobilized metals into groundwater.

Soil amendments: Organic matter, biochar, or lime can improve soil properties, reduce metal toxicity, and stimulate plant growth.

Microbial inoculants: Plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi enhance metal uptake, plant tolerance, and degradation of organic pollutants.

Genetic engineering: The development of transgenic plants with enhanced metal uptake, tolerance, or degradation capabilities is an emerging field.

Economic costs of soil remediation

The economic costs of soil remediation represent a critical challenge for governments, industries, and communities worldwide. Soil contamination, particularly with heavy metals and industrial pollutants, threatens agricultural productivity, environmental health, and human safety. Remediation efforts are essential to restore soil functionality and prevent further contamination of the food chain and water resources. However, the financial burden of cleaning contaminated soils is often substantial, complex, and influenced by the choice of remediation technology, site-specific conditions, and regulatory frameworks.

Health-related costs due to exposure to contaminated soils are challenging to quantify but potentially substantial. Chronic exposure to heavy metals increases healthcare expenses and reduces workforce productivity. While some analyses focus on carcinogenic and acute toxicity effects, non-carcinogenic impacts and ecosystem service losses further compound societal costs.

The economic costs of soil remediation are substantial and multifactorial, influenced by contamination extent, remediation technology, and socio-political context. While phytoremediation offers a cost-effective and sustainable option, its slower pace and operational challenges require strategic planning and complementary measures. Governments and stakeholders must leverage innovative financing, regulatory frameworks, and technological advancements to address the silent but costly crisis of soil contamination. Investing in soil remediation not only restores land productivity and environmental quality but also safeguards public health and supports sustainable economic development.

Conclusion

Heavy metal pollution remains a pressing global concern due to its persistence, bioaccumulation, and profound risks to human health. Metals such as cadmium, mercury, lead, and arsenic exhibit particularly severe toxic effects, ranging from neurotoxicity and carcinogenesis to organ damage and developmental disorders. Conventional remediation technologies, while useful, are constrained by high costs, technical limitations, and potential secondary pollution. Phytoremediation has emerged as a cost-effective, environmentally friendly alternative that leverages the natural ability of hyperaccumulator plants to extract, stabilise, or detoxify heavy metals. Species such as Brassica juncea, Thlaspi caerulescens, and Pteris vittata demonstrate significant potential for remediating contaminated soils and water. Nonetheless, challenges such as slow remediation rates, metal-specific accumulation, and environmental variability necessitate further optimization. Future research should focus on improving phytoremediation efficiency through genetic engineering, plant–microbe interactions, and agronomic management practices. Integrating these approaches with policy support and community awareness can accelerate the transition toward sustainable remediation. Overall, phytoremediation represents a promising, nature-based solution to mitigate heavy metal contamination and safeguard both ecosystems and human health.

Conflict of interest

The authors declare no conflict of interest.

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