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Environmental Dynamics and Remediation of Heavy Metals in Soil and Water: A Comprehensive Review

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ABSTRACT

Heavy metals in the environment pose significant risks due to their toxicity, persistence, and potential for bioaccumulation. This review focuses on metals of environmental concern, including Pb, Cd, As, Hg, Cr, Ni, Zn, and Cu, examining their classification as essential and non-essential elements and highlighting their toxicological impacts within regulatory thresholds. The environmental pathways of these metals are analyzed, including their primary sources, entry pathways, transport mechanisms, geochemical behaviour, bioavailability, bioaccumulation, and persistence in soil and water systems. Factors influencing their distribution and transformation, such as soil properties, water chemistry, climate variability, and anthropogenic activities, are also addressed. Advanced analytical techniques, including ICP-MS, AAS, portable XRF, speciation analysis, and AI/ML-enabled sensors, are evaluated for accurate detection and monitoring of heavy metal contamination. The review further assesses remediation strategies, encompassing physical, chemical, biological, and integrated approaches, as well as emerging technologies such as nanomaterials, engineered biochars, and multifunctional sorbents for enhanced removal efficiency. Risk assessment and management frameworks are discussed to address human and ecological exposure, highlighting the importance of site-specific, evidence-based interventions. The objectives of this review are to synthesize current knowledge on the occurrence, behaviour, and impacts of heavy metals; critically evaluate detection and remediation methods; examine management practices; and identify knowledge gaps to support sustainable environmental solutions and policy development. The synthesis provides a comprehensive understanding of heavy metal contamination and offers guidance for effective monitoring, remediation, and risk-informed management in soil and water systems.

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INTRODUCTION

Heavy metal pollution represents a persistent environmental concern due to the toxic, stable, and non-biodegradable nature of these elements (Bibi et al., 2023). Heavy metals are defined as elements with atomic densities greater than 5 g/cm^3, including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), nickel (Ni), copper (Cu), zinc (Zn), iron (Fe), cobalt (Co), manganese (Mn), selenium (Se), molybdenum (Mo), tin (Sn), antimony (Sb), thallium (Tl), vanadium (V), uranium (U), barium (Ba), beryllium (Be), silver (Ag), gold (Au), and platinum (Pt) (Bibi et al., 2023; Acharya, 2024). Certain elements such as Fe, Cu, Zn, Mn, Co, Se, and Mo serve essential biological functions at trace levels, whereas others such

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as Pb, Hg, Cd, As, Tl, and U exhibit toxicity even at minimal concentrations (Nucera et al., 2024; Raj and Das, 2023). The distinction between essential and non-essential metals is critical because essential elements become toxic when concentrations exceed physiological limits (Bibi et al., 2023). Emerging concerns include interactions of heavy metals with microplastics and phytochemicals in aquatic and geothermal systems (Maulydia et al., 2024).

Metal refining purifies impure metals by removing contaminants through physical, chemical, or electrochemical methods, thereby reducing the environmental burden of heavy metals in soil and water systems (Huang et al., 2024). Techniques such as electrolytic refining, zone refining, and chemical oxidation are essential for producing high-purity metals while minimizing the release of hazardous by-products (Adu and Aneke, 2025). These refining advancements are vital for mitigating heavy metal pollution, improving the ecological balance of contaminated environments, and promoting sustainable industrial practices that protect soil and water quality (Huang et al., 2024; Adu and Aneke, 2025). Heavy metals enter soil and water through both natural and anthropogenic pathways. Natural processes include volcanic activity, rock weathering, geothermal emissions, forest fires, and soil erosion, which release elements such as As, Pb, Cd, and Hg. Anthropogenic activities such as mining, smelting, fossil fuel combustion, electroplating, chemical and battery manufacturing, textile production, agricultural inputs, and wastewater discharge further contribute to metal contamination (Xu et al., 2025; Vijaya Kumar and Prasad Raju, 2025; Sharifi et al., 2023; Riani et al., 2024). Former battery smelting sites illustrate localized contamination hotspots, while atmospheric deposition adds Hg and Pb to ecosystems (Xu et al., 2025). Metals persist indefinitely in soils, sediments, surface waters, and groundwater, creating long-term ecological and health risks (Yang et al., 2024).

Heavy metal contamination varies globally, driven by industrialization, mining, agriculture, and regulatory frameworks. Asia exhibits the highest contamination, with elevated Cd, Pb, Cr, Hg, and As in soils, rivers, and sediments due to rapid industrial and agricultural expansion. Europe and Oceania generally show lower levels, though legacy industrial sites in Europe report Pb, Zn, and Cd hotspots. North and South America experience localized contamination near mining, smelting, and agricultural regions, with Hg, Pb, Cd, and Cu as common pollutants. In Africa, mining, urban-industrial activities, and informal e-waste recycling contribute to high Pb, Cd, Hg, and As levels, often exacerbated by limited regulation. Overall, contamination patterns reflect the interplay of anthropogenic activity, environmental governance, and natural geochemical conditions across continents. In soils, metal behaviour depends on pH, redox potential, organic carbon, clay content, and cation exchange capacity, affecting immobilization or mobility (Vijaya Kumar and Prasad Raju, 2025). In aquatic systems, metals occur dissolved or particle-bound, influenced by pH, oxygen, salinity, hardness, and chelating agents. Metals travel via runoff, leaching, and sediment deposition (Xu et al., 2025; Riani et al., 2024). Heavy metals cause severe biological effects. In plants, they disrupt chlorophyll synthesis, enzymes, and nutrient uptake, reducing productivity and biodiversity (Iqhrammullah et al., 2024; Maulydia et al., 2024). In animals and humans, chronic exposure affects nervous, renal, skeletal, and reproductive systems, and increases cancer and radiation risks (Bibi et al., 2023; Nucera et al., 2024). Metals bioaccumulate and biomagnify, posing highest risks to top predators, including humans (Abubakar et al., 2023). Environmental impacts include decreased soil fertility, microbial activity, biodiversity, and water quality (Huang et al., 2024; Takarina et al., 2024). Modeling studies using engineered materials, like zeolite sheets, highlight predictive tools for pollution management and remediation (Takarina et al., 2024).

Understanding environmental fate, including transformation, distribution, bioavailability, and ecological risk, is essential (Vijaya Kumar and Prasad Raju, 2025). pH, redox potential, organic matter, and microbial activity determine metal mobility (Li et al., 2025; Lu et al., 2025). Remediation strategies include containment, immobilization, phytoremediation, bioremediation, and chemical treatments (Alsafran et al., 2023; Zhakypbek et al., 2024), mitigating pollution and supporting sustainable land and water management (Iqhrammullah et al., 2024). This review examined heavy metals of environmental concern, classifying them as essential or non-essential, with a focus on Pb, Cd, As, Hg, Cr, Ni, Zn, and Cu and their toxicological impacts. Soil regulatory limits of these metals in India are Pb (85 mg/kg), Cd (0.8 mg/kg), Cr (100 mg/kg), Ni (35 mg/kg), Cu (36 mg/kg), Zn (140 mg/kg), Hg (0.3 mg/kg), and As (varies), guiding contamination assessment (CPCB, 2019). Drinking water BIS standards set limits at As (0.05 mg/L), Cd (0.01 mg/L), Cr (0.05 mg/L), Ni (0.02 mg/L), Cu (1.5 mg/L), Zn (5 mg/L), Hg (0.001 mg/L), and Pb (0.01 mg/L) to protect public health (BIS, 2012). It analyzed environmental fate, including sources, pathways, transport, behaviour, bioavailability, bioaccumulation, persistence, and distribution in soil and water. Detection methods and physical, chemical, biological, and advanced remediation strategies were evaluated, alongside risk assessment and management challenges. Objectives were to (i) synthesize current knowledge on occurrence and impacts, (ii) assess detection and remediation methods, (iii) evaluate management practices, and (iv) identify research gaps for sustainable solutions and policy development.

CLASSIFICATION OF HEAVY METALS

Heavy metals are classified as essential or non-essential based on biological significance (Fig. 1). Essential heavy metals include Fe, Cu, Zn, Mn, Co, Se, Mo, Ni, Cr(III), and V, with Fe, Cu, Zn, Mn, Co, Se, and Mo supporting enzymatic catalysis, cellular respiration, antioxidant defense, oxygen transport, growth, reproduction, and immune regulation and can become harmful at excessive levels (Bibi et al., 2023; Adu and Aneke, 2025). They are vital for hemoglobin synthesis, electron transport, connective tissue formation, bone development, and nitrogen metabolism (Bibi et al., 2023; Sharifi et al., 2023). However, excessive environmental accumulation causes oxidative stress, hepatotoxicity, nephrotoxicity, endocrine disruption, and neurotoxicity (Bibi et al., 2023; Ortiz-Aguilar et al., 2025), exacerbated by industrial discharges, mining, smelting, fertilizers, and fossil fuel combustion (Bibi et al., 2023; Ortiz-Aguilar et al., 2025).

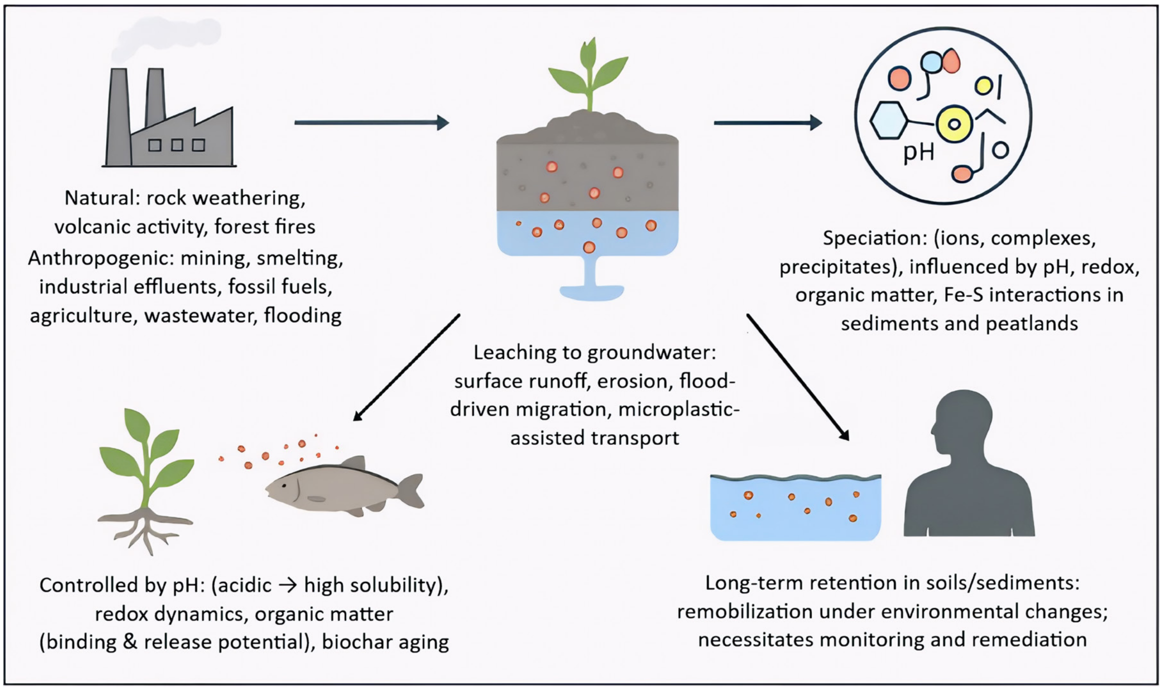

Fig. 1. Environmental pathways of heavy metals

Non-essential metals, including Pb, Cd, Hg, Cr, As, Tl, U, Ba, Be, Sn, Sb, V, Ag, Au, and Pt, have no physiological role in the human body and are toxic even at very low concentrations, interfering with enzymes, proteins, and cellular processes (Raj and Das, 2023; Ajibola et al., 2024). Among these, As, Cd, Cr(VI), Hg, and Pb are particularly dangerous and are classified as priority carcinogens because of their high toxicity, environmental persistence, and ability to accumulate in organisms and ecosystems, posing the greatest environmental and public health risks (Bibi et al., 2023). They disrupt enzymes and proteins, causing neurotoxicity, nephrotoxicity, hepatotoxicity, mutagenicity, reproductive harm, and carcinogenicity (Ortiz-Aguilar et al., 2025). Sources include mining, industrial emissions, pesticides, refining, and e-waste (Huang et al., 2024; Adu and Aneke, 2025). These metals bioaccumulate and biomagnify, contaminating soil, water, and food chains, and are linked to cardiovascular and other chronic diseases, particularly in high-risk regions (Moukadiri et al., 2024; Nucera et al., 2024; Ajibola et al., 2024). Both natural processes and anthropogenic activities contribute to their presence, emphasizing the need for monitoring, regulation, and remediation (Bibi et al., 2023; Vijaya Kumar and Prasad Raju, 2025; Adu and Aneke, 2025). Table 1 presents a detailed classification and sub-classification of heavy metals, describing their essential and non-essential types, their biological significance in human and environmental systems, and associated toxic effects at elevated concentrations.

Table 1. Classification and sub-classification of heavy metals, their biological significance, and toxic effects

Classification	Sub-classification	Examples	Biological Significance / Role	Toxic Effects / Risks	References
Essential Heavy Metals	Cofactors for enzymes & antioxidant defense	Fe, Cu, Zn, Mn, Co, Se, Mo	Enzymatic catalysis, cellular respiration, antioxidant defense, hemoglobin synthesis, oxygen transport, nitrogen metabolism	Harmful at excessive levels: oxidative stress, hepatotoxicity, nephrotoxicity, endocrine disruption, neurotoxicity	Bibi et al., 2023; Adu and Aneke, 2025; Sharifi et al., 2023; Ortiz-Aguilar et al., 2025
	Trace metals with minor roles	Ni, Cr(III), V	Support enzymatic reactions, growth, reproduction, immune regulation	Toxicity occurs at high concentrations; may affect metabolic processes	Bibi et al., 2023; Sharifi et al., 2023
Non-Essential Heavy Metals	High-priority carcinogens & neurotoxins	As, Cd, Cr(VI), Hg, Pb	No physiological role; highly toxic	Cause neurotoxicity, nephrotoxicity, hepatotoxicity, mutagenicity, reproductive harm, carcinogenicity; bioaccumulate and biomagnify in food chains	Bibi et al., 2023; Ortiz-Aguilar et al., 2025; Raj and Das, 2023; Ajibola et al., 2024
	Other non-essential metals	Tl, U, Ba, Be, Sn, Sb, V, Ag, Au, Pt	No physiological role	Toxic at low concentrations; disrupt enzymes and proteins, contaminate environment	Huang et al., 2024; Moukadiri et al., 2024; Nucera et al., 2024; Vijaya Kumar and Prasad Raju, 2025; Adu and Aneke, 2025

ENVIRONMENTAL PATHWAYS OF HEAVY METALS

Heavy metals originate from natural sources (rock weathering, volcanic activity) and anthropogenic activities (mining, smelting, industrial effluents, fossil fuels, agriculture, wastewater), dispersing via air, groundwater, runoff, erosion, flooding, and microplastic transport, with mobility governed by pH, redox, organic matter, and iron–sulfur interactions (Reymond & Sudalaimuthu, 2023). Their bioavailability drives accumulation in aquatic species, posing dietary risks in commercial fish and swamp eel, while long-term persistence and remobilization necessitate ongoing monitoring and remediation (Takarina et al., 2023; Nurhasanah et al., 2023). The environmental pathways of heavy metals, depicting their release, transport, transformation, and accumulation across ecosystems is presented in Fig. 1.

Sources and Entry Pathways

The primary sources of heavy metal contamination are both natural and anthropogenic. Natural sources include rock weathering, volcanic emissions, and forest fires, which release metals like Pb, Cd, Hg, and As into the environment (Angon et al., 2024). Anthropogenic sources dominate and include mining, smelting, industrial discharges, fossil fuel combustion, and agricultural activities using pesticides, fertilizers, and wastewater (Ismanto et al., 2023; Angon et al., 2024). These metals enter soil and water systems through pathways such as flooding, landfill leachates, urban runoff, atmospheric deposition of airborne particulates, and microplastic-mediated transport, enhancing mobility and environmental exposure (Yang et al., 2024; Yadav et al., 2025; Barus et al., 2024).

Transport Mechanisms

Once introduced, heavy metals move through environmental pathways. Leaching transports dissolved metals into groundwater, particularly in permeable soils with low buffering capacity (Ismanto et al., 2023). Surface runoff carries particulate-bound metals into water bodies, while erosion redistributes contaminated soils. Extreme weather and floods accelerate dispersal, and microplastics further enhance long-range mobility (Hossain et al., 2025; Yang et al., 2024). Engineered materials like zeolite sheets can influence transport and enable targeted removal (Takarina et al., 2024).

Geochemical Behaviour

Metal behaviour depends on speciation, occurring as free ions, adsorbed species, organo-metallic complexes, or precipitates. Redox conditions regulate transformations, such as As(III)/As(V) and Cr(III)/Cr(VI), affecting toxicity (Xu et al., 2025). pH influences solubility and adsorption, with acidic conditions increasing mobility (Aggarwal et al., 2025). Organic matter can temporarily immobilize metals, while decomposition may release them. Iron-sulfur interactions in wetlands and peatlands affect sequestration and remobilization (Lu et al., 2025).

Bioavailability Factors

Acidic soils enhance solubility and uptake of metals like cadmium and lead (Aggarwal et al., 2025). Biochar and organic matter can reduce bioavailability, though effectiveness declines over time due to aging (Li et al., 2025). Redox shifts may remobilize bound metals, maintaining ecological risk (Xu et al., 2025). Sediment–water interactions and climatic or hydrological factors influence metal redistribution, as observed in Nigerian wetlands and Peruvian lagoons (Chris et al., 2024; Jonah et al., 2024; Salas-Ávila et al., 2024).

Bioaccumulation and Persistence

Heavy metals bioaccumulate and biomagnify through food chains. Fish, shellfish, and even medicinal plants like *Chromolaena odorata* serve as vectors for human exposure to Hg, Cd, and As (Nriagu, 1979; Alloway, 1990; Järup, 2003; Almashhadany et al., 2024; Acharya, 2024; Abubakar et al., 2023). Early studies have laid the groundwork for understanding these processes. Nriagu (1979) provided a comprehensive global inventory of natural and anthropogenic emissions of trace metals to the atmosphere, highlighting the widespread presence of these pollutants. Alloway (1990) focused on the behavior of heavy metals in soils, emphasizing their mobility and potential for bioaccumulation. Järup (2003) reviewed the health risks associated with exposure to heavy metals, underscoring the importance of understanding their persistence and bioaccumulation in the environment. Metals persist for decades or centuries in soils, sediments, and aquatic systems. Sediments act as long-term sinks, but environmental changes can trigger release (Ghasemi et al., 2024; Polasko et al., 2024). Continuous monitoring and remediation strategies, including phytoremediation and agroecological practices, are essential (Zhakypbek et al., 2024; Perez-Vazquez et al., 2024). Heavy metals, though partially natural, are largely anthropogenic, posing critical environmental and health risks (Kotnala, 2025). Understanding their geochemical and biological dynamics, mobility, bioavailability, and toxicity is essential for effective monitoring, regulation, and remediation to protect ecosystems and human well-being (Chen et al., 2024).

INFLUENCES ON HEAVY METAL DISTRIBUTION AND TRANSFORMATION

Heavy metal distribution and transformation in the environment result from interactions among soil, water, air, and biological systems. These interactions are influenced by industrial activities, natural processes, and climatic factors, which collectively determine metal mobility, bioavailability, and ecological impact across ecosystems.

Soil Properties and Texture

Heavy metals interact with soils via adsorption, ion exchange, and complexation, with soil composition, texture, and organic matter controlling mobility and bioavailability. Soil properties such as pH, cation exchange capacity (CEC), and organic matter content play key roles in heavy metal behaviour. Lower pH generally increases metal solubility and bioavailability, higher CEC enhances retention of metal cations, and organic matter can form complexes that either immobilize metals or increase their bioavailability depending on the metal and type of organic compound present. Clay minerals, depending on their type and abundance, strongly influence metal retention. Smectite and montmorillonite, with high surface area and cation exchange capacity, enhance adsorption of metal cations, while kaolinite and sandy soils bind metals less effectively. Similarly, the amount and type of organic matter, including humic and fulvic acids, determine whether metals are immobilized in stable complexes or remain bioavailable in soluble complexes. Studies in Slovakia linked higher humic substance content to increased bioavailable Cd ($r = 0.692$) and Pb ($r = 0.709$), indicating that organic matter can enhance mobility under certain conditions (Feszterová et al., 2024). Disturbances such as conflict in Eastern Ukraine redistributed sediments, raising Mn, Fe, Co, Cu, Cd, Cr, Pb, and Ni levels (Solokha et al., 2023), while smelting activities increased local contamination (Riani et al., 2024). Microorganisms influence redox conditions, further mobilizing or immobilizing metals and providing opportunities for bioremediation (Joshi et al., 2024).

Water Chemistry (pH, Salinity, Dissolved Oxygen)

Metal mobility is influenced by pH, salinity, and oxygen. Redox potential, ionic strength, and dissolved organic carbon influence metal behaviour, with low redox mobilizing metals, high ionic strength enhancing desorption, and dissolved organic carbon forming soluble complexes that increase transport and bioavailability. Acidic or saline conditions increase solubility and release metals from sediments. In Wuliangsuhai Lake, low pH, high salinity, and temperature mobilized Cu and Zn, raising ecological risk (Zhao et al., 2024). Oilfield discharges in Libya contaminated soil and groundwater with Hg, Fe, and Pb, requiring reverse osmosis or electrocoagulation (Aghow and Idris, 2025). Geothermal systems need monitoring for natural metals (Idroes et al., 2024), while antibiotics form persistent metal complexes, complicating remediation (Ji et al., 2025).

Heavy Metal Fractions in Soil and Sediments

Building on the influence of soil and water chemistry, heavy metals in soils and sediments exist in multiple fraction**s**, which determine their mobility, bioavailability, and potential ecological risk. These fractions are commonly classified as exchangeable, carbonate-bound, reducible (iron and manganese oxide-bound), oxidizable (organic matter-bound), and residual forms. Exchangeable metals are weakly adsorbed and readily available for plant uptake or leaching, posing immediate environmental risks. Carbonate-bound metals can be released under acidic conditions, while reducible metals are associated with Fe/Mn oxides and can be mobilized under reducing conditions. Oxidizable metals are bound to organic matter or sulphides and may be released during decomposition or oxidation. Residual metals are incorporated into the mineral matrix and are the most stable and least bioavailable. Understanding these fractions is crucial for predicting metal behavior and informing remediation strategies, as treatments such as immobilization, phytoremediation, or chemical stabilization target specific metal fractions to reduce environmental contamination (Huang et al., 2024; Adu and Aneke, 2025).

Geochemical and Biological Controls

Building on the influence of soil and water chemistry on metal mobility, geochemical and biological processes further govern heavy metal transformation, persistence, and accumulation in the environment. Adsorption, precipitation, redox reactions, and complexation determine metal speciation, solubility, and mobility, while microbial activity, methylation, and plant uptake can either immobilize metals or enhance their transport. These processes collectively dictate whether metals remain in soils and sediments, enter food webs, or disperse across environmental compartments.

Climate and Seasonal Variations

Metal behaviour is affected by hydrology, sediment shifts, and biological activity. Climate variability and extreme weather events, such as heavy rainfall, floods, or droughts, influence the distribution, leaching, and remobilization of heavy metals by enhancing runoff, resuspension of sediments, and changes in soil or water chemistry, thereby altering metal mobility and bioavailability. In Gujarat, India, Cd, Cr, Cu, Co, Ni, and Pb increased during monsoon runoff (Thakkar et al., 2024). In Northern Japan, summer rainfall released Zn, Pb, and Cd, while winter snow reduced mobility (Tum et al., 2023). Monsoon-driven uptake in East Kolkata Wetlands caused maize to accumulate high Cd, Cr, Hg, and Pb (Agarwal et al., 2023), and monthly fluctuations near gold mines in Osun State, Nigeria, affected Cd, Pb, Cr, Hg, and As (Olalekan et al., 2023). Harbor and landfill sediments also show seasonal redistribution, impacting ecological risks (Sulistyowati et al., 2023).

Anthropogenic Activities

Industrial, mining, agricultural, and urban activities are major contributors to heavy metal pollution. Processes such as electroplating, ore refining, and chemical manufacturing release metals like Cd, Hg, Pb, and As into soils, water, and air. Mining generates metal-rich tailings, agriculture introduces metals through fertilizers, pesticides, and contaminated irrigation, and urban activities including waste disposal and traffic emissions further exacerbate contamination.

These metals persist in the environment, bioaccumulate in organisms, and biomagnify through food chains, posing health risks such as neurological disorders, kidney damage, and cancer (Daripa et al., 2023). Microplastics also act as vectors, enhancing metal transport and exposure (Sabilillah et al., 2023).

Integrated research addressing climate variability, emerging pollutants, and remediation limits, along with comprehensive soil-water-air analysis, predictive modelling, and sustainable strategies, is essential for ecosystem and human health protection.

ANALYTICAL TECHNIQUES FOR DETECTION AND QUANTIFICATION

Robust sampling, instrumentation, speciation analysis, and sensing technologies are essential for accurately detecting and managing heavy metals in environmental matrices, mitigating ecological and human health risks.

Sampling and Sample Preparation

Reliable analysis depends on representative sampling and rigorous preparation. Ashong et al. (2024) systematically sampled clariflocculator tanks to quantify Mn, Zn, and Pb in polymer post-treatment sludge (PTS) via FAAS; Ni, Cr, and Cd were below detection limits. Risk assessment showed low non-cancer and cancer risks, ingestion being the primary pathway, stressing evaluation beyond regulatory thresholds.

Instrumental Techniques

Instrumentation has improved sensitivity, precision, and throughput. AAS, including GF-AAS and HG-AAS, achieves low detection limits (Aggarwal et al., 2024), while ICP-MS provides higher sensitivity and multi-element analysis. pXRF accuracy improves with matrix corrections for large-scale monitoring (Zou et al., 2024). INAA with ICP-MS reduces digestion uncertainties in coal ash (Chajduk and Kalbarczyk, 2023), and ICP-MS is more reliable than XRF for trace metals (Guagliardi et al., 2025). Reviews highlight AAS, GC-MS, HPLC, portable devices (Durmishi et al., 2025), and innovations like LIBS, electrochemical, and nanomaterial-based sensors for improved sensitivity and portability.

Speciation Analysis

Total concentrations inadequately indicate risk; speciation determines bioavailability and mobility. Sequential extraction guides remediation, showing Pb and Zn in stable fractions near zinc smelters (He et al., 2024). High Cd mobility in abandoned farmland demonstrates phytoremediation potential (Dong et al., 2024). Lime and compost immobilize metals in mine soils (Gómez and Ruiz, 2023), while Gomishan wetland sediments show low ecological risk, with As as the only concern (Kachoueiyan et al., 2024).

Emerging Sensing Technologies

Portable, cost-effective, real-time monitoring is advancing, enabling more efficient assessment of heavy metal contamination. Emerging technologies such as AI/ML-enabled sensors and remote sensing enhance monitoring and predictive modeling through rapid, accurate, and continuous detection of pollutants. AI/ML algorithms analyze large datasets from sensors or satellite imagery to identify patterns, forecast contamination hotspots, and predict temporal changes. Remote sensing provides large-scale observation of water, soil, and vegetation, while AI/ML supports interpretation, risk assessment, and decision-making for targeted remediation and management strategies. These technologies improve efficiency, reduce human error, and enable proactive environmental protection. Ateia et al. (2024) highlighted the potential of portable sensors for water quality assessment, noting challenges related to cost, reliability, and stakeholder integration, which can be addressed through standardized validation and user-focused design. AI/ML improve detection, predict pollutant behaviour, and guide remediation (Khatri et al., 2025).

Among analytical techniques, ICP-MS, GF-AAS, HG-AAS, and portable XRF provide the most reliable and sensitive detection because they achieve low detection limits, high precision, and allow multi-element analysis. Sequential extraction and speciation analyses offer insights into bioavailability by revealing the chemical forms of metals and their potential mobility. Emerging nanomaterial-based and electrochemical sensors enhance cost-effectiveness and field applicability through portability, rapid response, and minimal sample preparation. Integrated detection, risk assessment, and remediation together enhance human and ecosystem protection. Evidence-based strategies support sustainable management, advance sensitive and selective analytical tools, and guide informed policy, enabling efficient monitoring, targeted remediation, and adaptive management to promote ecosystem resilience and human well-being.

REMEDIATION STRATEGIES FOR HEAVY METALS IN SOIL AND WATER

Heavy metal contamination in soil and water poses serious ecological and human health risks due to persistence, non-biodegradability, and bioaccumulation, driving remediation from conventional physical and chemical methods to innovative biological and integrated technologies.

Physical Remediation Methods

Physical remediation methods remove heavy metals from soil and aquatic systems through techniques such as soil washing, flushing, sediment dredging, filtration, and membrane separation. Soil washing and flushing extract contaminants using water or chemical solutions, while immobilization/stabilization, such as biochar-supported ZVI, reduces Zn and Pb mobility, though Cd stabilization may be limited. Sediment dredging lowers concentrations of Cu, Zn, Pb, and Cd, and filtration or membrane technologies, including ultrafiltration and nanofiltration, enable selective removal of metal ions from water (Sun et al., 2025; Anyebe et al., 2025). These methods provide rapid contaminant reduction but can be costly, generate secondary waste, and may require integration with chemical or biological techniques for long-term site stabilization and sustainable outcomes.

Chemical Remediation Methods

Chemical remediation removes heavy metals from soil and water through precipitation, coagulation, flocculation, redox manipulation, and chelation. Chemicals such as $Al_2(SO_4)_3$, $FeCl_3$, or PAC precipitate metals including Cu, Fe, Mn, Zn, Cr, Pb, and Cd, while redox manipulation forms less toxic species. Layered hydroxides, such as Fe(III)-Cr(III), and adsorption on activated carbon further enhance removal efficiency (Cao et al., 2025; Zhang et al., 2024). Biodegradable chelants like citric acid, oxalic acid, and GLDA improve solubilization for metal recovery or phytoextraction, reducing residual contamination (Anyebe et al., 2025; Khare et al., 2024; Chengatt et al., 2023; Zhang et al., 2024). These chemical methods are rapid and highly effective, but careful management is required to avoid secondary pollution, chemical residues, and excessive sludge generation.

Biological Remediation Methods

Biological remediation leverages plants, microorganisms, and fungi to remove or detoxify heavy metals from soil and water in a sustainable, eco-friendly manner**.** Phytoremediation uses hyperaccumulator species such as *Brassica juncea*, *Helianthus annuus*, and *Phragmites australis* to extract, stabilize, or transform metals like Cd, Pb, Zn, and Hg, reducing bioavailability and ecological risks. Its efficiency depends on plant species, soil conditions, and exposure duration, and it can be enhanced by amendments such as biochar or chelating agents (Khan et al., 2023; Priya et al., 2023; Anyebe et al., 2025**)**. Bioremediation employs bacteria, archaea, and fungi to detoxify metals through biosorption, bioleaching, biomineralization, and enzymatic transformation. Fungal species like *Pleurotus ostreatus* and *Aspergillus niger* bioaccumulate metals under harsh conditions, while bacterial strains such as *Pseudomonas* spp. facilitate reduction and immobilization (Dou et al., 2024; Singh et al., 2024). Biological methods are sustainable and cost-effective but may be slower and require optimization of environmental factors such as pH, temperature, and nutrient availability for field-scale application.

The review does not explicitly differentiate which remediation methods are most suitable for soil versus water, creating ambiguity for readers. Physical methods like soil washing, flushing, stabilization/immobilization, and sediment dredging are primarily suited for soil and sediment remediation, effectively reducing heavy metal concentrations in solid matrices (Sun et al., 2025; Anyebe et al., 2025). Chemical methods such as precipitation, coagulation, redox manipulation, and chelation are widely used in water treatment to remove dissolved metals like Cu, Zn, Pb, Cd, and Cr, though some can also be applied to soils for stabilization (Cao et al., 2025; Zhang et al., 2024; Khare et al., 2024). Biological methods, including phytoremediation and microbial or fungal bioremediation, can be applied to both soil and water systems but require careful selection of plant or microbial species and site-specific optimization (Khan et al., 2023; Priya et al., 2023; Dou et al., 2024). Clarifying the target medium for each method would improve the review's clarity, practicality, and utility for environmental management.

Integrated and Hybrid Technologies

Combining physical, chemical, and biological methods overcomes limitations, with green technologies, including advanced adsorbents, electrochemical treatments, hydrogels, membrane filtration, and photocatalysis, enhancing efficiency, reducing sludge, and supporting resource recovery (Singh et al., 2024). Hybrid systems optimize biological processes and scalability, providing cost-effective, sustainable remediation while informing policies that reduce contamination, protect ecosystems, and safeguard communities (Liu et al., 2024). Integrated approaches build on lessons from individual methods, combining their strengths to achieve more reliable and versatile remediation outcomes.

Table 2 provides the comparative overview of different physical, chemical, biological, and integrated strategies for heavy metal remediation in soil and water, including principles, target metals, advantages, limitations, and key references. Table 2 allows readers to quickly compare methods and understand their suitability for specific metals and environmental contexts.

Table 2 provides a comparative overview of heavy metal remediation strategies, showing that physical methods are rapid but may lack long-term stability (Sun et al., 2025), chemical methods are efficient but costly with potential secondary pollution (Cao et al., 2025; Anyebe et al., 2025; Khare et al., 2024; Chengatt et al., 2023; Zhang et al., 2024), and biological methods are eco-friendly but slower and species-dependent (Khan et al., 2023; Priya et al., 2023; Dou et al., 2024). Integrated/hybrid approaches offer enhanced efficiency, scalability, and resource recovery (Singh et al., 2024; Liu et al., 2024). The novelty lies in green technologies and hybrid systems, addressing gaps in traditional methods, while societal relevance includes restoration of contaminated soils and waters, protection of human health, and support for sustainable industrial and agricultural practices.

Advantages, Limitations, and Environmental Trade-Offs

Physical, chemical, and biological remediation methods each have distinct advantages and limitations. Physical methods, such as soil washing, flushing, and dredging, offer rapid contaminant removal but can be expensive, generate secondary waste, and may be less effective under variable

Table 2. Comparison of heavy metal remediation methods in soil and water

Method Type	Principle	Target Metals	Advantages	Limitations	References
Physical	Soil washing, flushing, stabilization / immobilization, dredging	Zn, Pb, Cu, Cd	Rapid removal, effective for highly contaminated sites	Limited long-term effectiveness, seasonal variability, incomplete Cd stabilization	Sun et al., 2025
Chemical	Precipitation, coagulation, redox manipulation, chelation	Cu, Fe, Mn, Zn, Cr, Cd	High removal efficiency, adaptable to water and soil	Chemical costs, sludge generation, potential secondary pollution	Cao et al., 2025; Anyebe et al., 2025; Khare et al., 2024; Chengatt et al., 2023; Zhang et al., 2024
Biological	Phytoremediation, microbial remediation, mycoremediation	Cd, Pb, Cr, Hg, Zn	Eco-friendly, low-cost, sustainable, bioaccumulation reduction	Slow process, species-dependent, sensitive to environmental conditions	Khan et al., 2023; Priya et al., 2023; Dou et al., 2024
Integrated / Hybrid	Combination of physical, chemical, biological, and advanced technologies	Cd, Pb, Cr, Hg, Cu, Zn	Enhanced efficiency, reduced sludge, scalable, supports resource recovery	Complex design, higher initial cost, requires multidisciplinary optimization	Singh et al., 2024; Liu et al., 2024

environmental conditions. Chemical methods, including precipitation, coagulation, redox manipulation, and chelation, achieve high removal efficiencies and can target specific metals, yet they may introduce chemicals into the environment, alter soil or water chemistry, and require careful management of residuals. Biological approaches, such as phytoremediation, microbial remediation, and mycoremediation, are eco-friendly, cost-effective, and can stabilize or remove metals under natural conditions, but they are slower, dependent on environmental factors, and may have limited effectiveness for high metal concentrations. Integrated and hybrid strategies combine these approaches to maximize efficiency, reduce environmental trade-offs, and enhance sustainability, though they require careful design, monitoring, and site-specific adaptation. Overall, the selection of remediation strategy must balance efficiency, cost, sustainability, and environmental safety to achieve both ecological and societal benefits.

PERFORMANCE OF EMERGING HEAVY METAL REMEDIATION STRATEGIES

Emerging heavy metal remediation strategies use advanced materials, biological systems, and hybrid technologies to enhance contaminant removal, depending on efficiency, sustainability, adaptability, and risk management.

Nanotechnology-Based Approaches

Nanomaterials provide high surface area and reactive sites for adsorption, redox, and complexation. Microbe–nanoparticle systems show synergy: Pd NPs from *Spirulina platensis* removed 12% Pd, iron oxide NPs from *Geobacter sulforeducens* achieved 100% Cr removal (Saleem et al., 2023). Carbon-, metal-, and nZVI-based nanomaterials offer high removal and regeneration but require ecological risk assessment (New et al., 2023; Naseer, 2024). A ZVI/NCM composite immobilized 74.10% As, 72.17% Cd, 95.67% Cu, 66.95% Pb, and 65.83% Zn (Guo et al., 2023).

Biochar and Engineered Sorbents

Biochar immobilizes metals via ion exchange, complexation, and precipitation. Cu(II), Zn(II), and Pb(II) removal exceeded 77% (Burachevskaya et al., 2023). Magnetic biochar spheres improved Cd, Pb, and As removal by 26.5–41%, with 98.8–99.8% separation and 92.3–95.4% regeneration (Wu et al., 2024). Modified and cemented biochar reduced Cd bioavailability >50% and enhanced sustainability (Hu et al., 2025; Wijeyawardana et al., 2024).

Electrochemical and Biosorption Techniques

Electro-dialysis has been effectively applied for removing Cd and tin (Sn) from electroplating industry wastewater. Experiments conducted at varying temperatures and agitation speeds using carbon and iron electrodes showed maximum Cd and Sn removal at 50 °C, 100 rpm, and 8 h contact time (Sivakumar et al., 2014). Biosorption using isolated fungi species such as *Aspergillus niger* achieved 96.3% chromium (VI) removal from tannery wastewater at pH 3 and 4 g biomass, indicating high bioreduction efficiency compared to other species (Sivakumar, 2016). Nickel removal from electroplating wastewater using bamboo activated carbon reached 98.7% efficiency at optimum conditions (adsorbent dosage 1.5 g/L, 25 rpm agitation speed, 0.6 mm particle size, 75% dilution, and pH 5.5), confirming its potential as a sustainable adsorbent (Sivakumar et al., 2018). Phytoremediation with *Eichhornia crassipes* (Mart.) Solms showed 88.3–93.4% zinc removal from electroplating industry wastewater, highlighting the plant's effectiveness in treating industrial effluents (Durairaj, 2024).

Genetic Engineering for Enhanced Bioremediation

GEMs use pollutant-binding proteins and metal-transforming enzymes. *Shewanella oneidensis* and *Cupriavidus metallidurans* removed 91% Pb at pH 7 (Muslim et al., 2024). GEMs offer specificity and efficiency but require biosafety precautions.

Smart and Sustainable Systems

Smart systems integrate multifunctional processes with low toxicity and circular economy benefits. Nanocomposite B adsorbed Pb (30 mg/g) and degraded phenol (68%) (Kumar et al., 2024). Eggplant-waste adsorbents removed ≥85% Pb with ~60% regeneration (Zhu et al., 2025). Hal-WS2 NC adsorbed Hg^{2+} (96.42%), Pb^{2+} (93.2%), Ni^{2+} (87.09%) while functioning as a supercapacitor (Mashkoor et al., 2023). Nanotechnology adoption correlates with practitioner expertise ($\rho = 0.59$, $p < 0.01$) (Al-Aqbi et al., 2024).

Advanced Materials for Efficient and Sustainable Remediation

Technologies such as nanomaterials, engineered biochars, multifunctional sorbents, nZVI, GEMs, microalgae, and microbes enhance heavy metal remediation by immobilizing, transforming, and promoting biological uptake, achieving 70–90% removal. Nanomaterials provide rapid and targeted removal through high surface area and reactive sites, engineered biochars stabilize metals and reduce bioavailability, and multifunctional sorbents enable simultaneous removal of multiple contaminants with potential for regeneration or reuse. These advanced materials reduce secondary pollution, lower energy and chemical inputs, and support site-specific, cost-effective remediation. Their integration with biological and hybrid approaches facilitates ecosystem restoration and long-term protection of water, soil, and public health, making remediation processes more sustainable and adaptable to complex contamination scenarios.

RISK ASSESSMENT AND MANAGEMENT

Risk assessment and management involve evaluation of heavy metal exposure probability and impact on human health and ecosystems. This process provides a foundation for prioritizing mitigation, shaping regulations, and guiding sustainable remediation strategies.

Human Health Risk Assessment Models

Heavy metal contamination in soil, water, and sediment poses age- and sex-dependent health risks. Panqing et al. (2023) reported low non-carcinogenic but high carcinogenic risks in children from Cr in Xinjiang, China. Eid et al. (2024) found significant oral and dermal risks from Cd, Cr, and Pb in NW Egypt, while Gupta and Gupta (2023) identified sediments as the main non-carcinogenic burden in India. Wang et al. (2023) mapped hotspots in Tongling, China, requiring targeted mitigation. Advanced risk assessment models now incorporate bioaccessibility, probabilistic exposure, and cumulative risk indices to account for mixed-metal exposure and variability among populations, enhancing the precision of risk predictions. Bioaccessibility and factors like age, sex, and exposure pathways refine risk estimates (Shentu et al., 2023; Budi et al., 2024), with ambient particulates, microplastic-mediated Cd, and river water highlighting human exposure (Yadav et al., 2025; Barus et al., 2024; Jonah et al., 2024).

Ecological Risk Assessment

Ecological assessments show Hg and Cd as key sediment pollutants requiring control (Yan et al., 2023), while sewage irrigation drives crop bioaccumulation, affecting children and ecosystems (Batool et al., 2023; Din et al., 2023). Soil adsorption improves risk indices and highlights site-specific variations (Wang et al., 2023), with Nigerian wetlands and Peruvian lagoons integrating sediment-water dynamics and governance (Chris et al., 2024; Salas-Ávila et al., 2024). Comprehensive ecological risk assessment now evaluates multi-trophic level impacts, including soil microbial activity, aquatic invertebrates, and plant bioaccumulation, and incorporates spatial modelling and sediment fractionation to identify priority intervention sites. These methods allow prediction of long-term ecological consequences and support management strategies for contaminated ecosystems.

Decision-Making Tools for Remediation

Remediation prioritization frameworks combine risk, uncertainty, and sustainability, using fuzzy aggregation to optimize bioremediation (Alolaiyan et al., 2024), policy and community engagement (Ogbeide and Henry, 2024), risk-based tools for dumpsites (Massoud et al., 2023), and life cycle assessments to compare methods (Liang et al., 2023). Non-carcinogenic (HI/OHI) and carcinogenic (CR) risks across populations and matrices, highlighting differences between immediate health risks and long-term cancer risks, with children and sediment-exposed groups being most vulnerable is shown in Fig. 2.

From Fig. 2, cross-study comparisons reveal diverse exposure pathways, risks, and mitigation priorities. In Xinjiang, China, Panqing et al. (2023) reported low non-carcinogenic risk ($HI < 1$) but high carcinogenic risks in children (77.52%), females (69.09%), and males (65.63%) from Cr. Eid et al. (2024) found high oral non-carcinogenic and significant dermal risks in NW Egypt, with carcinogenic risks for Cd, Cr, and Pb $>1\times10^{-4}$. Gupta and Gupta (2023) observed extremely high non-carcinogenic sediment risks in India (OHI: adults 1.26×10^{2}, children 1.11×10^{3}) but lower carcinogenic risk (TCR: adults 1.80×10^{-2}, children 3.37×10^{-2}). Wang et al. (2023) in Tongling, China, reported moderate non-carcinogenic risks (As > Ni > Cd > Hg > Cu) and carcinogenic risks in 70–80% of the population, with oral ingestion dominant (88–99.2%). Bioaccessibility-based assessments at abandoned sites reduced non-carcinogenic risks by 39–88% (adults) and 45–83% (children), and carcinogenic risks by 68–79% (adults) and 73–83% (children) (Shentu et al., 2023). Ecological studies show Hg and Cd as key sediment risks, with improvements in management reducing cumulative risks from 2015–2020 (Yan et al., 2023).

Improving Risk Assessment and Management Frameworks

Risk assessment and management frameworks can be improved by integrating multi-pathway exposure data, bioavailability, and age- or species-specific sensitivities into models,

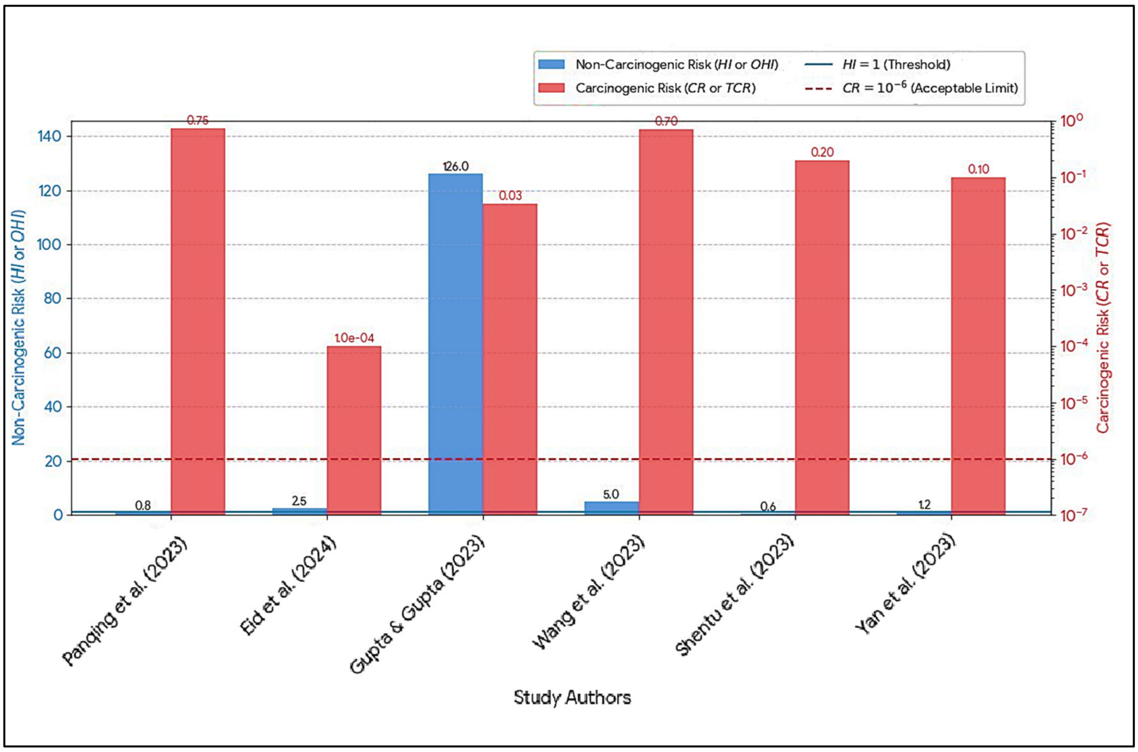

Fig. 2. Comparison of non-carcinogenic and carcinogenic risk across environmental studies

combined with real-time environmental monitoring and geospatial mapping. Incorporating both human and ecological endpoints, predictive modeling, and scenario analysis enables better identification of hotspots and exposure risks. Standardizing methodologies, including bioaccessibility and sediment-water dynamics, and linking results to regulatory thresholds and stakeholder engagement supports evidence-based, site-specific, and sustainable policy development for mitigation and remediation planning.

Overall, non-carcinogenic risks are immediate in sediment and water, while carcinogenic risks affect children and populations near industrial or coal-related contamination. Risk is influenced by matrix type, pollution source, and population vulnerability. These findings emphasize targeted monitoring, prioritization of high-risk sites, and use of probabilistic and bioaccessibility-based risk models. Integrating human and ecological risks with site conditions and sustainability metrics can guide remediation, protect public health, and enhance ecosystem resilience.

TECHNICAL AND ECONOMIC BARRIERS

Technical and economic barriers hinder the effective remediation of heavy metal contamination. Limited efficiency under complex conditions and high implementation costs restrict large-scale, sustainable applications.

1. **Technical Limitations:** Non-essential metals (Pb, Cd, Hg, Cr, As) are persistent and bioaccumulative, with mobility and site heterogeneity limiting the efficiency of conventional remediation methods.

2. **Economic Challenges:** Advanced and integrated technologies achieve high removal but involve high costs and long timelines, delaying site reuse and economic benefits.

3. **Long-Term Monitoring Issues:** Heavy metals can remobilize over time, requiring

continuous, resource-intensive monitoring to assess bioavailability and exposure risks.

4. **Unintended Environmental Impacts:** Physical, chemical, or biological interventions may alter soil and water properties, disrupt biodiversity, and create secondary contamination risks.
5. **Integrated Strategies:** Site-specific, adaptive approaches combining physical, chemical, biological, and emerging technologies are essential for long-term human and ecosystem protection.

Integrated, site-specific strategies combining physical, chemical, biological, and emerging technologies, along with adaptive management and risk-informed decisions, are essential to address persistence, mobility, and bioaccumulation, ensuring long-term human and environmental health protection.

FUTURE PERSPECTIVES AND RESEARCH NEEDS

Future perspectives and research needs focus on advancing innovative, sustainable strategies to address evolving challenges in heavy metal remediation and management.

1. **Climate-Adaptive Remediation** – Incorporate climate change impacts into heavy metal transport modeling, evaluate the resilience of remediation technologies (e.g., biochar, phytoremediation, nanomaterials) under extreme weather, and integrate climate risk into site-specific monitoring and management plans.
2. **Circular Economy-Driven Recovery** – Develop scalable metal recovery technologies (nanomaterials, engineered biochars, microbial-assisted systems) that extract valuable metals (Pb, Cd, Cu, Zn) while minimizing waste and secondary pollution through hybrid remediation-recovery systems and life-cycle assessments.
3. **Evidence-Based Governance** – Establish harmonized regulations, monitoring protocols, and remediation compliance frameworks across local to international levels, ensuring soil and water quality protection with adaptive management strategies.
4. **Stakeholder and Public Engagement** – Enhance community participation, education, and risk communication to improve acceptance of remediation and recovery initiatives, reduce socio-economic barriers, and incentivize industry participation in circular economy practices.
5. **Integrated Technological Innovation** – Bridge biological, chemical, and physical remediation advances with predictive AI/ML tools, hybrid systems, and resource-efficient approaches to strengthen long-term environmental resilience, human health protection, and sustainable development goals.

CONCLUSION

Heavy metal contamination in soil, water, and sediments poses serious risks due to the persistence, bioaccumulation, and toxicity of non-essential metals (Pb, Cd, Hg, Cr, As) and threshold-dependent toxicity of essential metals (Fe, Cu, Zn, Mn). Chronic exposure causes liver damage at Fe >50 mg/day, gastrointestinal and pancreatic dysfunction at Zn >40 mg/day, cognitive impairment at Pb >5 µg/dL, renal failure at Cd >5 µg/g creatinine, skin and lung cancer from As >10 µg/L in water, and mercury biomagnification up to one million-fold in aquatic predators, with neurotoxicity at >0.3 mg/kg/week. The transport of heavy metals depends on soil properties, water chemistry, climate variability, and human activities, with dispersal via leaching, runoff, erosion, and microplastic transport, and mobility influenced by pH, redox potential, organic matter, and iron–sulfur interactions. Temporary immobilization (e.g., biochar) reduces Cd and Pb by approximately 60%, phytoremediation removes 40–70%, nanocomposites and engineered sorbents remove more than 90%, and multifunctional nanomaterials remove 12–100% in complex matrices. Long-term monitoring is essential as environmental fluctuations can remobilize stabilized metals. AI/ML-enabled sensors, ICP-MS, and portable XRF support real-time bioavailability assessment and adaptive remediation. Integrated strategies combining physical (soil washing, dredging), chemical (coagulation, redox manipulation), and biological (phytoremediation, microbial remediation) methods enhance efficiency and sustainability. Future approaches should integrate climate-adaptive planning, circular economy-based metal recovery, and robust policies with public engagement. Evidence shows that combining technological, ecological, and policy measures effectively mitigates human and ecological risks while strengthening environmental resilience.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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