The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

# Environmental Fate and Remediation of Heavy Metals: A mini review

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**Article Info**

**Article type:**
Review Article

**Article history:**
Received: 30 August 2025
Revised: 16 November 2025
Accepted: 16 February 2026

**Keywords:**
*Heavy metals*
*Remediation strategies*
*Sustainable remediation*
*Nanoremediation*

**ABSTRACT**

Heavy metal contamination in soil and water has emerged as a pressing global concern due to its persistence, bioaccumulative potential, and severe ecotoxicological impacts. This review synthesizes recent advances in understanding the sources, environmental fate, and remediation of heavy metals. Natural processes such as volcanic activity and weathering, coupled with anthropogenic drivers including mining, industrial discharge, agriculture, and urbanization, are identified as primary contributors to heavy metal pollution. The review examines transport mechanisms—sorption–desorption, redox transformations, colloid-facilitated migration, and interactions with micro- and nanoplastics—that govern heavy metal mobility and bioavailability across soil–water systems. Ecotoxicological assessments reveal profound disruptions in microbial communities, soil fertility, plant physiology, aquatic food webs, and higher trophic organisms through bioaccumulation and biomagnification. Remediation strategies are critically evaluated, spanning physical and chemical techniques, biological methods, plant–microbial consortia), and sustainable approaches. Emerging research emphasizes sustainable soil amendments, green nanotechnology, electrokinetic–PRB integration, and community-based monitoring. Collectively, this review underscores the urgent need for multidisciplinary, eco-friendly, and scalable remediation strategies to mitigate heavy metal pollution and safeguard ecosystem and human health.

**Cite this article:** Marathaka Rani, S.A., Kamaraj, M., & Aravind, J. (2026). Environmental Fate and Remediation of Heavy Metals: a mini review. *Pollution*, 12(1), 366-380.
https://doi.org/10.22059/poll.2025.401445.3089


DOI: https://doi.org/10.22059/poll.2025.401445.3089

## INTRODUCTION

Heavy metals are metal ion contaminants whose presence threatens the environment. Due to their long environmental persistence and non-biodegradability, these pollutants have become a global concern, particularly in the wake of the 19th-century industrial revolution (Das *et al.,* 2023). Demand for heavy metals has been increasing ever since, which is expected to rise by 25% with the global increase in the population (DebRoy and Elmer, 2024**).** Anthropogenic activities such as inadequate mine spoil disposal, industrial waste discharge, coal combustion, excessive run off from agriculture disperses huge quantities of heavy metals like Pb, Cd, Hg, Zn etc into the environment (Mishra *et al.,* 2024). In the present scenario, heavy metals are indeed very useful, especially in the electronic industries, fertilizer industries etc. Though it is beneficial when present in trace amounts, it is considered highly toxic due to its tendency to bioaccumulate on a large scale (Zaynab *et al.,* 2022). These contaminants also have the potential to hinder DNA replication by attaching itself to protein molecules. Higher concentrations of

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Co have been found in the main organs, such as the skin, of those exposed to heavy metal pollution at work (Saravanan *et al.,* 2024). Heavy metals are not only detrimental to human lives but also have an adverse effect on the soil, air, and water ecosystem. Excessive discharge of heavy metals into the aquatic system disrupts the living organisms at different trophic levels and hinder the feeding patterns as well. Similarly heavy metal contaminates the soil ecosystems by leaching into the soil and affects its natural fertility (Haghighizadeh *et al.,* 2024).

Since heavy metals cannot be completely removed, these pollutants are deposited in sediments as a result of the ongoing release of household, industrial, and agricultural waste into rivers and lakes and it poses health risk to the general public once they enter the food chain. With the increased percolation of heavy metals into the food and food chain followed by the escalated health risks, the Department of Nutrition and Food Safety of World Health Organization has initiated a process for assessing and examining the impact of heavy metal that requires continuous monitoring and surveillance. Considering its deteriorating impact on all forms of life and ecosystems, it becomes imperative to remove the heavy metal contaminants from the environment (Mansor *et al.,* 2024). Several techniques are widely used for the heavy metal remediation in past decades (Bakhtiari *et al.,* 2024). In situ techniques like surface capping and encapsulation are convenient and requires less time. Ex situ techniques like excavations and thermal disruptions are highly efficient methods. Chemical methods like chemical solubilizations, chemical stabililzations can be used to modify the mobility and bioavailability of contaminants. The microorganism mediated techniques are called as biological methods which are economically viable and environmentally friendly that includes biosorptions, biotransformation and volatilization (Sánchez-Castro *et al.,* 2023).

Owing to the affordability, accessibility and the efficiency, adsorbent resin has also been studied as a sustainable remediation strategy for the removal of the Cd and Pd from aqueous solution (Fuentes Gandara *et al.,* 2025). Similarly, the fruit of *Prosopis juliflora* was studied for its potential to adsorb As (III) from the synthetic waste eater. The study demonstrated that non -edible parts of *P. juliflora* showed significant effectiveness in removing As (III) from aqueous ecosystems (Samimi and Nouri, 2025). This review focusses only the works that are published in heavy metals themes from the year 2023-2025.

## SOURCES AND TYPES OF HEAVY METALS IN SOIL AND WATER

There are numerous studies analysing the outcomes and consequences of higher concentrations of heavy metals in the environment. In order to take adequate management and mitigation steps, solely relying on the risk assessment would not be sufficient, rather it requires identifying the sources and types of the heavy metal pollution (Singh *et al.,* 2024). Heavy metals are generally classified into two types, namely, essential (e.g., molybdenum (Mo), manganese (Mn) , copper (Cu), nickel (Ni), iron (Fe), and zinc (Zn)) and non-essential (e.g., cadmium (Cd), arsenic (As), mercury (Hg), and lead (Pb)). Essential heavy metals are vital for various metabolic functions in living organisms. However, when absent or present in concentrations exceeding physiological requirements, they can become toxic and harmful for the organism. In contrast, non-essential heavy metals exhibit toxicity even at low concentrations and have no known beneficial role in biological systems (Jadaa and Mohammed, 2023).

Naturally, heavy metals are released through processes such as seismic activity, volcanic eruptions, and weathering. Seismic events are known to alter soil texture and composition by triggering the release and mobilizing the toxic chemicals and heavy metals. Notably, in areas near industrial activities, post-earthquake soils exhibit exceptionally high concentrations of heavy metals (Hore *et al.,* 2025). Similarly, volcanic eruptions have lasting impacts in the surrounding environment.Volcanic ashes increase the concentration of Cu, Fe, Mn, Zn, As, and Cd in the biosphere (Carrera-Beltran *et al.,* 2024). On-site processes like weathering, breaks down rocks, soil and minerals releasing heavy metals into the environment. Atmospheric reactions also play an important role, as sulfur dioxide ($SO_2$) and nitrogen oxides (NOx) contribute to the formation of acid rain. Stronger acids are produced when these oxides react with rain water. Oxidation of sulphide bearing minerals would enhance and enrich the soil and water with heavy metals (El-sharkawy *et al.,* 2025).

Anthropogenic sources such as agriculture, industrial activity and mining discharges are regarded as some of the major causes leading to higher heavy metal pollution. Among these, the agriculture sector plays an important role as it has many potential sources such as fertilizers, pesticides, livestock dung and waste water that contribute to heavy metal contamination. Soil serves as an ideal ecosystem for the accumulation of minerals, with both organic and inorganic fertilizers acting as significant sources of heavy metals. The fertilizers and pesticides combine to form a toxic combination, targeting a broad range of bacteria, fungi, weeds etc (Sarkar *et al.,* 2024). In recent years approximately 2 millions tons of pesticide have been used globally leading to the rise in Cd, Ni, Zn, Pb etc. Studying approximately 196 phosphate fertilizers from 12 European countries exhibited the average heavy metal contents were found to be 7.4 (Cd), 90(Cr), 166(Zn), 15(Ni) and 2.9(pb)mgkg-1 (Wan *et al.,* 2024). In India, approximately 60% of agricultural soils near industrial areas have been found to contain elevated concentrations of Cd, Pb, and Cr, particularly in the regions of Punjab and Uttar Pradesh. The cadmium concentration was reported to be 2.3 mg/kg, significantly higher than the WHO's safe permissible limit of 0.8 mg/kg (Sharma *et al.,* 2023). In addition to agriculture, arsenic-based compounds are still used in certain countries such as New Zealand and Australia to control cattle ticks and other pests. Moreover, in the timber industry, higher concentrations of Cu, Cr, and As are used in preservative formulations to prevent decay and insect damage in wood (Xu *et al.,* 2024). These compounds can leach into the surrounding environment during application or through the disposal of treated wood.

Mining or mineral extraction is another large-scale process of extracting and refining ores which apparently produce a colossal amount of waste including aqueous and gaseous emissions. Mine drainage often consist of higher concentration of pyrite ($FeS_2$), molybdenite ($MoS_2$), chalcocite ($Cu_2S$) etc (Cozma *et al.,* 2024). Improper waste disposal and smelting produces large volumes of sludge and debris in the soil impacting the environment, soil, vegetation and ultimately resulting in loss of biodiversity. Monitoring the spread of these minerals within the landscape becomes extremely difficult due to uneven distribution of metals. Even abandoned and closed mine sites also inflict negative impact on the ecosystem and humanity (Setu and strezov, 2025; Adnan *et al.,* 2024). Industrial advancement with a rapidly growing population is significant contributors of heavy metal in the environment. The waste material and residues arising from these procedures often spread and accumulate via leaching, erosion and runoff. Industrial processes like galvanization and electroplating generate higher quantities of Zn and Cd (Dehkordi *et al.,* 2024; Angon *et al.,* 2024). In a study assessing the quality of Chuhe river based in China, 33% of surface water samples were found to contain elevated levels of heavy metals due to industrial discharges. Arsenic was particularly concerning, with concentrations reaching up to 0.12 mg/L, significantly exceeding the safe limit of 0.01 mg/L (Rajasekar *et al.,* 2024).

A growing population raises demands of more energy. Although several renewable resources-based energy have emerged, still coal and petroleum-based energy remain the primary sources of energy. By-products such as coal fly ash and industrial effluents often contain elevated concentrations of heavy metals including Cu, nickel (Ni), and mercury (Hg), among others. These pollutants can easily enter surrounding ecosystems through air, water, and soil pathways, posing long-term risks to both environmental and human health. In addition to direct industrial discharges, illegal dumping of waste and surface runoff from urban areas further contribute to the accumulation of heavy metals in the environment, exacerbating the contamination of soil and water systems (Oladimeji *et al.,* 2024; Oyebamiji *et al.,* 2024). Table 1 list an overview of sources and impact of heavy metals.

## ENVIRONMENTAL FATE AND TRANSPORT MECHANISMS

Heavy metals enter the aquatic food chain and be potentially available for biotic accumulation. Industrial growth and agricultural advancements are increasingly generating environmental problems (Reymond and Sudalaimuthu, 2023). Heavy metals and metalloids (Cd, Pb, Cu, Zn, Ni, Hg, As, Cr) remain in soils and waters as they are not degradable and their speciation is regulated by an active interplay between mineral, organic, and microbial process that takes place across space (aggregate → profile → catchment) and time (minutes → decades). Their environmental destiny is controlled mainly by (i) sorption–desorption and surface complexation onto mineral and organic phases, (ii) redox processes and precipitation–dissolution, (iii) complexation with dissolved and particulate ligands (dissolved organic matter, colloids, micro/nanoplastics), and (iv) hydrologic transport by advection–dispersion, preferential flow, and colloid-facilitated movement. These controls are interlaced with climate variability (wetting–drying cycles, floods, salinization) and land use to regulate mobility, bioavailability, and risks at the soil–water interface. Recent syntheses point out that fate is extremely context-dependent and it may be immobilized in one microenvironment and mobilized within a few centimeters in another when redox, pH, or ligand fields are modified (Li *et al.,* 2024).

Few investigations are reported to be seen for heavy metals occurrence are less within the

**Table 1.** Comparative Overview of Heavy Metal Sources, Soil and Aquatic Impacts, and Trophic Transfer

| Heavy Metal | Key Sources | Primary Impacts on Soil | Impacts on Aquatic Systems | Bioaccumulation/Biomagnification | References |
|---|---|---|---|---|---|
| **Cd** | Mining, fertilisers, batteries | Microbial inhibition, phytotoxic | Gill damage in fish, enzyme inhibition | High (plants, invertebrates) | Xu *et al.,* 2021; Davidova *et al.,* 2023 |
| **Pb** | Paint, smelting, gasoline | Invertebrate toxicity, root damage | Neurotoxicity in fish and birds | Moderate | Kumar *et al.,* 2020; Ma *et al.,* 2022 |
| **Hg** | Coal power, mining | Enzyme disruption | Methylmercury neurotoxin; fish mortality | Very high (methylmercury) | Wu *et al.,* 2024; Chamoli and Karn, 2024 |
| **As** | Pesticides, mine tailings | Oxidative stress in plants | Carcinogenic to aquatic organisms | High | Speer *et al.,* 2023; Sinha *et al.,* 2023 |
| **Cr** | Tanneries, electroplating | ROS production in roots | Gill and liver toxicity | Moderate | Ali *et al.,* 2023; Hu *et al.,* 2023 |
| **Ni** | Metal refining, fossil fuels | Alters enzyme activity | Reduces growth in algae | Low | Rizwan et al., 2024; Mao et al., 2025 |
| **Cu** | Plumbing, fungicides | Reduces soil respiration | Disrupts zooplankton and periphyton | Moderate | Mebane, 2023; Wilson, 2025 |
| **Zn** | Galvanisation, tyres | Metal interference with microbes | Toxic at high concentrations to invertebrates | Moderate | Van and Nga, 2024; Hussain et al., 2022 |

limits acceptable by their respective national regulations. For instance, Sulistyowati et al. (2023) obtained surface sediment samples from eight stations (representing midstream and downstream area) with a van Veen sediment grab from the hypothesis that the heavy metal pollution was from land-related activities and migrated down the river estuaries. In their research, aside from Pb, which exceeded the interim sediment quality standard, the concentrations of heavy metals in the midstream and downstream portions of the Cisadane River were well below the guideline level. Under circumneutral pH, most divalent metals ($Pb^{2+}$, $Cu^{2+}$, $Zn^{2+}$, $Ni^{2+}$, $Cd^{2+}$) precipitate inner-sphere complexes on Fe/Al (oxyhydr)oxides, phyllosilicate edges, and carbonate surfaces, but outer-sphere complexes prevail under greater ionic strength or lower pH. Organic functional groups (carboxyl, phenolic) in humic substances and aged biochars enhance sorption; they release metals to porewaters upon protonation under acidification. Contemporary reviews stress that "mineral–organic matter associations" (MOMAs)—complexes where organics and reactive minerals are mixed intimately—are dynamic, important sinks that buffer porewater concentrations by reversible exchange and sorption–precipitation coupling. Microbial exudates and root-derived ligands can rearrange such associations, thus changing binding capacities and kinetics (Li *et al.,* 2024). Redox potential (Eh) significantly controls the mobility of multivalent elements.

Under anoxic conditions, reductive dissolution of Fe(III)/Mn(IV) (oxyhydr)oxides mobilizes trace metals and As already sorbed; simultaneous reduction of sulfate produces metal sulfides (e.g., CdS, PbS), which immobilize cations but can re-oxidize upon re-aeration. Flood pulses, waterlogging, and hyporheic exchange produce rapid Eh fluctuations that induce repeated release–capture cycles. Field evidence from floodplain sediments reveals high-magnitude floods to enhance sediment transport and modify trace-element partitioning; oxic reworking of the sequences can subsequently remobilize previously sequestered contaminants. Similarly, in river–aquifer mixing zones, changing water tables and organic carbon inputs regulate Fe/S cycling and therefore metal mobility on seasonal timescales (Xie *et al.,* 2025). DOM chelation stabilizes a wide array of cations in solution and can suppress or augment bioavailability based on ligand class and competing ions. Carboxyl-rich DOM enhances apparent solubility and long-range transport in freshwaters, but in hard or saline waters, $Ca^{2+}/Mg^{2+}$ and ionic strength collapse the double layer, inhibiting DOM–metal complexation and favoring sorption/precipitation (e.g., carbonates, hydroxides). Critical syntheses for surface waters highlight that pH–alkalinity–DOM interactions are first-order controls on speciation and transport with relevance to model K_d and biotic ligand models applied in risk assessment (Banithy *et al.,* 2023). In structured soils, a high percentage of percolation passes through the matrix by macropores (root channels, cracks, wormholes).

Preferential flow mobilizes dissolved metals during storm events and short-circuits sorption equilibria, exporting pulses to drains, ditches, and shallow groundwater. Under matrix flow, dispersion and diffusion allow prolonged contact with sorbents and precipitation fronts; under macropore flow, interaction times are reduced, so speciation at the time of event initiation (pH, Eh, ionic strength) disproportionately controls export. These interactions are particularly relevant in episodically irrigated or rainfed agroecosystems on slaking soils. New mechanistic evidence indicates that antecedent wetness has contrasting influences on colloid release and metal loading: drier conditions release more colloids but have lower colloid-bound Cd transport due to pH changes and size/ζ-potential alterations that reduce Cd affinity (Zhang *et al.,* 2023). Powerfully sorbing metals are bound to mobile colloids (1 nm to 1 μm), such as Fe/Al oxyhydroxide fragments, clays, organo-mineral particles, and biocolloids. This "hitchhiking" enables quick migration far beyond what predictions from dissolved species alone would indicate and is emphasized by rainstorms, irrigation initiation, wetting after dry periods, and freeze–thaw that break up aggregates. Colloids (organo-mineral particles, oxides) are capable of transporting powerfully sorbing metals beyond dissolved phase expectations, particularly with rainfall, thaw, or irrigation. Researchers in undisturbed soils identified colloids as major carriers of Cd and U, noting that dissolved-only measurements underestimate mobilization (Bergen *et al.,* 2023). An aspect further pointed out that redox oscillations control colloid formation, stability, and filtration by altering mineral surface charges and polymer bridging. In essence, this implies that risk assessments relying solely on dissolved concentrations may underestimate export in transient events. At the stream–soil interface, hyporheic exchange keeps cycling pollutants between water and sediments; fine, metal-enriched sediments are scoured by high flows, and low flows prefer deposition and diagenetic modification. The findings of Riani et al. (2024) indicated that sediment and water near the pond at Cinangka Village in Bogor Regency is a local used battery smelting center in West Java, Indonesia which was once a burning location of used battery smelting but 12 years post-ceasing activities, are contaminated by heavy metals, not just lead, zinc, arsenic, and iron. Additional metals exist due to lead and lead oxide plates being impure and related to other minerals. Microplastics (MPs) and nanoplastics (NPs) are recent sorbent carriers that sorb metals through hydrophobic regions and oxygenated functional groups formed during aging. MPs can reduce soil sorption potential (by occupying sites or changing pH/ionic strength), enhance colloidal transport, and co-deliver metals to biota.

A critical overview of Liu *et al.* (2024) integrated mechanisms and controlling factors in soils, citing that type of polymer, weathering, state of aging, and co-contaminants (e.g., dissolved organic ligands) regulate metal binding and desorption; combined exposures can increase bioaccessibility and plant uptake in paddy and upland systems. These results necessitate that transport models account for polymer–metal complexes in addition to traditional mineral colloids. Microplastics in soils affect metal fate at the same time through sorption and indirect bioavailability effects. A meta-analysis conducted in 2024 reported that MPs enhanced the bioavailability of Cu, Pb, Cd, Fe, and Mn with correlations to microplastic size, pH, organic matter, and exposure duration (Bodor *et al.,* 2024). Another research of proved that environmentally-simulated aged MPs possessed much greater adsorption capacities for Cd and Cr than single-type MPs, promoting potential transport of the metals (Liao *et al.,* 2025). Moreover, aged polyethylene microplastics adsorbed Cd more than pristine ones, and chemisorption dominated adsorption processes in rhizosphere biofilms (He *et al.,* 2023). Microplastics are capable of enhancing heavy metal uptake in plants. A greenhouse test confirmed that microplastics enhanced Cd uptake in red amaranth and affected nutrient acquisition and growth, significantly with biochar (Roy *et al.,* 2024). A more extensive meta-analysis (Chen *et al.,* 2024) showed that MPs enhanced shoot concentration of Cd by 11%, Pb by 30%, and Cu by 47%, and soil pH and total metal concentration were key factors of control. Risk depends not merely on overall concentrations but on bioaccessible fractions. Gastrointestinal bioaccessibility assays (in vitro) in conjunction with speciation measurements increasingly inform site decisions.

Bioaccessibility (available for uptake fraction) tends to differ from total concentrations. Research of Li et al. (2024) constructed an in vitro model integrating metal speciation fractionation and gut microbiota impact and revealed that Zn, Ni, Cd, and Cu bioaccessibilities were below 70%, with higher correlation with exchangeable and carbonate-bound fractions compared to total levels—meaning overestimation if only total concentration is considered. Wetting–drying cycles, drought breaks, and heatwaves redistribute metal speciation by periodically oxidizing and reducing iron and sulfur phases, concentrating salts, and altering DOM quality. The extreme events (wildfire ash additions, floods, hurricanes) introduce new ligands and fine grains, temporarily mobilizing them; by contrast, extended anoxia can sequester cations as sulfides until re-aeration. A climate-driven cycling of metalloids and metals accentuates these non-linear responses and the necessity to combine hydroclimate predictions with reactive transport models to predict pulses and legacy releases from soils and sediments (Zitoun *et al.,* 2024).

Current fate assessments integrate high-resolution measurements (DGT, diffusive gradients in thin films; X-ray absorption spectroscopy; voltammetry) with reactive transport modeling

(RTM) and data-driven methods. RTMs combining mineral equilibria, surface complexation, and kinetic redox/precipitation are capable of capturing event-scale flushing and longer-term aging, but parameterization is still difficult because of heterogeneity in reactive surface area and DOC/DOM composition. Meanwhile, machine-learning risk mapping is now widely applied to interpolate mobility indices within regions; however, interpretability demands the incorporation of chemical knowledge (pH, Eh, clay, SOC, carbonate, salinity) instead of purely empirical covariates. The random forest model is suggested by Takarina et al. (2024) for obtaining information and setting the threshold of heavy metal contents, hydrogen water potential and temperature for maximum heavy metal removal efficiency with the help of a zeolite-embedded sheet and minimization of pollutants in the environment. Recent studies emphasize that theory-based models and event-driven monitoring are crucial for predicting colloid-facilitated transport and redox-driven release under variable climates (Zhang *et al.,* 2023).

Heavy metals exert wide-ranging ecotoxicological effects across multiple trophic levels. In soil ecosystems, metals such as Cd, Pb, and Hg disrupt microbial enzyme activity, alter nutrient cycling, and reduce soil fertility. In plants, they interfere with photosynthesis, water uptake, and antioxidant metabolism, resulting in stunted growth and oxidative stress. Aquatic organisms experience enzyme inhibition, gill damage, and impaired reproduction, leading to population declines and food web instability. Bioaccumulation and biomagnification amplify these effects, transferring metals through the food chain to higher organisms, including humans. Chronic exposure in humans is linked to neurotoxicity (Pb, Hg), nephrotoxicity (Cd), carcinogenicity (As), and endocrine disruption. Emerging evidence also suggests that co-exposure with microplastics and organic pollutants enhances metal bioavailability and cellular toxicity. Understanding these cross-system effects is essential for designing remediation strategies that protect ecosystem function and human health (Ayub *et al.,* 2025; Davidova *et al.,* 2024).

## REMEDIATION STRATEGIES FOR HEAVY METAL CONTAMINATION

Adsorption and soil washing are widely validated and scalable approaches. Adsorbents include activated carbon, natural minerals, and engineered nanomaterials. Lab and pilot studies affirm their effectiveness in immobilizing or removing heavy metals like cadmium, lead, and arsenic from aqueous media. For instance, carbon nanotubes and graphene-based composites present high surface area and functional groups suited for adsorption of multiple metal ions (Fouda-Mbanga *et al.,* 2024; Trivedi *et al.,* 2025). Soil washing involves extracting heavy metals via aqueous solutions—commonly chelating agents like EDTA or acids—followed by treatment of the extract. While effective, it can be costly and generate secondary waste requiring safe disposal (Zhang *et al.,* 2022, Zu *et al.,* 2024).

ISCO utilizes strong oxidants (e.g., Fenton's reagent, permanganate, persulfate, ozone) to degrade or transform contaminants in situ. Though primarily used for organic pollutants, selective application can indirectly stabilize or remobilize metals when integrated with other methods. Challenges include handling safety (oxidants are hazardous and reactive), generation of side-products, and homogenous delivery into the subsurface (Ma *et al.,* 2018; Xu *et al.,* 2023). ISCR introduces reductants (e.g., zero-valent iron, dithionite) to chemically reduce metals such as Cr(VI), transforming them into less mobile or toxic forms. Often deployed within permeable reactive barriers (PRBs), ISCR is effective for passive, long-term remediation (Yang *et al.,* 2024; Verma *et al.,* 2025; Kondakindi *et al.,* 2024).

Nanoremediation: Nanoparticles—including nanoscale zero-valent iron (nZVI), metal oxide nanoparticles, and carbon-based nanomaterials—are at the frontier of remediation technology. nZVI is widely tested and has seen field deployments for groundwater remediation. Nanomaterials offer vast reactive surfaces and can be engineered for targeted remediation, yet demand careful monitoring due to their environmental fate and toxicity concerns (Galdames *et al.,* 2020; Verma

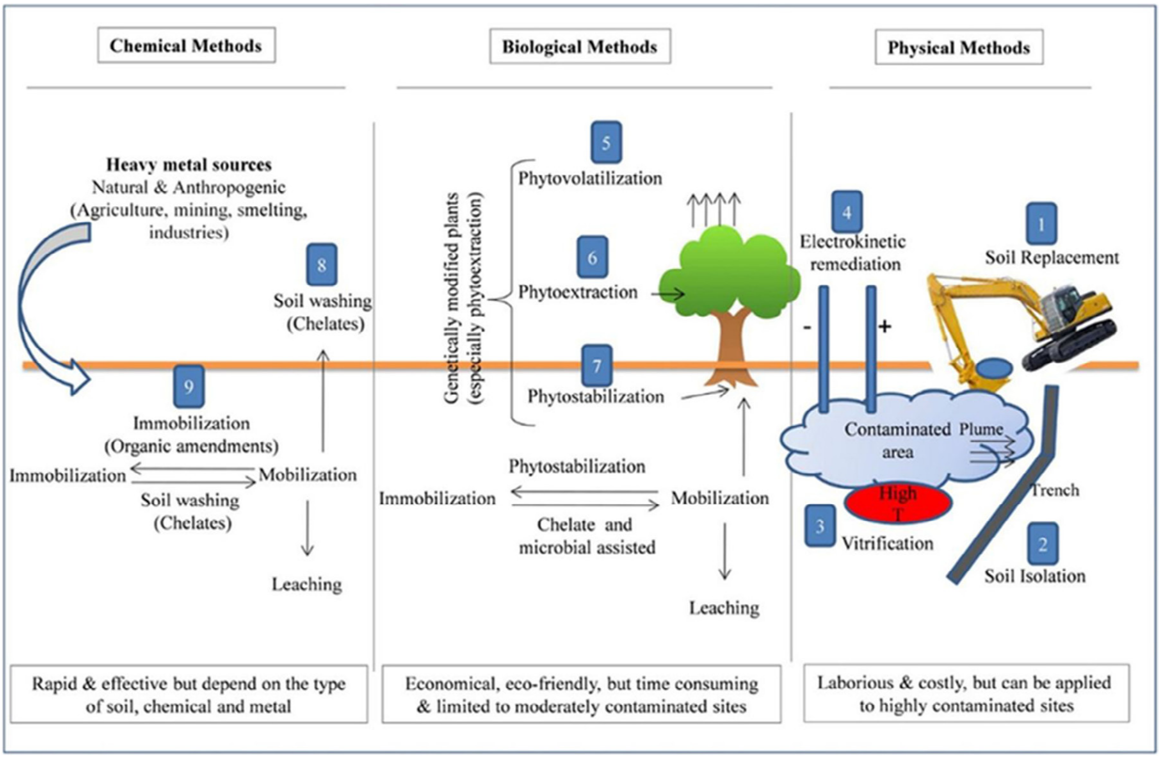


**Fig. 1.** Chemical, Biological, and Physical Approaches for Heavy Metal Removal from soil

*et al.,* 2025). Phytoremediation harnesses plants to uptake, accumulate, stabilize, or volatilize heavy metals. Key mechanisms include phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration. Uptake efficiency is influenced by plant biomass and metal bioavailability (Sharma *et al.,* 2023). A critical review highlights post-remediation biomass treatment strategies—essential for safe disposal or resource recovery of contaminated plant matter (Di Stasio *et al.,* 2025). Figure 1 shows an overview of methods of heavy metal remediation.

Mycoremediation employs fungi—such as Pleurotus, Aspergillus, Trichoderma—that absorb or sequester heavy metals through biosorption and bioaccumulation. They are cost-effective and adaptable across environments, producing valuable byproducts like enzymes or edible biomass. Mycorrhizal fungi, in symbiosis with plant roots, enhance metal tolerance and uptake. They sequester metals, increase plant biomass, and modify the rhizosphere chemically to facilitate phytoremediation (Dinakarkumar *et al.,* 2024; Akpasi *et al.,* 2023).

Integrated approaches combining plants and microorganisms—including bacteria, fungi, or mycorrhizae—can significantly improve remediation efficiency. Such synergy leverages complementary mechanisms: microbial transformation of metals, enhanced plant growth, and improved uptake or stabilization (Ayub et al., 2025; Dadhich et al., 2025). Table 2 summarizes the remediation strategies for heavy metal–contaminated soils, including representative methods, strengths, and key limitations. Green strategies focus on sustainability, often involving amendments like biochar, compost, or metal-binding materials to immobilize heavy metals in soil with minimal ecological disruption. These amendments reduce metal mobility and enhance long-term stabilization (Nie *et al.,* 2024; Mohammad *et al.,* 2025).

Combining physical, chemical, and biological methods enables tailored responses. Examples include embedding nZVI or reductive media within PRBs, pairing ISCO source treatment with downstream ISCR, or blending phytoremediation with amendment-based immobilization strategies for synergy and resilience (Teng *et al.,* 2023; Yoon *et al.,* 2025).

Table 2: Comparative Overview of Strategies for Heavy Metal Remediation in Contaminated Soils.

**Table 2.** Summary of remediation strategies for heavy metal–contaminated soils, including representative methods, strengths, and key limitations.

| Strategy Type | Example Methods & Mechanisms | Strengths | Limitations & Considerations |
|---|---|---|---|
| **Physical/Chemical** | Adsorption (activated carbon, CNTs, graphene), Soil Washing | Rapid, well-characterized; scalable and controllable | Costly; secondary waste; limited to accessible zones |
| | ISCO (oxidants), ISCR (reductants), Nanoremediation (nZVI) | In-situ, powerful chemical transformations | Safety risks; incomplete oxidation/reduction; nanoparticle risks |
| **Biological** | Phytoremediation (phytoextraction, stabilization, volatil.) | Sustainable, low cost; scenic; minimal disturbance | Slow; site- and species-specific; handling contaminated biomass |
| | Mycoremediation & Mycorrhizal Bioremediation | Enhances plant growth; fungal biomass may be valorized | Less field-proven; influenced by soil conditions and species |
| | Plant–Microbial Hybrids | Greater efficacy through synergy; adaptable | Complex implementation; ecological monitoring required |
| **Green/Amendments** | Biochar, compost, soil conditioners | Eco-friendly; supports immobilization and soil health | Effectiveness variable; may only immobilize, not remove metals |
| **Hybrid** | PRBs with nZVI, ISCO + ISCR combos, amended phytoremediation | Optimized for specific site conditions; robust mechanisms | Design complexity; multi-tier coordination; cost-intensive |

## CONCLUSION

Heavy metal contamination of soil and water remains one of the most persistent and critical environmental challenges of the 21st century. This review highlights how both natural and anthropogenic sources significantly contribute to the rising burden of pollutants such as cadmium, lead, mercury, and arsenic, which continue to accumulate in ecosystems and enter the food chain. Understanding the environmental fate of heavy metals—governed by complex interactions involving sorption–desorption, redox dynamics, colloid transport, and emerging factors like microplastic associations—is vital for accurate risk assessment. Their ecotoxicological impacts span soil, water, and biota, leading to microbial disruption, plant toxicity, aquatic system destabilization, and trophic-level biomagnification, with profound implications for human and ecological health. Remediation strategies, ranging from traditional physical and chemical methods to innovative biological and hybrid approaches, show promising potential but also limitations. Future efforts must focus on integrating eco-friendly, cost-effective, and scalable technologies while balancing efficiency with long-term sustainability. The advancement of nanotechnology, biochar-based amendments, plant–microbial consortia, and electrokinetic systems, coupled with predictive modeling and participatory monitoring, offers new avenues for progress. Future research should focus on developing field-scale validation of hybrid remediation systems that combine nanomaterials, microbial consortia, and soil amendments under variable environmental conditions. Long-term monitoring of metal speciation, transformation kinetics, and ecological recovery post-remediation is essential to ensure sustainability. There is also a need for integrating life-cycle assessment (LCA) and techno-economic analysis (TEA) into remediation studies to evaluate environmental trade-offs and economic feasibility. Additionally, incorporating remote sensing, AI-based predictive modeling, and community-engaged monitoring frameworks can enhance data-driven decision-making. Emphasizing circular bioeconomy principles—such as valorization of contaminated biomass and recovery of valuable metals—can transform remediation from a reactive to a resource-generating process, guiding future sustainable management of metal-contaminated ecosystems.

## ACKNOWLEDGEMENTS

The authors thank their institution for the facility provided to make this work possible.

## GRANT SUPPORT DETAILS

The work did not receive any financial support.

## CONFLICT OF INTEREST

The authors declare no conflict of interest and in addition declare no ethical issues including plagiarism, informed consent, misconduct, data fabrication and or falsification, double publication or submission and redundancy not has been violated by the authors.

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