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Heavy metal pollution: an alarming environmental threat and emerging remediation approaches

Vivek Kumar Patel[1*], Devendra Kumar Patel[1], Ashish Patel[1], Laxmani Verma[2], Kanya Verma[2], Vijaya Gupta[2]

[1]*Department of Botany, Guru Ghasidas Vishwavidyalaya (A Central University), Bilaspur, Chhattisgarh, 495009 India*

[2]*Department of Biotechnology, Guru Ghasidas Vishwavidyalaya (A Central University), Bilaspur, Chhattisgarh, 495009 India*

***Corresponding author details**
Name; Vivek Kumar Patel
E.mail: vivekpatel12061997@gmail.com
Contact No.: +91-8602226816

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Abstract: Heavy metal contamination is a critical threat to environmental and human health due to the toxicity, persistence, and bioaccumulative nature of metals such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg). Conventional remediation techniques including chemical Precipitation, reverse osmosis, nanofiltration, electrokinetic remediation is often limited by high costs and risks of secondary pollution. Recent advances, however, have introduced sustainable and interdisciplinary strategies, integrating biological, chemical, and nanotechnological approaches. Phytoremediation, through processes such as phytodegradation, phytovolatilization, phytoaccumulation, and phytoextraction, employs plants and associated soil microbes to mitigate pollutants. Bioremediation with metal-tolerant plants and microorganisms, nano-bioremediation utilizing engineered nanoparticles, and hybrid electrochemical methods have shown enhanced effectiveness in both aquatic and terrestrial systems. This review summarizes the current state of heavy metal remediation technologies, emphasizes recent innovations, and highlights the importance of integrated, eco-friendly approaches for scalable applications. Future research should focus on combined treatment strategies and real-time monitoring systems to effectively address complex, mixed-contaminant environments.

Keywords: *Heavy metals, Phytoremediation, Bioremediation, Nanotechnology, Environmental remediation*

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I.INTRODUCTION:

Heavy metals represent a diverse group of metallic elements that, due to their relatively high density (typically >5 g/cm³) and inherent toxicity at low concentrations, pose serious threats to ecosystems and public health. These elements include both essential trace metals such as copper (Cu), iron (Fe), and zinc (Zn), which are required in small quantities for enzymatic and physiological functions, and non-essential metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), which are toxic even at trace levels (Singh et al., 2024). Despite the fact that there is no universally accepted definition, heavy metals are often described in terms of their density, atomic weight, and toxicological properties. What sets them apart from many other pollutants is their persistence, non-biodegradability, and ability to undergo bioaccumulation and biomagnification, which amplifies their impact through ecological food webs (Zitoun et al., 2024).

The sources of heavy metal contamination can be broadly categorized into natural and anthropogenic. Natural processes such as rock weathering, volcanic eruptions, and soil erosion contribute to background levels of heavy metals in soil and water. However, it is human activities that have intensified their release to hazardous levels in recent decades. Industrialization and urbanization have accelerated the discharge of heavy metals through mining and smelting operations, coal and fossil fuel combustion, improper disposal of electronic waste, and emissions from vehicular traffic. Similarly, agricultural practices involving phosphate fertilizers, sewage sludge application, and pesticide use have become significant contributors to soil and water contamination (Oladimeji et al., 2024). As a result, heavy metals are now pervasive contaminants, affecting not only industrialized regions but also rural and agricultural landscapes. The environmental consequences of heavy metal pollution are profound. In terrestrial ecosystems, heavy metals alter soil physicochemical properties, disrupt microbial communities, and interfere with enzymatic processes critical for nutrient cycling and soil fertility. Long-term contamination results in reduced biodiversity and altered ecological balance. In aquatic systems, metals such as mercury and cadmium readily dissolve and accumulate in sediments, where they persist for decades. Aquatic organisms, including fish, crustaceans, and invertebrates, experience impaired growth, reproduction, and survival under heavy metal exposure. Through bioaccumulation and biomagnification, metals ascend the trophic levels, ultimately reaching humans and posing significant health risks (Jaishankar et al., 2014).

From a toxicological and human health perspective, exposure pathways include ingestion of contaminated food and water, inhalation of metal-laden dust and fumes, and dermal contact with polluted soil or industrial waste. The health impacts are well-documented and severe. Lead (Pb) exposure, for instance, is linked to cognitive impairments, behavioural changes, and reduced IQ in children, while in adults it contributes to hypertension, renal dysfunction, and cardiovascular diseases. Mercury (Hg), particularly in its methylmercury form, crosses the blood-brain barrier and placenta, leading to neurological and developmental disorders, especially during fetal development (Wu et al., 2024) . Cadmium (Cd) accumulates in kidneys and bones, causing chronic kidney disease and skeletal deformities such as Itai-itai disease. Arsenic (As), widely found in contaminated groundwater in South and Southeast Asia, is a Group I carcinogen associated with skin lesions, cardiovascular problems, and multiple cancers (Afzal & Mahreen, 2024). Vulnerable population such as children, pregnant women, industrial workers, and communities in developing nations with weak regulatory enforcement bear a disproportionate burden of these risks (Hu et al., 2024).

Addressing heavy metal pollution requires robust and efficient remediation techniques. Conventional physical and chemical methods such as soil excavation, stabilization/solidification, chemical precipitation, and membrane filtration—have been widely applied but are constrained by high operational costs, energy demands, and the risk of secondary pollution. Consequently, attention has shifted toward sustainable and eco-friendly approaches, including phytoremediation (use of plants to extract, stabilize, or transform metals), bioremediation (employing metal-resistant microorganisms), and nanotechnology-based strategies (engineered nanoparticles and nano-bio hybrids) (Yaldiz & Akan, 2025; Laoye et al., 2025). These approaches offer significant promise due to their scalability, cost-effectiveness, and environmental compatibility. However, practical challenges such as site-specific variability, incomplete metal removal, slow remediation rates, and uncertainties about the long-term behavior of introduced agents (e.g., nanoparticles, chelating agents) remain unresolved (Jomova et al., 2024).

Moreover, most existing studies have focused primarily on traditional heavy metals (Pb, Cd, Hg, As), with limited attention to emerging contaminants such as rare earth elements, metalloid-organic complexes, and engineered nanomaterials. Real-world contamination scenarios are further complicated by the co-occurrence of heavy metals with organic pollutants, microplastics, and other emerging toxicants, leading to altered mobility, bioavailability, and toxicity profiles. These complex interactions are poorly understood and remain a significant research gap. Additionally, the socioeconomic feasibility and community acceptance of remediation technologies are seldom discussed, yet they play a critical role in successful large-scale implementation, particularly in developing nations.

Therefore, heavy metal research is vital for understanding their fate, impacts, and for developing sustainable remediation strategies. This review summarizes the sources and health/ecological effects of heavy metal pollution, evaluates conventional and emerging remediation technologies, and highlights key challenges and future directions. By integrating interdisciplinary insights, it aims to advance scalable and eco-friendly solutions for mitigating heavy metal contamination.

1. Sources of Heavy metals

Understanding the origin of heavy metals is crucial for assessing environmental pollution, developing remediation strategies, and mitigating exposure-related health risks. Heavy metals are naturally occurring elements with high atomic weight and density, toxic to organisms even at trace concentrations. They are introduced into ecosystems through both natural processes and anthropogenic (human-induced) activities as presented in Table 1.

1.1. Natural Source of Heavy Metals

Natural sources contribute to the background levels of heavy metals in soil, water, and air. Although generally less concentrated than anthropogenic inputs, these sources play an important role in shaping baseline contamination levels and can significantly impact ecosystems in mineral-rich regions (Burakov et al., 2018; Singh et al., 2021).

1.1.1. Weathering and Erosion of Rocks

The primary natural source of heavy metals is the weathering of igneous and sedimentary rocks. Mechanical disintegration and chemical dissolution release metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), and arsenic (As) into soils, rivers, and groundwater (Dagdag et al., 2023). Factors like pH, redox potential, and organic matter influence the mobility and bioavailability of these metals in ecosystems. For example, natural arsenic-rich minerals have been linked to widespread arsenic contamination in groundwater in Bangladesh (Ahmed et al., 2004).

1.1.2. Volcanic Eruptions

Volcanic activity represents another significant geogenic source. During eruptions, large quantities of heavy metals including mercury (Hg), arsenic (As), and cadmium (Cd) are released via gaseous emissions and volcanic ash. These can travel long distances through the atmosphere before depositing into soils and water bodies, altering ecosystems and creating potential health hazards for humans and animals (Singh et al., 2024).

1.1.3. Hydrothermal and Marine Processes

Hydrothermal vents on the ocean floor naturally discharge trace metals such as cobalt (Co), copper (Cu), and zinc (Zn) into seawater. Similarly, coastal processes can mobilize heavy metals into marine sediments. Tar balls formed from oil residues naturally accumulate metals such as Pb and Cd, persisting in marine environments and posing bioaccumulation risks to aquatic organisms (Angon et al., 2024).

1.1.4. Serpentine and Ultramafic Soils

Soils derived from ultramafic rocks (e.g., peridotite and serpentinite) are naturally enriched with metals like chromium (Cr), cobalt (Co), and nickel (Ni). Known as serpentine soils, they are typically deficient in essential nutrients but contain toxic levels of heavy metals. Certain specialized plants, called metallophytes, have adapted to these environments and can hyperaccumulate metals in their tissues (Angon et al., 2024).

1.1.5. Groundwater and Geogenic Mobilization

Geogenic processes, influenced by redox conditions, microbial activity, and pH, can release heavy metals into groundwater. For instance, arsenic mobilization in aquifers is a natural phenomenon exacerbated by geochemical conditions, leading to widespread groundwater contamination in several parts of Asia (Angon et al., 2024).

1.1.6. Atmospheric Deposition

Natural atmospheric processes, such as dust storms and sea spray, also transport heavy metals over long distances. Metals settle onto terrestrial and aquatic surfaces, contributing to background contamination. Deposition rates depend on meteorological factors such as wind velocity, precipitation, and the physicochemical properties of the transported metals (Tchounwou et al., 2012).

2.2 Health Risks from Naturally Derived Heavy Metals

Although naturally occurring, many heavy metals exert toxic effects on animals and humans once mobilized into bioavailable forms. Their non-biodegradable nature allows them to accumulate in tissues, especially in the liver, kidneys, and bones, impairing physiological functions. In animals, toxicity is influenced by exposure level, age, sex, nutritional status, and chemical form of the metal. Chronic exposure often reduces productivity in livestock and increases mortality risk.

Arsenic (As): Known historically as the "Poison of Kings," arsenic enters the environment from both mineral ores and groundwater. In domestic animals, exposure occurs via contaminated feed, water, pesticides, and pastures. Absorbed arsenic accumulates first in the liver and then in the kidneys, lungs, and spleen, causing gastrointestinal, neurological, and cardiovascular symptoms. Acute poisoning is characterized by abdominal pain, respiratory distress, and restlessness (Afzal & Mahreen, 2024).

Lead (Pb): A widespread toxicant, Pb poisoning is more common in cattle and calves, owing to their indiscriminate feeding and licking behaviors. Sources include contaminated soil, feed, industrial waste, and fossil fuel combustion. Acute poisoning results in neurological disorders, loss of appetite, and in severe cases, death. Chronic exposure impairs growth, reproduction, and milk yield (Afzal & Mahreen, 2024).

Mercury (Hg): Naturally present in elemental, inorganic, and organic forms, mercury occurs in soils, rocks, and marine systems. While less common in domestic animals, accidental poisoning can occur through ingestion of contaminated substances. Toxic effects vary across species: cattle are particularly vulnerable, whereas sheep and horses show harmful effects at specific exposure levels. Mercury exposure disrupts the nervous system and can impair reproduction (Afzal & Mahreen, 2024).

2.3 Case Example: Harike Wetland, India

Natural weathering and erosion contribute to trace metal contamination in wetlands such as Harike, one of northern India's largest freshwater ecosystems. Here, metals like Fe, Mn, and Cr leach from surrounding rocks into surface water, altering ecological dynamics. Such ecosystems highlight the role of natural geogenic processes in baseline heavy metal loading, which may be further aggravated by anthropogenic inputs (Singh et al., 2024).

2.4. Anthropogenic sources of heavy metals

Human activities have drastically increased the concentration, mobility, and dispersion of heavy metals in the environment, often at rates far exceeding natural background levels. Industrialization, urbanization, mining, fossil fuel combustion, agriculture, and waste disposal are the dominant anthropogenic sources. Unlike natural processes, these sources typically generate concentrated and localized pollution that can rapidly degrade ecosystems and pose severe health risks.

2.4.1. Mining and smelting

Mining and smelting are among the most significant anthropogenic contributors to heavy metal contamination. During ore extraction and processing, waste rock and tailings are exposed to air and water, leading to the oxidation and leaching of metals such as Pb, Cd, As, and Hg into soils and waterways (Zhang et al., 2024). Smelting further releases metal particulates and vapors into the atmosphere, which can travel long distances before deposition.

Case studies:

- In China, large-scale mining and smelting have severely contaminated soils with Cd and Pb, posing high health risks, especially to children in nearby communities (Adnan et al., 2024).
- The EPA (U.S.) identified copper smelters as major sources of arsenic and lead emissions, prompting regulatory measures to cut emissions by ~8 tons annually.
- Mining areas such as Lengshuijiang, Hunan Province show elevated Mn, As, Se, and Sb in groundwater, threatening local water security.
- Thus, mining and smelting act as "hotspots" of heavy metal pollution, requiring stringent monitoring and remediation strategies.

Thus, mining and smelting act as "hotspots" of heavy metal pollution, requiring stringent monitoring and remediation strategies.

2.4.2. Industrial and Manufacturing Activities

Industrial operations release heavy metals during manufacturing, metal finishing, tanneries, battery production, pigment manufacturing, and electroplating. Effluents containing Cr, Ni, Zn, and Pb are frequently discharged into rivers and lakes, contaminating water sources (Zhang et al., 2024).

E-waste: Electronics industries contribute significantly through discarded devices containing Pb, Cd, and Hg. In countries with informal recycling (e.g., India, Ghana), acid leaching and burning release heavy metals into soil, air, and groundwater, causing chronic exposure risks (Hou et al., 2025).

Global incidents: In Zambia, the failure of a copper mine tailings dam released 50 million liters of toxic waste into the Kafue River. In Mexico, hazardous steel dust processing plants have led to soil contamination with Pb, Cd, and As, with widespread health impacts.

India: Untreated wastewater discharge into the Yamuna from industrial hubs in Gurgaon demonstrates localized but severe heavy metal loading.

Industrial sources are thus central to heavy metal contamination, demanding regulatory control, sustainable waste treatment, and cleaner technologies.

2.4.2. Agricultural sources

Agricultural activities contribute significantly to heavy metal accumulation in soils through fertilizers, pesticides, herbicides, and irrigation with contaminated wastewater. Phosphate fertilizers often contain Cd and U as impurities, which accumulate in soils and enter the food chain. Pesticides/Herbicides: Historically, arsenic and copper compounds were used, leaving persistent residues in soil and groundwater. Sewage sludge/wastewater irrigation: Rich in metals such as Pb, Zn, and Cd, when applied to fields, leads to long-term soil contamination (Wan et al., 2024). Recent studies estimate that 14–17% of global cropland is contaminated with toxic heavy metals (Sharma et al., 2025), with leafy vegetables frequently showing the highest levels of accumulation, thereby raising serious food safety concerns. The extent of bioaccumulation in agricultural soils is strongly influenced by factors such as soil pH, organic matter content, and redox conditions. To mitigate these risks, sustainable practices including phytoremediation, application of soil amendments, and careful crop selection have been suggested as effective strategies.

2.4.3. Urbanization, Transportation, and Domestic Sources

Urbanization intensifies heavy metal pollution due to traffic, construction, domestic waste, and outdated infrastructure. Vehicles release Pb (historically from leaded fuel residues), Cu (brake wear), and Zn (tire wear). Nanoparticles rich in metals accumulate in roadside dust, as reported in Delhi, where diesel vehicles produced 30% more nanoparticle emissions compared to CNG vehicles (Yu et al., 2025). Construction and demolition lead to disturb soils and release dust consisting Pb and Cr, contributing to air pollution. Household plumbing (lead pipes), batteries, paints, and cleaning agents leach metals into wastewater and urban soils (Hussain et al., 2023a) In Bangladesh, Pb and Ni concentrations in street dust reflect deteriorating environmental quality linked to rapid urbanization (Bartkowiak et al., 2024). Thus, cities act as major centres of heavy metal exposure through daily activities.

2.4.4. Waste disposal and landfills

Waste management is a critical source of heavy metal release, especially through landfills, sewage sludge, and e-waste Municipal solid waste (MSW) produces leachate rich in Pb, Cd, and Hg, contaminating soil and groundwater. E-waste is a rapidly growing global problem. In 2022, 62 million tonnes of e-waste were generated, with only 22.3% formally recycled (Bhardwaj et al., 2025). Guiyu, China, and Agbogbloshie, Ghana are infamous e-waste hubs where manual dismantling, burning, and acid leaching have created extreme contamination, with Pb concentrations exceeding safe limits by 100-fold. Workers and nearby communities face neurological disorders, respiratory illness, and developmental problems, especially children. Addressing landfill and e-waste risks requires formal recycling infrastructure, stricter regulations, and international cooperation to regulate transboundary e-waste movement.

2.4.5. Emerging contaminants and heavy metals

An emerging issue is the co-occurrence of heavy metals with emerging contaminants (ECs) such as microplastics, pharmaceuticals, endocrine disruptors, and PFAS. Microplastics adsorb metals like Pb and Cd, enhancing their transport and persistence. Antibiotics/surfactants can alter metal speciation, mobility, and toxicity (Manuguerra et al., 2024). Mixed contaminant exposures often cause synergistic toxicity, increasing oxidative stress and metabolic disruption. Traditional monitoring methods are insufficient; advanced techniques like HRMS and synchrotron spectroscopy are required. Most existing technologies target single pollutants. Co-contaminated sites require multifunctional and adaptive remediation strategies (Karnwal et al., 2024). This growing complexity highlights the need for integrated approaches in pollution control.

Table 1: Sources and Origin of Heavy Metals

Source Type	Specific Source	Heavy Metals Involved	Mechanism of Release	Reference
Natural	Rock weathering	Cd, Pb, As, Hg, Cr	Physical and chemical breakdown of metal-rich rocks	(Kabata-Pendias, 2010)
	Volcanic activity	As, Hg, Pb	Emission of metal-laden ash and gases during eruptions	(Kabata-Pendias, 2010)
	Hydrothermal vents	Zn, Cu, Co	Emission of metals into marine environments	(Alloway, 2012)
	Soil erosion	Various	Mobilizatio	(Kabata-

			n of naturally occurring metals in sediments	Pendias, 2010)
	Groundwater leaching	As, Fe, Mn	Natural leaching from mineral deposits into aquifers	(Robinson, 2009)
Anthropogenic	Mining and smelting	Pb, Cd, As, Hg	Tailings, slag, and gaseous emissions from ore processing	(Alloway, 2012)
	Industrial discharge	Cr, Ni, Zn, Pb	Wastewater from metal industries and factories	(Alloway, 2012)
	Electronic waste (e-waste)	Pb, Hg, Cd	Leaching from discarded electronics in landfills or burning	(Robinson, 2009)
	Agriculture (fertilizers, sludge)	Cd, As, Pb	Accumulation via contaminated fertilizers, pesticides, sludge	(McLaughlin et al., 1999)
	Fossil fuel combustion	Hg, Pb, As	Emissions from coal and oil burning	(Sharma et al., 2009)
	Traffic emissions	Zn, Cu, Pb	Wear of tires, brakes, and fuel combustion	(Sharma et al., 2009)
	Urban runoff	Cu, Zn, Pb	Transport of metals via stormwater into water bodies	(Sharma et al., 2009)
	Landfills and waste disposal	Hg, Cd, Pb	Leachate from solid waste into soil and groundwater	(McLaughlin et al., 1999)

2. Environmental and Health Impacts of Heavy Metals

Heavy metals pose a severe risk to both ecosystems and living organisms due to their toxicity, persistence, and bio accumulative nature. Their effects evident at multiple levels, from soil and water degradation to physiological disorders in plants, animals, and humans as designated in Table 2.

2.1. Impact on Soil Health and Fertility

Heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), and mercury (Hg) can substantially alter soils' physical, chemical, and biological properties. Inputs from industrial effluents, wastewater irrigation, excessive pesticide use, and atmospheric deposition lead to metal accumulation in soils, which undermines fertility and plant productivity.

Heavy metals diminish microbial biomass and suppress soil enzyme activities, including dehydrogenase, urease, and phosphatase, which are essential for nutrient cycling and organic matter decomposition (Moradi-Choghamarani & Ghorbani, 2024). A recent study showed that soils with elevated metal contamination had significantly lower microbial C, N, P cycling efficiency, highlighting how metal stress impairs soil nutrient turnover(Tian et al., 2025).

Persistent contamination leads to irreversible fertility loss (Hussain et al., 2023b) found that heavy metal pollution in agricultural soils led to stunted plant growth, reduced root development, and lower biomass accumulation, threatening ecosystemstability.
Similarly, in evaluations of remediation methods, physical and chemical remediation approaches often degrade soil nutrient content and enzyme activity, whereas biological approaches have more favorable outcomes for soil health though trade-offs exist (e.g., nutrient uptake by plants) (Xing et al., 2025).

Heavy metals can acidify soils, alter pH, increase electrical conductivity (EC), and reduce cation exchange capacity (CEC), thereby mobilizing toxic metals and diminishing nutrient retention (Engwa et al., 2019). Moreover, Liu et al. (2023) in the North China Plain found that metal accumulation was strongly correlated with policy, fertilization, pesticide use, and atmospheric deposition; these factors also influence soil chemical properties, exacerbating metal mobility and toxicity (Liu et al., 2023).

Indicated that total heavy metal concentration does not always correlate well with the fraction of metals that are bioavailable; soil properties (such as pH, organic matter) play a stronger role in determining how much of the metal is physiologically active (Wang et al., 2024). Thus, heavy metal contamination not only reduces soil fertility but can lead to cascading ecological and agronomic consequences.

Table 2: Heavy metal impact on environment and human health

Heavy Metal	Environmental Impact	Human Health Impact	Key References
Lead (Pb)	Contaminates soil and water; affects plant growth and microbial activity	Neurotoxic-impairs brain development, especially in children; cardiovascular and renal issues	(X. Cao et al., 2025)
Mercury (Hg)	Bioaccumulates in aquatic systems; toxic to fish and aquatic birds	Neurotoxin-causes tremors, memory loss, and cognitive impairment; congenital defects (Minamata)	(Harada, 1995)
Cadmium (Cd)	Disrupts soil enzymes; affects plant nutrient uptake	Renal dysfunction, bone damage, carcinogenic; bioaccumulates in kidneys	(Engwa et al., 2019)
Arsenic (As)	Groundwater contamination; reduces crop yield	Carcinogenic-skin, bladder, lung cancers; also causes skin lesions and diabetes.	Zhang et al. (2023); IARC (2023)
Chromium (Cr^{6+})	Persistent in soil and water; toxic to plants and microbes	Carcinogenic; causes respiratory issues, skin ulcers, and DNA damage	(Engwa et al., 2019)
Nickel (Ni)	Toxic to aquatic life; alters soil microbial structure	Allergic dermatitis; respiratory and kidney toxicity; potential carcinogen	(X. Cao et al., 2025)

2.2. Impact on Water Quality

Heavy metals enter aquatic systems through agricultural runoff, industrial discharge, mining leachates, and improper waste disposal. Because heavy metals persist and do not degrade, they can bind to sediments or remain dissolved, altering water chemistry and aquatic health.

Heavy metals affect water pH, dissolved oxygen levels, and biological oxygen demand (BOD), disturbing ecosystems and reducing suitability for aquatic life. Metals like Cr^{6+}, Cd, and Pb are especially harmful; exposure induces oxidative stress, DNA damage, and apoptosis in fish and invertebrates, leading to lowered survival, reproduction, and population declines. In study conducted by (Li et al., 2023) cadmium and lead contamination in rivers was linked to oxidative DNA damage in freshwater fish species. Moreover, the exposure to mixed metal stress can worsen outcomes due to synergistic toxicity mechanisms. Chronic ingestion of metal-contaminated water is associated with renal disease, developmental disorders, and cancer. Alarmingly, over 140 million people worldwide are estimated to be exposed to drinking water with arsenic concentrations exceeding safe limits (Cao et al., 2022; Engwa et al., 2019).

Heavy metals enter freshwater systems through agricultural runoff, mining, industrial discharge, and improper waste disposal. They bind to sediments or remain dissolved, altering pH, dissolved oxygen, and BOD. Cr^{6+}, Cd, and Pb have been shown to induce oxidative stress and DNA damage in fish, lowering survival and reproduction rates. Chronic exposure to contaminated water is linked to kidney disease, developmental disorders, and cancer. Over 140 million people globally are at risk from arsenic-contaminated drinking water (Cao et al., 2022; Engwa et al., 2019).

2.3. Impact on Air Quality

Heavy metals become airborne through industrial emissions, fossil fuel combustion, waste incineration, and vehicular emissions. They attach to particulate matter ($PM_{2.5}$, PM_{10}), impacting both air quality and human health. These metal-laden particles can travel long distances before depositing onto soil and water surfaces. High concentrations are often noted near smelters, industrial zones, and busy traffic corridors (Wei et al., 2023; Boorboori & Lackóová, 2023). Inhalation of particulate heavy metals induces oxidative stress, respiratory illnesses, cardiovascular damage, and neurological disorders. Additionally, atmospheric metals may influence cloud condensation processes, subtly affecting climate dynamics. Studies have observed that regions with coal-fired power plants tend to have higher ambient heavy metal concentrations, correlating with lower air quality indices and increased oxidant pollution like ozone.

Industrial emissions, fossil fuel combustion, waste incineration, and vehicles release metals such as Pb, Cd, Hg, As, and Cr into the atmosphere. These metals attach to particulate matter ($PM_{2.5}$ and PM_{10}), affecting air quality, climate, and human health. They can deposit on soil and water or be inhaled, causing oxidative stress, respiratory illness, neurological disorders, and cardiovascular problems. High atmospheric metal levels are linked to lower AQI and increased oxidative pollutants such as ozone (Wei et al., 2023; Boorboori & Lackóová, 2023).

2.4. Human Health Effects

The neurological, renal (kidney), and carcinogenic pathways are among the major health hazards associated with heavy metals. A well-known neurotoxic, lead (Pb) is particularly dangerous to children because it interferes with neurotransmitter function and brain development, resulting in behavioural problems, cognitive deficits, and a drop in IQ (X. Cao et al., 2025).

3.4.1 Neurological Effects

Pb, Hg, and As are potent neurotoxins, especially in children. Exposure impairs neurotransmission, synapse development, and brain growth, leading to cognitive deficits, behavioral issues, and lower IQ (X. Cao et al., 2025; Engwa et al., 2019).

3.4.2 Renal (Kidney) Effects

Cd, Pb, and U accumulate in kidneys, causing proteinuria, tubular dysfunction, and chronic kidney disease. Industrial exposure to Cd elevates kidney damage markers such as β2-microglobulin and NAG (Engwa et al., 2019).

3.4.3 Carcinogenic Effects

As, Cr^{6+}, and Ni are Group 1 carcinogens (IARC). Arsenic in drinking water is associated with skin, lung, bladder, and liver cancers, while Cr exposure in industrial settings increases lung cancer risk. Oxidative stress, DNA damage, and epigenetic changes mediate these effects

Industrial discharge of methylmercury into Minamata Bay led to bioaccumulation in fish and shellfish. Residents consuming contaminated seafood suffered neurological symptoms, paralysis, congenital disorders, and death. The disease highlighted the severe health and environmental consequences of mercury pollution (Harada, 1995). In 2014, Flint, Michigan's water supply was contaminated with lead from old pipes. Children experienced elevated blood lead levels, developmental delays, behavioral issues, and potential long-term cognitive deficits, disproportionately affecting low-income and minority communities (Hanna-Attisha et al., 2015).

2.5. Entry into Food Chains and Biomagnification

Heavy metals pose a critical risk due to their ability to enter the food chain and progressively magnify across trophic levels. Plants, especially leafy vegetables and root crops, readily uptake metals such as Cd, Pb, and as from contaminated soils and irrigation water, serving as the primary entry point for humans and herbivores. Aquatic systems also act as significant reservoirs, where metals accumulate in phytoplankton, algae, and benthic organisms, subsequently transferring to higher organisms like fish, birds, and mammals. Unlike essential nutrients, heavy metals are non-biodegradable and persist within tissues by binding to proteins and enzymes. This persistence results in bioaccumulation (progressive build-up in organisms over time) and biomagnification (increasing concentrations across food chain levels), often reaching toxic thresholds in top predators, including humans. Recent studies indicate elevated Cd and Pb levels in cereals and rice grains cultivated in contaminated soils, while Hg accumulation in fish is a well-documented global health concern. The consequences include neurological disorders, kidney and liver damage, reduced reproductive fitness in wildlife, and heightened risks of chronic diseases in humans. Mitigating this threat requires strict regulation of heavy metal emissions, regular monitoring of food products, and promotion of safer agricultural and aquaculture practices.

3.Mechanisms of Heavy Metal Contamination and Behaviour in the Environment

Heavy metals in the environment undergo a series of transformations and interactions that determine their mobility, persistence, and ecological or health risks. Their behaviour is controlled by speciation, mobility, persistence, and interactions with organic and inorganic matter, which together define their environmental fate (Fig 1).

4.1. Chemical speciation

Speciation defines the chemical form in which a metal exists free ions, complexes, or precipitates which strongly influences toxicity and bioavailability. For example, trivalent chromium (Cr^{3+}) is relatively stable and less toxic, while hexavalent chromium (Cr^{6+}) is highly soluble, mobile, and carcinogenic. Similarly, inorganic mercury (Hg^{2+}) can be transformed into methylmercury (CH_3Hg^+), a neurotoxin that biomagnifies in food chains.

Environmental parameters such as pH, redox potential, temperature, organic ligands, and competing ions regulate these transformations. Acidic or reducing conditions often increase solubility, while alkaline conditions favor precipitation or adsorption. Understanding speciation is thus critical for risk assessment and designing effective remediation strategies.

4.2. Mobility and persistence

The mobility of heavy metals in soils, sediments, and aquatic systems is strongly governed by physicochemical parameters including pH, redox potential, soil texture, organic matter, and competing ions. Metals such as Pb, Cd, and As are generally more soluble and mobile in acidic conditions, enhancing their leaching potential into groundwater and runoff. In contrast, alkaline environments favor adsorption and precipitation, which reduce mobility. Seasonal changes in soil pH and organic matter have also been shown to alter mobility in urban soils, directly influencing metal leaching into nearby water bodies (Zhang et al., 2024).

Heavy metals are also extremely persistent because they cannot be degraded biologically. Once introduced, they cycle between abiotic and biotic components for decades or centuries, often accumulating in sediments and organisms. This persistence contributes to bioaccumulation and biomagnification, creating long-term ecological and health risks (Li et al., 2024; Sarker et al., 2023). For instance, cadmium and mercury can remain in sediments for extended periods, forming stable complexes with minerals and organic matter that hinder natural attenuation.

Because of this persistence, remediation approaches often focus on reducing mobility and bioavailability rather than complete removal. Techniques such as soil washing, immobilization, and phytoremediation have been used, while bioremediation methods successfully reduced the mobility of Cr^{6+} by converting it to Cr^{3+}, thereby improving stability in groundwater (Muthusaravanan et al., 2018; Boorboori & Lackóová, 2023).

4.3. Interactions with organic/inorganic matter

The fate of heavy metals in the environment is profoundly influenced by their interactions with organic and inorganic matter. Organic matter such as humic and fulvic acids—contains functional groups (carboxyl, hydroxyl, phenolic) that can bind metals through complexation or chelation. This often reduces solubility and bioavailability, as seen with Cu, Pb, and Cd. However, in some cases, soluble metal organic complexes enhance metal mobility and transport. For instance, dissolved organic matter in river systems has been shown to increase As mobility by forming stable complexes (Li et al., 2024; Sarker et al., 2023).

Inorganic constituents such as carbonates, clays, and metal oxides (especially iron and manganese oxides) also play a key role. These materials provide adsorption sites via surface complexation, ion exchange, and precipitation, thereby immobilizing metals. For example, iron oxides strongly adsorb Ni and Cr, decreasing their bioavailability. pH and redox conditions further influence these interactions; under certain conditions, metals precipitate as hydroxides or carbonates. In chromium-contaminated soils, iron oxide coatings were found to immobilize Cr^{6+} effectively, reducing its toxicity and leaching risk (Muthusaravanan et al., 2018).

3. Conventional Remediation Techniques

Traditional methods for heavy metal remediation are primarily physico-chemical approaches aimed at removing or immobilizing contaminants.

Physicochemical techniques are widely used for their effectiveness and scalability. The most widely applied technique is adsorption due to its simplicity and cost-effectiveness. Materials like activated carbon, biochar, and synthetic resins bind heavy metal ions from solutions, reducing their mobility. Chemical Precipitation involves adding reagents (e.g., lime, NaOH, Na_2S) to convert soluble heavy metals into insoluble hydroxides or sulphides, which are then separated by sedimentation or filtration. Hydroxide precipitation works well for Pb, Cu, Zn, whereas sulphide precipitation is highly effective for Cd and Hg. The main drawback is sludge generation. Ion Exchange uses synthetic resins exchange toxic metal ions with innocuous ones, offering high selectivity even at low concentrations. This makes it effective for wastewater with trace metals. Moreover, ttechniques like reverse osmosis (RO) and nanofiltration (NF) physically separate heavy metal ions via pore size and charge. They provide high removal efficiency with minimal sludge, though fouling, high energy use, and brine disposal are challenges. There are processes such as electrocoagulation and electroflotation use electric currents to precipitate or float metal particles, minimizing chemical input and sludge production. Another is an ex-situ method where contaminated soils are washed with water, acids, chelating agents (EDTA, citric acid), or surfactants to desorb metals. Particle-size separation is often used since metals bind to fine particles (silt, clay). Eco-friendly amendments like biosurfactants and organic acids are being explored. Electrokinetic Remediation (EKR) involves applying a low-voltage direct current across electrodes inserted into soils. Metals migrate toward electrodes via electromigration, electroosmosis, and electrophoresis, where they are trapped or precipitated. Particularly effective in low-permeability soils (clays). However, conventional remediation techniques, while effective for rapid cleanup, suffer from high costs, generation of secondary pollution, limited sustainability, and ecological disturbance. This has prompted the exploration of biological and eco-friendly alternatives.

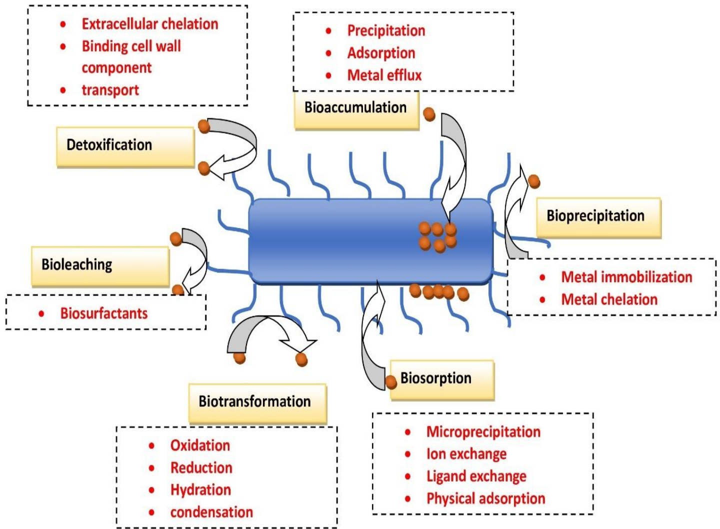

Figure 1: Various types of bioremediation process of heavy metal

4. Biological approaches to remediation

Biological remediation harnesses the natural capacity of plants and associated microbes to detoxify or immobilize heavy metals, offering cost-effective and eco-sustainable alternatives.

4.1. Phytoremediation

Phytoremediation is a green and cost-effective approach that utilizes plants to remove, stabilize, or detoxify heavy metals from contaminated soils and water. Plants possess specific physiological and biochemical mechanisms enabling them to tolerate and accumulate toxic metals (Fig. 2).

4.1.1. Mechanisms of Phytoremediation:

Phytoextraction: Uptake of metals (e.g., Cd, Pb, Zn, Ni) by roots and translocation to shoots, where they are stored in vacuoles. Hyperaccumulator plants like *Brassica juncea, Thlaspi caerulescens,* and *Pteris vittata* (arsenic hyperaccumulator) are widely studied (Abdullahi et al., 2025).

6.1.1.1. Phytoextraction

Heavy metals are taken up by plant roots and moved to above-ground sections, where they are then collected to eliminate the pollutants. This process is known as phytoextraction. *Brassica juncea* and *Sedum alfredii* are examples of hyperaccumulator plants that have demonstrated a considerable capacity to accumulate metals such as lead (Pb) and cadmium (Cd). According to recent research, combining different strains of plant

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growth-promoting bacteria (PGPB) can improve phytoextraction efficiency by boosting plant biomass and metal accumulation (Garbisu & Alkorta, 2024).

6.1.1.2. Phytostabilization

By using plants to immobilize heavy metals in the soil, Phyto stabilization lowers the mobility and bioavailability of these elements. Metals are frequently sequestered in the root zone or changed into less hazardous forms during this process. Vetiveria zizanioides is one plant that has been successfully used for this. By enhancing soil characteristics and metal adsorption capability, soil additions like biochar can further improve Phyto stabilization (Nedjimi, 2021).

6.1.1.3. Rhizofiltration

Heavy metals are absorbed, concentrated, and precipitated from aqueous solutions via rhizofiltration, which uses plant roots. This method works very well for treating wastewater and contaminated groundwater. Rhizofiltration has been used to extract metals like uranium (U), cadmium (Cd), and lead (Pb) from water sources using plants like Indian mustard (Brassica juncea) and sunflowers (Helianthus annuus) (Nedjimi, 2021).

6.1.1.4. Phytovolatilization

The process by which heavy metals are absorbed by plants and then released into the atmosphere in volatile forms is known as phytovolatilization. This technique has been used to remediate metals such as selenium (Se) and mercury (Hg). For example, some plants have the ability to transform mercury (Hg^{2+}) into elemental mercury (Hg^0), which is then volatilized. Although this method lessens soil pollution, it should be used with caution since it may release harmful materials into the atmosphere (Babu et al., 2021).

6.1.1.5. Rhizodegradation

Using the increased microbial activity in the rhizosphere (root zone), rhizodegradation, also known as Phyto stimulation, breaks down organic pollutants. Although this process is mostly linked to organic contaminants, it can also indirectly affect the mobility and availability of heavy metals by changing the microbial populations and soil chemistry (Adiloğlu et al., 2018).

6.1.1.6. Phytomining

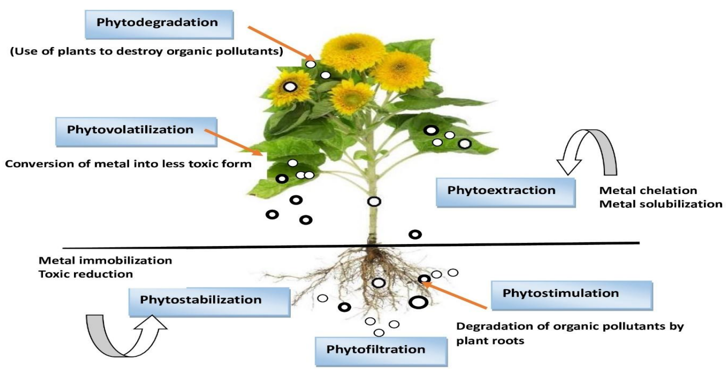

Figure 2: Heavy metal remediation through phytoremediation

The method of growing hyperaccumulator plants to remove valuable metals from the soil is called phytomining, or agromining. To recover the metals, the plant biomass is treated after harvest. For low-grade ores and contaminated areas in particular, this method provides a sustainable strategy to metal recovery (Adiloğlu et al., 2018).

6.2. Microbial-Assisted Phytoremediation

Microbial remediation exploits the ability of bacteria, fungi, and actinomycetes to detoxify or immobilize heavy metals through diverse biochemical pathways. Microorganisms employ mechanisms such as biosorption, where metal ions bind to functional groups on cell walls; bioaccumulation, involving active intracellular uptake and sequestration through metallothioneins and phytochelatins; biotransformation, in which microbes convert metals into less toxic oxidation states (e.g., *Pseudomonas putida* reducing Cr^{6+} to Cr^{3+}); and biomineralization, where metabolic activity leads to the precipitation of metals as insoluble phosphates, sulfides, or carbonates. Species such as *Bacillus subtilis*, *Pseudomonas fluorescens*, *Aspergillus niger*, and *Penicillium chrysogenum* have been widely reported for their efficiency in immobilizing Pb, Cd, and other toxic metals. Moreover, symbiotic rhizobacteria like *Rhizobium* and *Azotobacter* enhance phytoremediation efficiency by promoting plant growth under metal stress. This approach is highly specific, adaptable to diverse environments, and sustainable, although its efficiency can be influenced by environmental conditions and competition with native microbial populations.

6.3. Biosorption using Algae and Fungi

Biosorption using algae and fungi has emerged as an efficient, low-cost, and eco-friendly strategy for heavy metal remediation. Algal species, particularly microalgae such as *Chlorella vulgaris*, *Spirulina platensis*, and *Scenedesmus obliquus*, possess cell walls rich in polysaccharides, proteins, and lipids containing functional groups (–OH, –COOH, $–NH_2$, $–SO_3H$) that bind metal ions through ion exchange, chelation, and complexation. *Ulva fasciata* have shown substantial metal uptake: for achieves a maximum adsorption capacity of 26.88 mg/g for Cu^{2+} and 13.5 mg/g for Zn^{2+} in single-metal systems example, it(Karthikeyan et al., 2007) . In another study, composite membranes made from *Ulva fasciata* and cellulose acetate exhibited even higher capacities 95.2 mg/g for Cd^{2+} and 91.7 mg/g for Zn^{2+} demonstrating the enhanced performance when algal biomass is immobilized. Moreover, red algae *Jania rubens* pretreated with formaldehyde have achieved exceptionally high capacities for Pb(II), in some studies exceeding 700-1000 mg/g (in modified biomass forms) (RSC Advances, 2024). The halophilic microalga *Dunaliella salina* was the subject of another study that looked at how it responded to exposure to copper (Cu), lead (Pb), and cadmium (Cd). The removal efficiencies of *D. salina* for Cu, Pb, and Cd were 89.7%, 87.2%, and 72.9%, respectively, under ideal circumstances (pH 5–6, 30°C, and 6-hour contact time). These results highlight the algae's versatility and efficiency in the cleanup of heavy metals (Gao et al., 2024). The ability of Black Sea marine algae, particularly *Ulva lactuca* (green algae) and *Callithamnion corymbosum* (red algae), to adsorb Cu^{2+}, Zn^{2+}, and Co^{2+} ions has been shown in studies. According to Ciobanu et al. (2024), the study demonstrated the potential of using abundant algal biomass for heavy metal removal, providing a sustainable method of wastewater treatment. The study investigated the wood-rot fungus *Schizophyllum commune's* capacity for biosorption. Maximum biosorption capacities for Pb (II) were 81.5 mg/g, Sr (II) was 90.71 mg/g, Zn (II) was 70.18 mg/g, and Cd (II) was 66.18 mg/g in live mycelia. It was discovered that the process was spontaneous and endothermic, reaching equilibrium after 180–240 minutes (Mondal et al., 2024).

Similarly, fungi like *Aspergillus niger*, *Trametes versicolor*, and *Saccharomyces cerevisiae* have robust chitin- and glucan-rich cell walls that act as natural biosorbents, enabling the removal of toxic metals such as Pb, Cd, Cr, and Hg from aqueous environments. *Aspergillus niger*, when pretreated, shows Pb(II) adsorption of over 30 mg/g under optimized conditions (pH ~5, moderate biomass dosage), and *Penicillium* sp. has shown similar magnitudes (32-45 mg/g for Pb or Cu) depending on the metal and conditions. Dry mycelium membranes made from fungal biomass have been used in creative ways for lead cleanup. These membranes highlight the adaptability of fungal materials in environmental applications by providing a sustainable and effective way to remove lead from contaminated water sources (Parasnis et al., 2024). A study evaluated the biosorption of Pb^{2+}, Ni^{2+}, Mn^{2+}, and Zn^{2+} using dead fungal biomass, specifically from *Cladosporium* species. The study demonstrated the efficiency of using fungi produced from industrial waste in the removal of heavy metals, offering an economical and sustainable alternative (El-Gendy et al., 2023). The function of phosphate-solubilizing fungus in heavy metal cleanup has been acknowledged. These fungi can precipitate heavy metals as insoluble phosphates by solubilizing phosphate, which lowers the toxicity and bioavailability of the metals. A promising approach to bioremediation techniques is provided by this mechanism (Parasnis et al., 2024).

Moreover, fungal mycelia offer high surface area and porosity, enhancing metal binding efficiency. While biosorption is cost-effective and scalable, challenges such as regeneration of biomass, desorption of bound metals, and reduced efficiency in multi-metal systems still limit its large-scale application. Nevertheless, integrating algal and fungal biosorption with other remediation technologies offers a promising pathway toward sustainable heavy metal management.

5. Nanotechnology and nano bioremediation

Nanotechnology has emerged as a revolutionary strategy for heavy metal remediation, offering innovative, efficient, and versatile solutions. The unique physicochemical properties of nanomaterials including high surface area, reactivity, tunable surface chemistry, and nanoscale size enable them to adsorb, transform, or immobilize toxic metals in soil and water. Beyond direct remediation, nanoparticles can also be integrated with plants and microbes to enhance phytoremediation and bioremediation efficiency. However, their environmental risks, cost, and scalability remain critical challenges (Fig 3).

5.1. Nanoparticle assisted phytoremediation

Nanoparticles (NPs) can significantly boost phytoremediation efficiency by improving plant growth, stress tolerance, and metal uptake. For example, titanium dioxide (TiO_2) NPs enhanced cadmium elimination in soybean plants by promoting biomass production and metal translocation (Nedjimi, 2021). Iron oxide (Fe_3O_4) and TiO_2 NPs have also been shown to improve photosynthesis, chlorophyll content, and antioxidant defenses under heavy metal stress, making phytoextraction more efficient.

7.2 Advanced Phytoremediation Approaches

Advanced phytoremediation approaches refer to the innovative and enhanced plant-based techniques used to remove, degrade, or stabilize environmental pollutants such as heavy metals, pesticides, and organic contaminants. These approaches combine traditional phytoremediation with modern tools like nanotechnology, genetic engineering, microbial-assisted remediation, and plant–microbe interactions to increase efficiency and specificity.

5.1.1. Phytohormone-Assisted Phytoremediation

Auxins, gibberellins, and abscisic acid (ABA) are examples of phytohormones that can be applied exogenously to enhance plant growth and heavy metal tolerance. These hormones improve antioxidant defences, regulate physiological reactions, and promote metal absorption. Gibberellic acid (GA_3) has been shown in studies to dramatically boost biomass and phytoremediation effectiveness in plants such as Solanum nigrum (X. Cao et al., 2025).

5.1.2. Genetically Engineered Phytoremediation

Plants with improved heavy metal tolerance and absorption capabilities have been made possible by developments in genetic engineering, especially the application of CRISPR-Cas9 technology. Researchers have produced transgenic plants with enhanced phytoremediation capability by altering particular genes. For example, rice's metallochaperone genes have been edited using CRISPR-Cas9, which has decreased the buildup of cadmium (Khan et al., 2023)

5.2. Types of nanomaterials for heavy metal remediation

Nanomaterials play a vital role in removing toxic heavy metals from contaminated soil and water due to their high surface area, reactivity, and adsorption capacity (Table 3).

7.3.1. Carbon-Based Nanomaterials

Graphene oxide (GO) and carbon nanotubes (CNTs) are two examples of carbon-based nanomaterials that have shown remarkable heavy metal adsorption capabilities. Functionalization with carboxyl, hydroxyl, and amine groups improves their binding affinity and selectivity for particular metal ions. These materials are good in absorbing metals like lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}) because of their high surface area and chemical stability (Sadiq Hawezy et al., 2024).

7.3.2. Metal Oxide Nanoparticles

Because of their potent adsorption capacities and magnetic characteristics, metal oxide nanoparticles such as iron oxide (FeO_4), titanium dioxide (TiO_2), and zinc oxide (ZnO) are frequently employed in heavy metal remediation. For example, magnetic fields can be used to quickly separate iron oxide nanoparticles from aqueous solutions, making it easier to remove adsorbed metals. According to (Sadiq Hawezy et al., 2024), these nanoparticles efficiently target elements such as chromium (Cr^{6+}), lead (Pb^{2+}), and mercury (Hg^{2+}).

7.3.3. Metal-Organic Frameworks (MOFs)

MOFs are crystalline solids with porous architectures made of metal ions coordinated to organic ligands. They are appropriate for adsorbing a range of heavy metals due to their large surface area and adjustable pore diameters. Selectivity towards target metals can be improved by functionalizing MOFs with certain groups, and their structural adaptability enables customization to meet particular remediation requirements (Olawade et al., 2024).

7.3.4. Magnetic Nanoparticles

With the use of external magnetic fields, magnetic nanoparticles especially those based on iron oxides offer the benefit of simple separation from treated water. This characteristic makes the remediation procedure more effective by making it easier to retrieve and reuse the nanoparticles. Metals such as arsenic (As^{3+}), lead (Pb^{2+}), and cadmium (Cd^{2+}) have been successfully extracted from tainted water sources using these nanoparticles (Sibiya et al., 2024).

7.3.5. Green synthesized Nanomaterials

Green synthesis methods use biological organisms including bacteria, fungi, and plant extracts to create nanomaterials in an environmentally responsible way. The special surface characteristics of these biosynthesized nanoparticles frequently improve their ability to interact with heavy metals. Plant-mediated production of gold and silver nanoparticles, for instance, has demonstrated potential in the adsorption of metals such as lead (Pb^{2+}) and mercury (Hg^{2+}) (Sibiya et al., 2024).

7.3.6. Photocatalytic Nanomaterials

When exposed to light, photocatalytic nanomaterials, such ZnO and TiO_2 nanoparticles, can decrease harmful metal ions and break down organic contaminants. Reactive oxygen species produced by these substances aid in the degradation of pollutants. In wastewater treatment, recent research has shown that photocatalytic methods are successful in converting hexavalent chromium (Cr^{6+}) to its less hazardous trivalent form (Cr^{3+}) (Sibiya et al., 2024).

7.3.7. Nanosponges

Three-dimensional, porous materials called nanosponges have the ability to absorb a variety of pollutants, including heavy metals. These materials, which are made up of polymers like cyclodextrins, have the ability to effectively remove metal ions from aqueous solutions by encasing them in their cavities. They are effective in cleanup applications because of their high porosity and surface area (Olawade et al., 2024).

7.3.8. Chalcogels

Metal chalcogenides make up the family of aerogels known as chalcogels, which are distinguished by their large surface area and adjustable porosity. Because of their high affinity for soft metal ions, these materials can effectively capture heavy metals such as lead (Pb^{2+}) and mercury (Hg^{2+}). Selective adsorption is made possible by their special structural characteristics, and they can be renewed for further usage (Sibiya et al., 2024).

7.3.9. Zero-Valent Iron Nanoparticles (nZVI)

ZVI particles work well as reductants, changing harmful metal ions into less hazardous or soluble forms. For example, nZVI can help remove hexavalent chromium (Cr^{6+}) from water by reducing it to trivalent chromium (Cr^{3+}). They are appropriate for in-situ treatment of contaminated soils and groundwater due to their high reactivity and small size (Olawade et al., 2024).

The integration of nanotechnology with biological systems provides synergistic benefits: improved uptake by plants, enhanced microbial biosorption, and faster pollutant transformation. However, concerns remain regarding nanoparticle toxicity to soil microbiota, persistence in ecosystems, and potential secondary contamination. Additionally, large-scale application faces challenges such as high production costs, limited field trials, and lack of uniform safety regulations. Thus, the future of nano-bioremediation depends on green synthesis, biodegradable nanomaterials, and risk assessment frameworks to ensure sustainable and eco-safe applications.

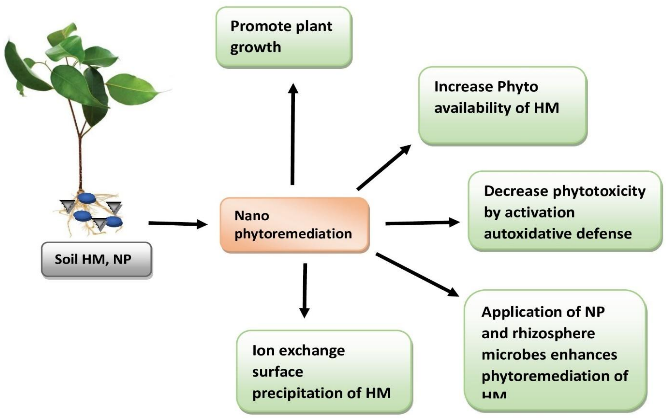

Figure 3: Benefits of using nanoparticles for heavy metal remediation

6. Merging and Hybrid Approaches

Hybrid remediation combines complementary technologies to overcome individual limitations (slow rates, site heterogeneity, high cost, secondary wastes) and to achieve higher removal efficiency, selectivity, or recovery of metals. Below we summarize major hybrid approaches, give concrete recent performance and outline monitoring needs.

6.1. Electrokinetic + chelate or conditioner

Adding chelating agents (EDTA, citric acid) or pH control strongly improves metal mobilization and collection. Laboratory and pilot work report substantial gains:

EDTA-assisted EKR increased Pb/Zn migration and extraction efficiencies to the range of ~50–>70% in multiple bench studies, versus much lower removal without chelate. For example, electrokinetic trials on Zn-polluted clay achieved measurable Zn extraction using optimized electrolyte management and novel chamber designs(Wang et al., 2023).

Reviews and techno-economic analyses confirm EKR's effectiveness in fine-grained soils but note pH gradients, energy use, and secondary leachate as constraints.

6.2. Electrobioremediation

Combining EKR with bioremediation (electro-bio) enhances biotransformation by improving nutrient/oxygen/mobility of electron acceptors and donors.

Field-scale and mesocosm evidence show improved degradation/immobilization of organics and enhanced heavy metal mobilization for downstream capture when EKR is coupled with biological barriers or in-situ biostimulation. Pilot studies demonstrate the promise but emphasize the need to manage electrode pH fronts and microbial sensitivity to electric fields.

6.3. Nano-assisted bio and phyto systems

Nanoparticles (nZVI, iron oxides, TiO_2, engineered carbon materials) can increase microbial metal-reduction rates or plant uptake and tolerance. Recent controlled studies show nano-amendments (magnetic Fe-oxides, TiO_2) can raise phytoextraction rates and plant biomass under metal stress, increasing extractable metal removed per growing season by tens of percent in greenhouse trials. However, field validation remains limited and ecotoxicological risk assessment is required.

6.4. Soil treatment trains

Ex-situ soil washing (chelator or citric acid) followed by biological stabilization (composting, phytostabilization) and final immobilization (biochar addition or mineral amendments) produce a reusable soil with much reduced leachability.

Citric-acid washing reported >80% removal for Pb/Zn in heavily contaminated soils in controlled trials (Li et al., 2024; related pilot reports). Hybrid electrokinetic-washing systems are also being trialed to improve efficiency in low-permeability soils.

Table 3: Methods of heavy metal remediation

Physiochemical					
Method	**Principle**	**Common Metals Removed**	**Advantages**	**Limitations**	**References**
Chemical Precipitation	Converts dissolved metal ions into insoluble compounds (e.g., hydroxides, sulphides)	Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}	Simple and cost-effective	Produces large volumes of sludge	(Jose & Dharsana, 2022)
Adsorption	Metal ions bind to surface of adsorbents (e.g., activated carbon, biochar)	Cr^{6+}, Pb^{2+}, Cu^{2+}, Zn^{2+}, As^{3+}	Effective at trace concentrations, renewable adsorbents	Adsorbent saturation, disposal issues	(Jose & Dharsana, 2022)
Membrane Filtration	Separation via pressure-driven membranes (e.g., reverse osmosis, nanofiltration)	Ni^{2+}, Pb^{2+}, Cr^{6+}, Cd^{2+}	High purity water, no chemical additives	High cost, membrane fouling	(Hubbe et al., 2011)
Electrochemical Treatment	Uses electric current for reduction/oxidation or electrodeposition	Cr^{6+}, Cu^{2+}, Zn^{2+}, Ni^{2+}	Enables metal recovery, environmentally friendly	High energy demand, sensitive to water matrix	(Afzal & Mahreen, 2024)
Coagulation-Flocculation	Aggregation of metal particles using coagulants like alum or Fe salts	As^{3+}, Pb^{2+}, Cr^{3+}, Cd^{2+}	Widely used, enhances sedimentation	Sludge production, pH-dependent	(Jose & Dharsana, 2022)
Solvent Extraction	Transfers metals from aqueous to organic phase using extractants	Cu^{2+}, Ni^{2+}, Zn^{2+}, U^{6+}	High selectivity, allows recovery	Solvent toxicity, complex operation	(Hubbe et al., 2011)
Cementation	Metal ion reduced and precipitated by more electropositive metal (e.g., Zn)	Cu^{2+}, Pb^{2+}, Cd^{2+}	Simple, good for metal recovery	Metal sludge generation	(Jose & Dharsana, 2022)
Electrodialysis	Uses ion-exchange membranes under electric field for ion separation	Pb^{2+}, Cd^{2+}, Ni^{2+}, Cr^{6+}	Suitable for dilute wastewater	Expensive membranes, limited by fouling	(Afzal & Mahreen, 2024)
Phytoremediation					

Technique	**Description**	**Heavy Metals Treated**	**Example Plants**	**Reference**
Phytoextraction	Uptake and accumulation of metals in plant shoots	Pb, Cd, Zn, Ni, Cu	*Brassica juncea, Helianthus annuus*	(Ansari et al., 2014)
Phytostabilization	Immobilization of metals in soil through root absorption or precipitation	Pb, Cr, As, Cd	*Vetiveria zizanioides, Populus spp.*	(Mensah, 2025)
Phytovolatilization	Volatilization of metals (e.g., mercury, selenium) through transpiration	Hg, Se	*Brassica juncea, Arabidopsis thaliana*	(Shaw, 2024)
Rhizofiltration	Use of plant roots (aquatic or hydroponic) to absorb metals from water	Pb, Cd, Cu, Ni, Zn	*Hydrilla verticillata, Lemna minor*	(Shaw, 2024)
Phytodegradation	Breakdown of organic contaminants (mainly), but also aids in metal complexes	Mainly organics, but also Cd, Pb	*Populus spp., Salix spp.*	(Mensah, 2025)
Hyperaccumulation	Natural accumulation of metals to high levels in plant tissues	Ni, Zn, Cd, Co	*Thlaspi caerulescens, Alyssum spp.*	(Ansari et al., 2014)
Bioremediation				

Bioremediation Strategy	Microorganism/Agent	Target Heavy Metal(s)	Mechanism	Reference
Bacterial Remediation	*Bacillus cereus* PSB^{2+} biochar	Pb, Cd	Bioaccumulation, immobilization	(Zhang et al.,2025)
Fungal Biosorption	*Schizophyllum commune*	Pb, Cd, Zn, Sr	Biosorption (live mycelia)	(Sarker et al.,2024b)
Algal Biosorption	*Ulva fasciata*	Cu	Surface adsorption	(Engwa et al., 2019)
Algal Biosorption	*Dunaliella salina*	Cu, Pb, Cd	Bioaccumulation, adsorption	(Zhang et al.,2025)
Mycorrhizal-Assisted Phytoremediation	AMF+*Brassica juncea*	As, Cd	Enhanced uptake, stress tolerance	(Sarker et al., 2023b)
Nano-remediation				

Nanomaterial Type	Target Heavy Metals	Mechanism of Remediation	Advantages	Reference
Nano Zero-Valent Iron (nZVI)	Pb, Cr (VI), As, Ni	Reduction, adsorption, precipitation	High reactivity, large surface area	Li et al., 2006; Fu et al., 2014
Carbon Nanotubes (CNTs)	Cd, Pb, Hg, Cr	Adsorption via surface functional groups	High adsorption capacity, customizable surface	(Guo & Ge, 2020)
Magnetic Nanoparticles (Fe_3O_4)	Cd, Pb, Cu, Zn	Magnetic separation, adsorption	Easy recovery with magnet, reusable	(Ghosh, 2021)
Titanium Dioxide Nanoparticles (TiO_2)	Cr (VI), Pb, As	Photocatalysis, adsorption	Stable, photocatalytic under UV light	(Ghosh, 2021)
Silica-Based Nanoparticles	Pb, Hg, Cd	Surface functionalization for adsorption	Tunable surface chemistry, high stability	(Ghosh, 2021)
Silver Nanoparticles (AgNPs)	Hg, Pb, Cd	Antimicrobial and adsorptive actions	Dual role: antibacterial + metal binding	(Ramalingum, 2022)
Graphene Oxide (GO)	Pb, Cd, Cr	Electrostatic adsorption, π–π interactions	Large surface area, high adsorption	(Ramalingum, 2022)

8.5 Role of Biosensors and Real-Time Monitoring

Robust hybrid strategies require real-time sensing to (i) detect contaminant plumes, (ii) optimize reagent doses/electric current, and (iii) prevent secondary pollution. The last 2–3 years have seen rapid advances in nanomaterial-enabled and electrochemical biosensors for heavy metals. Nanomaterial-modified electrodes (graphene, metal-nanoparticle composites) deliver low detection limits (ppb to ppt ranges), fast response, and multiplexing. Reviews and experimental studies (2023–2024) highlight portable electrochemical sensors with detection limits in the low µg/L or even ng/L range for Pb, Cd, Hg and As suitable for process control and environmental surveillance. Integrating online sensors (electrochemical probes, optical sensors) into hybrid trains supports automatic feedback for pH, redox and metal concentration control critical for electrokinetic and electrochemical steps.

9. Challenges and Limitations on heavy metal remediation

Effective cleanup techniques are required because heavy metal contamination presents serious health and environmental problems. Despite improvements, a number of restrictions limit the effectiveness and scalability of the repair methods used today.

9.1. Limited Bioavailability in Bioremediation

Heavy metals are immobilized or transformed by microorganisms and plants in bioremediation. However, elements including soil pH, organic matter content, and metal speciation frequently limit the bioavailability of metals. These circumstances may restrict microbial activity and lower the effectiveness of remediation (Qasem et al., 2021). Limited bioavailability of heavy metals in contaminated environments poses a significant challenge to effective bioremediation. In soils, heavy metals often bind tightly to organic matter, clay particles, and other soil constituents, rendering them less accessible to microorganisms responsible for bioremediation. This strong adsorption reduces the mobility and availability of metals, thereby limiting their uptake and subsequent detoxification by microbial communities. Additionally, environmental factors such as pH, redox potential, and the presence of competing ions can further influence the speciation and solubility of heavy metals, affecting their bioavailability. For instance, in acidic conditions, certain metals may become more soluble and bioavailable, while in alkaline conditions, they may precipitate and become less accessible to microbes (Olaniran et al., 2013).

The physical and chemical properties of the contaminated site also play a crucial role in determining heavy metal bioavailability. Soil texture, porosity, and moisture content can influence the diffusion and transport of metals, affecting their interaction with microbial populations. Moreover, the presence of co-contaminants, such as organic pollutants, can lead to complex interactions that alter the bioavailability of heavy metals. These co-contaminants may compete for binding sites or affect microbial metabolism, thereby impacting the efficiency of bioremediation processes. Furthermore, the aging of contaminants, where metals become increasingly sequestered over time, can reduce their bioavailability and pose additional challenges to remediation efforts (Kondakindi et al., 2024).

9.2. Environmental Constraints on Phytoremediation

Environmental variables like soil depth, pollutant content, and climate have an impact on phytoremediation. High concentrations of heavy metals can be harmful to plants, and the clean-up process is typically sluggish, taking a long time to produce noticeable results (Qasem et al., 2021). Moreover, large amounts of sludge are frequently produced by conventional techniques such chemical precipitation and coagulation/flocculation, which provide disposal issues and possible secondary environmental hazards. The operational expenses and environmental impact of restoration activities are increased by managing this sludge (Dagdag et al., 2023).

9.3. High Costs and scale up of Advanced Technologies

Although advanced remediation technologies, such as electrochemical treatments and nanotechnology, promise increased efficiency, they are frequently prohibitively expensive. Their broad acceptance is constrained by the expensive initial investment and ongoing costs, particularly in poor nations

(Dagdag et al.,2023). While many remedial strategies show promise in the lab, scaling them up for field use presents difficulties. Large-scale adoption may be hampered by elements such site heterogeneity, fluctuating pollutant concentrations, and logistical challenges (Dagdag et al.,2023).

9.4. Nanoparticle Stability and Environmental Impact

Although the use of nanomaterials in heavy metal cleanup has showed promise, questions remain regarding their stability, possible toxicity, and effects on the environment. More research is required to address problems such nanoparticle agglomeration and unintentional interactions with non-target organisms (Qasem et al., 2021).

9.5. Regulatory and Public Acceptance Issues

Public opposition and regulatory barriers may prevent the use of some remediation technologies, particularly those that use innovative nanomaterials or genetically modified organisms. For implementation to be successful, ensuring adherence to environmental standards and building public trust are crucial (Dagdag et al.,2023). Given the limitations of individual remediation methods, there is a growing recognition of the need for integrated approaches that combine multiple techniques. Such hybrid strategies can leverage the strengths of different methods to achieve more effective and sustainable remediation outcomes (Qasem et al.,2021).

10. Future prospects and research directions

10.1. Interdisciplinary perspectives for Heavy Metal Remediation

Heavy metal pollution presents multifaceted environmental, health, and socio-economic challenges that necessitate interdisciplinary approaches for effective remediation. Traditional single-discipline methods such as chemical treatment or physical removal often fail to address the complex interactions between metals and environmental matrices. By integrating disciplines like environmental engineering, microbiology, soil science, materials science, and public policy, remediation strategies can be optimized to enhance efficiency, sustainability, and real-world applicability (Karnwal et al., 2024).

10.2. Contributions from microbiology and biotechnology

Microbiologists contribute by exploring bioremediation mechanisms, such as microbial reduction, biosorption, and bioaccumulation. Certain bacteria, fungi, and algae can transform or sequester heavy metals into less toxic forms. Genetic engineering and synthetic biology further expand this potential by enabling the development of customized microbial strains tailored for specific contaminants. Interdisciplinary collaboration between microbiologists and chemical engineers is crucial to scale up these bio-based technologies from lab to field applications (Aziz et al., 2023).

10.3. Advances from materials science and nanotechnology

Materials scientists bring innovative tools to heavy metal remediation through the development of advanced sorbents, nanomaterials, and membrane systems. Engineered nanomaterials, such as zero-valent iron (nZVI) or carbon nanotubes, offer high surface area and reactivity for contaminant adsorption or reduction. However, collaboration with toxicologists and environmental risk assessors is essential to evaluate the long-term impacts of these materials on ecosystems and human health. An interdisciplinary feedback loop is needed to ensure technological innovation aligns with ecological safety (Machado et al., 2024).

10.4. Integration with Civil and Environmental Engineering

Engineers provide the infrastructure and system-level design expertise necessary for implementing remediation technologies at scale. This includes designing bioreactors, permeable reactive barriers, and electrokinetic systems. By working with geologists, biologists, and chemists, engineers can adapt technologies to local site conditions, enhance performance under variable contaminant loads, and ensure structural and hydraulic compatibility with ecosystems. This integration also aids in optimizing energy and resource efficiency (Karnwal et al., 2024).

10.5. Toward a Holistic Remediation Framework

Ultimately, heavy metal remediation requires a systems-thinking approach that integrates insights across disciplines. A holistic remediation framework must account for contaminant behaviour, ecological risks, technical feasibility, economic constraints, and societal impacts. Interdisciplinary collaboration enhances innovation, increases remediation success rates, and ensures that strategies are context-sensitive and sustainable. Future progress depends on continued knowledge exchange across scientific, technical, and societal boundaries, supported by cross-sectoral education, research funding, and collaborative networks (Bhattacharjee et al., 2023).

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II.CONCLUSION

Heavy metal contamination remains a persistent environmental challenge due to the non-degradable nature and high toxicity of metals such as lead, cadmium, arsenic, and mercury. While traditional remediation methods have proven effective in certain contexts, they are often costly, energy-intensive, and may lead to secondary pollution. In contrast, recent interdisciplinary approaches ranging from bioremediation and phytoremediation to nanotechnology and electrochemical treatments offer promising, sustainable, and more environmentally friendly alternatives. Integrating biological systems with engineered materials, such as nanoparticles and biochar, has enhanced metal removal efficiencies, especially in complex, mixed-contaminant settings. Moreover, the application of artificial intelligence, machine learning, and advanced sensing technologies has improved site assessment, real-time monitoring, and decision-making in remediation processes. Despite these advances, challenges remain in scaling up laboratory successes to field applications, addressing variability in environmental conditions, and ensuring long-term stability of treated sites. Future efforts must focus on developing cost-effective, multifunctional, and adaptable remediation strategies, alongside robust regulatory frameworks and stakeholder engagement. A multidisciplinary, systems-based approach is essential to address the evolving complexities of heavy metal pollution and to ensure the health of ecosystems and human communities.

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