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Exploring bioremediation strategies for heavy metals and POPs pollution: the role of microbes, plants, and nanotechnology

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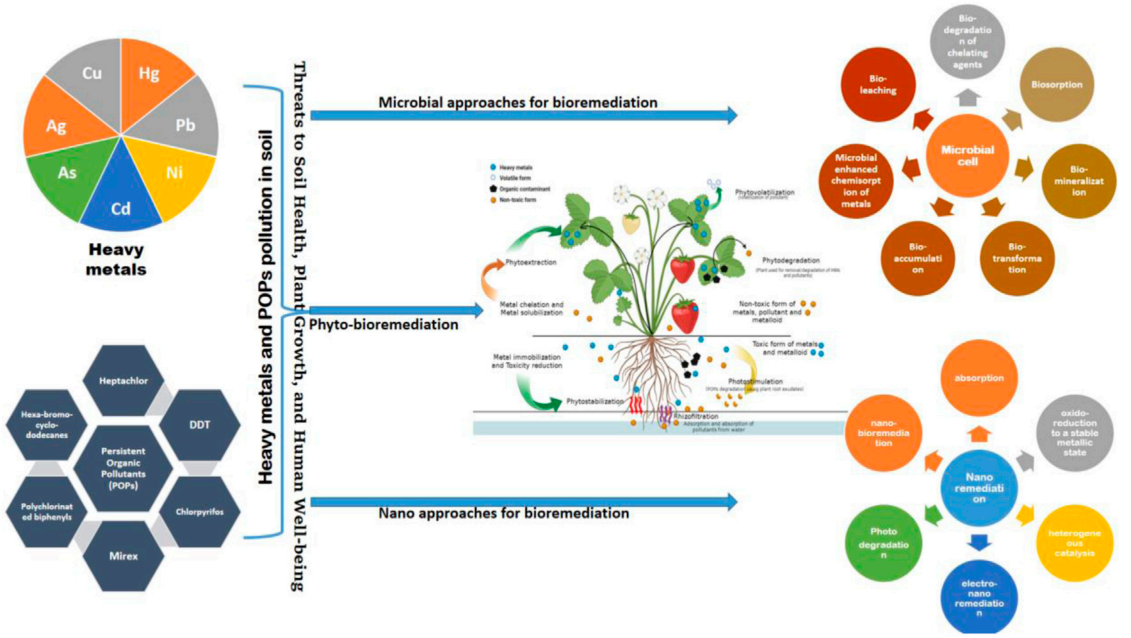
Heavy metal and Persistent Organic Pollutants (POPs) pollution stemming from industrialization, intensive agriculture, and other human activities pose significant environmental and health threats. These contaminants persist in the air, soil, and water, particularly in industrialized nations, adversely affecting human health and ecosystems. While physical and chemical methods exist for detoxifying contaminated soil, they often have drawbacks such as high cost and technical complexity. Bioremediation, utilizing plants and microbes, offers a promising solution. Certain microorganisms like *Streptomyces*, *Aspergillus* and plant species such as *Hibiscus* and *Helianthus* show high metal adsorption capacities, making them suitable for bioremediation. However, plants' slow growth and limited remediation efficiency have been challenges. Recent advancements involve leveraging plant-associated microbes to enhance heavy metal removal. Additionally, nanotechnology, particularly nano-bioremediation, shows promise in efficiently removing contaminants from polluted environments by combining nanoparticles with bioremediation techniques. This review underscores bioremediation methods for heavy metals using plants and microbes, focusing on the role of Plant Growth Promoting Rhizobacteria (PGPR) in promoting phytoremediation. It also explores the implementation of nanotechnologies for eliminating metals from polluted soil, emphasizing the significance of soil microbiomes, nanoparticles, and contaminant interactions in developing effective nano-remediation strategies for optimizing agriculture in contaminated fields.

KEYWORDS

heavy metals, nano-bioremediation, PGPR, phytoremediation, pollution



GRAPHICAL ABSTRACT

1 Introduction

Plenty of biochemical interactions in plants and animals require heavy metals (HMs), making them essential to manufacturing. When present in high concentrations, these heavy metals (HMs)/pollutants can disrupt essential metabolic activities in living beings, which makes them severely harmful pollutants in ecologically vulnerable regions (Ding et al., 2022; Mustapha and Halimoon, 2022). Natural disasters like volcanic eruptions and human activity have also contributed to this pollution of the environment. Municipal garbage, agricultural waste, and industrial activities like mining and electroplating all contain high amounts of heavy metals like lead (Pb), mercury (Hg), zinc (Zn), copper (Cu), cadmium (Cd), nickel (Ni), cobalt (Co), and chromium (Cr) (Hananingtyas et al., 2022; Mitra et al., 2022). Even though heavy metals, unlike organic materials, do not naturally degrade, the toxicity of heavy metals can be reduced through several different mechanisms, one of which is bioremediation (Kumar et al., 2022). Bioremediation has emerged as the most popular and effective solution for treating metal-polluted locations. Bioremediation refers to employing microorganisms to break down harmful contaminants in soil or water into less hazardous byproducts (Riyazuddin et al., 2022; Vanisree et al., 2022; Zaynab et al., 2022).

Plants (phytoremediation) (Gavrilescu, 2022) and microorganisms (rhizo-remediation) (Husain et al., 2022) working together in the root zone are crucial components of biological remediation (Sharma et al., 2021; Cepoi et al., 2022; Pande et al., 2022). Both *in-situ* and *ex-situ* technologies may be employed, depending on the specificity of the contaminated area. *In-situ* technologies are used for passive, non-invasive clean-up, while *ex-situ* technologies are used for cost-effective and safe clean-up (Sharma et al., 2021). In *In-situ* biodegradation, naturally occurring microorganisms are prompted to break down organic pollutants by supplying nutrients and oxygen via the uniform circulation of aqueous solutions extracted from soil containing hazardous heavy metals (Reddy and Parupudi, 1997). Groundwater and soil both respond well to *in-situ* bioremediation. Several bioremediation techniques, such as land farming and composting, are employed in *ex-situ* bioremediation (Concetta et al., 2013; Bandaru et al., 2020; Tufail et al., 2022), which entails the removal of contaminated soil from its original location. Table 1 outlines various *in-situ* and *ex-situ* bioremediation techniques employed for the effective removal of heavy metals and persistent organic pollutants (POPs), showcasing diverse methods essential in addressing environmental contamination challenges.

Various variables and factors in bioremediation, including electron acceptors, soil type, nutrients, oxygen presence, temperature, and pH, play an important role (Zhai et al., 2018). They can thrive in various temperatures and humidity levels, and microbes are extensively versatile for these environmental conditions. The versatility of microbes and other biological agents makes them capable of removing or remediating heavy metal pollutants in the environment. However, a deeper understanding of microbial ecology and bioremediation methods is essential to fully harness their potential. While enhancing bioremediation processes holds promise, the intricate interactions between microorganisms and heavy metal contamination can present challenges that may impede successful outcomes (Jabbar et al., 2022). Several methods, like protein engineering, whole-transcriptome profiling, metabolic engineering, and rhizo-remediation, can aid bioremediation by improving heavy metal binding for detoxification and xenobiotic chemical degradation. For example, genetically altered *Deinococcus geothermalis* expressed the mer-operon responsible for reducing Hg (II) after being inserted from *Escherichia coli*. This allowed the bacteria to reduce Hg (II) contamination (Brim et al., 2003). In addition, the

TABLE 1 *In-situ* and *Ex-situ* bioremediation techniques used for remediation of heavy metals and POPs (RoyChowdhury et al., 2018; DalCorso et al., 2019; Ravindra and Mor, 2019; Zwolak et al., 2019; Sharma et al., 2021; Cepoi et al., 2022; Pande et al., 2022).

Category	Technique	Description	Advantages	Disadvantages
In-Situ	Intrinsic bioremediation (natural attenuation)	Relies on naturally occurring microbes in the environment to degrade or immobilize metals.	Low cost, minimal disruption	Slow process, limited control over remediation rate
	Biostimulation	Enhances the growth and activity of indigenous microbes by adding nutrients (e.g., phosphorus, nitrogen) and oxygen.	Faster than intrinsic bioremediation, utilizes existing microbial populations	May require long-term maintenance, potential for unintended consequences
	Bioaugmentation	Introduces specially selected or engineered microbes to degrade or immobilize metals.	Faster and more targeted than biostimulation, applicable to sites with limited microbial populations	Expensive, risk of introducing invasive species
	Bioventing	Injects air into the contaminated soil to stimulate aerobic degradation and volatilization of some metals.	Effective for volatile metals, low energy consumption	Limited to specific metals, can spread volatile contaminants
	Biosparging	Injects air or other gases (e.g., methane) under pressure to enhance biodegradation and desorption of metals.	Faster and more targeted than bioventing, applicable to deeper contamination	Expensive, requires specialized equipment
	Phytoremediation	Uses metal-accumulating plants (hyperaccumulators) to extract and concentrate metals in their tissues.	Sustainable, aesthetically pleasing, applicable to large areas	Slow process, limited to bioavailable metals, requires proper plant management
Ex-Situ	Landfarming	Spreads contaminated soil over a prepared bed and stimulates microbial degradation through aeration and nutrient addition.	Relatively low cost, simple to operate	Requires large land area, potential for contaminant dispersal
	Composting	Mixes contaminated soil with organic bulking agents (e.g., manure, compost) to stimulate microbial degradation at high temperatures.	Effective for organic contaminants along with metals, creates useable compost product	Requires controlled conditions, potential for odor problems
	Bioreactors	Treats contaminated soil or water in a controlled environment with optimized conditions for microbial growth and degradation.	Highly efficient, fast treatment times	Expensive, complex to operate, requires transportation of contaminated material

gram-negative strain of *Ralstonia eutropha* underwent genetic engineering to express a mouse protein known as metallothionein on the cell surface. This rendered the strain resistant to heavy metals (Valls et al., 2000), and when added to Cadmium-contaminated soil, bacteria have shown a significant improvement in tobacco plant growth.

2 Heavy metal and POPS pollution: threats to soil health, plant growth, and human wellbeing

Polluting the environment is a major problem that has emerged as a major obstacle in the modern world. Heavy metals (about 65) pose the greatest environmental concern (Tufail et al., 2022). Metals with densities of more than 5 g/cm^3, known as “heavy metals,” are one of the world’s greatest dangers because of their widespread discharge into the environment (Roy et al., 2018; DalCorso et al., 2019; Ravindra and Mor, 2019; Zwolak et al., 2019). Various metals and metalloids like Cr, Cd, Cu, Pb, Zn, Ni, Hg, and As are discharged into the environment through sewage disposal, smelting, fertilizer applications, and industrial waste (Zwolak et al., 2019; Briffa et al., 2020; Sall et al., 2020). The available evidence indicates that a majority, exceeding 50%, of the total 10 million contaminated sites, equivalent to a land area exceeding 20 million hectares, are found to be contaminated with these substances (RoyChowdhury et al., 2018). A few HM concentrations available in soil are mentioned in Table 2.

Adsorption and desorption affect the availability of these metals in soil; these processes are, in turn affected by a wide range of soil parameters, including calcium carbonate, clay mineral, oxidation-reduction status, cation exchange, organic matter content, pH, Mn, and Fe oxide concentrations (Islam et al., 2017; Chen and Li, 2018; Sall et al., 2020). As a result of these factors, there is a range of heavy metal types and concentrations present in soils across diverse agro-climatic regions, each with its unique features and functions. The persistent, bioaccumulative, and inert nature of these metals in the soil-plant system contributes to complex issues related to their toxicity and long half-life (Wang Q. et al., 2018). Two significant issues are predicted to arise due to heavy metal accumulation in soils: i) a decrease in soil nutrition due to changes in the microbiota (Xie et al., 2016) and ii) a decrease in human health through plants and the food chain at and near contaminated locations (Zwolak et al., 2019). Besides causing damage to the soil, even low levels of metals can pose a significant risk to plant ecosystems due to their strong reactivity. Therefore, it is essential to swiftly comprehend how metals interact with the soil, microbiome, and plants’ systems to enhance crop yields in stress-prone soils. Moreover, affordable approaches to stress management should be devised. To prevent and eliminate metal pollution, stringent regulations must be enforced by the government or private entities, and detoxification procedures must be implemented to regulate the release of heavy metals from various sources (Baruah et al., 2019; Liu et al., 2019;

TABLE 2 Heavy metal minimum and maximum concentrations in soil documented worldwide (shorted as per Maximum concentration) (Saleem et al., 2022).

HMs	Available min. amount in soil (mg/kg)	Available max. amount in soil (mg/kg)
Pb	0.1	69,000
Zn	0.3	57,012
Mn	3.0	42,600
Cr	0.05	10,000
Ni	0	5,000
Hg	0	1,800
Cu	0.1	1,790
Cd	0	1,458
As	0.1	253

Dhaliwal, Singh, Taneja and Mandal, 2020). Removing heavy metals relies on or follows the regulatory standards set for soil heavy metal levels in numerous countries. These criteria can differ from one location to another and vary depending on the specific type of heavy metal in question. Also, such standards aid in developing more effective solutions for removing heavy metals from contaminated locations (Zhan et al., 2019). This review will briefly describe the toxic effects of a few metal pollutants on plants and microorganisms and how these effects can be mitigated. From a biological point of view, HMs can be broken down into two categories: necessary and harmful (Ullah et al., 2022). Micronutrients for plants and animals are called "essential metals" or "metalloids" and include elements like zinc, iron, nickel, and copper (Manoj et al., 2020). Toxic metals, classified as non-essential metals, pose severe risks even in minute quantities. Essential and non-essential metals exist in the environment as trace elements but accumulate in specific regions due to human activities like urbanization, industrialization, mining, agriculture, and smelting (Houri et al., 2020). The increased presence of Heavy Metals (HMs) in soil and the environment has garnered significant attention recently due to their widespread distribution, non-degradability, toxicity, accumulation potential, and persistence. Extensive evidence suggests that HMs adversely affect various soil properties, including physical, biological, and chemical characteristics. As a result of their prolonged presence in soil, HMs pose a significant threat to human health by enabling harmful metals to enter the food chain (Mao et al., 2019; Mitra et al., 2022). The widespread destruction of existing vegetation and the establishment of new vegetation exacerbate the adverse effects of HMs on soil surface, structure, fertility, nutrient cycles, and microbial communities. HMs indirectly impact soil enzymatic activities by altering soil microbial communities' size, composition, and activity (Ding et al., 2022). These chemicals interfere with essential metabolic functions like respiration, denitrification, and enzyme activity, leading to a reduction in the abundance of certain microbial populations. Furthermore, HMs negatively affect the development of cell membranes, hindering microbial cell division, transcription, and protein denaturation (Sobolev and Begonia, 2008; Abdu, Abdullahi and Abdulkadir, 2017). The composition of soil, encompassing factors such as texture, clay content, organic matter, pH, as well as the presence of inorganic anions, cations, and metal speciation, all play significant roles in shaping the impact of metals on soil biology. Similarly, heavy metal (HM) contamination significantly affects soil quality, fertility, plant health, and yield. HM contamination disrupts crucial biological processes including seed germination, water regulation, photosynthesis, electron transport, stomatal conductance, CO_2 assimilation, antioxidant defense mechanisms, solute balance, mineral uptake, and overall plant growth. Such disruptions can ultimately lead to plant mortality (Asati et al., 2016; Kalaivanan and Ganeshamurthy, 2016; Riyazuddin et al., 2022). Furthermore, HM toxicity impedes plant development and metabolism by causing oxidative damage to cellular structures and interfering with cytoplasmic enzymes (Kalaivanan and Ganeshamurthy, 2016). Reduced yields resulting from impaired plant growth contribute to escalating food insecurity. The extensive presence of HMs in soil poses risks to human health as these contaminants can leach into other environmental compartments such as groundwater, rivers, and crops (Briffa et al., 2020). Water exceeding allowable HM concentrations loses its quality, rendering it unsuitable for drinking and irrigation (Tan et al., 2016). HMs can enter the human body through various routes including ingestion, skin contact, food consumption, and water intake. Prolonged exposure to certain metals can have detrimental health effects, which may not manifest until years after exposure begins. The duration and intensity of exposure are critical determinants of toxicity levels (Jia et al., 2018; Mao et al., 2019; Briffa et al., 2020; Sall et al., 2020; Ding et al., 2022).

Persistent Organic Pollutants (POPs) are synthetic chemicals that endure in the environment, accumulate in organisms, and pose potential risks to human health and ecosystems (Adebusuyi et al., 2022; Tufail et al., 2022). Primarily human-made, these substances can traverse vast distances via air and water, impacting remote regions. The escalating apprehension over POPs' adverse impacts on human and plant health is evident (refer to Table 3), underscoring the global challenge of controlling and managing these pollutants.

POPs infiltrate the human body through consumption of contaminated food, water, and air. They are lipophilic and accumulate in fatty tissues, where they can stay for years, leading to chronic exposure (Devi, 2020). POPs are linked to a wide range of health problems, including cancer, reproductive disorders, immune system dysfunction, neurodevelopmental disorders, and endocrine disruption, as mentioned in Table 3. Exposure to POPs during pregnancy can also have adverse effects on fetal development, leading to congenital disabilities and developmental delays. One of the most well-known and widely studied POPs is polychlorinated biphenyls (PCBs) (Barker and Bryson, 2002; Grimm et al., 2020). These chemicals were previously utilized in various applications, such as electrical equipment, transformers, and hydraulic fluids, until their prohibition in the 1970s. Despite the ban, they persist in the environment, potentially accumulating in the food chain and posing risks to human exposure. PCBs have been associated with a spectrum of health issues, including cancer, immune system dysfunction, and developmental delays. Another category of Persistent Organic Pollutants (POPs) receiving recent attention is per- and polyfluoroalkyl substances (PFAs) (Wang et al., 2023). These compounds are used in various products, including non-stick

TABLE 3 A comprehensive overview of the effects of various heavy metals and persistent organic pollutants on both human health and plants, along with their common sources.

Substance	Effects on human health	Effects on plants	Common sources	References
Heavy Metals				
Lead (Pb)	- Neurological damage, developmental delays in children	- Inhibits photosynthesis, damages cell membranes	- Lead-based paints, contaminated soil, water	Li et al. (2022), Nawaz et al. (2021), Yu et al. (2022)
Cadmium (Cd)	- Kidney damage, bone disorders, lung cancer	- Inhibits root growth, disrupts mineral uptake	- Industrial emissions, phosphate fertilizers	Li et al. (2022), Nawaz et al. (2021), Yu et al. (2022)
Mercury (Hg)	- Neurological damage, birth defects, cardiovascular issues	- Inhibits chlorophyll synthesis, damages cell structure	- Coal combustion, mining, seafood contamination	Riseh et al. (2022), Verma and Sharma (2017), Wang, Wang, et al. (2023), Yang et al. (2023)
Arsenic (As)	- Skin lesions, cancer, cardiovascular diseases	- Inhibits growth, disrupts enzyme functions	- Natural occurrence, mining, agricultural pesticides	Al-Huqail and El-Bondkly (2022), Bhati et al. (2022), Eyankware and Obasi (2021)
Chromium (Cr)	- Respiratory issues, cancer, liver damage	- Inhibits seed germination, disrupts root growth	- Industrial discharges, leather tanning, mining	Al-Huqail and El-Bondkly (2022), Bhati et al. (2022), Eyankware and Obasi (2021)
Nickel (Ni)	- Skin allergies, lung cancer, kidney damage	- Inhibits enzyme activity, disrupts nutrient uptake	- Stainless steel production, batteries, metal plating	Wu et al. (2021), Xia et al. (2018)
Barium (Ba)	Renal and cardiac dysfunction, respiratory failure, pulmonary paralysis, and internal bleeding	- Photosynthesis inhibition	- Petroleum industry, medicinal applications, semiconductors production, steel industry	Dell'Anno et al. (2023), Ma et al. (2018)
Copper (Cu)	Increased levels cause liver cirrhosis and persistent anaemia in addition to the typical side effects of nausea, vomiting, and abdominal pain	- Negative effects on development and metabolic abnormalities	- Ore mining, bio-solids, fertilizers and pesticide manufacturing, smelting	Lin et al. (2003), Shabbir et al. (2020), Wu et al. (2018)
Zinc (Zn)	Electrolytic imbalance, nausea, fatigue, tiredness, stomach pains, diarrhea, muscle weakness, dehydration, and kidney failure	- Interferes with gene regulation	- Emission from tire industry, Food additives, High tension lines	Wyszkowska et al. (2013)
Persistent Organic Pollutants (POPs)				
Polychlorinated Biphenyls (PCBs)	- Cancer, reproductive issues, immune system disorders	- Inhibits photosynthesis, damages cell membranes	- Electrical equipment, insulation materials	Grimm et al. (2020), Xiang et al. (2020), Zhou et al. (2023)
Dioxins and Furans	- Cancer, hormone disruption, developmental issues	- Inhibits growth, disrupts reproductive functions	- Waste incineration, industrial processes, herbicides	Landa-faz et al. (2021)
Dichlorodiphenyltrichloroethane (DDT)	- Cancer, reproductive issues, developmental delays	- Inhibits photosynthesis, damages cell membranes	- Agricultural pesticides, insect repellents	Russo et al. (2019), Talukdar et al. (2020)
Polybrominated Diphenyl Ethers (PBDEs)	- Neurological damage, hormone disruption, thyroid disorders	- Inhibits growth, disrupts reproductive functions	- Flame retardants in electronics, furniture	Landa-faz et al. (2021)
Hexachlorobenzene (HCB)	- Liver damage, immune system disorders, cancer	- Inhibits photosynthesis, damages cell membranes	- Pesticides, industrial processes, incineration	Huang C. C. et al. (2021), Huang et al. (2020)
Endosulfan and derivates	Heart disease	Inhibitory effect on plant growth	Crops	Landa-faz et al. (2021)
Mirex	Malfunction of endocrine system, decreased body weight, hepatomegaly, induction of mixed function oxidases	Decreased dry biomass, reduced growth	Chemicals used for ant and mites removal	Thakur et al. (2023)
Chlorpyrifos	Cardiac system and central nervous system malfunction and disorders	Detrimental to plant growth and productivity.	Major chemicals used for eradiating insects	Huang et al. (2022), Shi et al. (2019), Ubaid ur Rahman et al. (2021)
Heptachlor	Disorders affecting the gastrointestinal and neurological systems.	Affect the shoot and root length of test plants	Major chemicals used for eradiating insects	Thakur et al. (2023), Thakur and Pathania (2019)

cookware, water-resistant clothing, and firefighting foam. PFAs exhibit high persistence in the environment and can accumulate in the human body, leading to adverse health effects similar to PCBs, including cancer, immune system dysfunction, and developmental delays (Saibu et al., 2023). Dioxins and furans, also categorized as POPs, are byproducts of industrial processes like waste incineration and paper bleaching. Exposure to these chemicals can result in adverse health effects, such as cancer, reproductive disorders, and immune system dysfunction.

Additionally, children exposed to dioxins and furans may experience developmental delays and cognitive impairment. In response to growing concerns regarding the detrimental impacts of POPs, the international community has initiated measures to control and manage these chemicals. The Stockholm Convention on Persistent Organic Pollutants, enforced in 2004, aims to eliminate or restrict the production and usage of POPs. Currently, the convention identifies 28 chemicals as POPs, including PCBs, dioxins, and furans (Yanitch et al., 2020; Saibu et al., 2023; Zhou et al., 2023).

3 Exploring the rhizosphere: importance and significance

The rhizosphere soil region is nutrient-rich, where plant roots stimulate chemical and biological processes (Barra et al., 2021). The plant and many macro- and microorganisms interact uniquely in the rhizosphere, such as viruses, bacteria, fungi, protozoa, algae, nematodes, and microarthropods. These interactions contribute to the plant's overall development (Ahkami et al., 2017; Abedinzadeh et al., 2019; Pathania et al., 2020; Adeyemi et al., 2021). Rhizospheric microorganisms that help plant growth can regulate plant development and yield. Rhizobacteria play a crucial role in the rhizosphere's functioning and significantly impact plant physiology and growth (Barra et al., 2021). Three distinct zones make up the rhizosphere (McGrath et al., 2001), The rhizosphere, the small zone of soil surrounding plant roots, is a dynamic environment characterized by intricate interactions between plants and microorganisms. Understanding the relevance of each rhizospheric zone is critical for comprehending the functions of microbial activity and plant interaction (Barra et al., 2021). The rhizosphere is divided into three zones: the endorhizosphere, the rhizoplane, and the ectorhizosphere. Each zone has a specific role in microbial activity and plant contact.

3.1 Endorhizosphere

The endorhizosphere refers to the plant root's interior tissues, including the cortex and vascular system. This zone is crucial for several reasons:

- Microbial Colonization: Beneficial microorganisms, such as endophytic bacteria and fungi, inhabit the endorhizosphere, providing improved nutrient uptake and growth promotion without harming the plant (Abedinzadeh et al., 2019).
- Nutrient Exchange: Close proximity to the plant's vascular system allows microbes to efficiently exchange nutrients, such as nitrogen from endophytic nitrogen-fixing bacteria.
- Disease Resistance: Endophytic microorganisms help resist diseases by producing antimicrobial compounds or inducing systemic resistance (Adeyemi et al., 2021).

3.2 Rhizoplane

The rhizoplane is the root surface where plant roots interact with the soil environment. This zone is significant for:

- Microbial Adhesion: Microorganisms, including bacteria, fungi, and archaea, attach to the root surface, often facilitated by root exudates (McGrath et al., 2001).
- Nutrient Utilization: Rhizoplane microbes utilize root exudates, which contain nutrients like sugars, amino acids, and organic acids, for their development and activity (Adeyemi et al., 2021).
- Biofilm Formation: Microbes on the rhizoplane often form biofilms, enhancing microbial viability, nutrient exchange, and defense against environmental stressors.

3.3 Ectorhizosphere

The ectorhizosphere is the outer zone of soil surrounding the root, influenced by root exudates but excluding the root surface itself. It plays a crucial role in:

- Microbial Diversity: This zone supports a diverse microbial community, including free-living bacteria, fungi, protozoa, and nematodes, often with greater diversity than bulk soil (Zhou et al., 2023).
- Nutrient Cycling: Ectorhizosphere microbes contribute to nutrient cycling processes like nitrogen fixation, phosphorus solubilization, and organic matter decomposition, enhancing nutrient availability for plants (Pathania et al., 2020).
- Plant-Microbe Interactions: Beneficial microorganisms, such as mycorrhizal fungi and rhizobia, form symbiotic relationships with plant roots, promoting nutrient uptake and plant growth.
- Soil Structure: Microbial activity in the ectorhizosphere improves soil aggregation and structure, enhancing soil porosity and water retention.

Understanding each rhizospheric zone's importance is crucial for optimizing agricultural practices and promoting sustainable farming. By managing rhizospheric microbial communities through strategies like crop rotation, cover cropping, and using biofertilizers and biopesticides, farmers can enhance plant health, improve nutrient uptake, and reduce reliance on chemical inputs. Additionally, insights into rhizospheric interactions can guide ecological restoration and natural ecosystem management, contributing to biodiversity conservation and soil health.

TABLE 4 Plant Growth-Promoting Rhizobacteria (PGPR) and their mechanisms in bioremediation (Abbasi et al., 2013; Gururani et al., 2013; Barnawal et al., 2017; Becze et al., 2021; Gulzar and Mazumder, 2022; Kuan et al., 2016; Sapre et al., 2021; Shabaan et al., 2021; Thokchom et al., 2017; Ullah and Bano, 2015).

Mechanism	Description	Example PGPR Genera
Biodegradation of Pollutants	PGPR can directly degrade organic contaminants like petroleum hydrocarbons, pesticides, and explosives. They break down complex molecules into simpler forms for easier utilization.	Pseudomonas, Rhodococcus, Burkholderia
Enhanced Plant Uptake and Metabolism of Pollutants	PGPR can stimulate plant growth, leading to increased root surface area and pollutant absorption. They may also facilitate the breakdown of pollutants within the plant tissues.	Azospirillum, Rhizobium, Enterobacter
Rhizodegradation	PGPR secrete enzymes that degrade pollutants within the rhizosphere (root zone). This localized degradation prevents wider contamination and promotes the breakdown of complex molecules.	Serratia, Bacillus, Alcaligenes
Bioimmobilization	PGPR accumulate and immobilize pollutants within their cells, preventing them from spreading further. This reduces the bioavailability of contaminants and their harmful effects.	Pseudomonas, Arthrobacter, Ochrobactrum
Biovolatilization	Certain PGPR can convert pollutants into volatile forms, allowing them to evaporate and disperse harmlessly into the atmosphere. This can be effective for some organic contaminants.	Pseudomonas, Bacillus, Variovorax
Phytostimulation	PGPR promote plant growth and root development, which enhances the overall soil health and microbial activity. This improved soil microbiome fosters biodegradation of various pollutants.	Azospirillum, Arthrobacter, Bacillus
Biocontrol of Pathogens	PGPR can compete with and suppress soilborne plant pathogens. This reduces competition for resources and protects plant health, indirectly aiding bioremediation efforts.	Pseudomonas, Bacillus, Actinomycetes

3.4 Plant growth-promoting rhizobacteria: key players in plant development and soil fertility

Rhizobacteria that promote plant development in addition to the plant's natural defense mechanisms are referred to as plant growth-promoting rhizobacteria (PGPRs). Plant-PGPR interaction is crucial to plant development and soil fertility in the rhizosphere (Barnawal et al., 2017; Manoj et al., 2020; Zafar-ul-Hye et al., 2020; Shabaan et al., 2021). PGPRs are a class of rhizospheric bacteria that affect plant development and yield in economically important crops. *Streptomyces*, *Serratia*, *Xanthomonas*, *Pseudomonas*, *Enterobacter*, *Klebsiella*, *Bacillus*, *Burkholderia*, *Azospirillum*, *Azotobacter*, and *Arthrobacter* are a few of the genera found in PGPRs (Abbasi et al., 2013; Gururani et al., 2013). The following is an overview of the roles performed by PGPRs (Barnawal et al., 2017; Becze et al., 2021; Gulzar and Mazumder, 2022; Kuan et al., 2016; Sapre et al., 2021; Shabaan et al., 2021; Thokchom et al., 2017; Ullah and Bano, 2015):

1. The process of plant nutrient uptake
2. Plant development through the synthesis and production of amino acids and other compounds that stimulate plant development
3. Improved microorganisms required for plant development
4. Phytohormone production (auxins, gibberellins, and cytokinins)
5. Nutrient solubilization (Zn, PO_4, Fe^{2+}, and Fe^{3+})
6. Reduced metal toxicity
7. Stimulating metabolic processes in roots using bacteria's other process, i.e., biological nitrogen fixing
8. Enhanced plant disease resistance

Despite their small size, bacteria are the most prevalent organism in the rhizosphere. *Pseudomonas*, a Gram-negative bacterium genus, is a particularly efficient root colonizer with 10^8–10^{12} bacterial cells per gram of rhizosphere soil. In addition to their usefulness as bio-fertilizers, bioenergy generation, and bioremediation (Table 4), PGPRs are efficient plant root colonizers because of the abovementioned characteristics. The primary reason for the efficient colonization of plant roots by PGPRs is their motility and chemotaxis, which contribute to their positive effects (Belimov et al., 2020).

Nitrogen (N) is a critical nutrient in agricultural production, playing a pivotal role in crop yield, particularly for grains such as rice, maize, potatoes, and wheat (Kuan et al., 2016; Rizvi and Khan, 2018). The application of nitrogen fertilizers significantly enhances the productivity of these crops. However, nitrogen utilization efficiency is often compromised due to ammonia volatilization, nitrogen leaching, and denitrification (Kumar and Saxena, 2019). Biological nitrogen fixation (BNF) presents a viable alternative to reduce chemical fertilizers applications. BNF responsible for the majority of Earth's fixed nitrogen (~60%). Given the increasing global food demand, optimizing BNF in agriculture is essential (Wickramasinghe et al., 2021). The nitrogen-fixing bacteria *Kosakonia radicincitans* was isolated from *Pennisetum giganteum* by Jia et al. (2020). They demonstrated that by combining this bacterium with chemical fertilisers, the total amount of fertiliser needed could be lowered by 25%. This integration significantly improved several plant characteristics, including alkali hydrolyzed nitrogen content, vitamin C and soluble protein amount, chlorophyll amount, soluble sugar amount, and available phosphorus amount. Similarly, Song et al. (2021) conducted a 2-year study assessing the replacement of urea with the cyanobacterium *Anabaena azotica* in rice cultivation. The investigation determined that using cyanobacteria in place of half of the urea had no negative effect on rice production.

Phosphorus (P) is another crucial macronutrient for plant growth and metabolic processes (Khan et al., 2009). Metal cations like calcium, iron, and aluminium quickly immobilise phosphorus in soils or bind it to mineral surfaces, reducing the amount of phosphorus that plants may access. Phosphates play vital roles in legume biological nitrogen fixation, crop maturation, flower and seed production, root and stem development, photosynthesis, and plant disease resistance (Nath et al., 2017; Wan et al., 2020). Therefore, phosphates are indispensable for agricultural productivity. In their 2020 study, Wan et al. tested eight different bacterial taxa for their ability to solubilize phosphorus. They found that *Acinetobacter* was the most effective, leading to improved soil fertility and quality. In addition, Liu et al. (2020) showed that specific bacteria release organic acids with low molecular weight, which dissolve inorganic phosphorus, alter soil characteristics, and indirectly affect the microbes in the rhizosphere. Iron, in its most common forms as Fe^{3+} and Fe^{2+}, is a mineral that plants cannot function without (Belimov et al., 2020). Plants are unable to absorb iron from soils because the element is typically present in insoluble forms such hydroxides and oxyhydroxides, especially under aerobic circumstances. Iron is insoluble in water, but bacteria in the rhizosphere manufacture siderophores—small molecules with a strong affinity for iron—those plants can use (Da Silva et al., 2023). *Rhizobium, Enterobacter*, *Pseudomonas*, *Azotobacter*, *Bacillus*, and *Azotobacter* are among the plant growth-promoting rhizobacteria (PGPR) that create siderophores (Din et al., 2019). In situations where there is a shortage of iron, these molecules—which are present both within and outside of cells—help dissolve organic compounds and minerals containing iron. They can also form stable complexes with heavy metals and radioactive particles (Din et al., 2019). Soil heavy metal contamination can be reduced and plant growth can be enhanced by PGPR strains that produce siderophore. Phytohormones including gibberellin, cytokinin, and indole-3-acetic acid (IAA) are produced by plant growth-promoting bacteria (PGPB), which impact the hormone balance in plants (Chen et al., 2017). The amount of auxin available to the plant and its sensitivity to the hormone determine how IAA influences root growth. While low concentrations of bacterial auxin stimulate growth, high concentrations of auxin from PGPB, when added to the ideal levels of auxin found in nature, can stunt plant development (Sukul et al., 2021). By encouraging the development of adventitious and lateral roots and boosting the secretion of root exudates, bacterial IAA improves nitrogen absorption. *Pseudomonas* sp. isolated from soil near *Vigna radiata* (L.) produced growth-regulating compounds such IAA, 1-aminocyclopropane-1-carboxylate (ACC) deaminase, and siderophores, according to Al-Enazi et al. (2022) investigation of pesticide-resistant plant growth-promoting rhizobacteria strains. Even when exposed to increasingly high quantities of metalaxyl, carbendazim, and tebuconazole, the PGR-11 strain persisted in producing PGP compounds. High pesticide concentrations have a negative effect on plant development and physiological and biochemical features, according to tests conducted on *V. radiata* (L.).

3.5 Relationship between heavy metals and the microbiome

Bioremediation technology currently focuses on the interactions between metals and microbes, which can be explained differently. The presence of soil microorganisms in different soil regions is crucial in deciding the fate of heavy metals in the soil (Becze et al., 2021; Gulzar and Mazumder, 2022). These microorganisms are not evenly spread throughout the soil, and heavy metals can severely impact their cellular, biochemical, and molecular processes, putting their survival at risk. Although heavy metals generally have an inhibitory effect at high concentrations, some heavy metals, such as Cadmium, can harm soil microbiota even at low concentrations (Sengupta et al., 2021). Heavy metals are toxic because they inhibit cell growth and development by directly destroying or deactivating critical cellular components, among other things. For example, HMs can cause oxidative stress by ROS production (Husain et al., 2022), disrupting the structure (Camargo et al., 2018) and function of several active biomolecules like DNA, RNA, and proteins (Gulzar and Mazumder, 2022). For instance, metals like cadmium, mercury, and lead disrupt the ionic balance, harm cell membranes, and even denature proteins (Sobolev and Begonia, 2008; Abdu et al., 2017). In addition to causing ionic imbalance and enzyme inhibition in bacterial systems, copper, nickel, and zinc toxicity has been documented (Ding et al., 2022). Metal ions can block the activity of many enzymes, including superoxide dismutase, catalase, and ascorbate peroxidase (Mitra et al., 2022). In a similar vein, arsenic damages DNA, while mercury impedes the transcription process (Bobaker et al., 2019).

It has been suggested that microorganisms residing in metal-contaminated soil can transform toxic metals into less harmful molecules. The microbiome can dissolve or solubilize heavy metals, and transition metals can undergo oxidation or reduction without impacting the microbiome's ability to promote plant growth (Hlihor et al., 2022). In addition, the soil microbiome replenishes the environment by binding, volatilizing, oxidizing, immobilizing, and converting harmful metals into less harmful forms. Consequently, the soil microbiome can remove, restore, precipitate, and detoxify metals by modifying their environmental characteristics and solubility (Barra et al., 2021). These ecological interactions between the microbiota and toxic metals are essential for regulating mobility and decontaminating polluted environments. Nevertheless, the effectiveness of microbial activities depends on various factors, including metal concentration and species, the composition and function of microbiomes, and the environmental state (Kim et al., 2020; Liu et al., 2019).

4 Remediation approach used for HMs and POPs

Understanding chemical characteristics and eliminating heavy metals and pollutants (POPs) from the soil requires efficient solutions. Several strategies have been tried to reduce the harmful effects of POPs, the most prevalent of which involves concentrating on HMs and PAHs found in soil and water, respectively (Tufail et al., 2022). Depending on whether the remediation is conducted on-site (*in-situ*) or away from the contaminated area (*ex-situ*), soil and water remediation techniques can be categorized as chemical (using chemicals), physical (using physical agents), or biological (using living organisms) (Cepoi et al., 2022; Kumar et al., 2022; Li et al., 2020). To alleviate POPs, modern techniques have been developed that incorporate the compounds' molecular size, water solubility, polarity, and volatility, increasing extraction efficiency (Sun et al., 2017). Table 5 presents a compilation of methods utilized for HMs and POPs remediation from the environment, showcasing a summary of different approaches.

TABLE 5 Techniques for the physical, chemical, and biological remediation of metals at both laboratory and field scales.

Remediation strategies	Methods adopted	Metals removed	Description	Limitations	Benefits	References
Physical processes	Froth floatation	Cu, Pb, Zn, As	Uses air bubbles in soil slurry to extract metal-bearing granules from the soil medium by exploiting hydrophobic variation	Expensive	High Removal efficiency	Park and Son (2017)
	Electrokinetic remediation	As, Cu, Pb	Applying electrical current to the electrolytic tank de-stresses contaminated soil	Depth and soil heterogeneity limit	Fast, low-energy recovery	Kim et al. (2013)
	Vitrification	Cr	The contaminated soils are heated to melting point in order to stabilise them	Complicated, expensive, and damaging to soils with high organic matter, dampness, and volatile or flammable organics	It's quick, it works for a long time, and it can be used in various different situations	Ballesteros et al. (2017)
	Thermal treatment	Hg, Zn, Cu	Heating polluted soils removes volatile contaminants	Causes potential damage to soil structure, necessitating costly capital expenditures and strict regulation of gas emissions	Rapid, risk-free, and producing negligible amounts of secondary pollutants	Song et al. (2017), Wang et al. (2018)
	Soil replacement	Hg, Cd, Ni, Cu, Cr, Pb, Zn, As, Sb, Ba, Be	Soil that has been contaminated is either totally or partially replenished with clean soil	Expensive, useful only in a restricted area	For heavily contaminated soil	Derakhshan et al. (2018), Valentim dos Santos et al. (2016)
	Magnetic separation	As, Cu, Hg, Pb	Use the magnetic differences between particles to sort them	costly, has the potential to destroy physical and chemical properties	Suitable for both small and large particles; exceptionally productive, simple, fast	Boente et al. (2017)
	Hydrodynamic separation	As, Cu, Hg, Pb	Use centrifugal force and particle settling velocities in water flows	The process is expensive, and it might change the soil's qualities (texture and particle size), resulting in less fertile soil	Economical, simple, and fast, appropriate for many sands	Boente et al. (2017)
Chemical processes	Stabilization	Cd, Pb, Zn, As, Cr	Reduces soil metal mobility and bio-availability	Induces a shift in the soil's physical characteristics	Good effectiveness, simple, fast, reasonably affordable	Ullah et al. (2020), Epelde et al. (2014)
	Treatment with nanoparticles	Metals and metalloids	Activated by the NP-specific surface area, this process includes co-precipitation, precipitation, redox reactions, and adsorption	Controversial because the effects of NP on soil composition, biodiversity, and NP-plant interactions are unknown and may constitute a long-term harm	Rapid, precise	Sun et al. (2020)
	Electrochemical remediation	Cd, Co, Cr, Cu, Pb, Zn	Includes the processes of electrolysis, electrophoresis, electro-osmosis, and electromigration	Extensively difficult to implement	effective even in soils with low permeability, and it does not cause substantial alterations to the soil's attributes	Xu et al. (2019), Yang X. et al. (2020)
	Soil washing	Pb, Cd, Zn, Cu	Metals in contaminated soils can be leached with the help of reagents and extractants	Costly damage to soil structure and nutrient levels	Metals are eliminated permanently; the process is user-friendly and quick	Feng et al. (2020), Wang et al. (2020)

(Continued on following page)

TABLE 5 (*Continued*) Techniques for the physical, chemical, and biological remediation of metals at both laboratory and field scales.

Remediation strategies	Methods adopted	Metals removed	Description	Limitations	Benefits	References
	Stabilization/ solidification	Pb, Zn	Waste is enclosed in a monolithic solid of high integrity	Time-consuming	Efficient, straightforward, fast	Liu et al. (2015)
Biological processes	Biobleaching	Any metals	Substances produced by microorganisms are capable of dissolving metals	Slower, environment-sensitive bacteria cannot bind to cell surfactants	affordable and low impact on the environment	Yang X. et al. (2020)
	Biosorption	All forms of metals	Metals are attached to the membranes of both living and nonliving cells	Influenced by nutrition and atmosphere	Quick, risk-free, and cheap as well as very efficient	Rizvi and Saghir Khan (2019), Rizvi et al. (2020), Saleem et al. (2022)
	Microbial remediation	All types of metals	Inoculating soil/seeds/ roots with metal-tolerant plant beneficial microorganisms	The process is slow, and environmental influences may affect it	Affordable, environmentally friendly, and not generating secondary pollutants	Rizvi and Khan (2018), Rizvi et al. (2020), Saleem et al. (2022)
	Microbes with plants	Almost all metals	Metal-tolerant bacteria boost plant development when seeded	Competition from natural microflora, environmental variables	Effective, inexpensive, environmentally friendly, and a source of vital nutrients for plant growth	Khan et al. (2009)
	Phytoremediation	Cr, Zn, As, Cd, Pb, As, Zn, Pb, Cd	High-biomass plants are used	Long duration	Economical, low-impact on the environment, and time-saving	Sigua et al. (2019), Yang et al. (2017)

4.1 Physicochemical approaches utilized for remediation

Ultrafiltration, solvent extraction, osmosis, nanofiltration, incineration, flotation, ion exchange, electrodialysis, fixation (i.e., nitrogen), conventional and advanced oxidation, coagulation, and precipitation are some of the physicochemical processes that have been used to get rid of HMs and POPs (Kadam et al., 2019). As a physicochemical technique, adsorption has great promise for eliminating HMs and POPs from the environment. Adsorption is widely used in industry because of its remarkable potential efficiency, low energy requirements, molecular level preference, malleability, and capacity to separate various chemical substances (Priyadarshanee and Das, 2021).

Another standard method of water purification is electro-coagulation (Bandaru et al., 2020; Titchou et al., 2021). Research studies (Bandaru et al., 2020) have shown the application of iron electro-coagulation to remove As (III) from the environment. After being subjected to microfiltration, the concentration of additional HMs (Cr, Pb, and Ni) in oily water dropped to 10 mg/L from 35 mg/L (Changmai et al., 2019). Commercial electro-coagulation systems maintain a steady current of 5–20 mA/cm^2 for optimal effluent removal. Advanced oxidation processes (AOPs) and conventional oxidation processes (COPs) are two types of chemical treatments (Silvianti et al., 2020). Photocatalysis processes, solar-Fenton, electron-Fenton, and Ferrate ion, all AOPs, have greatly facilitated the remediation process of HMs (Mazumder et al., 2020). Nevertheless, ozonization, hydrogen peroxide (H_2O_2), chlorination, and photolysis are used in COPs to clean water, and their application will produce byproducts and radicals. Fruit waste, such as banana peel, egg shells, coconut husks, and nutshells, as well as tannin-rich materials like rice husk and fertilizer wastes, are all examples of bioadsorbents to treat water and soil (O'Connell et al., 2008; Zhao et al., 2018). Furthermore, several soil-derived adsorbents, such as fly ash and red mud (Dash et al., 2018), zeolites and clays (Titchou et al., 2021), new carbon nanomaterials (NMs), and metal oxides, showed improved removal effectiveness when tested on a variety of contaminants and HMs (Chakraborty et al., 2022).

4.2 Biological approaches utilized for remediation

Microbial bioreactors (MBRs) have been shown to effectively decontaminate wastewater using a combinatorial approach of microbial biodegradation and physical retention at the membrane surface (Tufail et al., 2022; Zhang et al., 2020). However, Membrane fouling makes it challenging to eliminate specific POPs. As a result, a hybrid technique involving an electrochemical MBR has been developed to remove nearly all toxins at a fixed electric potential from wastewater (Hube et al., 2020). Compared to controlled MBR, this approach is three times more reliable and may be used for three times as long. The build-up of pesticides, PAHs, and HMs in natural resources is a topic of discussion on a global scale. Pollutants remained in the soil for a long and leaked into the ground and surface water. In order to produce sustainable habitats, it is crucial to break down harmful chemicals in the soil (Russo et al., 2019; Rigoletto et al., 2020; Saha et al., 2021). Bioremediation is superior to the conventional physicochemical approach of removing pollutants from soil and water. Microbe-mediated biodegradation of HMs and organic

FIGURE 1
Interactions between metal and microbes can impact the process of bioremediation.

pollutants is emerging as a modest but feasible answer to all these problems, often known as bioremediation (Tyagi and Kumar, 2020; Sreedevi et al., 2022; Tufail et al., 2022; Liaqat et al., 2023; Masotti et al., 2023; Saibu et al., 2023). Compared to chemical and physical approaches, this technology is more cost-effective, less invasive, environmentally benign, and long-lasting.

4.2.1 Bacterial-mediated bioremediation

Bacteria might adapt or be resistant to metal toxicity using various approaches, i.e., synthesis of metallothioneins, active transport or efflux mechanisms, morphological changes, synthesis of siderophores, biotransformation of toxic metals, and synthesis of exopolymeric compounds (Funtikova et al., 2023; Liaqat et al., 2023; Sevak et al., 2023; Wang et al., 2023; Zhou et al., 2023). Figure 1 presents the few microbial approaches used for HM remediation from the soil.

Bacteria are well-known for their ability to degrade or mineralize pollutants through enzyme-catalyzed catabolic action (Tables 6, 7). Numerous catabolic genes that rely on PAHs and are remarkably conserved have been identified during bioremediation studies (Barker and Bryson, 2002; Ali et al., 2022). These genes are present in gram-positive bacterial species and include phd, pdo, nid, and nar, and in gram-negative bacterial species and include phn, pah, ndo, nah, and nag (Sakshi and Haritash, 2020). Analysis showed that crude oil might be biodegraded by the bacteria *Pseudoalteromonas agarivorans, Isoptericola chiayiensis, Rhodococcus soli*, and *Bacillus algicola* in less than 2 weeks (Lee et al., 2018). Most small molecules with carbon atoms between C9 and C14 were entirely decomposed, while those with C15 and C20 were almost completely broken down. The larger-sized molecules, on the other hand, were substantially broken down. Another study reported that after 30 days of remediation, bacterial consortiums obtained from China's Yangtze River Delta broke down 44.5% of total petroleum hydrocarbon (TPH) (Jia et al., 2018). Chlorpyrifos (CPF) breakdown was studied in two different bacterial species *Bacteroides megaterium* CM-Z19 and *Pseudomonas syringae* CM-Z6. Five days of incubation at 37°C resulted in a 92.6% and 99.1% degradation of chlorpyrifos-methyl-Z19 and chlorpyrifos-methyl-Z6, respectively, at an initial 100 mg/L concentration (Zhu et al., 2019). Nevertheless, 200 µg per liter of CPF can be degraded by *Cupriavidus nantongensis* X1T in about 48 h. *C. nantongensis* X1T species may *survive* in temperatures between 30°C and 42°C, and pH ranges between 5 and 9. It has a CPF tolerance of 500 mg/L (Shi et al., 2019). *Cupriavidus* sp. DT-1 has been shown to successfully degrade CPF in liquid media, mineralizing both CPF entirely after 14 h at pH 7°C and 30°C. In the same settings, 90% of chlorpyrifos in soil media degrades after 30 days (Lu et al., 2013). The most efficient microorganisms, *P. putida* MAS, can break down 90% of CPF in 24 h (Kamika and Momba, 2013). Recent studies indicate that aerobic bacteria, such as Sphingobium sp. strain BHC-A and *Schistosoma japonicum* UT26, can fully degrade lindane in an aerobic environment (Perera and Hemamali, 2022). Atrazine-contaminated soil from the Vetiver rhizosphere reported two bacterial species: *Paenarthrobacter*

TABLE 6 A comprehensive breakdown of various bioremediation mechanisms employed by microorganisms for the removal of heavy metals (HMs) and persistent organic pollutants (POPs) (Guo et al., 2019; Huang et al., 2021; Jia et al., 2021; Huang et al., 2022).

Mechanism	Description	Examples of microorganisms
Bioremediation mechanisms of heavy metals (HMs)		
Biosorption	Microorganisms absorb heavy metals onto their cell surfaces or within their biomass.	*Pseudomonas aeruginosa, Bacillus subtilis, Saccharomyces cerevisiae*
Biomineralization	Microorganisms convert soluble heavy metals into insoluble forms or minerals, reducing their bioavailability.	*Desulfovibrio desulfuricans*, *Bacillus* sp., *Pseudomonas putida*
Bioaccumulation	Microorganisms accumulate heavy metals within their cells to concentrations higher than those in the surrounding environment.	*Spirodela polyrhiza* (Duckweed), *Chlorella vulgaris* (Algae), *Thlaspi caerulescens* (Metal hyperaccumulator plant)
Bioreduction	Microorganisms reduce heavy metal ions to less toxic or less mobile forms.	*Geobacter sulfurreducens*, *Shewanella oneidensis*, *Clostridium* sp.
Bioremediation Mechanisms of Persistent Organic Pollutants (POPs)		
Biodegradation	Microorganisms enzymatically degrade organic pollutants into simpler, less harmful compounds.	*Pseudomonas* putida, Rhodococcus sp., *Mycobacterium* sp.
Phytoremediation	Plants absorb and detoxify organic pollutants from the environment, with associated microorganisms enhancing degradation processes.	*Populus* spp. (Poplar trees) with mycorrhizal fungi, *Brassica juncea* (Indian mustard) with rhizospheric bacteria, *Phragmites australis* (Common reed) with mycorrhizal fungi
Cometabolism	Microorganisms metabolize pollutants using enzymes produced during the degradation of other compounds.	*Methylosinus trichosporium*, *Sphingomonas* sp., *Mycobacterium* vaccae
Anaerobic Biodegradation	Biodegradation of organic pollutants under anaerobic conditions, often involving microbial consortia.	*Dehalococcoides* sp., *Methanosarcina* sp., *Desulfitobacterium* sp.

aurescens TC1 and *Arthrobacter* MCM B-436. Atrazine degradation in *P. aurescens* TC1 is controlled by trzN, atzC, and atzB genes. *Arthrobacter* sp CW-1 breaks down dimethyl phthalate (DMP) in anaerobic environments (Jia et al., 2021). Nicotine degradation in *Arthrobacter nicotinovorans* is mediated by the plasmid pAO1 (Guo et al., 2019). *Rhodococcus pyridinivorans* SS2 and *Rhodococcus ruber* SS1 can effectively remediate triCB and dichlorobiphenyl (diCB) (Xiang et al., 2020). *Pseudomonas* sp. breaks down - Hexabromocyclododecanes (HBCD) at concentrations as low as 50 mg/L in about 5 days, but at 640 mg/L, it takes 8 days to break down (Huang L. et al., 2021; Huang et al., 2022). *Bacillus* sp. can break down HBCDs at 320 mg/L in about 4 days (Huang et al., 2022). *Pseudomonas aeruginosa* HS9 can degrade 69% of 1.7 mg/L HBCDs in 14 days. Table 6 provides a detailed overview of diverse bioremediation strategies utilized by microorganisms to effectively eliminate Heavy Metals (HMs) and Persistent Organic Pollutants (POPs) from contaminated environments.

Halophilic bacteria possess extremozymes that can operate effectively in severe conditions, which makes them a promising choice for bioremediation applications. These halophilic bacteria produce an extremozyme with unusual properties, including resistance to heat, acidity, organic solvents, and strong ions. Microprecipitation or proton exchange aids in attaching these bacteria to HMs via an extracellular polymeric material (Kaushik et al., 2021). The negative charge on cell surfaces can be attributed to various functional groups, including sulfate, carboxyl, phosphoryl, and amino functional groups. These functional groups possess negatively charged atoms or groups of atoms, such as oxygen or sulfur, which contribute to the overall negative charge of the cell surface (Dawwam et al., 2023; Syed et al., 2022). The negative charge of these functional groups plays an essential role in the interaction of biomass with metal ions. These groups serve as ion exchange sites and can bind metal ions through a process known as cation exchange. During cation exchange, metal ions, such as hydrogen ions, are exchanged for positively charged ions on the biomass surface (Kaushik et al., 2021). Microorganisms employ various mechanisms to eliminate heavy metals from contaminated soils. These include precipitation, biosorption by sequestering them in intracellular metal-binding proteins (metallothioneins), and converting them into harmless forms through an enzymatic transformation, as presented in Figure 2.

In addition, the anionic functional groups in the cell walls of gram-positive and gram-negative bacteria have an essential function in binding metals. The negatively charged groups allow the bacteria to bind metal ions on the surface or within the cell wall. Binding metals is vital for bacteria's survival as metal ions are necessary for many cellular processes, such as enzyme activity and energy metabolism (Pachaiappan et al., 2021). It has been reported that *Methanothermobacter thermautotrophicus* can convert chromium (VI) to chromium (III) and then immobilize chromium (III) as hydroxide or oxide. *Bacillus cereus* and *Shewanella* have been shown to decrease Cr (VI) and its immobilization (Chen et al., 2012) as shown in Figure 2. Table 7 enumerates diverse bacterial species employed in soil for the remediation of heavy metals (HMs), showcasing their effectiveness in mitigating environmental contamination.

4.2.2 Fungi-mediated bioremediation

Fungi are a diverse group of eukaryotic organisms that obtain their nutrients from organic matter in their environment, and they are often referred to as saprophytic organisms. Fungi have been present on Earth for millions of years, and they play essential roles in various ecological processes such as decomposition, nutrient cycling,

TABLE 7 Various bacteria used for remediation of HMs in soil.

Microorganism	HMs	Outcome or result	References
Bacillus megaterium	Pb	cytoplasmic accumulation	Chen et al. (2019)
Bacillus simplex	Pb	Metal accumulation endogenously ranges from 88.5% to 98.5%	Chamekh et al. (2021)
Lactic acid bacteria	Pb	Metal accumulation endogenously up to 99.9%	Liu et al. (2019)
Ralstonia metallidurans	Pb	Trivalent-cation efflux systems (chemi-osmotic pumps) used for metal accumulation	Wang et al. (2023)
Pseudomonas marginalis	Pb	lead extracellularly remediated	Liaqat et al. (2023)
Pseudomonas aeruginosa ASU 6a	Pb	Both dead (123 mg/g) and alive cells (79 mg/g) showed lead accumulation	Gabr et al. (2008)
Bacillus sp. ATS-2	Pb	91.73% Pb(II) accumulation intracellular	Çabuk et al. (2006)
Bacillus subtilis PbRB3	Pb	*Bacillus subtilis* PbRB3 removed >80% of Pb from culture solution	Arif et al. (2019)
Staphylococcus aureus and *Citrobacter freundii*	Pb	Deposition of lead-phosphate intracellularly	Suresh et al. (2021)
Frankia sp.	Pb	Pb–PO_4 compounds produced from cells deposited Pb^{2+} with maximum rates	Furnholm et al. (2017)
Frankia	Cu	Frankia had copper in its cells or on its surface	Liu et al. (2015)
Acidithiobacillus ferrooxidans	Cu	Regulating phosphate aggregates by stimulating polyphosphate degradation and copper-phosphate complexation	Zhu et al. (2022)
Bacillus genus	Cd	The Cd concentration demonstrated a reduction of between 28% and 40%	Zhang et al. (2021) Zhang et al. (2023)
Bacillus mycoides and *Micrococcus roseus*	Cd	Bacterial growth and maize shoot nutrient uptake	Monachese et al. (2012)
Burkholderia dabaoshanensis sp. *nov*	Cd	The cell surface's amide, carboxy, and phosphate produce low-molecular-weight (LMW) organic acids to complex or chelate Cd^{2+} in the adsorptive pathway for cadmium	Zhu et al. (2022) Zhu et al. (2020)
Lactic acid bacteria	Cd	The Cd concentration reduced from 69.45% to 79.91%	Li et al. (2021)
Acidophilic strain 62BN	Cd	Reduction in concentration by 50% within 60 days	Rani et al. (2009)
Bacillus licheniformis sp	Cd	Reduction of Cd up to 24.51 mg/g	Baran and Duz (2021)
Pseudomonas sp.	Cd	Intracellular accumulation of Cd^{2+} up to 93.5%	Azzam and Tawfik (2015)
Halobacillus sp. KN57	Ni	Reduction of Ni up to 111.11 mg/g	Torabia and Kardel (2019)
Bacillus thuringiensis and *Staphylococcus capitis*	Cr	In 96 h of treatment, >90% reduction of Cr(VI)	Suresh et al. (2021)
Pseudomonas putida	Zn and Cd	P-type ATPases and two CBA transporters	Gentry et al. (2004) Lu et al. (2017)
Streptococcus thermophilus	Zn and Cd	cadCSt and cadASt genes responsible for cadmium/zinc resistance	Schirawski et al. (2002)
Pseudomonas aeruginosa	Zn, Cd, and Hg	Up to 99% reduction in HMs concentration	Imron et al. (2021)
Enterobacter cloacae	Pb, Ni, Cd, and Cr	Heavy metal toxicity headed Cd > Cr > Pb > Ni. Heavy metals decreased P solubilization, pH, and bacterial biofilm growth	Syed et al. (2022)
Burkholderia fungorum	Cd, Pb, and Zn	The accumulation of metals in the cell wall and the interior region of bacterial cell occur. High metal tolerance and catabolic activity	Yang et al. (2015)
Thiobacillus thiooxidans	Cu, Zn, and Cr	Reduction in a final concentration of HMs Cu (81.89%), Zn (64.05%), and Cr (71.08%)	Nagashetti et al. (2013)

(Continued on following page)

TABLE 7 (*Continued*) Various bacteria used for remediation of HMs in soil.

Microorganism	HMs	Outcome or result	References
Klebsiella variicola	As, Cd, and Pb	Removal of HMs from polluted soil using genetically engineered *Klebsiella variicola*	Yetunde Mutiat et al. (2018)
Burkholderia sp.	Cu, Cd, Mn, and Pb	HMs-contaminated soil minerals adhere to Burkholderia sp. and produce a biosurfactant-metal complex	Yang Y.-C. et al. (2020)
Bacillus cereus KMS3-1	Pb, Cu, and Cd	Pb(II) (78.74 mg/g), Cu(II) (71.42 mg/g), and Cd(II) (54.05 mg/g) maximum adsorption capacity (Q_{max}).	Mathivanan et al. (2021a), Mathivanan et al. (2021b)

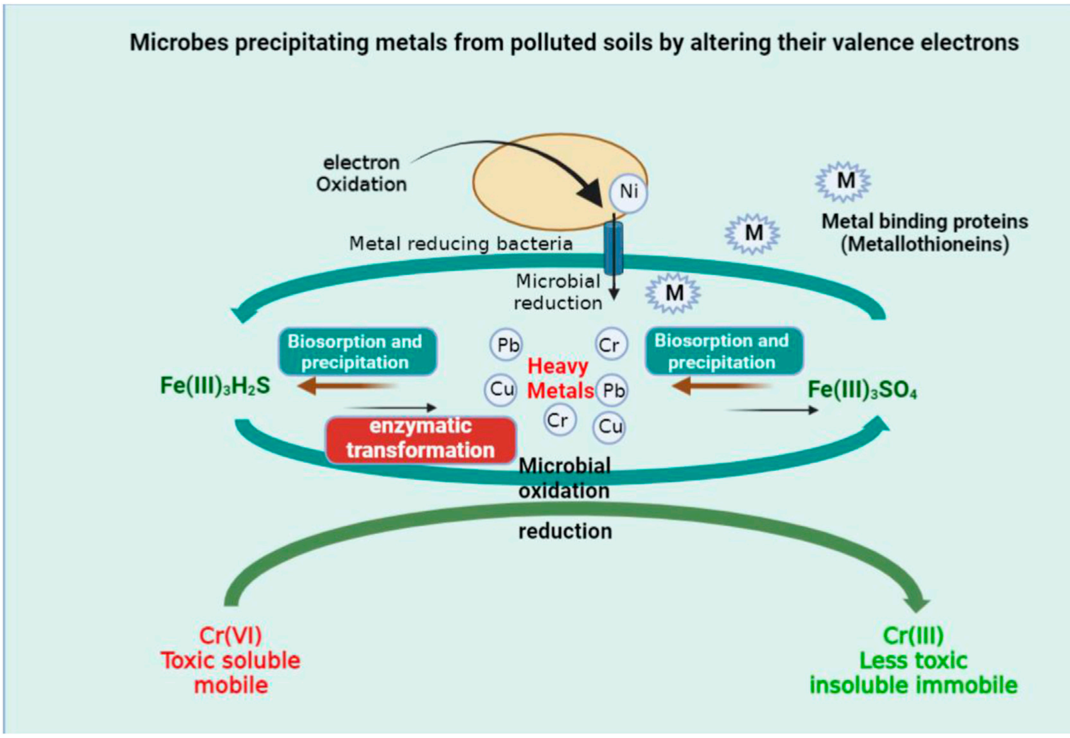


FIGURE 2
Precipitation, biosorption via sequestration by intracellular metal-binding proteins (metallothioneins), and enzyme-catalyzed metal conversion to nontoxic forms are all mechanisms used by microorganisms to remove heavy metals from contaminated soils (enzymatic transformation) (Ojuederie and Babalola, 2017).

and symbiosis. They are exceptionally efficient in decomposing PAHs and HMs due to their specificity for excessive refractory chemicals and survival potential in harsh natural habitats, i.e., elevated temperatures and reduced pH (Arwidsson et al., 2010; Bano et al., 2018; Chen et al., 2022; de Moura Dickel et al., 2022). Moreover, the fungus may digest PAHs and HMs "*in situ*" by producing extracellular enzymes (Liu et al., 2017), which can be done due to the extensively branched mycelia. Fungi have two main approaches for metal detoxification: biosorption (Bano et al., 2018), which includes adhering metals to the membrane, and bioaccumulation, which includes absorbing metals into the cell and metabolizing them (Soleimani et al., 2010). It has been shown that certain fungi, including *Gloeophyllum sepiarium*, *Penicillium chrysogenum*, *Aspergillus versicolor*, *Aspergillus terreus*, *Aspergillus niger*, *Aspergillus fumigatus*, and *Rhizopus oryzae* can breakdown PAHs and HMs (Hota et al., 2021). Recently, Chen et al. (2022) evaluated the potential of white rot fungus for the remediation of heavy metal contamination. However, heavy metal concentrations, organic pollutants, and unfavorable environmental conditions can slow this remediation process. Table 8 presents a comprehensive overview of various fungi, algae, and plants utilized for remediating heavy metals (HMs) in soil, emphasizing their mechanisms and target HMs. These organisms play crucial roles in bioremediation by absorbing, accumulating, or transforming HMs through mechanisms such as biosorption, bioaccumulation, and biotransformation. Understanding these biological agents and their specific interactions with HMs is essential for developing effective strategies for soil remediation and environmental protection.

The remediation outcomes appear to be highly sensitive to the types of strains, the types of pollutants, and the reaction conditions. Concentrations of heavy metals or organic pollutants that are too

TABLE 8 A comprehensive details of various fungi, algae, and plants used for remediating heavy metals (HMs) in soil, highlighting their mechanisms and target HMs (Soleimani et al., 2010; Arwidsson et al., 2010; Bano et al., 2018; Hota et al., 2021; Chen et al., 2022; de Moura Dickel et al., 2022).

Organism type	Organism	Mechanisms	Target heavy metals (HMs)
Fungi (Mycorrhizal)	*Glomus intraradices* (AMF)	* Mycorrhizal symbiosis: Enhances plant metal uptake and tolerance through increased root surface area. * Metal chelation: secretes organic acids that bind and immobilize HMs.	As, Cd, Pb, Zn, Cu
	Rhizophagus irregularis (AMF)	* Mycorrhizal symbiosis. * Metal chelation	As, Cd, Pb, Zn, Cu
	Laccaria bicolor (EMF)	* Mycorrhizal symbiosis: forms a sheath around plant roots, increasing HM absorption. * Metal chelation	As, Cd, Pb, Zn, Cu
	Paxillus involutus (EMF)	* Mycorrhizal symbiosis. * Metal chelation	As, Cd, Pb, Zn, Cu
	Pisolithus tinctorius (EMF)	* Mycorrhizal symbiosis. * Metal chelation	As, Cd, Pb
Fungi (White Rot)	*Trametes versicolor* (Turkey Tail)	* Extracellular enzyme production: degrades organic matter, potentially releasing bound HMs. * Metal chelation	As, Cd, Pb, Zn, Cu, Hg
	Phanerochaete chrysosporium	* Extracellular enzyme production. * Metal chelation	As, Cd, Pb, Zn, Cu, Hg
	Pleurotus ostreatus (Oyster mushroom)	* Metal chelation. * Bioaccumulation: accumulates HMs within fungal tissues.	Cd, Pb, Zn, Cu
	Lentinula edodes (Shiitake mushroom)	* Metal chelation. * Bioaccumulation	Cd, Pb, Zn
	Bjerkandera adusta (Fomes fomentarius - Tinder Bracket)	* Extracellular enzyme production. * Metal chelation	As, Pb, Cu
Algae	*Chlorella vulgaris*	* Biosorption: passively binds HMs to their cell walls due to high surface area and functional groups. * Bioaccumulation	As, Cd, Cr, Pb, Hg
	Scenedesmus sp.	* Biosorption * Bioaccumulation. * Metal precipitation: can precipitate HMs as insoluble complexes within or outside cells	As, Cd, Cr, Pb, Hg
	Chlamydomonas reinhardtii	* Biosorption * Bioaccumulation. * Metal precipitation	As, Cd, Cr, Pb, Hg
	Spirulina platensis	* Biosorption. * Bioaccumulation	As, Cd, Pb, Hg
	Dunaliella salina	* Biosorption. * Metal precipitation	Cd, Pb, Hg
Plants (Hyperaccumulators)	*Brassica juncea* (Indian mustard)	* Phytoextraction: Extracts HMs from soil and accumulates them in harvestable plant parts. * Metal chelation	Pb, Zn, Cd
	Salix spp. (Willows)	* Phytostabilization: Reduces HM mobility by accumulating and immobilizing them within plant tissues. * Metal chelation	As, Cd
	Pteris vittata (Chinese Brake Fern)	* Phytoextraction. * Metal chelation	As
	Thlaspi caerulescens (Alpine Pennycress)	* Phytoextraction. * Metal chelation	Zn, Cd, Pb
	Alyssum murale (Wall Alyssum)	* Phytoextraction. * Metal chelation	Ni, Zn, Pb
Plants (Non-hyperaccumulators)	*Festuca arundinacea* (Tall Fescue)	* Phytostabilization. * Metal chelation	Pb, Zn
	Lolium perenne (Ryegrass)	* Phytostabilization. * Metal chelation	Pb, Cd
	Agrostis stolonifera (Creeping Bentgrass)	* Phytostabilization. * Metal chelation	Zn, Cu
	Salix viminalis (Golden Willow)	* Phytostabilization. * Metal chelation	Cd, Pb
	Helianthus annuus (Sunflower)	* Phytostabilization. * Metal chelation	Pb, Cd

high or too low, or reaction conditions that are too slow or too fast, might impede the cleaning process (Kumar et al., 2023; Palanivel et al., 2023; Tessaro et al., 2023). Zhuo and Fan (2021) have reported an in-depth analysis to evaluate the most current developments in using white rot fungus to degrade organic pollutants. In addition, they deduced that most current bioremediation investigations of white rot fungus are undertaken in controlled laboratory settings. Further research must consider the challenges associated with treating pollution in practice. The white-rot fungus most likely uses laccases, lipases, lignin peroxidase (LiP), manganese peroxidase (MnP), and cytochrome P450 versatile peroxidase to breakdown and decrease PAHs and HMs (El-Khoury et al., 2022; Sanchez-Hernandez et al., 2023; Syed et al., 2014). *Lasiodiplodia theobromae*, isolated from PAH-polluted soil in Beijing, China, removed 53% of benzo[a]pyrene (BaP) within 10 days of incubation (Punetha et al., 2022). Increasing the incubation period to 2 weeks enhanced the biodegradation potential of *Peniophora incarnate* strain KUC8836, resulting in the removal of 97.9% of pyrene, 95.3% of phenanthrene, and 95% of fluoranthene, attributed to elevated laccase, LiP, and MnP production (Lee et al., 2014). Within 30 days, *Rhizoctonia zeae* SOL3, *Scopulariopsis brevicaulis*, and *Pleurotus pulmonarius* FO43 achieved near-complete decomposition of pyrene at concentrations of 42%, 64%, and 99%, respectively (Bhattacharya et al., 2014; Mao and Guan, 2016). *Aspergillus terreus*, *Trichoderma viride*, *Trichoderma longibrachiatum*, and *Aspergillus niger* were observed to absorb Pb, Cd, Cr, and Ni at rates of 59.67 mg/g, 16.25 mg/g, 0.55 mg/g, and 0.55 mg/g, respectively (Dell'Anno et al., 2022; Kumar and Dwivedi, 2021). In another study, the highest remediation potentials for Cr (III), Pb (II), Cr (VI), and Cu (II) were found to be 226.6 mg/g, 208.5 mg/g, 207.3 mg/g, and 205.1 mg/g, respectively, when the fungus was immobilized in living form (Hanif et al., 2015). The fungus *Aspergillus fumigatus* (FS6) and *Aspergillus flavus* (FS4) eliminated almost 70% of the Cr (VI) from the liquid PDB medium. Cd (II) removal by *Aspergillus fumigatus* (FS9) was as high as 74% (Talukdar et al., 2020). *Sterigmatomyces halophilus*, *A. restrictus, A. penicillioides*, *A. gracilis*, and *A. flavus* and all of which are obligate halophilic fungi, showed efficient biosorption for cadmium, copper, ferrous, manganese, zinc, and lead (de Moura Dickel et al., 2022; Hota et al., 2021; Kumar and Singh, 2023; Tessaro et al., 2023). *S. halophilus* and *A. flavus* demonstrated the highest adsorption levels, averaging 83%–86%. The fungi *Mucor alternans*, *Phanerochaete chrysosporium*, *Trichoderma viride*, *Rhizopus arrhizus* FBL 578, *Fusarium oxysporum*, and *Trichoderma hamatum* FBL 587 are long-established as DDT degraders (Russo et al., 2019). When endosulfan is exposed to *Trichoderma harzianum*, it is oxidized to endosulfan sulfate and then degraded naturally (Landa-faz et al., 2021). In PAH-contaminated industrial soil, the fungus *Irpex lacteus* and *Pleurotus ostreatus* can break down the PAHs. In 5 days at 26.8°C and pH 6.5, *Cladosporium cladosporioides* degrades 50 mg/L CPF (Bhattacharya et al., 2014).

4.2.3 Microalgal-mediated bioremediation

Algae offers various advantages as a decontaminating agent, including low cost, easy handling, non-pollution, quick metal contamination removal for recovery, and no additional wastage. Microalgae exhibit the capability of bio-remediating environmental-contaminants (ECs) through three distinct approaches: bio-uptake, bio-adsorption, and bio-degradation (Table 8) (Goswami et al., 2022; Kashem et al., 2023; Tambat et al., 2023). Bio-adsorption is the process by which contaminants are adsorbed onto the surface of the microalgae cells without any cellular uptake or degradation. This process depends on the physicochemical properties of both the contaminant and the microalgae cells, and it can be affected by factors such as pH, temperature, salinity, and ionic strength (Goswami et al., 2022). Bio-adsorption can be an effective method for removing low concentrations of contaminants from the environment, but it is not a long-term solution, as the contaminants can be released back into the environment over time (Dubey et al., 2023). Bio-uptake is the process by which contaminants are taken into the microalgae cells and accumulated within the cells (Dubey et al., 2023). This process can occur through passive diffusion or active transport, depending on the contaminant's physicochemical properties and the cellular membrane. Bio-uptake can be an effective method for removing moderate to high concentrations of contaminants from the environment, as the contaminants are sequestered within the cells and are not released back into the environment. Bio-degradation is the process of metabolizing contaminants and breaking them down by the microalgae cells into less toxic or non-toxic compounds (Cameron et al., 2018; Goswami et al., 2022). This process depends on the microalgae cells' metabolic pathways and the contaminants' nature. Bio-degradation can effectively remove complex or persistent contaminants from the environment, but it requires specific conditions and nutrients to support the growth and metabolism of the microalgae cells. Bio-adsorption occurs when environmental contaminants (ECs) link to organic substances released by cells or components of the cell wall (Das et al., 2022; Satya et al., 2023). Alternatively, bio-uptake occurs when pollutants bind to intracellular proteins and other substances and involve the subsequent intracellular transit through active transport, assisted diffusion, or simple diffusion. Microalgae use a catalytic metabolic process to break down the chemicals into their parts to biodegrade ECs. Bio-degradation is an essential approach for cleaning up hazardous toxins, which works more like a bioreactor than a biofilter by breaking down the contamination into less dangerous chemicals (Sher and Rehman, 2019; Leon-Vaz et al., 2021; Chebotaryova et al., 2023). It could take place inside cells, outside cells, or in a hybrid form. *Spirulina, Scenedesmus, Phormidium, Oscillatoria, Nodularia, Desmodesmus, Cyanothece, Chlorella, Botryococcus*, and *Arthrospira* are a few of the microalgal genera used in bioremediation (Dwivedi, 2012; Dubey et al., 2023). *Chlorella vulgaris* is effective at degrading acenaphthene and fluoranthene, according to research by Touliabah et al. (2022). The microbes *Lyngbya digueti, Phormidium mucicola, Oscillatoria princeps, Anabaena variabilis*, and *Westiellopsis prolific* were helpful in the reduction of quantity of various petroleum hydrocarbons in oil refinery effluent, which ranged from 24% to 92% reduction (Takáčová et al., 2014). It was reported that *Chlorella kessleri* could degrade 3,4-benzpyrene (29%) when exposed to light at a strength of 13.5 W per square meter. Similarly, *Chlamydomonas reinhardtii* was reported to decompose benz(a)anthracene at a rate of 10 mg/L in 11 days (Luo et al., 2020; Luo et al., 2020). The breakdown of homogentisate resulted in a rise of gene expression that encodes for ubiquinol oxidase, carboxy-methylene-butenolide, carboxylase/oxygenase (Rubisco), ribulose 1,5-bisphosphate, and homogentisate 1,2-dioxygenase (HGD) enzymes. *Chlorella vulgaris* biomass is an effective biosorbent for the removal of copper (Cu^{2+}), Cadmium (Cd^{2+}), and lead (Pb^{2+}) from a mixed solution containing 50 mg dm^3 of each metal ion (Goher et al., 2016). After being treated with Spirulina sp, Ca^{2+} was reduced by 98% and Cu^{2+} by 91% in municipal wastewater. Another study (Yang et al., 2015) found that *Chlorella minutissima* could remove 84% of Cu^{2+}, 84% of Mn^{2+}, 74% of Cd^{2+}, and 62% of Zn^{2+} from municipal garbage. Microalgal biochar has been shown to remove Cr (VI) from water with 100 percent efficiency by Daneshvar et al. (2019), while Cheng et al. (2017) have studied the biosorption and kinetics of Cd (II) removal using both live and dead *C. vulgaris*. The research findings indicate that both viable and decaying cells of *C. vulgaris* exhibit a notable ability for adsorbing Cd, demonstrating efficiencies of 95.2% and 96.8% respectively.

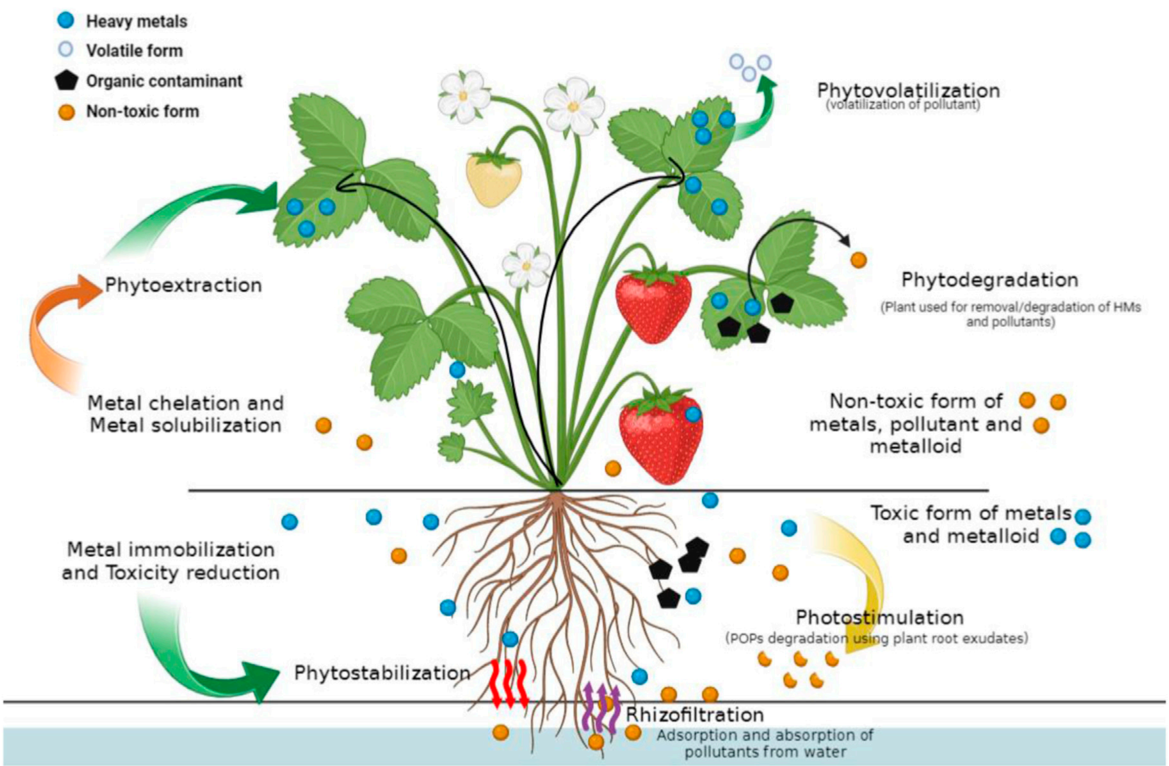


FIGURE 3
A diagrammatic depiction of various plant-based methods being investigated for phytoremediation purposes.

4.2.4 Plant-mediated bioremediation

Plants are used in phytoremediation, a form of bioremediation, to clean up polluted environments such as soil, water, and air. Methods include phytotransformation, phytostabilization, rhizofiltration, phytostimulation, rhizodegradation, phytodegradation, phytovolatilization, and phytoextraction are all part of the broader field of phytoremediation (Nedjimi, 2021; Shabaan et al., 2021; Oladoye et al., 2022) as shown in Figure 3 and Table 8.

Many plant species can absorb, bioaccumulate, immobilize, and degrade environmental pollutants. Some plants that can be utilized for HMs and POPs phytoremediation of soil include *Cucurbita pepo*, *Zea mays*, *Nicotiana tabacum*, *Medicago sativa*, *Alyssum murale*, *Achillea millefolium*, *Aeolanthus biformifolius*, *Arabis gemmifera*, *Phytolacca americana*, and *Pteris vittata* (Kurniawan et al., 2022; Li et al., 2023; Rahman and Singh, 2020; Tauqeer et al., 2016). In order to effectively remove pollutants from water, certain plant species are utilized, i.e., *Eichhornia crassipes*, *Ipomoea aquatica*, *Phragmites australis*, *Potamogeton natans*, *Ruppia maritima*, *Vallisneria americana*, *Hygrophila corymbosa*, *Nuphar lutea*, *Salvinia minima*, *Pistia stratiotes*, and *Lemna minor* (Wei et al., 2021). The impact of certain bacterial species, which are associated with the growth of plants underground, can enhance plant development, promote metal translocation within the plant, alter the bioavailability of metals in the soil, and reduce metal phytotoxicity. This leads to an increase in the effectiveness of phytoremediation. Evidence from a few research shows that bacterial inoculations considerably alter the expression pattern of various metal transporters, including the ZIP, NRAMP, HMA, F-box, and AtALS3 gene families, employing these shared and unique growth-promoting functions (Dash and Osborne, 2023; Dash et al., 2018; Manobala et al., 2021; Dash and Osborne, 2023).

In *Arabidopsis* tissues, *Bacillus amyloliquefaciens* alters the transcriptional activity of the IRT1, FRO2, and FIT1 genes, increasing Fe and Cd accumulation (Sukweenadhi et al., 2015). It has been shown that the endophytic *Pseudomonas fluorescens* Sasm05 strain significantly increases Cd accumulation and tissue growth after inoculation, a process that mimics the overexpression of the SaHMAs, SaNRAMPs, and SaZIPs gene families (Chen et al., 2017). Much research has been conducted on the ZIP transporter gene family, which regulates zinc transportation through membranes and cytoplasmic concentrations in plant cells. *Enterobacter cloacae*–Zn solubilizing bacterial inoculation in rice plants had altered OsZIP1, OsZIP4, and OsZIP5 gene expression, resulting in enhanced Zn accumulation in plant tissues (Krithika and Balachandar, 2016). In *Arabidopsis thaliana* (Sukweenadhi et al., 2015), inoculations with Plant Growth-Promoting Rhizobacteria (PGRP) under Aluminum (Al) stress offer a promising strategy to alleviate heavy metal toxicity and enhance plant development. This is achieved by modulating the expression of key genes, including AtAIP, AtALMt1, and AtALS3. Notably, the activation of AtALS3 gene in response to Al stress results in synthesizing an ABC transporter-like protein within phloem cell membranes. This protein aids in effectively relocating Aluminum away from vulnerable areas, thus protecting the plant. While the specific role of the AtALP gene in Aluminum tolerance remains uncertain, it likely contributes to the overall adaptive response. Additionally, the collaboration between the HMA gene family and AtALS3 plays a vital role in facilitating the translocation of Heavy Metals (HMs) from the plant's roots to the shoots, primarily accomplished through the xylem. This mechanism assists in regulating the distribution of HMs within the plant, ultimately supporting its resilience to metal-induced stress.

Unfortunately, plant cells do not include any natural transporters specific to organic environmental pollutants. Hence, they move around without actively doing anything. Root microbiome components such as rhizosphere bacteria and endophytes have long been appreciated for their role in the phytoremediation of PAHs. Diesel-contaminated soil remediation using petroleum hydrocarbons was less harmful due to the presence of endophytic microbial species such as *Stenotrophomonas* spp., *Pseudomonas* spp., *Pantoea* spp., and *Flavobacterium* spp (Agarwal et al., 2019; Pinel-Cabello et al., 2023). To remove organic pollutants from the environment, rhizobial symbiotic consortiums use organic molecules as a C and N source in phytoremediation. *Rhizobium* strains that nodulate the hyperaccumulator plant Leucaena have been shown to aid in rhizoremediation by using plant toxins (such as the aromatic chemical Mimosine) as C and N sources (Sytar et al., 2021). The bacterial species help plants detoxify HMs and PAHs by increasing their metabolic growth rate. Plant growth and metabolic gene regulation by PGPR inoculations facilitate the systematic development of plant physiology (specifically, "biomass, bushiness, lateral root production, lateral root number, surface area, and thickness"). Inoculating rice seedlings with *Bacillus altitudinis*, for instance, improves root architecture by regulating auxin metabolism and modulating the expression of OsIAA1, OsIAA4, OsIAA11, and OsIAA13 (Ambreetha et al., 2018). The antioxidant defenses of the host plant are also strengthened by PGPR inoculations, making them more effective in combating stress.

The improvement of *Solanum tuberosum* Zn tolerance by *Bacillus* isolates is achieved by adjusting the expression of SOD, GR, DHAR, CAT, and APX genes (Gururani et al., 2013). Moreover, the growth-promoting qualities of ACC-deaminase are critical in aiding hosts to resist the toxicity of petroleum hydrocarbons, which is just one of the many ways endophytic bacteria can help. The use of arbuscular mycorrhizal fungus (AMF) and endophytic fungi to bio-enhance plant growth is a current focus in phytoremediation (Kumar and Saxena, 2019; Ordookhani et al., 2010). The underground network of mycelium belonging to AMF aids in phytoremediation by expanding the rhizosphere, enabling plants to access contaminants and nutrients. This is facilitated by a symbiotic relationship between AMF species, such as *Rhizophagus irregularis*, *Glomus versiforme*, and *Funneliformis mosseae*, which can increase the GRSP (Glomalin related soil protein) in soil (González-Chávez et al., 2004). As a direct result of this, the levels of lead and cadmium in maize decrease while the pH of the soil rises.

To further reduce heavy metal toxicity on host plants, AMF secrete extracellular polymeric substances (EPS) from their fungal surface through surface precipitation, ion exchange, and chelation (More et al., 2014; Riaz et al., 2021). EPS can absorb minerals and elements that are smaller than plant roots. Recent research suggests that phosphate groups with negative charges can cause Cr (III) to precipitate on the surface of fungi (Wu et al., 2021). The importance of glomalin and organic acid excretion by fungi and plants cannot be overstated when it comes to immobilizing 85% of heavy metals (HMs) in soil. By manipulating endophytic fungi, it is possible to minimize metal toxicity to plants, and some of these fungi can even flourish in environments rich in metals. Endophytic fungi possess a range of tolerance mechanisms contributing to their effectiveness in phytoremediation. These mechanisms include extracellular metal sequestration and precipitation, internal metal sequestration and complexation, compartmentation, volatilization, and metal binding to fungal cell walls. Such diverse strategies bolster the potential of phytoremediation efforts (Aly et al., 2011; Sharma and Kumar, 2021). The *Festuca pratensis* and *Festuca arundinacea*, infested with endophytic fungi, grew more biomass in their roots and shoots while significantly degrading the petroleum hydrocarbons in the soil despite growing in ancient petroleum-contaminated soil (Soleimani et al., 2010). The gibberellin-producing endophyte *Penicillium janthinellum* LK5 protects host plants from Cd-induced oxidative stress and membrane damage by decreasing lipid peroxidation and electrolytes and increasing reduced glutathione content and catalase activity (Khan et al., 2014). Canola biomass and Cd extraction efficiency were both increased when the endophytic fungus *Lasiodiplodia* sp. MXSF31 was introduced to *Portulaca oleracea* stems grown in Pb and Cd-contaminated soils (Zanganeh et al., 2022).

4.3 Nanoparticle-soil systems

Nanotechnology has become an essential tool to overcome various agricultural restrictions, including improving nutrient utilization efficiency, reducing toxicity from heavy metals, and enhancing soil fertility through bio-nano formulations (Dave and Chopda, 2014). Sustainable nano-formulations have been shown to improve both plant health and yield. However, the disproportionate usage of nanoparticles (NPs) in numerous fields has contributed to the buildup of these particles in soils, which kill microbiota and plant systems like heavy metals (Malik et al., 2022). Despite these challenges, the soil's physicochemical and biological properties can influence the microbiome's ecophysiology and the stability, toxicity, complexation, and mobility of NPs. NPs accumulated in soil can undergo biological, chemical, and physical changes when interacting with soil systems' inorganic and organic components. Physical phenomena such as aggregation can reduce the mobility of NPs in soils, whether through hetero or homo interactions between the ambient particles and NPs (Balusamy et al., 2021; Goswami et al., 2022; Malik et al., 2022; Chebotaryova et al., 2023).

Furthermore, chemical changes to NPs can occur through surface dissolution, coating degradation, surface modification, abiotic and biotic routes, oxidation, and reduction. These changes are crucial in understanding the behavior of NPs in the soil and their potential impact on plant and soil health. Overall, the use of nanotechnology in agriculture has promising benefits, but careful consideration and monitoring of the behavior of NPs in the soil are necessary to minimize any potential adverse effects (Usman et al., 2020). Soil organic matter (SOM) has a role in the stabilization and absorption of NPs, making it one of many elements that affect their nature (stability and mobility), aggregations, and cohesiveness.

Nanoparticles (NPs) can have their potential impacts mitigated by being absorbed by SOM, reducing the NPs' surface-active area. Soil organic matter (SOM) has been found to increase the solubility of NPs in soil; for instance, CuO NPs were more soluble after SOM addition (Fato et al., 2019; Hemlata et al., 2020).

4.3.1 In what ways do nanoparticles and metals interact?

Heavy metals (HMs) and nanoparticles (NPs) coexist in agricultural settings can have devastating consequences for the soil, crop yields, and microbiota. However, the behavior of NPs can be influenced by several biological and environmental factors due to their distinct physicochemical properties. Therefore, various biotic variables may affect the interaction between HMs and NPs (da Silva et al., 2023; Sabourian et al., 2020). Moreover, the uptake, transport, and accumulation of NPs in different plant organs are also influenced by biotic factors. When present in polluted areas, heavy metals interact with NPs through physical adsorption, chemical interactions, and electrostatic binding (Noman et al., 2020). Such interactions can significantly impact the environment, accumulating these harmful substances in the soil and the food chain. Therefore, it is essential to understand the complex interactions between HMs and NPs in agricultural settings to minimize their adverse effects on the environment and public health. Examples include the adsorption of Cd from the soil by FeO NPs, which were able to do so because of their unique qualities, including reactivity, electrostatic attraction, a wide surface area, and the ability to cap molecules (Manzoor et al., 2021). In this situation, Ca and Fe transporters bring Cd into plant cells. This results in a lower metal concentration within the plant tissues as Cd and FeO NPs compete to enter the plant systems via the same transporter channel (Ahmed et al., 2021).

Similarly, Noman et al. (2020) found that Cu-NPs reduced Cd translocation from soil to aerial parts of wheat because of their wide surface area, reactivity, and electrostatic attraction. Hence, the biogenic CuNPs' capping molecules boosted soil Cd immobilization. As a result, the wheat's development was aided by the plant's ability to absorb Cu-bound nutrients. It functions as a coenzyme in essential reactions and stimulates plant growth and development in polluted soil. As another example, graphene oxide (GO), which has a similarly huge surface area, has been utilized to clean up HMs contaminated areas (Etemadi et al., 2017). For instance, graphene oxide sheets, which, due to their functional group, may conjugate with metals like Cr (VI), speed up the adsorption kinetics of HMs ions (Wang et al., 2017). In conclusion, NPs' metal complexing abilities are anticipated to aid in elucidating how the NPs may effectively reduce metal toxicity.

4.3.2 Techniques for reducing exposure to hazardous metals using nano-bioremediation

Across the globe, researchers have employed multiple approaches, such as physical, chemical, and biological techniques - including phyto and microbial remediation - to decontaminate soil polluted with heavy metals (Yadav et al., 2017; Singh et al., 2020; Sunanda et al., 2022). This is done to ensure that the soil becomes suitable for farming, considering the risks heavy metals pose to diverse life forms. Nevertheless, most of these techniques have only been tested in the lab at bench scales, and those tested in real-world settings have met with scant success for various reasons. Physicochemical methods include excavation and landfill (Funtikova et al., 2023), chemical reduction, evaporation acid leaching, soil washing, soil flushing, precipitation, electrokinetic extraction, vitrification, thermal treatment, and surface capping pose significant issues as mentioned in Table 9 (Rahman and Singh, 2020). The adverse impacts on soil, microbiota, and plant ecosystems are a direct result of the production of secondary metabolites, which can be costly and difficult to eradicate (Gaur et al., 2014; Wang P. et al., 2018). Table 10 outlines the utilization of nanoparticles in the remediation of heavy metals (HMs) and persistent organic pollutants (POPs), showcasing their efficacy in tackling environmental contaminants through innovative nanotechnology-based solutions.

For instance, According to Lambert et al. (2000), FRTR (Federal Remediation-Technologies Roundtable) statistics suggest that excavation and disposal costs \$270 to \$460 per tonne (Feng et al., 2020; Hu et al., 2021). The United States Environmental Protection Agency (USEPA) estimates that, depending on the size of the polluted site, the cost of soil cleaning ranges from \$150 per tonne up to \$250 per tonne.

Selection and placement of plants, irrigation, soil amendment, field monitoring, harvesting, and residue management all add to the price tag of a treatment that relies on phytoextraction. The cost of remediation could range from \$10 to \$35 per ton of soil with low levels of toxins, which also depends on the contamination level and size of the site (Fulekar et al., 2012). Due to the plant-based nature of phytoremediation, the soil treatment process, which typically takes 3 months to 5 years, becomes more expensive and time-consuming (Gavrilescu, 2022; Oladoye et al., 2022). However, the clean-up has failed under natural field conditions due to reliance on specific pollutant characteristics, soil qualities, low efficiency, changing environments, and site conditions. Metal clean-up programs rely heavily on nanotechnology because of the unique physicochemical properties of nanosized particles (NPs) ranging in size from 1 to 100 nm. Furthermore, the nano remediation procedure has successfully removed heavy metals from soil ecosystems and other habitats by exploiting NPs' potential mobility, reactivity (catalysis), and adsorption properties (Corsi et al., 2018; Baragaño et al., 2020; Del Prado-Audelo et al., 2021). Nanoremediation technology is one of the most promising remediation alternatives, and it removes toxic metals through a variety of mechanisms, including

(i) absorption,
(ii) oxide reduction to a stable metallic state,
(iii) heterogeneous catalysis,
(iv) deployment of electrical fields (electro-nano remediation),
(v) photodegradation, and
(vi) the use of biological materials (nano-bioremediation).

Various materials such as polymers, carbon-based compounds, metallic oxides, metals, and nanocomposites have remarkably removed metals (Baragaño et al., 2020). However, the type of metal and pollution source (e.g., biogenic) can affect the efficacy of these materials. Such materials include carbon nanoparticles (fullerenes), semiconductors, noble metals, and magnetic nanoparticles (such as zinc oxide and titanium dioxide). One specific example is Spirulina platensis supported PdNP, which

TABLE 9 Summary of the optimal conditions required for different types of bioremediation processes (Ali et al., 2022; Bhatt et al., 2022; Cepoi et al., 2022; Goswami et al., 2022; Chebotaryova et al., 2023).

Bioremediation process	Optimal conditions (°C)	Key microorganisms involved	Common pollutants treated	Key considerations
Biostimulation	Nutrient addition (N, P), moisture: 15%–30%, pH: 6–8, temperature: 15–45	Indigenous soil bacteria and fungi	Hydrocarbons, petroleum products, pesticides	Ensure adequate nutrient and moisture levels
Bioaugmentation	Specific pollutant presence, pH: 6–8, temperature: 20–35	Introduced specialized bacteria or fungi (e.g., Pseudomonas, Phanerochaete chrysosporium)	PCBs, chlorinated solvents, hydrocarbons	Select appropriate microbial strains for specific pollutants
Phytoremediation	Sunlight, nutrient-rich soil, pH: 5–7, temperature: 15–30	Plants (e.g., poplar trees, sunflowers, Indian mustard)	Heavy metals, radionuclides, organic contaminants	Choose plants with deep roots and high biomass
Bioventing	Aerobic conditions, pH: 6–8, moisture: 10%–20%, temperature: 15–35	Indigenous soil bacteria and fungi	Volatile organic compounds (VOCs), hydrocarbons	Ensure sufficient oxygen supply and monitor gas emissions
Biosparging	Aerobic conditions, Groundwater table control, pH: 6–8, temperature: 10–25	Indigenous or introduced aerobic bacteria	VOCs, BTEX (benzene, toluene, ethylbenzene, xylene)	Optimize air injection rate and pressure
Composting	Aerobic conditions, Moisture: 40%–60%, pH: 5.5–8.5, temperature: 40–60	Thermophilic bacteria and fungi	Organic wastes, explosives, petroleum hydrocarbons	Maintain proper aeration, temperature, and moisture levels
Landfarming	Aerobic conditions, Moisture: 15%–30%, pH: 6–8, Temperature: 15–35	Indigenous soil microorganisms	Petroleum hydrocarbons, pesticides, heavy metals	Regularly till soil to maintain aeration and monitor contaminant levels

TABLE 10 Nanoparticles for remediation of heavy metals (HMs) and persistent organic pollutants (POPs) (Gaur et al., 2014; Wang et al., 2018; Singh et al., 2020; Sunanda et al., 2022; Yadav et al., 2017; Fulekar et al., 2012; Gavrilescu, 2022; Oladoye et al., 2022).

Nanoparticle type	Mechanism for HMs remediation	Mechanism for POPs remediation	Target contaminants (examples)
Metal Oxides (e.g., iron oxide, aluminum oxide)	* Adsorption: high surface area allows for physical binding of HMs. * Surface complexation: functional groups on the nanoparticle surface complex with HMs, reducing mobility. * Precipitation: nanoparticles can induce precipitation of less soluble HM forms.	* Adsorption: organic pollutants can adhere to the nanoparticle surface through hydrophobic interactions. * Degradation: some metal oxides have catalytic properties that degrade organic pollutants.	As, Pb, Cd, Cr, PCBs, PAHs
Metal sulfides [e.g., zero-valent iron nanoparticles (nZVI)]	* Reduction: nZVI can reduce Cr(VI) to the less mobile Cr(III). * Sulfidation: react with dissolved metal ions to form insoluble metal sulfides.	* Dechlorination: can break down chlorinated organic pollutants by removing chlorine atoms.	Cr, Hg, Pb, Cd, PCBs, DDT
Carbon nanomaterials (e.g., carbon nanotubes, fullerenes)	* Adsorption: large surface area for strong adsorption of both HMs and organic pollutants. * Encapsulation: can encapsulate pollutants within their structure, preventing further interaction with the environment.	* Degradation: some carbon nanomaterials exhibit catalytic activity for POP degradation.	As, Pb, Hg, PAHs, PCBs
Biopolymeric Nanoparticles (e.g., chitosan nanoparticles)	* Chelation: functional groups on the nanoparticle bind HMs through chelation, reducing mobility. * Biodegradation: enhance microbial degradation of pollutants by providing a surface for attachment and colonization.	* Adsorption: can adsorb organic pollutants through various interactions.	As, Cd, Pb, PAHs, Pesticides
Dendrimers (synthetic polymers with a branched structure)	* Size-exclusion: can trap HMs within their internal cavities due to size limitations. * Surface modification: functional groups on dendrimers can be tailored for specific HM binding.	* Encapsulation: encapsulate organic pollutants within their cavities, preventing environmental release. * Solubilization: enhance solubility of hydrophobic POPs.	Pb, Cd, Hg, PAHs, PCBs

removed between 12%–90% of Pd from polluted environments (Sayadi et al., 2018). On the other hand, an iron oxide nanoparticle-based on Geobacter sulfurreducens could remove chromium from chromium-polluted soils altogether (O'Neil et al., 2008). Overall, these findings highlight the potential of using different materials and approaches for effective metal removal, which could be tailored based on the type of pollutant and the specific environmental conditions. Nanoscale metal oxide particles (MONPs) made of iron, silver, nickel, and palladium have been remarkably successful in removing toxic metals and other chemicals from polluted areas. Detoxifying Cd stress in wheat plants using FeO NPs increased plant growth, antioxidants, and chlorophyll levels (Manzoor et al., 2021). Cd-phosphate production appears to be the leading cause for decreased bioaccumulation of Cd in soil, and treatment of the soil with $Fe_3(PO_4)_2$ NPs successfully immobilized the Cd by 70% (Gong et al., 2018).

Similarly, another study found that applying biochar-supported FeNPs reduced plant Cr bioavailability (Neeli et al., 2020). Wheat's development and nutrient profile were found to be improved when Cu NPs were present, and vice versa (Noman et al., 2020). Notwithstanding the progress, new NPs that are effective in nano remediation technologies must be discovered. However, this requires researchers to collaborate with local governments, which can back innovations and fund research to identify sustainable nano-solutions for contaminated soils. Compared to traditional clean-up methods, nano remediation technology is typically swift, may be deployed over a broad contamination region, and costs less. According to the USEPA, about 70 potentially harmful trace elements have been effectively cleaned worldwide using nano-remediation techniques, considerably reducing time and operational costs (Feng et al., 2023; Tufail et al., 2022; Yang et al., 2023).

4.3.3 Microbiome-mediated nano-bioremediation of toxic metals

Microbes have long been used in various settings, including the medical, agricultural, and environmental sectors. However, as explained below, the application of microbiome to further optimize nanoparticle usage in the nano-bioremediation process has also shown promising results in detoxifying various inorganic contaminants, hence reducing the limiting potential of bioremediation (Bhatt et al., 2022). Microbiome-based nano-bioremediation has demonstrated substantial progress in detoxifying carcinogenic and mutagenic chromium by employing palladium nanoparticles (Alexakis, 2016). These nanoparticles are synthesized using Pd (II) ions, with the mediation of *Clostridium* pasteurianum. The process involves the conversion of hexavalent chromium into an insoluble trivalent form, resulting in hydrogen gas production.

Similarly, a matrix composed of carbon nanotubes (CNTs), sodium alginate, and polyvinyl alcohol (PVA) immobilized on *P. aeruginosa* has been shown to detoxify Cr (VI) selectively (Pang et al., 2011). At 80 mg/L Cr (VI), the immobilized bacterial cells converted 84% of the compound to the soluble Cr (III), and this process was completed within 24 h. Biotransformation of poisonous Cr (VI) into less harmful Cr (III) has been demonstrated by immobilised cells of Shewanella oneidensis stabilised with CNTs (Yan et al., 2013). Immobilized *S. oneidensis* and carbon nanotubes were four times more effective at removing hexavalent chromium from a solution than the test bacteria or calcium alginate beads alone. Based on these results, it is plausible that nano-bioremediation methods targeting habitats contaminated with inorganic pollutants could benefit from incorporating CNTs with bacteria. Magnetic iron oxide nanoparticles, known as MIONPs, have become popular for removing metals due to their extensive surface area, strong reactivity, adjustable features, distinctive magnetic qualities, potent reducing ability and capacity to soak up various dangerous metals and metalloids (Kumar et al., 2019; Verma et al., 2023). For instance, the *Lysinibacillus sphaericus* prepared magnetic oxide nanoparticles have been shown to release exopolysaccharides (EPS) that act as a complexing, stabilizing, and capping agent and have several binding sites for different metal ions. The EPS-functionalized magnetic oxide nanoparticles (VI) improve the ability to absorb Cr (Kumar et al., 2019).

Similarly, adding iron nanoparticles, produced by Chlorococcum sp. green algae, led to a 92% reduction of Cr (VI) to Cr (III). These nanoparticles were highly reactive, stable, and had a practical ability to reduce (Subramaniyam et al., 2015). Further strengthening algae's role in detoxifying carcinogenic chromium is the incorporation of *C. vulgaris* as a functionalized agent in ultrafine bi-metallic (TiO_2/Ag) chitosan nanofiber mats. According to this study, combining *C. vulgaris* algae with TiO_2/Ag chitosan nanofiber mats significantly boosted the photocatalytic reduction of hexavalent chromium. The researchers observed that various organic compounds secreted by the algae played a crucial role in enhancing the process. As a result, the study implies that the synergistic effect between the algae and TiO_2/Ag hybrid nanomaterial could offer a cost-effective solution for removing chromium from polluted environments (Goher et al., 2016; Awasthi et al., 2018). *Rhodosporidium diobovatum* was responsible for generating lead sulfide (PbS) nanoparticles, which effectively converted toxic Pb (II) ions into less harmful and advantageous compounds (Seshadri et al., 2011). Combining *B. subtilis* and nanohydroxyapatite and the production of CdS nanoparticles from *P. aeruginosa* (NHAP) successfully eliminated Cd from a Cd-contaminated environment. Implementing this remediation approach stimulated the rhizosphere community, leading to a notable rise in bacterial diversity in rapeseed (*Brassica campestris* L.) cultivated in previously contaminated soil (Liu et al., 2018).

4.3.4 Nanoparticles in remediation of POPs

Economic and technological variables must be considered when selecting a treatment technique for POP removal, as they significantly impact POP destiny, transport, and degradation (Zhou et al., 2023). With the rise of nanotechnology, a powerful tool is now available to tackle environmental problems, specifically in purifying polluted treatment solutions. Nanoremediation is a state-of-the-art method that may safely and effectively remove organic contaminants from the environment. Nanomaterials are highly beneficial in many fields due to their extraordinary electromagnetic, structural, mechanical, thermal, and optical capabilities, i.e., in wastewater treatment (Del Prado-Audelo et al., 2021). Various forms of nanomaterials can be created through different methods, including physical, chemical, or biological processes. Many researchers also utilize green chemistry principles to ensure environmentally friendly synthesis. Cutting-edge multifunctional nanomaterials such as nanowires, nanoflowers, and nanocomposites are designed to optimize performance and address existing obstacles (Corsi et al., 2018).

Higher specific surface area (SVR) of nanomaterials enhances their reactivity with POPs. In the upcoming sections, we will delve into nanocatalysis, nano adsorbents, and nanomembranes in POP treatment.

4.3.4.1 Nanocatalysis

Traditional technologies have proven ineffective in completely breaking down and eliminating organic pollutants, leading to a need for a more sustainable approach that minimizes energy and chemical consumption. Exploring advanced oxidation processes (AOPs) as cost-effective solutions due to their powerful oxidizing radicals. Nanocatalysis has emerged as a promising approach for transforming contaminants into eco-friendly compounds by utilizing semiconducting wide-bandgap nanomaterials (Baragaño et al., 2020). Metal and metal-oxide nanomaterials are increasingly recognized for their potential in addressing persistent organic pollutants (POPs) sustainably. Different nanocatalysts, such as Fenton-based, electrocatalytic, and photocatalytic, are used to degrade POPs. Photocatalysis, a widely recognized advanced oxidation process (AOP), utilizes light to activate nanocatalysts, producing reactive oxygen species (ROS) that efficiently break down organic pollutants (Fei et al., 2022). This process is highly effective in dealing with volatile organic compounds (VOCs) such as Dioxins and polychlorinated biphenyls (PCBs) by producing free radicals. When certain nanocatalysts, like ZnO, TiO_2, or WO_3, are exposed to light and oxygen, they become excited and can break down POPs through photocatalysis. Currently, TiO_2 and ZnO are the primary semiconductors employed to degrade POPs (Nandini et al., 2023). Their ability to effectively remove highly hydrophobic POPs is impressive. Important considerations for catalyst selection involve surface characteristics, pore volume, and material structure. Optimizing surface properties and crystal structure improves degradation efficiency. On the other hand, one downside of photocatalysis is the difficulty in eliminating nanomaterial after the reaction.

Lwin et al. (2019) previously produced a cube-shaped ZnO-SnO_2 nanocomposite, showing that it effectively degraded tetracycline hydrochloride. This material showed exceptional photostability throughout its four cycles, which suggests it is suitable for its potential use in cleaning up organic pollutants like POPs. Amir et al. (2016) introduced a nanocatalyst designated $MnFe_2O_4$@PANI@Ag to break down azo dye in their investigation. This nanocatalyst has demonstrated sustained performance during numerous cycles and has the added benefit of being quickly separated with an external magnet. Khan et al. (2018) developed a magnetic Fe-ZnO nanocomposite that efficiently removed the insecticide Chlorpyrifos. Keeping its excellent stability and reusability, the nanocomposite showed remarkable performance, degrading the pesticide quickly. A recent study by Chen et al. (2022) focused on Mn-based nanocomposites and their ability to degrade bisphenol A. The researchers found that these nanocomposites exhibited impressive mineralization and BPA removal efficiency, maintaining their high performance even after multiple cycles. Photocatalysis is a popular choice for wastewater treatment due to its high efficiency and sustainability in combating a wide range of pollutants.

4.3.4.2 Nanoadsorption

With their extensive surface area, adjustable pore size, minimized intraparticle-diffusion distance, and powerful surface activity, nano adsorbents demonstrate exceptional sorption efficiency, effectively trapping a diverse range of pollutants. They can be easily tailored to target specific pollutants, which enhances their selectivity. This technology has effectively eliminated persistent organic pollutants (POPs) such as hydrocarbons, dyes, phenols, and pesticides (Chen et al., 2022). Nanoadsorption has proven to be a highly effective technique for POP remediation by utilizing electrostatic, hydrogen bonding, and hydrophobic interactions. Numerous nanomaterials, such as carbon-based nanomaterials, metal oxides, zeolite, and clay, are widely used in this process. Introducing innovative magnetic separation strategies, magnetic nanoparticles, especially iron oxide, play a crucial role. The microporous structure of activated carbon improves the efficiency of removing POPs, while nano adsorbents made from carbon can interact with contaminants. Carbon nanotubes can significantly boost their adsorption capacity with surface modifications, making them highly efficient in removing pollutants. The adsorption of cyanazine through iron nanocomposites produced using green technologies was examined in a study by Ali et al. (2022). The results showed that cyanazine was rapidly removed, which can be attributed to the short contact time. In recent years, Mahdavi et al. (2021) successfully applied magnetic-graphene oxide treated with amino-guanidine to eliminate chlorpyrifos pesticide. The researchers observed significant desorption through HPLC-MS analysis using a synthesized nano adsorbent. In a recent study, Izanloo et al. (2019) created a nano adsorbent (Fe_3O_4@SiO_2@NH_2@SH) that effectively removed 2,4-D and lead from contaminated environments. The researchers found that the pH level played a critical role in the adsorption of organic contaminants.

Additionally, the nano adsorbent demonstrated consistent desorption efficiency even after multiple cycles. In a recent study, Mohammadi et al. (2018) researched a modified magnetic nano adsorbent. They focused on its ability to rapidly separate pollutants and effectively remove phenoxy-acid herbicides such as 2,4-D and MCPA. Dehghani et al. (2019) evaluated the potential of multi-walled carbon nanotubes (MWCNTs) to remove the herbicide diazinon. They discovered that at pH 6, diazinon was completely removed after 15 min, demonstrating the efficacy of MWCNTs in pesticide cleanup. Utilizing nano adsorbents in wastewater treatment can provide a practical and environmentally friendly approach to removing heavy metals. Additionally, the magnetic variants of these adsorbents can be conveniently separated using external magnets, resulting in reduced operational expenses.

4.3.4.3 Nanofiltration

The introduction of nanofiltration membranes has significantly transformed water treatment systems, bringing about a revolution in nanotechnology. These membranes, along with microfiltration (MF), reverse osmosis (RO), and ultrafiltration (UF), provide highly efficient methods for wastewater treatment, offering alternatives to conventional techniques. Membrane processes are known for their remarkable removal efficiency, especially in organic micropollutants, although they can be quite expensive (Corina-Petronela and Teodosiu, 2007). Their functionality is significantly enhanced by incorporating nanoparticles into membranes using different techniques such as surface immobilization or blending. Electrospinning allows the creation of polymeric or composite nanofibrous membranes that provide incredibly precise filtration ranging from 10 to 1,000 nm. Micro/trace organic pollution can be effectively filtered using membrane techniques like reverse osmosis (RO) and nanofiltration (NF). NF, in particular, is known for its effectiveness thanks to its smaller pore sizes and user-friendly nature (Tibi et al., 2020). Nanofiltration membranes are constructed using a variety of polymers, some of which are naturally occurring and others of which are synthetic. These comprise polyvinyl fluoride, polypropylene, polyacrylonitrile, and cellulose acetate. With their stable adsorption structures, nanofibers effectively eliminate pesticides from wastewater through molecular propagation. Incorporating semiconducting materials into nanofibers enhances their efficiency in dye compound remediation by giving them photocatalytic properties (Oatley-Radcliffe et al., 2017). These nanocomposite nanofiber membranes, such as ZnO-cellulose acetate and TiO_2-graphene, exhibit remarkable photocatalytic efficiency. In addition, combining magnetic nanoparticles with membranes and adding TiO_2 can significantly improve the ability to remediate organic pollutants.

Different filtration techniques, such as ultrafiltration, microfiltration, and nanofiltration, are used to eliminate organic and inorganic pollutants effectively. When combined with biological or chemical methods, filtration can significantly improve the efficiency of remediation. However, the success of this approach depends on various factors, including the type of membrane, modules, composition, and how well it interacts with pollutants. Using pressure dynamics, nanofiltration efficiently targets compounds with low molecular weight (1–10 nm) and reduces the hardness of organic pollutants, decreasing ionic strength. Electrospinning creates nanofibrous membranes that are essential for achieving optimal filtration performance. Nanofiltration is an excellent method for removing arsenic from water because it can effectively separate soluble minerals and other ions.

Karimi-Shamsabadi et al. (2016) examined the efficacy of a thin-film composite poly-amide nanofiltration membrane in removing atrazine and diazinon from wastewater. The researchers found that the membrane had a higher rejection rate for diazinon than atrazine. The modified membranes showed improved water permeability and diazinon rejection, suggesting better pesticide removal performance. In a recent study, Wang et al. (2020) introduced a new type of nanocomposite catalyst. This catalyst, called Al-MOF/Fe_3O_4/PDA@Ag, contains silver nanoparticles and has shown impressive performance in eliminating organic pollutants such as CIP, NOR, and MO. One of the notable advantages of this catalyst is its ability to be easily separated using an external magnet. Additionally, it has demonstrated good reusability and stability, making it a promising option for future applications. Membrane filtration, especially nanofiltration, is widely acknowledged as a secure technology for effectively eliminating low-molecular-weight compounds and pesticides. However, the issue of membrane fouling remains a persistent challenge that can be overcome by utilizing blended techniques.

5 Factors affecting bioremediation

Bioremediation, the process of using living organisms to remove or neutralize contaminants from the environment, is influenced by many factors. These factors can significantly impact the efficiency and effectiveness of bioremediation efforts (Yang Y.-C. et al., 2020). Understanding these factors is crucial for designing and implementing successful bioremediation strategies. One of the primary factors affecting bioremediation is the type and concentration of contaminants present in the environment. Different contaminants require specific microbial communities and enzymatic pathways for degradation. For instance, hydrocarbon-degrading bacteria effectively remove petroleum-based pollutants, while heavy metal-contaminated sites may require metal-resistant bacteria or plants with metal-accumulating capabilities (Yetunde Mutiat et al., 2018).

Additionally, high concentrations of contaminants can inhibit microbial activity, so it is essential to optimize conditions to ensure microbial growth and activity. Environmental conditions such as temperature, pH, oxygen availability, and moisture content also play a critical role in bioremediation (Yadav et al., 2017). Most microbial activity occurs within specific temperature and pH ranges, and extreme conditions can hinder microbial growth and metabolism. Adequate oxygen levels are necessary for aerobic degradation processes, while anaerobic conditions may be required to reduce specific contaminants. Similarly, moisture content affects microbial activity and nutrient availability, with excessive dryness or water saturation inhibiting bioremediation processes (Wang et al., 2023).

The availability of nutrients such as carbon, nitrogen, and phosphorus is another critical factor influencing bioremediation (Tufail et al., 2022). Microorganisms require these nutrients for growth and metabolism, and their availability can limit microbial activity in contaminated environments. Supplementing nutrients through techniques like fertilization or bioaugmentation can enhance microbial growth and biodegradation rates, particularly in nutrient-poor environments. The microbial community present in the contaminated site also significantly influences bioremediation outcomes (Talukdar et al., 2020). Indigenous microorganisms may already possess the metabolic capabilities required for contaminant degradation, potentially reducing the need for external intervention. However, in some cases, the indigenous microbial community may be insufficient to effectively remediate contaminants, necessitating the introduction of specialized microbial consortia or genetically engineered microorganisms. The accessibility and permeability of the contaminated matrix also impact bioremediation efficiency. Contaminants within soil aggregates, pores, or dense matrices may be less accessible to microbial degradation, requiring physical or chemical pretreatment to enhance accessibility. Similarly, contaminants in groundwater or deep soil layers may be more challenging to reach and treat effectively (Sreedevi et al., 2022).

Furthermore, external factors such as regulatory requirements, public perception, and economic considerations can influence bioremediation project planning and implementation. Compliance with environmental regulations, stakeholder engagement, and cost-effectiveness are essential considerations in designing bioremediation strategies.

6 Conclusion

In conclusion, the issue of heavy metal and POPs pollution poses a significant threat to both the environment and human health. To address this problem, bioremediation utilizing microorganisms and plants has emerged as a promising technology to detoxify contaminated soil. Certain microorganisms and plants exhibit strong metal adsorption capabilities, making them well-suited for bioremediation efforts. However, the effectiveness of phytoremediation has been hindered by the slow growth of plants and low remediation efficiency. To overcome these limitations, using plant-associated microbes, particularly PGPR, can enhance the removal efficiency of heavy metals in contaminated soil.

Moreover, nanotechnology offers the potential to remediate hazardous metals, and integrating nanoparticles with bioremediation, known as nano-bioremediation, holds promise for removing harmful contaminants. Understanding the interactions between the soil microbiome, nanoparticles, and contaminants is pivotal for successfully implementing nano-remediation strategies and optimizing crops in contaminated fields. Overall, developing and implementing efficient and sustainable bioremediation strategies for heavy metal pollution are crucial in safeguarding the environment and human health.

Author contributions

AK: Conceptualization, Formal Analysis, Resources, Supervision, Writing–original draft. SM: Conceptualization, Formal Analysis, Resources, Writing–original draft, Validation. AD: Validation, Visualization, Writing–review and editing, Data curation. AA-T: Data curation, Writing–review and editing, Formal Analysis, Investigation, Visualization. TM: Resources, Validation, Writing–review and editing, Data curation, Formal Analysis.

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