Heavy Metal Pollution Mitigation through Bioremediation: Innovations and Prospects

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ABSTRACT

The heavy metals, which include cadmium, chromium, copper, lead, mercury, selenium, cobalt, nickel, zinc, and arsenic, pose a threat to ecosystems and human health as they are toxic, persist in the environment, and bioaccumulate. The entry of these metals into the environment occurs both due to natural processes, such as weathering of rocks and volcanism, as well as due to man-made processes such as mining, industrial effluents, and agricultural runoffs. They reduce agricultural productivity and soil health, and cause drastic health conditions, especially cancer and nerve disorders. Bioremediation is a sustainable and very cheap way of treating the environment as compared to conventional methods because it employs the use of microorganisms (e.g., *Pseudomonas aeruginosa*, *Aspergillus niger*), hyperaccumulator plants (e.g., *Brassica juncea*), and other advanced techniques. The current review focuses on metal-specific approaches of bioremediation, highlighting microbial-based bioremediation and phytoremediation together with newer bioremediation methods like nanotechnology, genetic engineering, bio-electrochemical systems, and artificial intelligence. High removal efficiencies are demonstrated through case studies such as the use of innovative techniques to eliminate heavy metal contamination in industrial sites. However, metal toxicity, environmental fluctuations, and constraints of genetically modified organisms limit scalability. Potential developments are the use of omics technologies and AI-based monitoring in combination with bio-electrochemical systems to increase efficiency and enable applicability in wider fields, which will assist in the sustainability of heavy metal pollution mitigation.

Keywords: Heavy metals, Bioremediation, Genetic engineering, Nanotechnology, Integrated systems, Bio-electrochemical systems

INTRODUCTION

Cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), selenium (Se), cobalt (Co), nickel (Ni), arsenic (As) and zinc (Zn) are the heavy metal contaminants that pose a serious threat to ecology and human health because of their toxicity, persistence, and bio-accumulative ability (Obasi et al., 2022). The sources of such metals are both natural (weathering of rocks in nature and volcanic activities) and human-made (mining, smelting, electroplating, battery manufacturing, and agricultural waste drainage). Their buildup in the soil, water, and living organisms compromises microbial communities, decreases crop production, and leads to serious health complications, such as kidney damage, neurological illnesses, and even cancer (Zahra et al.,

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2017; Wan et al., 2024). Unlike organic pollutants, heavy metals are not biodegradable, and hence there is a need to develop sustainable remediation methods to reduce their effects on the environment and human health.

Traditional treatment techniques, including chemical precipitation and ion exchange, are time- and energy-consuming and do not produce clean end products (Dixit et al., 2015). A cheaper and environmentally friendly alternative is bioremediation achieved by biosorption, bioaccumulation, and biotransformation by microorganisms, including *Pseudomonas aeruginosa* and *Aspergillus niger*, and hyperaccumulator plants, such as *Brassica juncea* (Wolejko et al., 2016). New technologies have even boosted the effectiveness of bioremediation. Genetic engineering offers different tools and technologies to modify microorganisms, like *Escherichia coli*, and overexpress metal-binding proteins, metallothioneins, to increase the uptake and detoxification of metals. Nanotechnology uses nanomaterials with a large surface area and adsorption capacity (e.g., biologically synthesized silver nanoparticles) to remove metals like hexavalent chromium, even when present in low concentrations (Sharma & Sharma, 2022; Ha et al., 2016). The use of microbial fuel cells in bio-electrochemical systems can be used to reduce metal ions, such as by changing the toxic Cr(VI) to harmless Cr(III) ions at the cathodes, helping to recover them and reduce environmental impacts (Gustave et al., 2021; Wang et al., 2022). Artificial intelligence is also widening its use to optimize bioremediation through forecasting of metal behavior in soils and water, screening of efficient microbes, and monitoring of real-time site conditions to enhance bioremediation performance (Alabssawy & Hashem, 2024). Also, several bioremediation limitations are involved that inhibit widespread implementation of bioremediation, such as metal toxicity, the fluctuation of the environment, and regulatory limitations connected to genetically modified organisms (Sinha, 2022).

The current review outlines the process of bioremediation of heavy metals, which is divided into two main categories that include: (1) Heavy metal-specific bioremediation, which outlines the sources, effects, and remediation of each metal, and (2) Technological advances, which discusses genetic engineering, synthetic biology, nanotechnology, bio-electrochemical systems, and AI-driven methods. An application section through case studies demonstrates various applications, including integrated systems to remove copper and zinc at industrial plants located at the Lebanon power plant (Chugh et al., 2022). The article discusses problems and opportunities, such as omics and integrated systems, to enhance the persistent remediation of heavy metals.

Table 1 gives an overview of the sources of pollution from heavy metals, both natural and anthropogenic causes, their environmental and health consequences, and provides an overview of the metals covered in the present review.

Table 1: Sources and Impacts of Heavy Metal Pollution

Heavy Metal	**Natural Sources**	**Anthropogenic Sources**	**Environmental Impacts**	**Health Impacts**	**References**
Cadmium (Cd)	Rock weathering, volcanic activity	Mining, electroplating, battery production, phosphate fertilizers	Soil/water contamination, reduced crop yields, microbial disruption	Kidney damage, cancer	Saini & Dhania, 2019
Chromium (Cr)	Volcanic dust, mineral leaching	Leather tanning, electroplating, textile dyeing	Ecosystem disruption, water contamination	Carcinogenic, cellular damage	Wolejko et al., 2016
Copper (Cu)	Mineral weathering	Mining, smelting, fungicide application	Oxidative stress, reduced plant growth	Cellular damage, liver toxicity	Ali et al., 2013
Lead (Pb)	Tectonic activity	Battery production, smelting, leaded	Soil fertility loss, microbial disruption	Neurological damage, kidney malfunction	Obasi et al., 2022

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		gasoline			
Mercury (Hg)	Volcanic emissions, geothermal activity	Industrial discharges, mining	Bioaccumulation in food chains, ecosystem damage	Neurological disorders, developmental issues	Naz et al., 2022; Chandanshive et al., 2020
Selenium (Se)	Sedimentary rocks	Mining, agricultural runoff	Toxicity at high concentrations, algal blooms	Endocrine disruption, hair loss	Wadgaonkar, 2018; Zgoreleć et al., 2023
Cobalt (Co)	Mineral deposits	Mining, electroplating	Soil contamination, plant stress	Lung irritation, heart issues	Mahey et al., 2020
Nickel (Ni)	Volcanic activity, soil parent material	Smelting, battery production	Reduced microbial activity, plant toxicity	Lung cancer, dermatitis	Chugh et al., 2022
Zinc (Zn)	Rock weathering	Mining, galvanizing, fertilizers	Soil microbial imbalance, plant stress	Gastrointestinal issues, immune suppression	Dixit et al., 2015
Arsenic (As)	Geothermal activity, mineral dissolution	Mining, pesticides	Water contamination, ecosystem disruption	Cancer, skin lesions	Irshad et al., 2021; Prasad et al., 2021

Heavy Metal-Specific Bioremediation

A comprehensive analysis of bioremediation methods that are specific to different heavy metals and their specific properties, performance in the environment, and relative toxicity is important. It outlines potential green solutions to the issue of heavy metal pollution through the lens of the specific difficulties associated with metals, i.e., bioavailability and environmental variability. It presents a link to advanced technologies as well, including genetic engineering and nanotechnology, catering to the potential of sustainable interventions, which are backed by operational case studies (Chugh et al., 2022).

Cadmium (Cd) is one of the highly toxic heavy metals that presents a serious environmental and health hazard because of its persistence and bioaccumulation in the ecosystem. It enters the environment as a result of natural processes, such as rock weathering, as well as human activities, like mining and electroplating, battery production, painting, plastic manufacturing, and phosphate fertilizers (Saini & Dhania, 2019). It can move easily among soil, water, and plants, and it accumulates in crops like rice and leafy vegetables, which could cause serious health implications like kidney damage, loss of bone minerals, and an elevated risk of cancer (Singh et al., 2011; Zahra et al., 2017). Its slow rate of environmental degradation and long half-life make ecosystem destruction more likely, decreasing crop productivity and altering soil microbial composition (Kumar et al., 2022). In contrast to chemical precipitation and other traditional remediation strategies that are expensive and can create secondary pollutants (Dixit et al., 2015), bioremediation is an environmentally friendly and cost-reducing strategy that may be used to treat cadmium pollution using microorganisms and plants.

Microbial bioremediation utilizes microorganisms, i.e., bacteria, fungi, yeast, and cyanobacteria, to remove or decontaminate cadmium-contaminated sites by biosorption, bioaccumulation, and biotransformation. Biosorption involves the immobilization of cadmium to the functional groups of the cell wall of microbes such as *Pseudomonas aeruginosa* and *Bacillus subtilis* (e.g., carboxyl, amine) (Naz et al., 2022). The process of bioaccumulation includes intracellular storage; *Bacillus cereus* and *Rhodobacter sphaeroides* are especially successful when sequestering cadmium in polluted soils (Chellaiah, 2018; Peng et al., 2018). Microbial metabolic processes and efflux pumps (including those encoded by the *cadA* gene, which expels cadmium, or the *czc* operon, increasing resistance to cadmium, zinc, and cobalt) are fundamental elements of microbial resistance mechanisms mediated through biotransformation processes (Naz et al., 2022). It has been found that fungal species, especially *Lentinula edodes* and *Aspergillus niger*, are highly efficient in biosorption because their cell wall has a large chitin content and metal-chelating agents; the biosorption performance of *Lentinula edodes* also appears to be enhanced by its cadmium-binding protein (LECBP) (Dong et al., 2019). Strains of cyanobacteria and yeast also reveal potential in the treatment of cadmium in water bodies.

At the same time, phytoremediation is used to remove cadmium through phytoextraction or rhizofiltration by the use of hyperaccumulators, including *Brassica juncea*, *Helianthus annuus*, *Sedum alfredii*, and *Thlaspi caerulescens* (Wolejko et al., 2016). The induced rhizobacteria, such as *Pseudomonas fluorescens* and *Bacillus megaterium*, enhance plant growth and cadmium accumulation by producing siderophores, ACC deaminase, and indole-3-acetic acid, which increase metal solubilization and plant stress resistance (Wolejko et al., 2016). However, when employing chelating reagents like EDTA to optimize cadmium bioavailability, safety concerns are introduced in the environment, and it is important to carry out proper risk evaluation (Wolejko et al., 2016).

The bioremediation of cadmium is still constrained because environmental factors (pH, temperature, and competitor-metal concentrations) can alter microbial activity and Cd removal by *Arthrobacter nicotiana* and other species (Dixit et al., 2015). In addition, Cd removal is also limited by low soil bioavailability (Wolejko et al., 2016). Laboratory data translation into reality at a field scale has been hindered by variation in bioformulation stability and the high levels of variation in situ. A large-scale implementation of GMOs is also restrained by regulatory aspects, such as the possibility of horizontal gene transfer in genetically modified organisms (GMOs) and social opposition (Sinha et al., 2022).

Recent advances in the bioremediation of cadmium are converging with newer technologies in the treatment of cadmium by microbes. Genetic engineering using the CRISPR/Cas9 system, overexpressing metal-binding proteins in microbes, e.g., metallothioneins, in *Escherichia coli* or *Pseudomonas*, increases Cd bioremediation (Rafeeq et al., 2023). Synthetic biology maximizes synergetic elimination with constructed microbial consortia using Cd-resistant species, as demonstrated in paddy field soils. Nanotechnology enhances adsorption through carbon nanotubes and functional biochar that also shields microbes against adverse conditions (Sharma & Sharma, 2022). Other alternative measures are synergistic plant-microbe systems, such as those of *Brassica juncea* and *Pseudomonas fluorescens*, that make plants more efficient in the uptake of Cd. At the same time, artificial intelligence (AI) is used to select strains and optimize environmental parameters, and the use of nano-biosensors makes it possible to monitor Cd in real-time (Dhanapal et al., 2024). The use of multi-omics profiling approaches reveals the molecular basis of Cd resistance and allows designing durable bacterial strains (Kumar et al., 2022).

Future bioremediation strategies of cadmium should focus on the production of biodegradable and stable carriers, e.g., biochar, to maintain microbial activities in the field. Long-term pilot-level testing presents an essential step to prove the results of laboratory work and demonstrate scale (Kumar et al., 2022). Eliminating regulatory barriers via containment measures and meaningful stakeholder interactions is a necessity in the effort to embrace the use of genetically modified organisms (Sinha et al., 2022). With the involvement of modern technologies, plant-microbe associations, and AI-based optimization, cadmium bioremediation can be transformed into a highly sustainable solution, and thus, the ecosystem and human health will be safer from the effects of this widespread pollutant.

Chromium (Cr) is a naturally occurring heavy metal present in rocks, soils, and volcanic dust that became a major pollutant because of anthropogenic processes that include leather tanning, electroplating, stainless steel production, textile dyestuff manufacturing, and chromate synthesis (Prasad et al., 2021). There are two forms of Cr, the first is trivalent chromium (Cr (III)), which is less toxic, non-soluble, and a trace nutrient, and the second is hexavalent chromium (Cr (VI)), which is highly toxic, soluble, mutagenic, and carcinogenic, has high permeability to biological membranes, and poses serious health effects, such as cancer and cellular destruction (Wolejko et al., 2016). The high mobility of Cr (VI) in aqueous conditions compounds the environmental effects, affecting water ecosystems and water pollution (Patra et al., 2020). Compared to costly and long-term conventional approaches, such as chemical precipitation (Dixit et al., 2015), bioremediation is a

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cost-effective solution capable of removing chromium by reducing Cr (VI) to Cr (III) based on the metabolic properties of microorganisms and plants.

Microbial remediation is a viable technology for chromium removal or detoxification by using the mechanisms of biosorption, bioaccumulation, and biotransformation. The mechanism of biosorption is passive adsorption of chromium (VI) on cell-wall receptors, including carboxyl and phosphate functional groups, as shown in *Pseudomonas aeruginosa* and *Bacillus subtilis* (Naz et al., 2022). In bioaccumulation, active uptake and intracellular sequestration of chromium (VI) take place with a concomitant reduction to chromium (III) by chromate reductases, e.g., ChrR *Bacillus* sp., ltds1, *Acinetobacter junii*, and *Stenotrophomonas acidaminiphila* proved to be better at the reduction of chromium (VI), with *Bacillus* sp. ltds1 growing at 100 mg/L and *Acinetobacter junii* surviving up to 200 mg/L. The process of using extracellular polymeric substances (EPS) by *Stenotrophomonas* allows better sequestration of chromium. Fungi such as *Aspergillus niger* and *Penicillium chrysogenum*, and yeast such as *Saccharomyces cerevisiae* use biosorption capability, like chitin in the cell wall and redox-active metabolites, respectively, for Cr (VI) reduction (Naz et al., 2022). The mixed microbial consortia and biofilm-forming bacteria, such as *Providencia rettgeri* in combination with *Bacillus altitudinis*, demonstrated better chromium (VI) reduction due to the production of extensive extracellular polymeric substances and large surface areas (Naz et al., 2022).

Phytoremediation is also used to remediate chromium by Cr-resistant plants, such as *Brassica juncea* and *Leersia hexandra*, and to aid in phytoextraction, phytostabilization, and phytovolatilization. Chromium is solubilized by root exudates and organic acids through chelation, while antioxidant enzymes control oxidative stress (Kafle et al., 2022). *Bacillus megaterium*, *Pseudomonas fluorescens*, and other plant growth-promoting bacteria (PGPR) can be used to improve the availability of chromium to plants by generating siderophores and acidifying the rhizosphere, which increases its uptake and metal tolerance in plants (Wolejko et al., 2016; Rashid et al., 2021). Bioremediation of chromium faces a number of challenges. Microbial performance is affected by changes in environmental parameters (pH, temperature, and the amount of chromium and nutrients available), with an example being that the bacterium *Providencia rettgeri* is most active at an optimal pH of 9. Chromium bioavailability is also limited in soils, further limiting absorption, and bioformulations are not stabilized, limiting translation of laboratory findings to fields (Wolejko et al., 2016). Other regulatory limits are due to the reluctance to use genetically modified organisms (GMOs) and the risk of horizontal gene transfer, thus limiting large-scale implementation (Sinha, 2022).

Chromium bioremediation is undergoing a revolution owing to complementary advanced technologies. Genetic engineering is the most effective way to increase chromium (VI) reduction, which involves overexpression of chromate reductase genes in microbial hosts, and CRISPR/Cas9-based genome editing of *Pseudomonas* strains is used to optimize resistance (Kumar et al., 2022; Gupta, 2021). Applications in synthetic biology include the engineering of microbial communities that will remediate as many different contaminants as possible and the introduction of biosensors to monitor chromium levels in real-time. Nanotechnology uses magnetic nanoparticles and carbon nanotubes to ensure high capacities of chromium adsorption as well as recovery (Aslam & Mazhar, 2023; Sharma & Sharma, 2022). Bioelectrochemical systems further increase chromium reduction by separating microbes from high concentrations of chromium (VI) through the production of pyocyanin or electroconductive materials such as vertically aligned carbon nanotubes (VACNTs). Integrated strategies such as *Leersia hexandra-Aspergillus niger* combinations further enhance chromium elimination through plant-fungal interactions (Malaviya et al., 2020). The tools powered by artificial intelligence forecast the effectiveness of treatment and nano-biosensors facilitate constant chromium tracking (Dhanapal et al., 2024). Lastly, multi-omics help to understand chromium metabolic routes to successfully build effective engineered strains (Kumar et al., 2022).

Prospective approaches to chromium bioremediation suggest the necessity of the optimization of microbial consortia and the plant-microbe system under variable conditions. Assessment of scalability requires long-term field trials. Biochar (a biodegradable carrier) improves microbial stability (Kumar et al., 2022). The challenge of regulatory factors (by engaging stakeholders and applying containment measures) will enable the adoption of GMOs (Sinha, 2022). With the incorporation of these sophisticated biotechnologies, the Cr (VI) bioremediation technology will significantly protect the ecosystem and human being against its toxicity.

Likewise, Copper (Cu) is a critical toxic pollutant at high levels, which is anthropogenically caused by mining, smelting, electroplating, and fungicide application (Dixit et al., 2015). The accumulation in soils, water, and industrial effluents causes oxidative stress, cellular injury, and ecosystem disturbance, which endanger plant growth and microbial communities. Traditional mitigation technologies are also pricey and produce by-products, which makes bioremediation a more economical, sustainable solution that uses the potential of microorganisms and plants to eliminate or deactivate copper.

Microbial bioremediation of Cu utilizes microbes that remove the metal through biosorption, bioaccumulation, biotransformation, and biomineralization (Palanivel et al., 2020). Biosorption involves passive interaction of metal ions with cell wall functional groups, such as amine, carboxyl, and phosphate residues, which is exemplified by *Pseudomonas stutzeri* LA3 that decreased Cu(II) concentrations from 50–200 mg/L and accumulated around 1.62 mg/g biomass (Palanivel et al., 2020). Bioaccumulation refers to active capture together with the intracellular copper accumulation. Toxicity is reduced through biotransformation in the form of enzymatic reactions typically facilitated by efflux pumps coded by *copA*, *copB*, and *cueO* genes (Andreazza et al., 2011; Wolejko et al., 2016). The result of the process of biomineralization is that the copper is precipitated into stable biominerals, and therefore its mobility is reduced. *Stenotrophomonas maltophilia* PD2, which was optimized using surface response methodology, and *Bacillus cereus*, which was isolated in vineyard soils, stand out as being highly effective in copper removal (Andreazza et al., 2011). The fungi *Aspergillus niger* and *Trichoderma koningiopsis* accumulate copper through chitin cell wall and produce copper nanoparticles, which accelerates the process of bioremediation (Srivastava et al., 2017; Salvadori et al., 2014). The treatment of copper wastewater is even more efficient, along with *Saccharomyces cerevisiae* yeasts and cyanobacteria.

The plants used to perform phytoremediation are copper-tolerant, including *Brassica juncea*, *Helianthus annuus*, and *Zea mays*. Other methods such as phytoextraction, phytostabilization, and rhizofiltration can be also applicable to this process (Bortoloti and Baron, 2022). The siderophores, ACC deaminase, and organic acids produced by plant growth-promoting rhizobacteria (PGPR) such as *Pseudomonas fluorescens* and *Bacillus megaterium* also contribute to the increased uptake of copper by the acidification of the rhizosphere and increasing its bioavailability (Wolejko et al., 2016; Patra et al., 2020). *Penicillium chrysogenum* and *Trichoderma harzianum* are also important fungi that facilitate phytoremediation by strengthening the plant stress defense mechanism and metal solubilization. There are myriad hindrances to bioremediation of copper-contaminated environments. To begin with, microbial efficiency can be significantly affected by environmental heterogeneity, such as a changes in pH, temperature, and copper concentration, among others, as shown by a well-documented strain of bacteria, *Pseudomonas stutzeri* (Palanivel et al., 2020). Second, the low bioavailability of copper in soils limits microbial uptake, and scaling up of lab results to the field is even further compromised due to the instability of current bioformulations (Wolejko et al., 2016). Third, the use of genetically modified organisms (GMOs), especially their possible horizontal gene transfer, is still restricted by certain regulations (Sinha, 2022).

Modern technology is already working against these challenges. Overexpression of the *copA* and *cueO* genes has been demonstrated to be able to promote copper sequestration in a microbial system (Chandanshive et al., 2020; Kumar et al., 2022). On a complementary note, the exploration of stress response pathways has been achieved using multi-omics strategies in order to support targeted metabolic improvements (Chandanshive et al., 2020). Copper nanoparticles synthesized by the fungus *Trichoderma koningiopsis* and biofilm reactors are effective at the nanoscale in enhancing adsorption and overall microbial performance (Salvadori et al., 2014; Chandanshive et al., 2020). *Brassica juncea* and *Pseudomonas fluorescens* are integrated plant-microbe systems that have been constructed to synergistically increase the rates of copper removal (Patra et al., 2020). Simultaneously, models powered by artificial intelligence are being created to optimize the composition of the consortia and site-specific factors, and nano-biosensors allow real-time tracking of copper concentrations (Dhanapal et al., 2024). Lastly, biochar or bioreactors make biomass immovable, hence stabilizing microbe communities that exist in the environment (Hassan, 2023).

Future copper bioremediation studies ought to focus on the development of stable bioproducts, including biochar-immobilized microbes, in order to increase in-situ effectiveness. Extended pilot-scale field tests are

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essential in establishing scalability and optimization of nitrogen dynamics in the soil-plant system to manage copper pollution (Kumar et al., 2022). Eliminating regulatory barriers by developing containment measures, like genetic kill switches, and involving various stakeholders will simplify the use of genetically modified organisms (Sinha, 2022). By blending microbial resistance coping strategies, phytoremediation, and the scaling-up of biotechnology sustainably, copper bioremediation would be sufficient to counter-balance contamination and safeguard ecosystems against its harmful effects.

Lead (Pb) is an extremely toxic, non-biodegradable heavy metal with no biological purpose that contaminates the soil, water, and air through both natural (weathering of rocks) and anthropogenic (battery manufacturing, smelting, mining, leaded petrol, paint, plumbing) processes (Srivastava et al., 2017; Kumar et al., 2022). Its tenacity causes severe health consequences, including anaemia, neurologic harm, kidney failure, and child development dysfunction, and also significantly reduces plant fertility and microbial life. Traditional remediation strategies, especially chemical precipitation, are prohibitively expensive and produce secondary pollutants, which makes the use of both microorganisms and plants in bioremediation a more long-lasting and cost-effective solution (Rigoletto et al., 2020).

Microbial bioremediation applies bacteria, fungi, and algae by means of processes such as biosorption, bioaccumulation, biotransformation, and bioprecipitation. Biosorption is a passive uptake of Pb ions by functional groups in the cell wall, as observed in case of *Bacillus amyloliquefaciens* ON261680.1, which has high lead resistance in industrial effluent (Ridene et al., 2023). Bioaccumulation refers to the active intake and internal storage of lead, whereas biotransformation lowers harm in lead poisoning through redox responses. The bioprecipitation process creates insoluble lead compounds, including lead sulfide or lead phosphate, that result in decreased bioavailability, which was also observed in *Rhodobacter sphaeroides* in contaminated soils. *Klebsiella pneumoniae*, *Pseudomonas*, and *Microbacterium oxydans* (strains CM3 and CM7), and others, use their efflux pumps encoded by *pbrA* and *pbrB* genes to get rid of Pb, thus increasing their resistance (Khan et al., 2023; Patra et al., 2020). Biosorption by fungi such as *Aspergillus niger* and *Trichoderma viride* takes place in chitin cell walls, and endophytic fungi of fescue grasses such as *Festuca arundinacea* are supported by fescue grasses and *Agrostis stolonifera* (Naz et al., 2022).

Phytoextraction, phytostabilization, and rhizofiltration using lead-tolerant plants, including *Brassica juncea*, *Helianthus annuus*, *Vetiveria zizanioides*, and *Solanum nigrum*, are among the phytoremediation strategies used to address lead pollution and mainly bind the metal to the roots because of its low mobility (Bauddh et al., 2015). The mobilization of lead is obtained by organic acids (citrate and oxalate), whereas plant growth-promoting rhizobacteria (PGPR), *Bacillus subtilis* and *Pseudomonas putida,* increase uptake by metal chelation and producing hormones (Wolejko et al., 2016). Plant-fungal consortia, including those between *Solanum nigrum* and native fungi, can increase the remediation of lead-polluted mine tailings. Lead cleaning has some issues, such as low bioavailability, hypertoxicity, and environmental variations (pH, organic matter, temperature etc) that decrease microbe and plant effectiveness (Wolejko et al., 2016). Unstable bioformulations impede the scaling of lab results to the field, and there are regulatory barriers to the deployment of some genetically modified organisms (GMOs) and the risk of horizontal gene transfer (Sinha, 2022).

Lead bioremediation is being improved through advanced technologies. Genetic engineering maximally utilizes lead-binding proteins in microbes, whereas multi-omics allows revealing the pathways associated with the response to stress, which can be increased (Chandanshive et al., 2020; Kumar et al., 2022). Nanotechnology, also biochar-based carriers that improve microbial stability, improves lead absorption. With *Brassica juncea* and *Pseudomonas putida*, integrated plant-microbe systems have the greatest removal capacity by exhibiting synergistic effects (Wolejko et al., 2016). The AI-trained models also optimize the consortia and site-specific conditions, and nano-biosensors allow real-time monitoring of lead (Akintola, 2024; Dhanapal et al., 2024).

The directions to follow are lead-resistant bioaugmentation using microorganisms, biostimulation to create perfect conditions in the environment, and field-ready bioformulations including biochar to increase scalability (Xie et al., 2024). Regulatory solutions, including genetic kill switches and stakeholder interactivity, and long-

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time field tests will ease the adoption of GMOs (Kumar et al., 2022; Sinha, 2022). By combining these methods to safeguard the health of the environment and human society, lead bioremediation can be effective in alleviating its impacts on the environment and human health.

Mercury (Hg) is among the highly toxic heavy metals that cause severe harm to ecozones and human life because of its persistence and bioaccumulation abilities. Mercury is released into the environment via volcanic emissions, as well as through mining and industrial releases, and is present in the form of elemental (Hg0), ionic (Hg2+), and highly toxic methylmercury (CH_3Hg) forms, which biomagnify through food chains, inflicting neurotoxicity and developmental effects (Wu et al., 2021; Tang et al., 2018). Bioremediation is considered a green and economical solution to remove mercury contamination in the soil, water, and wastewater because traditional processes are expensive and unsustainable (Rani et al., 2021; Kumari et al., 2020).

Microbial bioremediation employs biosorption, bioaccumulation, biovolatilization, biomineralization, or enzymatic transformation. Mercury resistance is encoded by the *mer* operon that encodes mercuric reductase (*merA*) and organomercurial lyase (*merB*) and reduces Hg2+ to Hg0 (volatile) and methylmercury to Hg2+, as observed in *Pseudomonas putida*, *Bacillus cereus*, and *Enterobacter cloacae* (Naz et al., 2022; Chandanshive et al., 2020). *Pseudomonas aeruginosa* CH07 can degrade Polychlorinated Biphenyl (PCB) congeners, whereas *Cupriavidus metallidurans* MSR33 can clean soil that has been polluted by mercury (Bravo et al., 2020; De et al., 2006). *Enterobacter* sp. stores mercury in the form of nano-sized particles, and *Pseudomonas veronii* volatilizes Hg2+ intracellularly (Sinha & Khare, 2011; McCarthy et al., 2017). Chemical wastewater remediation is boosted by adsorption in bioreactors through the use of mercury-reducing biofilms (von Canstein et al., 2002). *Aspergillus niger* and *Trichoderma viride* bind Hg using chitinous cell walls, and *Aspergillus* sp. A31 and *Curvularia geniculata* P1 utilise biosorption and bioaccumulation (Pietro-Souza et al., 2020; Ghosh et al., 2023). Mercury is precipitated to form stable minerals by the process of biomineralization and made less mobile.

The phytoremediation of mercury is a perplexing task due to the volatility and strong toxicity of the metal. These are the graminaceous plant *Brassica juncea*, salt-marsh reed *Typha latifolia*, and the floating aquatic fern *Eichhornia crassipes* (Tiodar et al., 2021). Hg detoxification is further improved through expression of the *mer* operon and transgenic insertion of *merA* and *merB* genes. On the other hand, uptake and stress tolerance are enhanced by the presence of beneficial micro-organisms including rhizobacteria and mycorrhizal fungi through glutathione and phytochelatins biosynthesis (Yan et al., 2020; Kumar et al., 2022). Bioremediation of mercury in plants and microbes is often limited by low bioavailability, innate toxicity, and environmental factors such as pH and temperature. Also, commercial bioformulations have low stability, and the use of genetically engineered organisms is subject to regulatory barriers due to the potential transfer of transgenes (Sinha, 2022).

Modern technologies are also important to improve mercury bioremediation. The CRISPR-based editing of the *mer* operon can make the microbes more resistant, whereas nano-biosensors would allow tracking the Hg levels in real-time (Gupta, 2021; Dhanapal et al., 2024). The trapping of bacteria on biochar, especially *Pseudomonas*, significantly increases the degree of remediation, and the application of exoenzymes from earthworm to vermibiochar also increases the process (Rohmah & Retnaningrum, 2023). Artificial intelligence–driven modelling identifies the optimal use of microbial consortia and environmental conditions, and multi-omics studies uncover new resistance pathways (Akintola, 2024; Kumar et al., 2022). Hg removal is also significantly increased through the operation of integrated plant-microbe modules, such as *Brassica juncea* in cooperation with *Enterobacter* (Yan et al., 2020).

Future mercury mitigation approaches for mercury contamination should focus on enhancing Hg bioavailability, developing and implementing field-ready bioformulations, and conducting extended field experiments (Kumar et al., 2022). The incorporation of methods such as microbial consortia and phytoremediation, as well as ways of controlling the process like genetic kill switches, will enhance scalable mercury clean-up (Dave et al., 2020; Sinha et al., 2022). The combination of these innovations allows mercury bioremediation to reduce environmental and public-health risks, thereby allowing ecosystems to be protected.

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Selenium (Se) is an important trace element in biology that is necessary in small amounts, however, it causes serious ecological and human-health problems at large concentrations. It is found as the mobile selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}) forms in aquatic environments, and as the much less-toxic, insoluble elemental selenium (Se^0) form (Eswayah et al., 2016). Mining, agricultural runoff, coal burning, and oil refining are some of the anthropogenic activities that contribute to the main sources of selenium contamination that cause adverse ecological effects, such as altered wildlife reproduction, and human health effects, including the development of selenosis and long-term toxicity (Wadgaonkar, 2018). Bioremediation is a cost-effective and eco-efficient approach that includes the use of biological mechanisms to transform toxic forms of selenium into less-toxic species without causing harm to humans and animals; therefore, it offers a sustainable solution to handling selenium pollution (Versini et al., 2016; Ciobanu et al., 2024). Microbial reduction is commonly achieved by *Thauera selenatis*, *Bacillus* species and *Pseudomonas stutzeri* that are applied to convert selenate and selenite into insoluble Se^0 under anaerobic or anoxic conditions through dissimilatory respiration involving the use of lactate, glucose, or algal biomass as electron donor (Lawson et al., 1995).

Bacillus sp. strain SF-1 converts selenate to selenite and then to the non-toxic Se^0 form. It attains selenium removal almost 99 % in continuous-flow bioreactors that have long residence times (Kashiwa et al., 2001). In contrast, 93.2 % of 5.0 mM selenite is converted into selenium nanoparticles (SeNPs) in *Proteus* sp. YS02 in 24 h. *Thauera selenatis* precipitates selenium as intracellular or extracellular biominerals, which leads to the increased recovery of resources. Testing at the field scale in the San Joaquin Valley showed virtually total removal of selenium. Selenium also can be methylated by microorganisms to volatile compounds that are passed into the atmosphere, including dimethyl selenide and dimethyl diselenide. Nevertheless, control of gaseous emissions is still a challenge (Eswayah et al., 2016; Reamer & Zoller, 1980). Selenium can be attached to the surfaces of microbial cells by biosorption and taken up into their cells by bioaccumulation; recovery of selenium granules can be facilitated using magnetotactic bacteria to form a magnetic nutrient concentrate. The community structure of microorganisms affects the levels of selenium transformation and the efficiency of bioremediation to a great extent, as does the presence of competing electron acceptors (Lai et al., 2014). Fungi also play an important role in selenium bioremediation due to their bioaccumulation, volatilization, biosorption, and myconanotechnology capability; *Trichoderma* strains have been successfully used to produce biogenic selenium nanoparticles (SeNPs), thus improving the process (Lampis et al., 2014). The recovery of toxic Se(IV) by fungal isolates in bentonite clay transforms it into more immobile Se^0 nanostructures, which represent a type of resource recovery bioremediation (Ruiz-Fresneda et al., 2024). Phytoremediation is complementary to microbial methods; *Typha* and *Scirpus* spp. used in phytoremediation facilitate phytovolatilization, where the selenium is converted into volatile organo-seleniums in the root system, and these organo-seleniums are released into the air (Zayed et al., 2020). Selenium is biofortified by plants to stabilize, filter, extract, or even bioaccumulate in soils or water, and antioxidants in crops like lettuce are biofortified, as inorganic Se is transformed into the organic forms.

The anaerobic bioreactors have been reported for an incredible selenium removal efficiency, as some studies reported a complete removal of selenium (Fadaei & Mohammadian-Hafshejani, 2023). A field-scale in-situ trial that employed the saturated rock fill system achieved an equivalent reduction in Se(VI) to less than 3.80 g/L in 114 to 141 days (Hendry et al., 2024). In-situ remedy involves the processes of biostimulation and bioaugmentation, in contrast to ex-situ, which applies the use of bioreactors and the biopile approaches. A microbial reduction/polymeric coagulant, Nalmet 8072 combination, has been used successfully with greater than 97 % selenium recovery in agricultural drainage water. In the meantime, refinery wastewater was successfully treated by pilot-scale units containing *Pseudomonas stutzeri* NT-I (Cantafio et al., 1996; Soda et al., 2012). The critical factors that affect environmental conditions (pH, temperature, and other pollutants), selenium speciation, and microbial community structure determine bioremediation efficiency (Eswayah et al., 2016). In-situ measures involve a combination of soil amendments and microbial consortia, and dredged water plants to treat seleniferous soils and leachates (Wadgaonkar, 2018; Soda et al., 2012). The weak bioavailability of selenium and its toxicity at high concentrations are among the challenges, and higher Na_2SeO_3 concentration also causes dandelion seedling reduction of chlorophyll (Cheng et al., 2024). Future studies ought to emphasize enhancing microbial assemblages, clarifying the selenium respiration pathways, and using cheap electron donors, which can be organic wastes. Integrated solutions involving bioremediation methods with

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genetic engineering can also be used to enhance selenium removal capacities and are essential in the further development of field-scale sustainable selenium solutions (Chauhan et al., 2024).

Cobalt (Co), an essential substrate used in the synthesis of vitamin B12 and various enzymatic mechanisms, is also toxic to living organisms at high levels of exposure because it causes neurotoxicity and oxidative stress in plant, animal, and human organisms (Kosiorek & Wyszkowski, 2020). Natural processes that cause contamination are weathering of Co-rich rocks and volcanic emissions, whereas anthropogenic sources are mining activities, electroplating processes, smelting processes, farm fertilizers and pesticides, nuclear waste storage, battery production, and improper waste disposal. These operations promote the buildup of Co in agricultural land and water, hence reducing yields and leading to threats to human health (Mahey et al., 2020). Bioremediation is a sustainable, economical option to traditional physical and chemical methods of Co removal or detoxification in polluted land or water (Alabssawy & Hashem, 2024). To fulfil remedial purposes, microbial bioremediation uses cyanobacteria like *Spirulina platensis* and bacterial species like *Pseudomonas putida* through mechanisms comprising biosorption, bioaccumulation, biotransformation, bioleaching, and metal precipitation. As an example, *Alphaproteobacterium* MTB-KTN90 is notable in terms of Co removal. In addition, *Bacillus* and *Pseudomonas* isolates that can tolerate metal working in municipal dump sites, agricultural lands, and electroplating sludge are utilized in ex-situ bioreactors to remediate Co (Dusengemungu et al., 2020). Moreover, chosen marine macroalgae, *Ulva fasciata* and *Colpomenia sinuosa*, have powerful biosorption potential.

In some fungal taxa, there are widely differing biosorption capabilities. Fungal strains of *Aspergillus flavus*, *Penicillium citrinum*, *Mucor racemosus*, *Neurospora crassa*, *Mortierella* sp., and *Trichoderma* sp. have biosorption efficacies greater than 1000 mg/g, and as compared to those, *Fusarium oxysporum, Geotrichum* sp. and *Aspergillus tamarii* have low biosorption activity (Rashmi et al., 2004; Pal et al., 2006; Zafar et al., 2007). Filamentous fungi collected in serpentine soils of the Andaman Islands, such as *Aspergillus, Mortierella, Paecilomyces, Penicillium, Pythium, Rhizopus* and *Trichoderma*, were found to be resistant to cobalt and had strong biosorption capacity. The phytoremediation methods apply *Trifolium repens*, *Helianthus annuus*, and *Nicotiana tabacum* to perform phytoextraction (i.e., the accumulation of cobalt in harvestable parts), phytostabilization (i.e., immobilization of cobalt in the soil), and rhizofiltration (i.e., the filtration of cobalt out of water) (Saha et al., 2021; Havryliuk et al., 2021; Jiang et al., 2022; Mahey et al., 2020). In the case of hyperaccumulator plants, e.g., *Elodea canadensis*, an increase in their uptake is observed in co-culture with plant growth-promoting rhizobacteria (PGPR), including *Pseudomonas, Bacillus, and Aspergillus*. The plant growth regulators in the form of the most well-known indole-3-acetic acid (IAA) and ACC deaminase are secreted by rhizosphere microorganisms that favor the growth of plants exposed to cobalt stress. Biochar compost and activated charcoal organic amendments enhance cobalt retention and microbial activity. Bioaugmentation with engineered microbes as well as biostimulation, which involves the addition of nutrients to native microbiomes, lead to more effective bioremediation (Purbalisa & Dewi, 2019; Mahey et al., 2020). Biosurfactants increase the cobalt solubility and bioavailability, which further makes the removal easier (Dusengemungu et al., 2020). Cobalt bioremediation performance is influenced by environmental factors (pH, temperature, nutrient supply, and the presence of co-components of pollution), the chemical form of cobalt (which determines bioavailability and toxicity), and the characteristics of microbial population (Mahey et al., 2020).

Cobalt (Co) bioremediation has three main challenges, including low bioavailability, toxicity at high concentration, and lab-to-field scaling difficulty. To eliminate these barriers, prospective research must focus on biosurfactants, biofilms, and genetically engineered organisms with metal-binding proteins, in order to improve cobalt remediation. Cross-integration of microbial systems with plants and nano-based technologies is another potential direction in this area.

Nickel (Ni) is a transition metal, used in electroplating, alloys, batteries, electronics, and fertilizers, but is necessary only in minor concentrations as an essential element. Nickel causes oxidative stress and photoinhibition at high concentrations in plants. Its industrial and agricultural release to soils and water demands efficient bioremedial techniques and effectively provides a cost-effective and ecologically sound solution to physical and chemical techniques. *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Ralstonia*

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metallidurans, and *Streptomyces* sp. are used for microbial bioremediation. These microbes use mechanisms such as biosorption, bioaccumulation, bioprecipitation, and efflux, using genes like *nreB* and *nikABCDE* to bind nickel using carboxyl, amine, phosphate, and hydroxyl groups. An example of biosorption is mediated by *Acinetobacter baumannii* and *Pseudomonas aeruginosa*, where the rates of adsorption are 8.8 and 5.7 mg•g^{-1}, respectively at pH 4.5.

The intracellular uptake and sequestration of nickel by probiotic lactic acid bacteria is also possible, and the mechanisms of such bioaccumulation are well-characterized nowadays (Beglari et al., 2022; Chugh et al., 2022). In addition, the biogenic precipitation of carbonates catalyzed by *Bacillus cereus* NS4 is said to mitigate the levels of nickel in the soil contaminated with around 900 mg kg^{-1} (Zhu et al., 2016). Biostimulation (addition of nutrients or improving the conditions of growth) and bioaugmentation (addition of nickel-tolerant microorganisms, e.g., *Lysinibacillus* sp. BA2 with the most optimal properties of biosorption at pH 6.0) both proved to be more effective (Abdel-Monem et al., 2010; Prithviraj et al., 2014; Wróbel et al., 2023). Biosorption of nickel by fungi, especially *Aspergillus niger* and *Trichoderma viride*, occurs mainly through the coordination of chelating ligands and enzymatic reactions, also playing a significant part in detoxification. Hyperaccumulator species such as *Alyssum murale, Alyssum corsicum, Brassica juncea*, or *Hybanthus floribundus* are used in phytoremediation through phytoextraction, where nickel is accumulated in plant vacuoles or cell walls. It is often enhanced by the presence of plant-growth-promoting rhizobacteria (PGPR), like *Pseudomonas fluorescens* and *Bacillus megaterium*, which provide increased efficiency due to acid and siderophore manufacturing (Wolejko et al., 2016). Plants also produce phytostabilization, where nickel is immobilized in soils, and rhizofiltration and root systems extract nickel to aqueous solutions.

The efficiency of nickel bioremediation is strongly influenced by environmental conditions, including pH, temperature, nutrient availability, redox conditions, and soil characteristics. These factors affect microbial growth, nickel speciation, metal bioavailability, and the interaction of nickel with soil organic matter and mineral surfaces. The efficiency of microbial remediation can therefore vary considerably among sites, and low metal bioavailability, incomplete removal, microbial toxicity, and difficulties in transferring laboratory-scale results to field conditions remain important challenges. Among the future solutions, genetic editing of microbes and plants and omics approaches to determine nickel-tolerance genes are proposed, as well as nano-enabled delivery platforms to access nickel soil fractions (Chandanshive et al., 2020; Kumar et al., 2022). Research focus in the future must be put on optimized bioremediation strategies, including bioaugmentation, biostimulation, and microbial consortia, in parallel with genetic engineering and integrated microbial-plant solutions in order to increase nickel removal efficiency by the use of molecular biology and consequently achieve sustainable and efficient clean-ups (Tyagi et al., 2011; Dave et al., 2020).

Zinc (Zn) is an essential micronutrient and plays an essential role in tissue repair, enzyme activation, membrane formation, and protein synthesis. However, its increase over physiological levels, which can take place under mining, galvanization, steel manufacturing, smelting, fertilizer distribution, and electroplating, can be harmful, causing phytotoxicity, microbial growth retardation, and wider ecosystem imbalance. To address this, bioremediation presents an environment-friendly and economically viable solution to remove or neutralize zinc pollutants using biosorption, bioaccumulation, bioprecipitation, and biotransformation as major technologies. Microbial bioremediation specifically makes use of bacteria like *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Enterobacter cloacae*, *and Rhizobium leguminosarum* that react with zinc through biosorption, bioaccumulation, and complexation using genes such as *zntA* and *czcCBA* and attach or bind with hydroxyl, phosphate, and carboxyl groups. As an example, *Tsukamurella paurometabola* A155, *Pseudomonas aeruginosa* B237 and *Cupriavidus taiwanensis* E324 isolated from the zinc mines show biosorption/bioaccumulation, while microbial consortia found in nickel smelter sludge and sulfate-reducing bacteria like *Desulfotomaculum nigrificans* lead to bioprecipitation. *Streptomyces* K11 of alkaline aluminum mud also exhibits zinc biosorption. Fungi such as *Aspergillus niger*, *Penicillium chrysogenum*, and *Saccharomyces cerevisiae* provide zinc depletion through biosorption using chitinous cell wall and organic acids, and the use of enzymatic activity and mycelial networks, whereas microalgae act by nutrient removal, carbon dioxide utilization, and biodegradation. Taken together, it indicates the flexibility and efficiency of bioremediation in addressing zinc contamination.

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Marine microorganisms, which include fungi, yeast, bacteria, and microalgae, are a high-potential source of bioremediation of zinc pollution. They are more competent in remediation because of biosorption, bioaccumulation, bioleaching, and biotransformation processes (Alabssawy & Hashem, 2024). Phytoremediation, on the other hand, uses hyperaccumulator species of plants like *Brassica juncea*, *Thlaspi caerulescens*, *Sedum alfredii*, *Helianthus annuus*, and *Populus deltoides*. These vegetations utilize phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization mechanisms (Wolejko et al., 2016; Patra et al., 2020). The bioconcentration factor of zinc is high in aquatic macrophytes such as *Typha latifolia* and *Eichhornia crassipes*, as well as *Zygnema pectiantum* and different types of *Spirogyra* species of algae (Wei et al., 2021). Plant growth-promoting rhizobacteria (PGPR), such as *Pseudomonas fluorescens* and *Azospirillum brasilense*, together with mycorrhizal fungi, increase zinc absorption and plant protection through secreting siderophores and regulating plant hormones (Wolejko et al., 2016; Patra et al., 2020). Environmental factors including soil pH, temperature, nutrient supply, the chemical form of zinc, and plant physiology have an overall impact on the effectiveness of the zinc bioremediation process (Kargar & Shirazi, 2020). Enhancement strategies may be genetic modification of the organism that will increase metal uptake, its degradation, and improve tolerance, or add nanobiotechnological processes that utilize nanoparticles and are more effective. Additionally, microbial/phytoplankton remediation strategies have also become potential targets.

There are many issues with the application of bioremediation to deal with heavy metal contamination, such as the low efficacy in heavily polluted sites, zinc poisoning of existing microorganisms, and the high variation effect, which interferes with the uniformity of the treatment. Hence, the direction of future research should be focused on omics-based mechanisms governing metal transport, applying synthetic biology to the design of high-performing strains, the creation of bio-composite materials, and the integration of AI-based monitoring to support optimized zinc bioremediation (Chauhan et al., 2024; Abo-Alkasem et al., 2023). These initiatives ought to be supplemented with studies on organism adaptations, improvement in genetic modification processes, integration of nanotechnologies, and experimentation with new sustainable clean-up methods (Chandanshive et al., 2020; Kumar et al., 2022).

Arsenic (As) is a carcinogenic metalloid, ubiquitously occurring in mining, smelting, coal combustion, pesticide manufacture, and groundwater, as arsenate (As(V)) and arsenite (As(III)). It imposes severe health issues including skin lesions, cardiovascular disease, and a number of cancers (Srivastava et al., 2017). Due to its environmental and public-health importance, bioremediation is a viable, cost-competitive, and environmentally effective technique to eliminate As, which depends on microorganisms and plants to transform or remove the metlloid (Preetha et al., 2023; Irshad et al., 2021). The microbial pathway to arsenic bioremediation includes proteins *ArsC*, *ArsB*, and *ArsM* that are involved in oxidizing, reducing, methylating, demethylating, and biosorbing arsenic (Chandanshive et al., 2020; Naz et al., 2022). *ArsC* catalyzes arsenate to arsenite, which is exported out of the cell via *ArsB*, and the resulting arsenite is oxidized back to less toxic arsenate through *AioAB*. At the same time, *ArsM* promotes methylation to form volatile methylarsines (Chandanshive et al., 2020; Naz et al., 2022).

A variety of arsenic metabolism processes are observed in microorganisms, especially bacteria, fungi, and algae, among them arsenic oxidation (through the oxidation of As(III) to As(V)), reduction (e.g., arsenate to arsenite or precipitation as orpiment-like As2S3, realgar-like AsS, or arsenopyrite-like FeAsS), methylation, biosorption, bioaccumulation, and biovolatilization are most important (Irshad et al., 2021). The most striking examples are those of arsenic-resistant bacteria growing on contaminated soils, like *Deinococcus radiodurans* R1, which produce iron nanoparticles to chelate As(V), or microbial consortia that can increase the effectiveness of the bioremediation process (Kim et al., 2019). Biosorption and biotransformation abilities were shown by fungi like *Aspergillus niger* and *Penicillium* sp.; viable quantities of *Aspergillus, Trichoderma*, and *Fusarium* grown in media supplemented with sodium arsenate reduce arsenic efficiently (Srivastava et al., 2011). Algae play their part in phycoremediation, which promises low-cost, high-efficiency arsenic removal, making them abundant and environment-friendly (Obuekwe & Ajuzie, 2024; Leong & Chang, 2020). The hyperaccumulator plants, such as *Pteris vittata*, *Brassica juncea*, *Oryza sativa*, *Phragmites australis*, and *Vetiveria zizanioides,* are important for phytoremediation, with *Pteris vittata* showing particularly high performance when used in arsenic removal processes. Plants enhance arsenic uptake, stabilization, or

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degradation, which are mediated by plant-growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF) that enhance root and shoot growth, nutrient uptake, and microbial diversity under arsenic stress, because of trapping of arsenic in spores, vesicles, arbuscules, or adsorption, methylation, bioaccumulation, oxidation, reduction, sequestration, and precipitation. *Bacillus cereus* and *Pseudomonas fluorescens* are types of plant-growth-promoting rhizobacteria that can increase arsenic mobilization through siderophores and antioxidant enzymes, although arsenic speciation and mobility, and interaction with other elements (such as iron and phosphorus) are key factors that hinder their effectiveness (Wolejko et al., 2016; Kumar et al., 2022).

The bioremediation techniques include biostimulation (a change in environmental conditions to activate microorganisms), bioaugmentation (intentional addition of selected microorganisms), genetically modified organisms (GMOs) with their engineered microbial strains, biochar as an effective arsenic absorption material, and bioflocculants to remove arsenic. The occurrence of coexisting elements, pH, and temperature, all environmental factors, increases or decreases the mobility and effectiveness of arsenic sequestration; arsenic trioxide (AsIII) is considerably more toxic and mobile than arsenic pentoxide (AsV). The existing constraints are the natural complexity of the biological ingredients, the spatial and temporal environmental variability, and the continued need to adopt more cost-effective and efficient ways of remediation (Irshad et al., 2021; Shukla & Srivastava, 2017). Future research directions may include addressing omics to explain arsenic detoxification processes, genetically engineered microbes and plants that can overexpress *arsC*/*arsM*, nano-particle-based inoculants, real-time monitoring of arsenic biosensors, and new, more cost-effective approaches to arsenic bioremediation.

In conclusion, the current information outlines the bioremediation methods specific to cadmium, chromium, copper, lead, mercury, selenium, cobalt, nickel, zinc, and arsenic, highlighting their peculiarities in terms of environmental behavior and toxicology. The management of these metals involves classical bioremediation processes that use microbe- and plant-based agents to minimize water and land pollution. These strategies are summarized in Table 2, which shows the bioremediation agents, the heavy metals under investigation, and the molecular or cellular mechanisms that serve as the underlying basis, providing an in-depth glimpse.

Table 2: Mechanistic Overview of Biological Agents in Heavy Metal Remediation

Mechanism	**Bioremediation Agent**	**Heavy Metals**	**Molecular/Cellular Pathway**	**Reference(s)**
Microbial Biosorption	*Pseudomonas aeruginosa*	Cd, Cr, Cu, Ni, Zn	Cell wall binding (carboxyl, amine)	Naz et al., 2022; Alabssawy & Hashem, 2024
	Bacillus subtilis	Cd, Cu, Ni, Zn	Surface binding (carboxyl/phosphate)	Palanivel et al., 2020
Microbial Bioaccumulation	*Bacillus cereus*	Cd	Intracellular storage	Dixit et al., 2015
	Rhodobacter sphaeroides	Pb	Intracellular storage	Su et al., 2020
Microbial Bioreduction	*Providencia* / Cr-reducers	Cr	Cr(VI) → Cr(III)	Dixit et al., 2015; Wolejko et al., 2016
	Pseudomonas aeruginosa CH07	Hg	*mer* operon (Hg^{2+} → Hg^0)	De et al., 2006
	Bacillus / Se-reducers	Se	Selenate → elemental Se	Eswayah et al., 2016; Cantafio et al., 1996
	Deinococcus / As-oxidizers	As	As(III) → As(V)	Irshad et al., 2021; Preetha et al., 2023
Microbial	*Bacillus*	Pb	Lead sulfide/phosphate	Ridene et al., 2023

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Bioprecipitation	*amyloliquefaciens*			
	Streptomyces / Ni-efflux	Ni	Ni efflux (*nreB*)	Naz et al., 2022
Fungal Biosorption	*Aspergillus niger*	Cd, Cr, Cu, Pb, Hg, Zn, As	Chitin-mediated binding	Naz et al., 2022; Ghosh et al., 2023
	Trichoderma koningiopsis	Cu	Nanoparticle synthesis	Salvadori et al., 2014
Plant Phytoextraction	*Brassica juncea*	Cd, Hg	Enhanced uptake / *mer* genes	Yan et al., 2020; Tiodar et al., 2021
	Pteris vittata	As	As uptake in fronds	Irshad et al., 2021; Preetha et al., 2023
Plant Phytostabilization	*Zea mays*	Pb, Zn	Root zone immobilization	Kumar et al., 2022
	Leersia hexandra	Cr	Root zone Cr immobilization	Wolejko et al., 2016
Plant Phytovolatilization	*Typha latifolia*	Se	Conversion to dimethyl selenide	Zayed et al., 2020

This section overviews the key mechanisms and agents of traditional bioremediation in the case of heavy metal pollution. Based on microbial and plant-based procedures, these methods are fundamental to sustainable remedial actions towards the metals discussed in the present manuscript. This part discusses emerging practices, including genetic engineering, nanotechnology, integrated systems, bio-electrochemical systems, and artificial intelligence, which, among other things, enhance metal removal, detoxification, and monitoring. This progress, explained below and summarized in Table 3, builds on current science to overcome previously existing obstacles and introduce achievable remediation methods.

Genetically Engineering and Synthetic Biology for Heavy Metal Bioremediation

The use of genetics and bioengineering is revolutionizing the field of heavy-metal bioremediation by enhancing the capabilities of microorganisms and plants to eliminate, detoxify, and immobilize toxic metals, such as mercury, lead, cadmium, nickel, copper, zinc, among others, from contaminated soils and water bodies, saving the environment and human health (Sattayawat et al., 2021). Compared to conventional physicochemical techniques that can be expensive and produce by-products, these techniques are more sustainable and cost-effective (Thai et al., 2023). Genetic engineering and synthetic biology increase the efficiency and specificity of bioremediation, as well as its adaptability, because they can manipulate genes and build new biological systems step by step, avoiding the constraints of traditional methods (Sharma et al., 2022). Genetic modifications enhance the process of heavy-metal bioremediation by modifying genes involved in heavy-metal transport, transformation, and sequestration (Chen & Wilson, 1997; Barkay et al., 2003; Dixit et al., 2015). As an example, the *mer* operon has been overexpressed in *Escherichia coli*, *Deinococcus geothermalis* and *Pseudomonas putida*, allowing effective detoxification of mercury even at high temperatures (Chen & Wilson, 1997; Barkay et al., 2003; Dixit et al., 2015). In *E. coli*, overexpression of metallothioneins demonstrated greater tolerance and bioaccumulation of heavy metals; among these critical amino-acid residues that optimize the binding of metals, the molecular-docking calculations have established precise alignment of several amino-acid residues. Similarly, *Cupriavidus metallidurans* genetically engineered with plasmid pTP6 that has *merB* and *merG* genes has shown effective mercury detoxification potential (Rojas et al., 2011). These microorganisms can use metal transporters (e.g., MerT/P, GlpF, CopA) and metal-binding proteins (e.g., phytochelatins, metallothioneins) to enable metal uptake and sequestration, and the engineering of the pathways can transform metals to less harmful forms (Manoj et al., 2020; Diep et al., 2018).

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Synthetic biology builds on existing genetic engineering, creating new biological parts, designing or recombining existing parts, or redesigning natural systems in such a way that bioremediation methods would run more smoothly. In this manner, scientists can create genetically modified microorganisms (GMMs) that house a targeted mode of functionality, for instance, high levels of metal transporters or enzymes that process harmful Hg2+ into less hazardous, volatile Hg0 (Sattayawat et al., 2021). Sequential detoxification is also promoted by the creation of synthetic microbial consortia, as different species perform various complementary functions such as the uptake, transformation, or degradation of metals. A good example is the engineered heavy-metal-absorbing strain of *Comamonas*, which offers an environmentally sound solution, whereas, in collaboration with leguminous plants, *Rhizobia* augment phytoremediation efforts. Another facet of synthetic biology includes metal-responsive biosensors detecting heavy metal levels that induce the expression of remediation genes in response to environmental changes so as to adapt and control them in real time (Gupta & Singh, 2017). Field tests with engineered phytoremediation also add value to the subject matter (Yan et al., 2020). Transgenic *Brassica juncea* with *merA* and *merB* genes enhances the speed of mercury volatilization, whereas plants genetically modified with metallothioneins or phytochelatins may accumulate high metal doses in shoots (Yan et al., 2020). However, in combination with nanotechnology, synthetic biology becomes even more efficacious (Thai et al., 2023). Nanoparticles and nanofibers can be used as nanoscale carriers to enable the deposition of catalytic enzymes or microbial strains in polluted environments or to promote adsorption of metals (Thai et al., 2023). An illustrative example includes the use of engineered microbes in arsenic bioremediation to combine the concepts of molecular biology and nanotechnology.

Genome engineering with CRISPR now rivals or replaces the previous tools of ZFNs and TALENs, allowing highly specific changes to be made to confer metal resistance and detoxification. Together with omics technologies, genomics, transcriptomics, proteomics and metabolomics, which are coupled to computational analyses, these tools make it possible to identify new genes and pathways that form the basis of microbial adaptability. These strategies further boost bioremediation options by facilitating the breakdown of organic contaminants, such as 1,2,3-trichloropropane and other pesticides. However, genetic engineering and synthetic biology face a number of constraints (Wolejko et al., 2016). A high level of heavy-metal toxicity may lower enzymatic activity and microbial fitness, whilst field conditions, including changing pH, temperature, and moisture, can frequently decrease performance compared to lab environments (Wolejko et al., 2016). Organic matter enhances soil properties such as redox potential, which decreases the bioavailability of metals and restricts interactions with microbes (Srivastava et al., 2017). In addition, it is difficult to maintain stable inoculants in the field, since bioformulations often face a loss of activity (Patra et al., 2020). Genetically modified microorganisms raise regulatory, ecological, and ethical issues, such as the possibility of horizontal gene transfer, instability of replicating plasmids, and ecological imbalance (Yan et al., 2020; Kumar et al., 2022). Many of the promising microbial species are non-model organisms lacking molecular information or gene-editing systems, constraining their individual manipulation (Kumar et al., 2022). Genetic biosafety methods like kill switches and auxotrophic strains are paramount for limiting unregulated proliferation of GMOs, whereas open dialogue and fair evaluation of risks are significant for societal approval and regulatory guidelines (Sinha et al., 2022).

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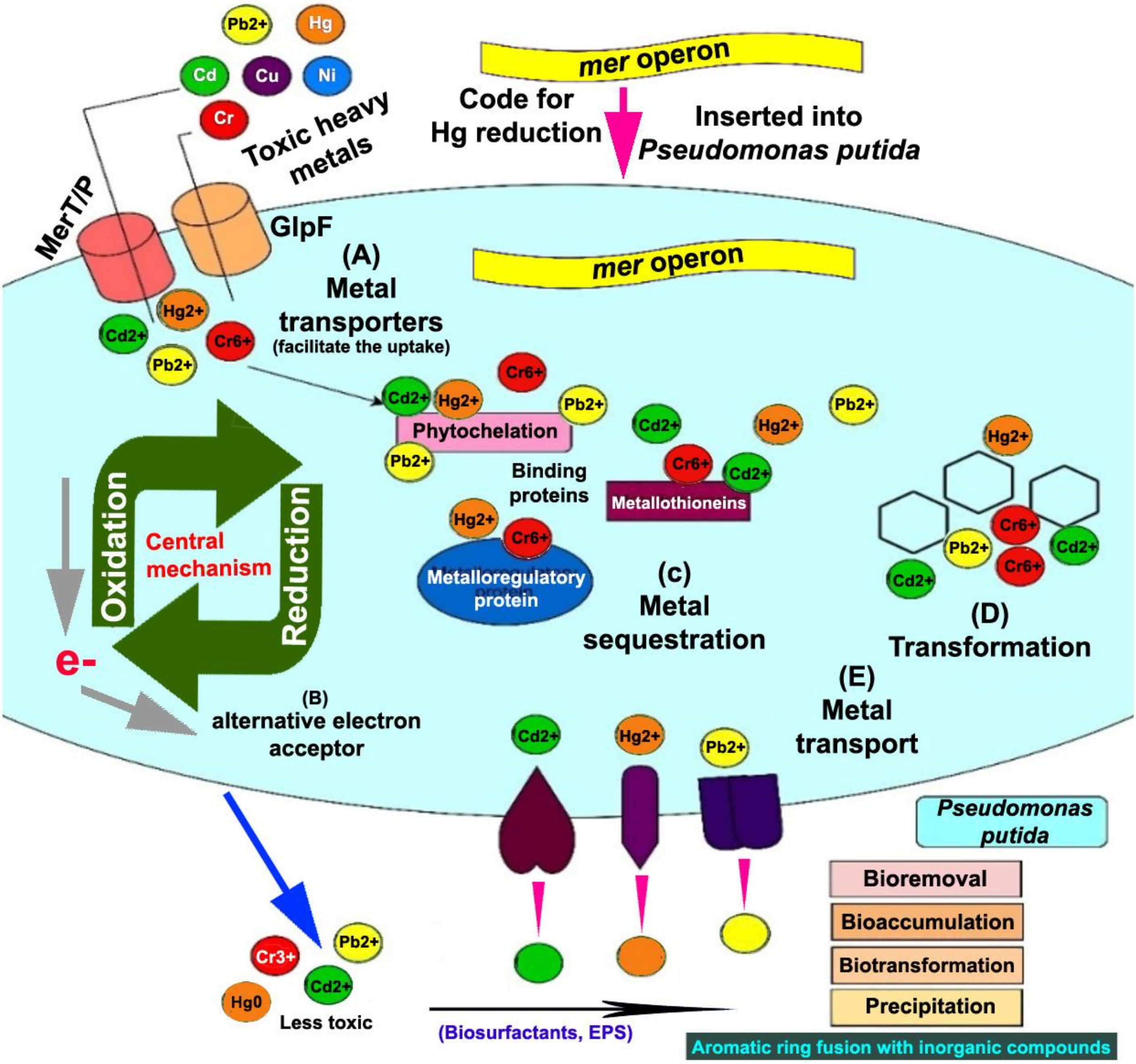

Figure 1: Bioremediation by Genetically Engineered Microbes (Created in http://app.diagrams.net/)

The day should come when the academic community will focus on engineering resilient genetically engineered microbes (GMMs) that will be able to withstand and operate within a broad range of environmental conditions. This can be aided by adaptive laboratory evolution along with the insertion of stress-response genes. The integration of synthetic biology with nanotechnology is another way to achieve improvement, as the optimized microbial consortia could be used to target more specific metals and, at the same time, achieve increased scalability and safety. Responsible deployment requires the involvement of stakeholders and long-term environmental assessment, speaking to the possibility of the value of genetic engineering and synthetic biology in sustainable heavy-metal bioremediation.

Nanotechnology in Bioremediation of Heavy Metals

Nanotechnology provides a potential, sustainable process of bioremediating heavy metals, which leverages the intrinsic characteristics of nanomaterials, i.e., large surface area, strong adsorption capacity, and more functional surface groups, to trap even picomolar levels of metals (Sharma & Sharma, 2022; Malik et al., 2022). Incorporating nanotechnology in bioremediation (nanobioremediation) reduces the toxicity, persistence,

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and bioaccumulation of heavy metals including lead, cadmium, arsenic, and mercury, protecting both the environment and human health (Sudhakar et al., 2020; Ningombam et al., 2024; Bhandari et al., 2021). Unlike traditional methods of remediation, which may become economically unviable and create other pollutants, nanobioremediation allows on-site remediation with little ecological disturbance (Kolluru et al., 2021).

Many nanomaterials, including metal nanoparticles, carbon nanotubes, carbon nanofibers, zeolites, metal oxides, and polymer-based composites, stand out due to efficient binding capacity and short reaction rates in heavy-metal removal (Olawade et al., 2024; Karnwal & Malik, 2024). These substrates allow multiple remediation processes: adsorption through carbon nanotubes or carbon-based surfaces, bioaccumulation to increase microbial uptake, and biomineralization to transform metals into non-toxic forms, redox chemistry to reduce Cr(VI) to Cr(III), biosorption through plant biomass, phytostabilization to reduce the mobility of metals, and phytostimulation to increase plant uptake by microbial action (Chugh et al., 2022; Kanwar et al., 2020). Gels and thin-film nanocomposite nanofiltration membranes, especially those assembled via carbon nanomaterials, demonstrate excellent selectivity and effectiveness in cleaning the water. Nanostructured surface-functionalized nanomaterials and hybrid nanocomposites also improve metal selectivity, stability, and recovery (Dhanapal et al., 2024). Carbon nanomaterials enhance the transfer of electrons, contributing to enhanced microbial reduction of metal ions and an increase in the capacity of bioremediation processes (Dhanapal et al., 2024). Among the nanomaterials, carbon nanotubes, graphene, metal-organic frameworks, magnetic nanoparticles that can be used for rapid separation, and bio-based nanoparticles such as nanocellulose, chitosan, and lignin stand out, as they enhance sustainability (Chen et al., 2022; Sudhakar et al., 2020). By using bacteria, fungi, or plants in the green synthesis process, eco-friendly nanomaterials are produced, which increases cost-effectiveness and sustainability. Nanobioremediation is achieved by microorganisms consisting of bacteria (*Pseudomonas*, *Bacillus*), fungi, algae, and genetically modified organisms (Choudhary et al., 2022; Chan et al., 2024; Leong & Chang, 2020). Palladium and silver nanoparticles produced by biological methods, exhibit robust catalytic properties in reducing hexavalent chromium and degrading dyes (Ha et al., 2016; Ramos et al., 2020).

Nanoparticles prepared by using *Aspergillus tubingensis* are highly efficient in the removal of lead (98%), nickel (96.45%), copper (92.19%), and zinc (93.99%) from wastewater, and they can be regenerated within a short time frame (Mahanty et al., 2023; Kimber et al., 2018). Compared to standalone bioremediation, nanobioremediation increases adsorption, absorption, biotransformation, and bioaccumulation (Kolluru et al., 2021; Bhandari et al., 2021; Hemalatha et al., 2022). It has been used in water purification, such as the decontamination of lead, cadmium, arsenic, and mercury, soil restoration through immobilization or phytoextraction, and the purification of industrial effluents using bio-based nanomaterials (Kolluru et al., 2021; Bhandari et al., 2021; Hemalatha et al., 2022). Further enhancement of metal removal from soil is achieved through nano-phytoremediation, where metal-tolerant plants use nanoparticles to aid soil cleanup (Prakash & Chandran, 2023). The entrapment of microbes, such as *Halomonas* sp., in polyvinylpyrrolidone-coated iron oxide nanoparticles significantly improves the extraction of Pb(II) and Cd(II) (Cao et al., 2020). Nano-biosorbents, with low resistance to diffusion and high chemical activity, outperform traditional biosorbents and can be functionalized to provide specific interactions with metals using groups such as $-NH_2$, -COOH, and -OH (Khati et al., 2017). Phosphorus-enhanced biochar also increases water-remediation stability and reactivity. Magnetic nanoparticles provide recovery and separation, while nanomaterials can act as electron donors in microbial reduction processes or facilitate the delivery of microbes and enzymes, improving their mobility in complex environments. As nano-biosensors, nanomaterials with the capability to change color or fluoresce can facilitate real-time monitoring of contaminant concentrations (Dhanapal et al., 2024).

Despite its promising potential, nanobioremediation still faces several limitations, such as the aggregation of nanomaterials, environmental toxicity, lack of scalability, and difficulties in recovering metals from nanomaterials (Olawade et al., 2024). Other issues include the toxicity of nanoparticles to microbes and ecosystems, the high cost of synthesis, non-targeted adsorption, limited field applicability, lack of regulatory frameworks, and alteration of microbial communities (Mensah et al., 2021; Kaur et al., 2024). The scalability of biosynthesis and nanoparticle purification also remains a problem. Future research should therefore focus on developing biocompatible and biodegradable nanomaterials, such as nanocellulose and chitosan; optimizing nanomaterial–microbe interactions through surface modification; stabilizing and dispersing materials;

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developing cost-effective synthesis methods; and establishing regulatory guidelines (Malik et al., 2022). The utilization of plant–microbe synergies, advanced characterization methodologies, the design of nanomaterials specific to particular metals, and the adoption of sustainable synthesis strategies may further enhance the field of nanobioremediation and minimize its environmental consequences (Malik et al., 2022). Moreover, biocompatibility studies, long-term environmental effects, and compatibility with wastewater treatment systems are vital to guarantee the safe implementation of this technology.

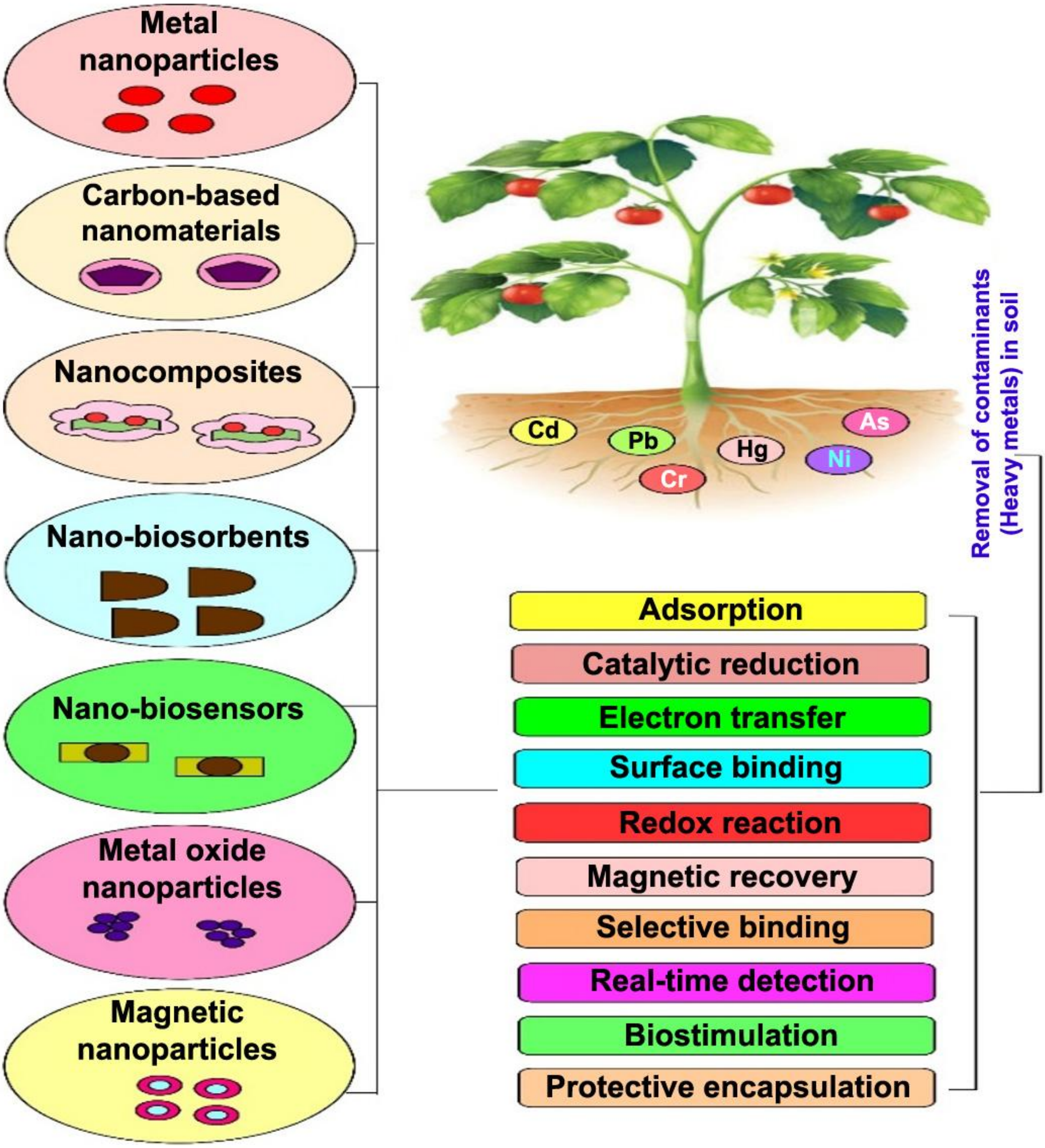

Figure 2: Nanotechnology in Heavy metal Bioremediation (Created in http://app.diagrams.net/)

Integrated Bioremediation Systems for Heavy Metal Remediation

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The multidisciplinary approach of integrated bioremediation systems combines phytoremediation, microbial remediation, phycoremediation, and mycoremediation techniques to remove heavy metals and xenobiotic pollutants from soils and water bodies and offer practical, economical, and environmentally friendly solutions (Arshad et al., 2024; Xu et al., 2024). They take advantage of the synergistic effects of plants, bacteria, algae, and fungi and are often coupled with physical or chemical techniques to augment the elimination or detoxification of pollutants, such as cadmium, copper, zinc, and explosives, including TNT, RDX, and HMX, and to overcome the shortcomings of individual strategies (Sarker et al., 2024). Among biological agents, these coordinated mechanisms can increase the bioavailability of a wide range of pollutants, such as heavy metals, pesticides, and radionuclides. Microorganisms associated with plants, especially plant growth-promoting rhizobacteria (PGPR), significantly improve phytoremediation by producing organic acids and siderophores that increase the mobility and absorption of metals, while metal-tolerant bacteria also increase nutrient uptake and plant growth in response to stress (Rajkumar et al., 2010). PGPR also release growth regulators, such as indoleacetic acid, which strengthens plant resistance and, under some conditions, moderates metal uptake as well. With plant roots, mycorrhizal fungi establish symbiotic relationships that increase the root surface area, enhance nutrient uptake, and sequester metals to counter toxic levels; phytoremediation efficiency has been shown to increase by up to 90%, 127%, and 131% for cadmium at levels of 1, 10, and 100 mg/kg, respectively (Joner & Leyval, 1997). Microbial communities, which include Sphingomonadaceae, Actinobacteriota, Proteobacteria, and Bacteroidota, contribute to soil biodiversity by stimulating nitrogen-cycle enzymes and enhancing the breakdown of pollutants and nutrient cycling through adsorption, intracellular retention, and bioprecipitation (Yang et al., 2021). These bacterial communities are activated by plant root exudates and create a thriving rhizosphere, which also increases the removal of contaminants (Brereton et al., 2020).

Phycoremediation by microalgae, e.g., *Chlorella* and *Spirulina*, can fix heavy metals through extracellular fixation by cell-wall polysaccharides and intracellular complexation with phytochelatins, consequently lowering cadmium, copper, and zinc levels (Chugh et al., 2022). Phycoremediation is more efficient when combined with phytoremediation or microbial systems, although biomass remains a limiting factor. Genetic engineering enhances these capabilities even further (Kurade et al., 2021; Cary et al., 2021). As an example, wheatgrass genetically modified to express bacterial XplA and XplB produced 87% RDX removal, compared to 67% removal in wild-type plants, and 98% RDX reduction was achieved in switchgrass over three years at military ranges in the same study (Kurade et al., 2021; Cary et al., 2021). Through transgenic plants containing nfsI nitroreductase genes, plants were more tolerant of TNT and thus helped to clean up nitroaromatic compounds, while plants engineered to overproduce metallothioneins or phytochelatins can help clean up heavy metals in soil through phytoremediation. The presence of nanomaterials in bioremediation, known as nanobioremediation, has the advantage of providing a more effective and safer option than physicochemical remediation, as they enhance the adsorption and chemical transformation of pollutants. It can be combined with electrochemical or chemical precipitation using biosorption, in which microbial biomass is used to immobilize metals (Alabssawy & Hashem, 2024). Bioleaching, in which metals are dissolved by acids produced by microorganisms, is also combined with other types of remediation to enhance its effectiveness (Alabssawy & Hashem, 2024). Low-cost, scalable remediation includes rhizoremediation, fuelled by root exudates that promote microbial degradation, and mycoremediation using fungal enzymes; in situ mycoremediation is estimated to cost between 10 and 150 per ton of soil in 60 days (Singh et al., 2020). Coupled with thermal treatment, thermo-enhanced bioremediation aims to overcome slow reaction rates; experiments exploring these approaches in soil, groundwater, and microorganisms have been published (Wang et al., 2022). Ammunition testing zones have mycorrhizal communities with greater than 400 ppm of TNT and RDX concentrations, which complement the catalysts in detoxification processes through nitrogen fixation and pollutant polishing (Kumar et al., 2017).

The enzymes secreted by *Podospora anserina, Phanerochaete velutina*, and *Kuehneromyces mutabilis* are reported to enhance the efficacy of remediation manyfold by promoting fungal demethylation of explosives and xenobiotics (Deshmukh et al., 2016; Singh et al., 2022). A significant type of phytoremediation, such as large-scale phytoremediation, most often implemented through inexpensive irrigation, is adaptable to rural or military locations due to its capability to sustain plant and microbial growth (Brereton et al., 2020). Empirical case studies have been successful: cadmium-contaminated soils were inoculated with Salix plants, and the microbial community improved while bioavailable metals decreased; genetically modified switchgrass

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achieved almost 100% RDX degradation (Wang et al., 2021; Cary et al., 2021). Moreover, composite phytoremediation, algal, and microbial approaches have shown significant copper and zinc removal at industrial research stations, such as the Lebanon power plant and the Zadar steel plant (Chugh et al., 2022; Yang et al., 2021). Some of its current uses include phytoremediation of heavy metals, combined pesticide systems, rhizofiltration, biosorption, and bioaccumulation of radionuclides (Karnwal et al., 2024; Sarker et al., 2024). Also, exposure to biochar and selected bacteria contributes to the rehabilitation of soil polluted with metals.

Despite the significant benefits associated with the use of integrated bioremediation systems, they also face a number of challenges. These limitations encompass long-term ecological hazards associated with persistent bioremediation materials, for example, algal biomass or transgenic plants; location specificity caused by unequal soil qualities and recalcitrant compounds; progressively lower treatment speeds compared to traditional methods; governmental restrictions involving genetically engineered organisms; and effective management of biomass to prevent contamination (Sarker et al., 2024). Other issues concern estimating economic viability, ensuring sufficient field performance under complicated conditions, reducing the generation of secondary pollutants, and solving technical or logistical barriers. Future work should focus on optimizing microbial consortia for targeted pollutants, improving genetic engineering strategies for degradation pathways and stress tolerance, assessing long-term ecological implications, developing hybrid systems that combine biological and cost-effective physicochemical treatments such as biochar supplementation, and addressing regulatory approval and stakeholder acceptance (Otaiku et al., 2020).

Bio-Electrochemical Systems (BESs) for Heavy Metal Remediation

Bio-electrochemical systems (BESs) are a novel, sustainable approach to heavy metal bioremediation, combining electrochemical principles with microbial metabolism (Li et al., 2021). The systems rely on the metabolic capabilities of electroactive bacteria (EABs) to mediate extracellular electron transfer (EET) to the electrodes, which support redox reactions to remove, recover, or transform heavy metals in wastewater, soils, and sediments (Li et al., 2021). Unlike traditional physicochemical methods, which can be very expensive and may cause the formation of secondary pollutants, BESs provide a more environmentally friendly, relatively low-cost alternative that is potentially applicable in situ and can have little impact on the immediate surroundings. In BESs, EABs oxidize organic materials at an anode and release electrons to a circuit and the cathode, where heavy metal ions are reduced or transformed (Liu et al., 2024). The electric field causes charged heavy metal ions to move towards the cathode, which is separated from the contaminated matrices (Gustave et al., 2021). The ions are reduced at the cathode and deposited as solid metals, whereby the products may be recovered for reuse or safely disposed of (Wang et al., 2022). EABs also catalyze redox reactions, e.g., the reduction of toxic hexavalent chromium (Cr(VI)) to less toxic trivalent chromium (Cr(III)). Furthermore, the local pH can be regulated in BESs, consequently impacting the solubility and movement of metals; increased pH around the cathode favors the precipitation of metals and reduces the bioavailability of heavy metals (Gustave et al., 2021). Bioprecipitation also relies on microbial activity, which precipitates dissolved metals to entrap contaminants in insoluble complexes.

Biological electrochemical systems (BESs) represent an interdisciplinary field consisting of diverse arrangements, comprising microbial fuel cells (MFCs), microbial electrolysis cells (MECs), and sediment microbial fuel cells (SMFCs) (Wang et al., 2022). MFCs produce electricity while cleaning up metals through anodic oxidation, whereas MECs use an external source of power to reduce the metals (Wang et al., 2022). SMFCs focus on polluted sediments, where they destroy organic waste and eliminate metals by depositing them at the cathode. The microbial community composition affects performance, with heterogeneous electroactive bacterial (EAB) consortia leading to better remediation rates, and the identity of electrode material should be selected based on its ability to transfer electrons; highly conductive, high-surface-area substrates such as carbon nanotubes and graphene are recommended. Metal reduction rates and EAB activity are also affected by operational conditions, such as pH, temperature, and applied voltage (Gustave et al., 2021). BESs have achieved the goals of removing metals from industrial and municipal wastewater, recovering metals from contaminated soils, and reducing metal bioavailability in sediments (Wang et al., 2022; Li et al., 2021). Compared to conventional remediation strategies, BESs have a sustainability advantage as they use

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renewable resources and generate little or no waste, are economical through electricity generation or production of valuable co-products, and can accomplish in situ remediation by eliminating the need for excavation. However, laboratory-to-field scaling is also an issue, particularly where complex mixtures of contaminants and tight economic constraints are involved.

Future research must focus on the development of electrode materials with enhanced conductivity and biocompatibility, the optimization of bacterial-based electroactive systems with increased metal-reduction capabilities, the design of electroactive bioremediation systems to suit specific operational needs, and the integration of electroactive bioremediation with other complementary biotechnologies to enhance overall performance (Chauhan et al., 2024; Gustave et al., 2021).

Artificial intelligence (AI) and machine learning (ML) in heavy-metal bioremediation

Artificial intelligence (AI) and machine learning (ML) have taken central position in advancing heavy-metal bioremediation in several major areas (Akintola, 2024; Abo-Alkasem et al., 2023; Jeyakumar et al., 2022). First, there is an opportunity to use comprehensive genomic, proteomic, and metabolomic data to rapidly identify and optimize microbial strains with high metal-removal capacities (Alabssawy & Hashem, 2024). AI can screen the genomes of bacteria, fungi, yeast, and microalgal species to identify those that are well suited for the transformation or removal of metals such as cadmium, copper, and zinc. Second, ML models can predict the effectiveness of bioremediation processes under a range of environmental conditions, such as pH, temperature, and metal concentration, thereby allowing optimization of the process before field application (Alabssawy & Hashem, 2024). Third, the understanding of important processes, such as biosorption, bioaccumulation, bioleaching, and biotransformation, can be enhanced through AI, which provides insights into complex microbe–metal interactions. These insights can help optimize microbial-remediation approaches (Alabssawy & Hashem, 2024).

AI can also guide the engineering of GMMs designed to perform more effectively in bioremediation. Based on the analysis of genetic information, AI applications can identify modifications that increase metal absorption or detoxification, including engineering bacterial strains to produce large quantities of metal-binding peptides such as metallothioneins. At the same time, AI-based monitoring tools can gather real-time data on contamination levels, soil pH, temperature, and heavy-metal concentrations, and can instantly generate feedback and predictive interventions (Akintola, 2024; Maurya et al., 2024; Blessing & Olateru, 2025). One leading example is the modelling of heavy-metal behavior in soil and water, which allows contamination to be managed and predicted (Yaseen, 2021). The application of AI in river pollution control involves optimized bioremediation measures that address the limitations of conventional approaches and adapt microbial applications in real time (Blessing & Olateru, 2025).

Hybrid forms of artificial intelligence, such as the integration of particle swarm optimization with Extreme Learning Machine (ELM), have been used to predict the costs of in-situ bioremediation systems and increase the accuracy of economic planning. Despite these promises, the use of artificial intelligence and machine learning in bioremediation is hampered by several limitations, including difficulties in acquiring large and high-quality training datasets, the complexity of microbial interactions in heterogeneous environments, and the possibility of unexpected ecological side effects (Table 3 and Maurya et al., 2024; Blessing & Olateru, 2025). Future research should focus on developing advanced AI models capable of handling complex datasets, integrating AI with other emerging technologies such as nanobioremediation and genetic engineering to optimize performance, and addressing ethical and regulatory challenges to ensure the safe implementation of such systems (Maurya et al., 2024; Blessing & Olateru, 2025). The combination of bioremediation approaches with the power of artificial intelligence and machine learning can help researchers develop more efficient, predictive, and sustainable strategies for heavy-metal removal, representing another step towards improving the overall environmental cleanup process (Maurya et al., 2024; Blessing & Olateru, 2025).

Table 3: Technological Advancements in Heavy Metal Bioremediation

Advanceme	Technology	Mechanism	Applications	Examples	Challenges	References

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nt	/Approach					
Genetically Engineered Microbes and Plants	Gene insertion (*mer* operon)	Enhances metal reduction, transport, sequestration	Mercury detoxification in soils, water	*Pseudomonas aeruginosa CH07* with *mer* operon; *Enterobacter sp.*	Gene transfer risk, public resistance	De et al., 2006; Sinha & Khare, 2011
	CRISPR/Cas9 gene editing	Precise gene regulation/editing	Enhanced resistance to Cd, Pb, Hg	Engineered microbes	Limited tools for non-model organisms	Yan et al., 2020; Shapiro et al., 2018
	Engineered plants	Overexpression of detoxification genes	Hg, As volatilization	*Brassica juncea* transfected with *merA*, *merB* genes	Regulatory barriers, ecological concerns	Yan et al., 2020
	Multi-omics and computational biology	Maps resistance pathways, optimizes strains	Co-contaminant removal (metals, organics)	*Arthrobacter*, *Chlorella*, *Stenotrophomonas*	Data complexity, limited field validation	Bose et al., 2019
Nanotechnology in Bioremediation	Green-synthesized nanoparticles	Adsorption, reduction	Cr^{6+} removal	NPs from fungi/plants	Scalability, potential toxicity	Sharma & Sharma, 2022
	Functionalized nanomaterials	Selective metal binding	Pb, Cd, Ni, Zn removal	Carbon nanomaterials	Aggregation, environmental toxicity	Malik et al., 2022
	Nano-bioremediation	Synergistic biological–nano systems	Pb, Cd, Cr detox	*Halomonas* with NPs	Toxicity, ecological safety	Dhanapal et al., 2024
	Nano-phytoremediation	Nanoparticle (NP)-assisted plant uptake	Soil remediation	Engineered plants + NPs	NP release, bioaccumulation risk	Prakash & Chandran, 2023
	Nano-biosensors	Real-time monitoring	On-site detection of metals	Fluorescent/colorimetric NPs	Standardization, durability	Dhanapal et al., 2024
Integrated Approaches	Algal bioremediation (phycoremediation)	Extracellular/intracellular metal sequestration	Cd, Cu, Zn detox	*Chlorella*, *Spirulina*	Biomass handling, persistence	Liu et al., 2024
	PGPR and mycorrhizal fungi	Improves uptake, solubility, tolerance	Phyto-assisted remediation	*Pseudomonas fluorescens*, *Bacillus megaterium*	Field variability, consistency	Rajkumar et al., 2010
	Bacterial	Synergistic microbial	Multi-metal	Biofilms	Competition, stress	Wolejko et al.,

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	consortia	action	remediation		survival	2016
	Mycoremediation	Enzymatic breakdown, biosorption	Lead, TNT remediation	*Trichoderma*	Moisture, scale-up	Deshmukh et al., 2016
Bio-electrochemical Systems (BESs)	Microbial fuel cells (MFCs)	Electricity generation + metal reduction	Cr, Hg removal	Anode-colonizing EABs	Electrode fouling, cost	Gustave et al., 2021
	Sediment microbial fuel cells (SMFCs)	Organic degradation + metal reduction	Sediment remediation	Sediment EABs	Limited field data	Abbas et al., 2019
Artificial Intelligence and Machine Learning	Strain optimization	Enhances microbial performance	Cd, Pb monitoring	ML models	Data needs, ecological risks	Akintola, 2024
	Predictive modeling	Simulates metal behavior	River pollution control	AI-optimized bioremediation	Model complexity	Yaseen, 2021

A look at the modern life-changing innovations of genetic engineering, nanotechnology, integrated systems, bioelectrochemical methods, plus artificial intelligence reveals the state of preparedness in the application of these technologies. The case studies published in this section show how these tools are already being contextualized to the treatment of contaminated sites, as they have been proven to achieve the removal or render harmless heavy metals including cadmium, chromium, and nickel, thus facilitating the foundation of scalable and cost-effective remedial actions.

Case Studies: Experiential Uses of Heavy Metal Bioremediation

The industrial and agricultural activities that cause heavy metal contamination are a grave environmental challenge accompanied by human-health issues (Saini & Dhania, 2019; Rehman et al., 2023; Hassan et al., 2017). One such solution is bioremediation, which makes use of the natural metabolic capabilities of organisms in order to sequester or detoxify pollutants in a natural, environment-dependent, and sustainable solution (Padhan et al., 2021; Wróbel et al., 2023). In the sequel, examples of bioremediation efficacy are given regarding metals such as Cd, Cr, Cu, Co, Hg, Se, As, and Ni in landscapes (soils and sediments) and water bodies (Table 4).

In microbial bioremediation, bacteria play a major role. Chromium (Cr), copper (Cu), and cadmium (Cd) in electroplating wastewater have been removed using the gram-positive *Bacillus cereus* (Trihadiningrum, 2014). Sulfate-reducing bacterium SRB1-1, which was obtained from cadmium- and lead-polluted paddy fields, was shown to be highly resistant to both metals and demonstrated strong potential for their removal (Shan et al., 2019). *Pseudomonas aeruginosa* holds prospects in chromium removal (Chellaiah, 2018), whereas various metal-resistant *Pseudomonas* strains extracted from Bleeding Mire Lake sediments bioaccumulate zinc, cesium, lead, arsenic, and mercury and, in the meantime, solubilize copper (Li & Ramakrishna, 2011). A number of *Klebsiella* species isolated from diesel-contaminated soil exhibit heavy metal removal potential from effluent water (Aransiola et al., 2017). Biofilm-forming marine bacterium *Pseudomonas chengduensis* PPSS-4 can sustain bioremediation in the presence of lead (Pb(II)), chromium (Cr(VI)), and cadmium (Cd(II)) (Priyadarshanee & Das, 2021). At the same time, *Jeotgalicoccus* sp. CR2 isolated from the Yamuna River exhibited high removal rates of nickel (Ni), copper (Cu), lead (Pb), and zinc (Zn) (Kumari et al., 2022). The combination of *Paenibacillus jamilae* and *Bacillus subtilis* with *Moringa* and nano-silicon decreases the amount of metals in soil where spinach is grown (Eltahawy et al., 2022). Metal immobilization is biogeochemically mediated by microbial consortia in landfill soil.

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Phytoremediation depends on plants to immobilize or sequester heavy metals. *Acalypha indica* and *Amaranthus viridis* intercropped in multi-metal-contaminated soil bioaccumulate lead (Pb), cadmium (Cd), chromium (Cr), cobalt (Co), and nickel (Ni), with consistent Pb and Cd translocation factors (Ramanlal et al., 2020). In floating vegetated systems, *Pistia stratiotes* can uptake lead (Pb), zinc (Zn), chromium (Cr), copper (Cu), and nickel (Ni) through phytoaccumulation and rhizofiltration. *Amaranthus dubius* removes and sequesters nickel within polluted locations (Mellem et al., 2009).

Microalgae have important potential for heavy-metal bioremediation because they can remove metals through mechanisms including biosorption and bioaccumulation (Leong & Chang, 2020). *Arthrospira*/*Spirulina* and other microalgae have been investigated for the removal of several heavy metals, including Cd, Cr, As, and Hg (Leong & Chang, 2020). Integrated systems can further improve remediation performance. For example, membrane distillation coupled with microalgal bioremediation has been investigated for arsenic-contaminated river water, with *Botryococcus* sp. used to bioremediate the arsenic-rich retentate (Hubadillah et al., 2020). Similarly, a biochar–microalgae complex based on coconut-shell activated carbon and *Chlorella* was investigated for arsenic and mercury removal (Jiang et al., 2023). Chitosan-modified biochar has also been shown to enhance Cr(VI) bioreduction and Cr(III) adsorption through processes involving extracellular electron transfer (Yu et al., 2023). Ion flotation using sodium dodecyl sulfate (SDS) has been demonstrated for Cd, Cu and Cr removal from aqueous solutions, with particularly high removal efficiencies for Cd and Cu (Benmansour et al., 2024). Microbial remediation approaches more broadly include biosorption, bioaccumulation, biotransformation, biomineralization and bioleaching (Pande et al., 2022).

Table 4: Summary of Case Studies in Heavy Metal Bioremediation

Organism/Method	**Targeted Metals**	**Remediation Method**	**Key Findings/Applications**	**References**
Bacillus cereus	Cr, Cu, Cd	Microbial bioremediation	Removal in electroplating wastewater	Trihadiningrum, 2014
SRB1-1 (sulfate-reducing bacterium)	Cd, Pb	Microbial bioremediation	High resistance and removal in paddy fields	Shan et al., 2019
Pseudomonas aeruginosa	Cd	Microbial bioremediation	Cd remediation	Chellaiah, 2018
Pseudomonas strains	Zn, Cs, Pb, As, Hg, Cu	Microbial bioremediation	Bioaccumulation and Cu solubilization	Li & Ramakrishna, 2011
Klebsiella species	Heavy metals (effluent)	Microbial bioremediation	Treatment of contaminated water	Aransiola et al., 2017
Pseudomonas chengduensis PPSS-4	Pb, Cr, Cd	Microbial bioremediation	Biofilm-based removal	Priyadarshanee & Das, 2021
Jeotgalicoccus sp. CR2	Ni, Cu, Pb, Zn	Microbial bioremediation	60–100% removal efficiencies	Kumari et al., 2022
Paenibacillus jamilae + B. subtilis	Heavy metals (soil)	Microbial + nano-silicon	Reduced metal in spinach soil	Eltahawy et al., 2022
Pistia stratiotes	Pb, Zn, Cr, Cu, Ni	Phytoremediation	70–85% removal via phytoaccumulation	Samal & Dash, 2024
Amaranthus dubius	Ni	Phytoremediation	Translocation and accumulation	Mellem et al., 2009

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Arthrospira platensis + Spirulina sp.	Cd, Cr, Hg, Se	Microalgal bioremediation	CO2 sequestration + metal removal	Singh et al., 2024
Membrane distillation + microalgae	As	Integrated bioremediation	Excellent As rejection	Hubadillah et al., 2020
Biochar-microalgae complex	As	Integrated bioremediation	As removal	Jiang et al., 2023
Biochar + chitosan	Cr(VI)	Biochar-enhanced bioreduction	Accelerated electron transfer	Yu et al., 2023
Ion flotation (SDS)	Cd, Cu, Cr	Chemical-biological hybrid	Removal from aqueous solutions	Benmansour et al., 2024
Halo-alkaliphilic microbes	Heavy metals (extreme)	Microbial bioremediation	Remediation in high-pH/salinity	Li & Liu, 2020

Challenges In Heavy Metal Bioremediation

Bioremediation is a long-term, economic solution to overcome heavy-metal contamination of soils and water, with the potential to exemplify significant promise within controlled laboratory conditions (Dixit et al., 2015). However, the ability to transfer these methods to a real-setting field environment is riddled with biological, environmental, technical, and regulatory challenges that limit scaling and efficacy (Wolejko et al., 2016; Sinha et al., 2022). The challenges and the suggested solutions are outlined in Table 5. The inability of heavy metals to support the growth of microbes or their enzyme activities due to their inherent toxicity must rank top on this list (Rashid et al., 2021; Patra et al., 2020). Increased levels of Cd, Cr, and Hg, to name a few, lower the survivability of other resilient species, including *Bacillus cereus*, *Pseudomonas putida*, *Aspergillus niger*, and *Rhizopus arrhizus*, thus restricting their detoxifying effect (Rashid et al., 2021; Patra et al., 2020). Microbial performance is also compounded by the real-world conditions in the field, where pH changes, temperature differences, and moisture swings are observed, and optimal conditions in the lab (e.g., pH 9 for *Providencia stuartii* in Cr bioremediation) are seldom reflected in the field (Wolejko et al., 2016; Kumar et al., 2022). Moreover, soil characteristics also introduce other challenges: pH, redox potential, organic matter, as well as chelating agents influence the bioavailability of metals, which reduces microbial interaction with those contaminants, including Pb and As (Srivastava et al., 2017). The performance of microbial inoculants in the field is also affected because bioformulations can deteriorate in efficacy over time or in response to severe environments, leading to unreliable performance (Patra et al., 2020; Lu et al., 2022). Such novel technologies as genetic engineering and synthetic biology may improve the ability of microbes to resist and transform metals like Ni and Cu (Srivastava et al., 2017; Yan et al., 2020), although introducing them into the environment poses serious challenges.

Complicated regulatory concerns and ecological uncertainties surrounding horizontal gene transfer, plasmid instability, and alterations to the native microbial community affect the research and deployment of genetically modified organisms (GMOs), such as *Escherichia coli* engineered to harbor genes that sequester metals (Gupta, 2021; Yan et al., 2020). Only a small number of non-model organisms have well-rounded molecular data and gene-editing infrastructure, representing one of the main barriers to fine-scale manipulation (Kumar et al., 2022). Regulatory frameworks on the use of GMOs still need more development, and strong public opposition slows their usage, especially in developing areas (Sinha et al., 2022). Such issues are made worse by technical challenges, including electrode fouling of bio-electrochemical systems (BESs) or nano-aggregation in nanotechnology (Gustave et al., 2021; Sharma & Sharma, 2022). The site-specific complications highlighted by the case studies are variable Ni and Cu removal efficiencies (Kumari et al., 2022) and biomass management, which may cause recontamination (Sarker et al., 2024). To tackle these barriers, thorough risk evaluation, prolonged ecological surveillance, and effective stakeholder participation are required in order to ensure safe and successful bioremediation in a variety of environments.

Table 5: Challenges and Solutions in Heavy Metal Bioremediation

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Challenges	Observed Issues	Biological Impacts	Proposed Solutions	References
Microbial Stress	Ni inhibits microbial activity.	Metabolic impairment	Optimize pH (5.0–6.0)	Kumar et al., 2022
	Hg toxicity reduces survival.	Enzyme inhibition	Biochar stabilization	Kumar et al., 2022
Environmental Variability	Temperature impacts Cu biosorption.	Reduced activity	Bioreactor temperature control	Palanivel et al., 2020
	Low Pb/As bioavailability	Limited microbial access	Chelators (e.g., EDTA)	Wolejko et al., 2016
Technical Limitations	Unstable bioformulations	Inconsistent field performance	Biochar-based carriers	Lu et al., 2022
	Scaling lab to field	Incomplete metal removal	Pilot-scale trials	Kumar et al., 2022
Regulatory Concerns	GMO gene transfer (E. coli)	Horizontal gene transfer	Kill switches	Kumar et al., 2022
	Public resistance to GMOs	Delayed deployment	Stakeholder engagement	Sinha et al., 2022

Existing challenges facing heavy metal bioremediation limit the potential of remediation, but they also serve to highlight the strategies that can be viable (Chandanshive et al., 2020). These shortcomings will help the next generation of discovery in the field of bioremediation.

Future of Heavy Metal Bioremediation

To make headway in the world of heavy metal bioremediation, molecular biology, material science, and data-driven technologies must be used to create contaminant-specific, scalable, and sustainable alternatives for Cd, Cr, Cu, Pb, Hg, Se, Co, Ni, Zn, and As (Chandanshive et al., 2020). The use of multi-omics, including genomics, proteomics, transcriptomics, and metabolomics, can reveal the pathways of microbial resistance and identify genes and proteins that can be engineered into robust strains that have improved uptake and detoxification of the metals (Kumar et al., 2022). These forms of molecular biomarkers allow real-time bioremediation performance monitoring in situ (Gupta, 2021). Genetic engineering and synthetic biology have large potential: CRISPR/Cas9-enabled overexpression of metal-resistance genes or detoxifying factors, such as *Pseudomonas aeruginosa* to volatilize Hg or *Brassica juncea* to accumulate Cd and Pb (Yan et al., 2020). Sequential metal removal can be optimized through synthetic microbial consortia: in the case of Cr reduction, *Providencia rettgeri* and *Bacillus altitudinis* were used. Nanotechnology can enhance the ability of bioremediation with techniques such as enhancing metal solubility and mobility using nanomaterials such as carbon nanotubes or bio-based nanocellulose to enable access to Pb- and As-contaminated sites by microbes (Sharma and Sharma, 2022). Real-time observations of metal levels will be possible with nano-biosensors, whereas nanocarriers will enhance a steady release of bioinoculants or enzymes that can resist soil stressors (Srivastava et al., 2017). Microbial resilience to toxicity, desiccation, and pH changes will be enhanced by the use of biofilms and immobilization matrices such as alginate and chitosan (Wolejko et al., 2016). The development of new 3D-printed biocarriers and novel delivery systems will allow further performance in this field (Lu et al., 2022).

The use of artificial intelligence (AI) and machine learning in the design of bioremediation is yet to change the field because it can be used to predict the outcome of bioremediation in real time, optimize the choice of strains, and dynamically adjust the parameters used, such as pH and temperature, based on field information (Akintola, 2024). The synergistic effects will be exploited through integrated systems that incorporate multiple processes that strive to fully remove a specific pollutant, like phytoremediation-microbial remediation-nanotechnology integration (i.e., *Pteris vittata* and *Aspergillus niger* for As removal (Raj et al., 2015)). Field

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trials are necessary to verify the lab outcomes and reproduce the scalability in the long term (Kumar et al., 2022). At the same time, regulatory procedures need to focus on the safety of GMOs in terms of stringent risk analysis and stakeholder consultation to avert apprehensions on the part of the population (Sinha et al., 2022). The interdisciplinary developments aim to remediate 70 percent of polluted sites by the year 2030, thus creating ecological balance and sustainability (Table 6).

Table 6: Future Prospects in Heavy Metal Bioremediation

Future Direction	**Application**	**Heavy Metals Addressed**	**Expected Outcome**	**Reference**
Multi-Omics Analysis	Genomics, proteomics mapping	Cd, Hg, Pb, As	Identify resistance genes	Kumar et al., 2022
Genetic Engineering	CRISPR/Cas9 for microbial strains	Hg, Cd	Enhanced metal tolerance	Gupta, 2021
	Plant modification (e.g., *Brassica*)	Cd, Pb	Improved phytoextraction	Yan et al., 2020
Nanotechnology	Carbon nanotubes, nanocellulose	Pb, As	Enhanced adsorption	Sharma & Sharma, 2022
	Nano-biosensors	Hg, As	Real-time monitoring	Dhanapal et al., 2024
Integrated Systems	Plant-microbe (e.g., Pteris + Aspergillus)	As, Cd	Synergistic removal	Raj et al., 2015
AI and Biosensors	AI-driven optimization	All metals	Predictive modeling	Akintola, 2024
	Biosensor deployment	Hg, As	Real-time detection	Gupta, 2021
Field Trials	Long-term pilot studies	All metals	Validate scalability	Kumar et al., 2022
Regulation	GMO biosafety frameworks	All metals	Address public concerns	Sinha et al., 2022

Knowledge Gaps and Research Needs

Other metals, such as cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), selenium (Se), cobalt (Co), nickel (Ni), zinc (Zn), and arsenic (As), have knowledge gaps and research priorities despite significant progress in bioremediation of heavy metals (Kumar et al., 2022). A deeper understanding of the molecular processes, namely biosorption, bioaccumulation, and biotransformation, is needed, at least concerning the genes and proteins that coordinate such processes (Kumar et al., 2022). These targets are potentially identifiable using omics approaches like metagenomics and transcriptomics, but their applicability is limited by the fact that the interactions of microbial consortia are incredibly complicated and the amount of on-site data is limited (Chandanshive et al., 2020). Case studies such as the usage of *Pistia stratiotes,* which had removal efficiencies of 70–85% under controlled conditions (Samal & Dash, 2024), state that microbial consortia must be refined and, therefore, require synergistic effects to be studied across several pH, temperature, and salinity conditions. Stability and scalability in the process, however, are troublesome; environmental parameters and co-contaminants often inhibit microbial action (Wang et al., 2022). Non-pure research, including bioelectrochemical and sediment microbial fuel cells (BESs and SMFCs), holds potential, but longer-term field information is unavailable (Fu et al., 2024). The potential ecological impacts of reawakening metal immobilization in an altering environment may hazard soil health and microbial communities, highlighting the rationale for better surveillance techniques (Ali et al., 2022). The technical challenges related to nanotoxicity and biocompatibility (Sharma & Sharma, 2022) and the performance of AI

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models due to the paucity of datasets (Akintola, 2024) also should be examined further. The availability of economic feasibility studies comparing bioremediation to physicochemical alternatives is quite limited (Lu et al., 2022), and there is a need to develop regulatory frameworks on GMOs due to concerns raised by gene-transfer potentials (Sinha et al., 2022). Such research is therefore essential between microbiology, nanotechnology, and data science disciplines, which together provide the required research collaboration to tackle these challenges and prove field-scale applications.

The problem of pollution with heavy metals, including Cd, Zn, Pb, and As, is a serious menace to habitat preservation and human health (Obasi et al., 2022; Mansor et al., 2024). Microbial, fungal, algal, and plant-based remediation methods are being investigated as high-potential scalable options, including biosorption, bioaccumulation, and phytoextraction, and complemented with the newly emerging genetic engineering, nanotechnology, and multi-omics approaches (Gupta, 2021; Sharma & Sharma, 2022). Case studies show empirical data in which *Jeotgalicoccus* sp. CR2 has shown Ni removal ranging between 60% and 100% (Kumari et al., 2022), and integrated systems have enhanced capabilities to remove arsenic (Hubadillah et al., 2020). Despite such achievements, formidable barriers remain, such as toxicity to microbes, poor bioavailability of metal species, fear of genetically modified organisms, and regulatory hurdles (Sinha et al., 2022). The combination of microbial consortia, multifunctional hyperaccumulator plants, nano-biosorbents, and artificial-intelligence-based monitoring promises to promote a sustainable remediation platform (Akintola, 2024). Further research plans demand their successful testing in the field, assessment of their biosafety, cost-efficiency, and societal acceptance to enable widespread implementation. These combined efforts could clean up between 80 percent of contaminated sites by 2030, thus protecting environmental health and people.

Among the contaminants of concern, the heavy metals such as cadmium, chromium, copper, lead, mercury, selenium, cobalt, nickel, zinc, and arsenic pose a significant risk to both ecosystems and public health, a risk whose genesis is both natural and anthropogenic, i.e., mining and industrial effluents (Obasi et al., 2022; Mansor et al., 2024). Bioremediation strategies that use microorganisms such as *Bacillus subtilis* and *Aspergillus niger*, and plants, especially *Brassica juncea*, utilize biosorption, bioaccumulation, biotransformation, and phytoextraction to strip these metals of their toxicity or eliminate them (Naz et al., 2022). These methods offer an inexpensive and sustainable alternative to conventional physicochemical techniques. Bioremediation has been significantly boosted by the recent improvement of genome editing, synthetic biology, nanotechnology, and artificial intelligence (Gupta, 2021; Sharma & Sharma, 2022; Akintola, 2024). CRISPR/Cas9 architecture improves the resistance of microbes to metals; nanoparticles increase their adsorption capacity; and AI offers real-time oversight and predictive modelling (Gupta, 2021; Sharma & Sharma, 2022; Akintola, 2024). The synergistic effect of integrating systems that use microbial consortia, phytoremediation, and nanotechnology has been observed in selenium removal through *Thauera selenatis* and *Typha latifolia* (Zayed et al., 2020). Still, field deployment is limited by such factors as metal toxicity, environmental fluctuations, instability of the bioformulation, and the regulatory hurdles connected with genetically modified organisms (Wolejko et al., 2016; Sinha et al., 2022). To promote the success of eco-friendly methods of heavy-metal cleanup and, therefore, maintain ecosystem health and protect human health, future work should focus on strong strain engineering, scalable nanobioremediation, and regulatory acceptance.

Declarations

Authors' Contributions

Literature search and initial stage arrangement of information were done by Heena Rohilla, and Niti Chawla. The review article was written by Heena Rohilla, Niti Chawla, Neelam Pawar, Lalita Gupta, and Sanjeev Kumar. Editing and finalization of the manuscript for publication was done by all authors.

Competing Interest

"On behalf of all authors, the corresponding author states that there is no conflict of interest.”

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Availability of Data and Materials

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