Microbial Remediation of Heavy Metals in Polluted Soil

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ABSTRACT

Heavy metal contamination poses a significant threat to the environment and public health because of its persistent toxicity and the bioaccumulation of pollutants. Microbial remediation, leveraging the metabolic capabilities of microorganisms, has emerged as an efficient and sustainable path to reduce and remove substantial, heavy metal pollution. This chapter provides a comprehensive overview of microbial remediation studies, focusing on the mechanisms used by various bacteria, fungi, and algae to remove toxic substances and immobilize heavy metals. This chapter deals with several biochemical pathways in biosorption, bioaccumulation, biotransformation, and bioprecipitation. The role of genetic engineering and synthetic biology in increasing the microbial ability for targeted heavy metal removal was highlighted. The case studies explained here are the details of the booming field application of microbial remediation and the analysis of challenges and limitations in scaling up these technologies. In this chapter, insight for future research direction emphasizes the need for an interdisciplinary approach to optimize and integrate microbial remediation for its maximum efficacy within the broader environmental management framework discussed in the conclusion.

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INTRODUCTION

We live in an environment that is composite and internally connected to natural and artificial surroundings. The various components of the environment include the atmosphere, lithosphere, hydrosphere, and biosphere, all of which play a part in maintaining the Earth's ecologic balance. Weather and temperature are regulated by the atmosphere and the layer of gases surrounding the earth. Next is the lithosphere, where the planet's solid outer shell is used for various human activities and land ecosystems. The hydrosphere includes all water bodies required for survival and climate regulation. The biosphere is home to all living organisms and interacts with the physical components, forming a dynamic system where each element affects the other. However, due to human activities, notable environmental challenges have disrupted natural processes (United Nations Environment Programme, 2019).

Pollution is the addition of contaminants and harmful substances into the environment, which causes adverse effects on human health and disrupts the ecological balance. The different types of pollution

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include air, water, noise, and soil pollution, which are particularly concerning as they cause hazardous and direct impacts on agriculture and croplands. Soil becomes unsuitable for plants and agriculture when hazardous substances, chemical waste, and heavy metals, including lead, cadmium, mercury, and Asarsenic, accumulate in the soil. Heavy metals from industrial activities, mining, improper waste disposal, and agricultural practices involving pesticides and fertilizers can persist in the soil for a long time. They affect plants, animals, and humans throughout the food chain. Polluted soil will have reduced fertility, leading to barren land and altered microbial growth, which will ultimately cause health issues in humans, such as developmental and neurological disorders (Alloway, 2012; Khan et al., 2008; World Health Organization, 2018).

Heavy metals, a class of metallic elements, are potentially dangerous even at low concentrations because of their high atomic weight and density, at least five times greater than water. Some metals are naturally present in soil. However, they can accumulate because of human activities, such as mining, waste disposal, industrial operations, and agricultural practices, such as lead, cadmium, mercury, arsenic, chromium, and nickel. Owing to their persistent nature in the environment and bioaccumulation tendency, they pose a severe soil pollution risk. Heavy metals have a broad range of toxic and detrimental effects on human health, flora, and fauna (Alloway, 2012; Zhang et al., 2010).

EFFECTS OF HEAVY METALS CONTAMINATION

Several factors contribute to heavy metal toxicity in plants, including disruption of cellular processes, oxidative stress, and nutrient intake. Cd causes chlorosis and stunted growth by disrupting photosynthesis and replacing essential metals in chlorophyll. Lead can limit root elongation and cause structural damage to cell membranes. Mercury (Hg) is toxic and can affect seed germination and root development. All these ill effects often disrupt crop yields, compromise food quality, and increase food security (Alloway, 2012; Liu et al., 2018). Furthermore, heavy metals can induce oxidative stress in plants by generating reactive oxygen species, which damage proteins, lipids, and DNA, further impacting plant health and productivity (Tangahu et al., 2011).

Animals, including livestock and wildlife, are prone to the toxic effects of heavy metals through soil ingestion, plant consumption, and water intake. Renal system dysfunction, skeletal damage, and reproductive problems have often been reported in animals exposed to heavy metals. Neurological and hematological problems with symptoms such as anemia, encephalopathy, and retarded growth are caused by lead poisoning. Exposure to Hg affects the central nervous system and leads to mental abnormalities and motor dysfunction. These health problems have a vast impact on agriculture and biodiversity conservation, in addition to affecting animal welfare and production (Gadd, 2004; Wuana & Okieimen, 2011).

Human exposure to heavy metals, primarily through contaminated food, water, and air, poses severe health risks. Pb exposure in humans often leads to neurodevelopmental disorders in children, cardiovascular diseases, and renal dysfunction. Renal damage, bone demineralization, and increased cancer risk are common issues faced by humans after Cd accumulates in the liver and kidneys. Mercury is poisonous to nerve tissue and affects cognitive and motor functions; it becomes more hazardous in the form of methylmercury. It can cause cardiovascular issues, skin lesions, and an increased risk of skin, bladder, and lung cancers (Abatenh et al., 2017; Khan et al., 2008). Even at low concentrations, prolonged exposure to these metals can result in long-term health complications, highlighting the need to monitor and reduce soil pollution (World Health Organization, 2018).

Heavy metals can persist in the environment for a longer time and have the potential for long-range transport, which ultimately causes contamination in residential areas. Industrial waste and other discharges result in the deposition of heavy metals in the atmosphere, which can lead to extensive soil pollution. Urban and rural areas are affected by improper handling and disposal of industrial and municipal wastes, resulting in heavy metals in the soil. Therefore, to manage and diminish the effects of heavy metal pollution on the environment and public health, it is essential to understand the sources and pathways of heavy metal contamination (Tangahu et al., 2011).

SOURCES OF HEAVY METALS CONTAMINATION IN SOIL

Soil is contaminated by heavy metals that have both natural and anthropogenic origins. Natural sources of heavy metals come from the weathering of rocks, which contain metals that also form the baseline levels of metals in the soil. Industrial activities have also increased the level of metals in soil. Industrial activities release heavy metals into air and water bodies. The dust particles and fumes that contain metals settle on the soil's surface, which is contaminated with these heavy metals. Fertilizers, pesticides, and industrial sludge also cause soil contamination in agriculture. Uncontrolled urbanization also causes contamination because no proper waste disposal system has been established for urban waste (Alloway, 2012; Liu et al., 2018).

Soil contains heavy metals available in various chemical forms that affect bioavailability, toxicity, and mobility. These various chemical forms of heavy metals can cause long-term contamination. However, Cd is more soluble and can be readily taken up by plants that enter the food chain. Speciation, including inorganic forms such as arsenite and arsenate, determines its toxicity, with arsenite being more harmful and mobile. These metals can disrupt soil microbial communities, hamper nutrient cycling, and reduce soil fertility, negatively affecting plant growth (Gadd, 2004; Khan et al., 2008).

METHODS FOR REMEDIATION OF HEAVY METALS IN SOIL

Various remediation techniques can be implemented for the remediation of heavy-metal contamination (Figure 1). These techniques can be broadly divided into physical, chemical, biological, and combined approaches, each with advantages, disadvantages, and specific mechanisms.

Physical Remediation

Soil excavation and landfill: This process involves digging contaminated soil through physical methods and transporting it to land designated for hazardous waste landfill. Despite being a simple process, this method is not cost-effective and disturbs nearby ecosystems and soil structures. In cases where other methods are not feasible, this technique is often helpful in severely polluted areas (Li et al., 2014).

Solidification/stabilization: To prevent leaching, contaminated soil is mixed with binding agents such as cement to incorporate heavy metals. This approach effectively binds heavy metals. However, soil binding with cement can degrade soil quality and its further applications in agriculture (Lindh & Lemenkova, 2022).

Chemical Remediation

Soil Washing: This method involves mixing soil with washing solutions to extract heavy metals from the soil. This method is quite functional for almost all heavy metals but can lead to large volumes of contaminated wastewater that require additional treatment (Babu et al., 2021).

Chemical Stabilization: In this method, chemical substances such as phosphates, lime, and iron oxides are added to the soil to convert heavy metals into less soluble and bioavailable forms. These compounds are known as stabilizing agents. It reduces metal mobility but does not remove contaminants from the soil, which may cause potential risks if the stability of the bound metals fluctuates over time (Moghal et al., 2020).

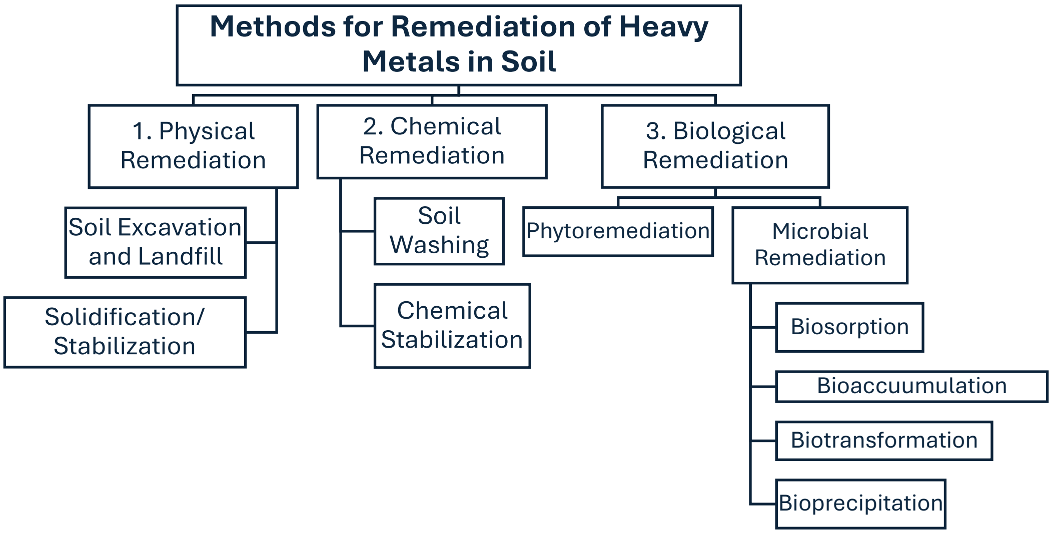

Figure 1: Methods for Remediation of Heavy Metals in Soil

Biological Remediation

Phytoremediation: This method uses plants to absorb, accumulate, and stabilize heavy metals in the soil. There is a process used to remove heavy metal contamination from the soil, in which plants are grown in soil contaminated with heavy metals for several growing seasons, and the plant absorbs heavy metals from the soil. Phytostabilization is a cost-effective and ecologically safe method (Ali et al., 2013.

Microbial Remediation: Microbes are used for remediation to remove heavy metal contamination from soils, that is, to detoxify soil. Microbes, such as bacteria, fungi, and algae, are used for the remediation process, and this process is known as microbial remediation. This efficient and eco-friendly method can be maintained over a long period by optimizing environmental conditions for microbial activity (Li et al., 2023).

Apart from the above, there are several other methods for soil remediation; however, these methods have limitations. During the chemical remediation process, soil washing is performed to remove heavy metals, but it is not very effective. This process also produces a large quantity of contaminated wastewater that requires repurification (Park et al., 2011). Chemical stabilization also minimizes metal mobility, but this process does not remove soil contamination. Instead, this process leads to the risk of long-term heavy metal leaching; thus, chemical stabilization is not entirely safe (Shahid et al., 2017). The process of physical remediation is also considered to remove soil contamination, but it is a costly and laborious method in which soil excavation and landfilling activities are undertaken. This method hampers the soil structure and ecosystem because contaminated soil is excavated and transferred elsewhere (Li & Thornton, 1993). Another contamination removal process is solidification/stabilization, but this method can affect soil properties and agricultural land use (Rizwan et al., 2017). Phytoremediation techniques, such as phytoextraction, are inefficient and limited to the root zone because they require several growing seasons and depend on plant efficiency (Ali et al., 2013). The method of detoxifying the soil by growing plants, known as phytoremediation, is also inefficient because decontamination and plant efficiency are limited only to the root zone and take several seasons. However, this method is not efficient or helpful. The effectiveness of the phytostabilization process depends entirely on the environmental conditions for its effectiveness (Bhargava et al., 2012).

MICROBIAL REMEDIATION OF HEAVY METALS FROM SOILS

Removing soil contamination by microbial remediation is a practical and feasible approach. The natural metabolism of microorganisms, such as bacteria, fungi, and algae, is used to immobilize, transform, and remove heavy metals from the soil. Microbial remediation involves four important mechanisms: biosorption, bioaccumulation, biotransformation, and bioprecipitation.

Biosorption

The biosorption process of microorganisms, including bacteria, fungi, and algae, is a passive method for binding heavy metals to their cell walls through various physical and chemical interactions. This method is cost-effective, efficient, less toxic, and healthier. Therefore, this method has gained significant attention for removing heavy metal contaminants in soil. Compared with traditional remediation techniques, this method is cost-effective and efficient. We can study biosorption mechanisms in detail to understand this function.

Cell wall structure and functional groups:

The cell walls of microorganisms comprise polysaccharides, proteins, and lipids in a complex structure that serves as a binding site for metal ions. Now, we study the functional groups involved in the biosorption mechanisms:

- Carboxyl groups: these groups in polysaccharides, such as peptidoglycans in bacterial cell walls, exhibit a high affinity for metal ions. In this functional group, the negative charge on the carboxyl group attracts and binds positively charged metal ions, and because of this affinity, heavy metals are collected in the cell wall.

- Hydroxyl Groups: in this functional group, the metal ions are bound by coordinate and hydrogen bonds to form a more stable metal microbe complex in the cell wall.

- Sulfhydryl Groups: the sulfhydryl groups have affinity with specific metal ions and bind with covalent bonding and thiolate formation, and by this functional group, the heavy metals like mercury (Hg) and cadmium (Cd) get confined in the cell wall.

- Amino Groups: the amino groups that form proteins in the cell wall and chemically react with metal ions. The ions under coordinate bonds, electrostatic interactions, and chelation form a stable complex with metal ions in this reaction. Thus, the amino groups donate electron pairs to convert the metal ions into complex stable metal ions to remove heavy metal contamination from the soil.

Mechanisms of metal binding:

In the functional group, metals are bound by several mechanisms-

- Ion exchange: the ion exchange involves the exchange of ions in the cell walls of microbes and metal ions. The positive ions, that is, protons (H^+) and other cations (Na^+ and K^+) of the heavy metals, are exchanged with the cations of the cell wall in the given environment. This mechanism works on the functional groups' concentration gradient and the metal ion's affinity (Priyadarshanee & Das, 2021).

- Complexation: complexation is a complete compound formation process involving coordination of the reaction between the functional groups and metal ions. In this process, metal ions are surrounded and encircled by carboxyl, hydroxyl, and amino groups to form coordinated covalent bonds. Thus, this process is known to form complex coordinate compounds (Hadi & El-Naas, 2019).

- Chelation: this is a process of metal binding in the cell wall, in which a single metal ion can bind to form several bonds on the cell wall of microorganisms with different binding sites. In this process, the stability of the metal–microbe complex increased significantly, which improved the uptake capacity of heavy metal microorganisms from the soil. Proteins and peptides are common chelating agents that provide multiple functional groups to form ringlike structures after binding with a single metal ion (Priya et al., 2022).

- Precipitation: in this process, the metal ions sometimes precipitate as insoluble salts and deposit on the surface of the microorganism cell. Precipitation occurs in a conditioned environment that induces the precipitation of hydroxides, sulfides, or carbonates of metals on the cell wall surfaces of microorganisms. In this process, the metal ion interacts with the functional group, and the nucleation and growth of these precipitates are promoted (Joshi et al., 2023).

Examples:

- *Bacillus subtilis*: when applied for metal binding, this bacterium is adequate for efficient cadmium and zinc metal binding. This bacterium is also effective in the biosorption of copper and chromium (Rajalakshmi & Thatheyus, 2022).

- *Aspergillus niger*: this bacterium is effectively used for biosorption of metal cadmium, and the biosorption rate has been measured up to 81.07%, whereas for nickel, this rate is approximately 43.69%, which depends on the concentration of and the period of exposure. Therefore, it can be said that *A. niger* has significant potential to absorb heavy metals from contaminated soil surrounding it (Oyewole et al., 2019).

- *Rhizopus arrhizus*: this bacterium effectively removes Cu from an aqueous solution of Cu metal contamination. When this bacterium was used for the biosorption of heavy metals, it achieved a 97.32% removal of copper. Furthermore, this bacterium has shown an efficient biosorption rate for heavy metal lead, with a maximum recorded rate of 45.54%. Thus, it is clear that this bacterium is efficient in removing heavy metal contamination from soil (Oyewole et al., 2019).

- *Saccharomyces cerevisiae: this fungus can be used for biosorption of heavy metals from wastewater. This fungus has exhibited its potential efficacy for removing heavy metals, and the maximum biosorption rate has been achieved at* 99.5% from the contaminated water. This indicates the potential use of these fungi to remove heavy metal contaminants from their surroundings (Oyewole et al., 2019).

- *Pseudomonas aeruginosa*: this bacterium can bioactively absorb copper and chromium from contaminated surroundings with heavy metal contamination. The copper removal rate from the contaminated surroundings was calculated to be up to 90.89%, and for chromium, the biosorption rate was 89.67% at a given concentration level. The biosorption rate makes this microorganism a valuable microbe for the remediation of heavy metals from its surrounding environments (Oyewole et al., 2019).

Bioaccumulation

As the name suggests, bioaccumulation is a process by which living organisms actively absorb and retain heavy metals in their cells. This involves complex biochemical and physiological processes in which microbes concentrate metals from their surrounding environments into their biomass. The bioaccumulation process depends on energy and is an active transport system, which differs from the passive transport system used in biosorption.

Transport proteins and metal uptake:

The accumulation process is initiated by transporting metallic ions throughout the cell membranes, and the process can be regulated by a specific method of transporting proteins, which mainly recognize heavy metals and bind to the metal ions. These proteins include:

- ATP-binding cassette transporters: using energy from the ATP hydrolysis process, this transporter translocates metal ions across the cell membrane. This transport method is particularly efficient because it allows the cell to absorb metals, even at low temperatures (Rekha et al., 2021).

- P-type ATPases: this transporter also uses energy from ATP to pump metal ions throughout the cell membrane. This transporter is active and vital for maintaining meal homeostasis within the cell wall by monitoring the absorption and removal of metals from cells, such as copper and zinc (Argüello et al., 2007).

- Metal-ion permeases: This membrane protein assists in moving the metal ion passively throughout the concentration gradient. It works with an active transporter for efficient metal absorption (Srivastava & Kowshik, 2013).

Intracellular accumulation and sequestration:

Heavy metals are absorbed by the cells to prevent their harmful effects. The mechanism of this method includes several processes.

- Binding to metallothioneins: metallothioneins are cysteine-rich proteins that bind metal ions via thiol groups. Metallothioneins remove heavy metals such as cadmium, copper, and zinc during absorption and avoid changes in molecular function (Devi et al., 2021).

- Formation of polyphosphate Granules: microorganisms form polyphosphate granules that store metals. Polyphosphate granules can accumulate and hide metal ions by reducing their toxicity and bioavailability within the cells (Saraswat & Rai, 2011).

- Incorporation into vacuoles: The vacuoles collect heavy metals and store them in some bacteria and fungi as a storage space. In fungi and some bacteria, vacuoles provide a storage space where heavy metals are transported from the contaminated environment, and the heavy metals are stored in vacuoles within the cell. The vacuolar sac's critical method for sequestration is hiding it (Priyanka & Dwivedi, 2023).

Metabolic pathways and resistance mechanisms:

Microorganisms survive in heavy metal-contaminated environments, cope with mental stress, and have developed their metabolic processes and resistance mechanisms:

- Efflux Pumps: in the process, microorganisms actively use protein movement to exclude metal ions from the cytoplasm to the extracellular environment, and by this process, the concentrates of heavy metal ions are minimized, and toxicity is eliminated from the cell (Nnaji et al., 2023).

- Reduction and Precipitation: some microorganisms can use their enzymatic metabolism to reduce the toxicity of metal ions in the cell. In some bacteria, Cr(VI) is converted into Cr(III), a less toxic form of chromium, and this Cr(III) is expelled from the solution (Nnaji et al., 2023).

- Oxidative Stress Response: in this process, the cells of microorganisms escape from exposure to heavy metals, and oxidative stress develops the level of antioxidant enzymes such as superoxide dismutase and catalyzes, thereby reducing oxidative damage and preserving cellular integrity of cell preserved (Nnaji et al., 2023).

Examples:

- *Pseudomonas aeruginosa*—This bacterium can bioaccumulate various heavy metals. It has shown cadmium accumulation capacity at a rate of approximately 45%, and its eliminating efficiency is approximately 57%. This bacterium has shown potential for bioremediation by removing heavy metals from contaminated soils (Nnaji et al., 2023).

- *Pseudomonas putida*- The bioaccumulation ability of *putida* has shown its potential ability. The ability of this microbe to accumulate cadmium was assessed at a rate of 90%, and this microbe has also shown its ability to bioaccumulate lead and zinc. This microbe has proven to be a valuable organism for the remediation of heavy metals in contaminated agricultural soil (Nnaji et al., 2023).

- *Bacillus cereus*- This bacterium has shown its ability to bioaccumulate cadmium at a higher rate (81.4%). It has also shown its efficiency in removing lead, with a rate of lead removal of 57%. This shows the potency; thus, the bacterium is an agent for the bioremediation of contaminated soil (Nnaji et al., 2023).

- *Cupriavidus taiwanensis*- This microbe accumulates heavy metals, particularly Cd and Zn. Under laboratory conditions, this microbe exhibits an absorbing ability of up to 96%, effectively eliminating the contamination of heavy metals from the environment (Nnaji et al., 2023).

- *Klebsiella pneumonia- this microbe has exhibited its ability to accumulate heavy metals from the environment*, including chromium and nickel. This bacterium exhibits tolerance and accumulation capacity for these heavy metals in a very high concentration range. For Ni, it is 700–10,000 µg/ml; for Cr, it is 500–10,000 µg/ml, highlighting its potential for bioremediation applications (Nnaji et al., 2023).

Biotransformation

In this process, microorganisms convert heavy metals into less hazardous and less accessible forms using enzymes for their transformation. In this mechanism of detoxification of contaminated soil, redox reactions are used, such as those catalyzed by specific enzymes generated by microbes, and these enzymes, after the reaction, lower the toxicity and bioavailability of heavy metals in soil.

Enzymatic redox reactions:

This is the basic process for biotransformation mechanisms wherein microorganisms reduce or oxidize heavy metals through the redox reaction of specific enzymes. The enzymes used in this process are as follows:

- Oxidases: enzymes such as oxidases enhance the oxidation of metal ions. For instance, manganese (II) can be oxidized to manganese (IV) oxide by manganese-oxidizing bacteria, making it less soluble and accessible (Olaniran et al., 2013).

- Reductases: reductases can reduce toxic metal ions to their less toxic forms. For example, the reduction of highly toxic hexavalent chromium (Cr(VI)) to the less toxic trivalent chromium (Cr(III)) by the enzyme chromium reductase in bacteria such as *P. putida* (Alsherif et al., 2021; Olaniran et al., 2013)

Molecular pathways and mechanisms:

- Mercury Reduction: mercury is a suitable example of metal detoxification via biotransformation. The mercury reductase enzyme (merA) in bacteria converts toxic ionic mercury (Hg(II)) into a less toxic form, which is elemental mercury (Hg(0)) and can be volatilized out of the cell (Peng et al., 2024).

- Arsenic Methylation: inorganic arsenic species are transformed into less toxic and organic forms through methylation by some fungi and bacteria. Some microbes have the ArsM enzyme, which adds methyl groups to arsenic, transforming it into methylated arsenic species that are less poisonous and more easily excreted from the cells (Liu et al., 2025).

- Uranium Reduction: some microbes can reduce soluble hexavalent uranium (U(VI)) to insoluble tetravalent uranium (U(IV)). Phylae such as Proteobacteria, Firmicutes, and Actinomycetes have enzymes such as cytochromes that facilitate this reduction, leading to the precipitation of uranium as uraninite, which is less bioavailable (You et al., 2021).

- Cu and Pb transformation: some bacteria possess enzymes that can reduce Cu and Pb ions to their elemental states or transform them into less soluble mineral forms. Copper resistance proteins, such as CopA, in *Escherichia coli* help detoxify and reduce copper ions (Ashkan, 2023; Rensing & Grass, 2003; Xu et al., 2023).

Cellular mechanisms:

- Efflux Pumps: microorganisms use efflux pumps to eliminate transformed metals from cells, thereby reducing intracellular metal concentrations. These pumps are beneficial because they are energy-dependent and upgrade the overall detoxification process (Nies, 2003).

- Intracellular Sequestration: after transformation, metal ions are often sequestered in the cellular compartments and, in the cellular compartment, bind to metalllothioneins and other intracellular proteins, thereby reducing their bioavailability and toxicity (Jeyakumar et al., 2023).

Regulation and genetic control:

Specific genes and regulatory proteins are responsible for the expression of metal-transforming enzymes. For example, the *mer* operon in mercury-resistant bacteria coordinates the expression of Hg reductase and related proteins. The regulatory pathway is generally induced in the presence of metal ions, ensuring that the biotransformation mechanisms are active only when required (Dash & Das, 2012).

Examples

- *Pseudomonas putida*: this bacterium can biotransform up to 85% of cadmium (Cd) in polluted soils (Verma et al., 2021).

- *Bacillus subtilis* is known for its ability to biotransform lead (Pb), which has an efficiency rate of 78% (Arantza et al., 2022).

- *Escherichia coli*: 90% of mercury (Hg) from contaminated environments (Saha et al., 2021) can be biotransformed by this microbe.

- *Saccharomyces cerevisiae* is effective in biotransforming 70% of arsenic (As) in soils (Li et al., 2023).

- *Aspergillus niger* can biotransform various heavy metals, including chromium (Cr) and zinc (Zn), with significant efficiency (Emenike et al., 2018).

Bioprecipitation

The process by which microorganisms convert soluble heavy metal ions into insoluble metal precipitates and subsequently remove them from the environment is known as bioprecipitation. This is the process by which microbes use their metabolic activities to change the chemical stage of heavy metals from a polluted environment, leading to the formation of stable minerals.

Mechanisms of bioprecipitation:

- Sulfate Reduction: as the name suggests, a reduction process took place to reduce the sulfate compound into sulfide with the help of bacteria, which can reduce sulfate, known as sulfate-reducing bacteria (SRB). Sulfide, which SRB produces, combines with metal ions to form insoluble metal sulfides, and the metals are effectively reduced from the solution (Xu & Chen, 2020).

- Phosphate Precipitation: Certain bacteria release phosphate ions into the environment. The released phosphate ions react with the metal ions to produce insoluble phosphate compounds. The bacteria that complete this process are phosphate-solubilizing bacteria. These bacteria can generate inorganic phosphate from organic phosphate. Heavy metals such as Pb, Zn, and uranium can be removed using this method (Lin et al., 2023).

- Carbonate Precipitation: the microorganisms that induced and initiated carbonate precipitation by changing the pH value and thus produced carbonate ions, which further reacted with the metal ions to produce metal carbonate. During this microbial activity, metals such as calcium, magnesium, and iron precipitate as carbonate compounds (Zhang et al., 2023).

- Oxide and hydroxide Formation: some microorganisms can oxidize metals to form insoluble metal oxides and hydroxides. This method involves the production of extracellular polymer substances that bind and immobilize metals. Heavy metals such as manganese, iron, and aluminum can be removed, which form oxides and hydroxides by microorganisms and can precipitate from polluted soil (Kumar et al., 2021).

Cellular and molecular mechanisms:

- Enzymatic Reduction: it is an important step in precipitation. The hydrogenases and reductases in SRB cause a reduction of sulfate to sulfide. The enzymes that perform this function encode specific genes that increase in response to the presence of heavy metals in the soil (Jayaram et al., 2022).

- Extracellular Polymer Production: microorganisms produce extra polysaccharides (EPS), mainly composed of polysaccharide proteins and nucleic acids. EPS can also chelate the metal ions to form a soluble complex of heavy metals to facilitate their precipitation, and the EPS also acts as a platform for nucleation and growth of metal precipitates to increase the precipitation process (Jayaram et al., 2022).

- pH and redox potential alterations: microbial metabolism substantially affects the pH and redox potential of the surrounding environment. For example, organic acids or bases released by microbes can change the pH and increase the precipitation of metal ions. Similarly, microbial enzymes can help in the redox reaction and regulate metal oxidation, ultimately resulting in precipitation (Jayaram et al., 2022).

Examples:

- *Pseudomonas fluorescens*: this variety of bacteria has indicated its effectiveness for bioprecipitation of the heavy metal lead, which removes lead contamination from soil up to 91.13% (Atuchin et al., 2023).

- *Achromobacter denitrificans*: for the bioprecipitation of heavy metal cadmium, the study of *Achromobacter denitrificans* suggests that this microbe is efficient, with an efficiency rate of 56.39% observed (Atuchin et al., 2023).

- *Klebsiella oxytoca*: this microorganism has shown its ability to precipitate metals such as lead and chromium. In an experiment, it was observed that the ability exhibited by this microbe was 80.8% for lead and 66.4% for chromium in contaminated soils (Atuchin et al., 2023).

- *Rhizobium radiobacter*: this microbe can remove nickel from the environment. This microbe is significantly capable of removing nickel and is effective at up to 98.22% (Atuchin et al., 2023).

- *Bacillus cereus*: this bacterium has shown efficiency in bioprecipitation several heavy metals from contaminated soil, including cadmium and lead (Saha et al., 2021).

Based on the above discussion, microbial remediation is a better option to detoxify soil from heavy metals because traditional methods have limitations. Under microbial remediation, the natural abilities of microbes, such as bacteria, fungi, and algae, are used to detoxify heavy metals from the soil, and microbes can sustain their lives in severe environmental conditions. Microorganisms can also target specific heavy metals and function under various environmental conditions. It also improves soil health and fertility by increasing microbial diversity and productivity (Gadd, 2004). Microbial remediation is a stable, cost-effective, and eco-friendly method that can be applied without physical remediation, such as excavation and transportation. Thus, it is cost-effective, and there is no risk of environmental imbalance. Using genetic engineering, microbial remediation can further strengthen the capability of microorganisms, making microbial remediation a more cost-effective, efficient, and viable solution for detoxifying heavy metal contamination from the soil (Adetunji & Anani, 2021).

CHALLENGES OF MICROBIAL REMEDIATION OF HEAVY METALS IN SOIL

Microbial remediation has good potential for the remediation of heavy metals; however, it is coupled with several challenges that can hamper its efficacy and practical application. The primary concern is the variability in environmental conditions such as pH, temperature, and the presence of competing ions of heavy metals or other pollutants, which can significantly alter microbial activity and metal intake efficiency. Furthermore, the high concentration of contaminating heavy metals is also hazardous to microorganisms, hampering their growth and metabolic pathway and resulting in lower efficiency in overall remediation.

The next challenge is that the availability of heavy metals in the soil varies greatly, which impacts the rate and extent of microbial uptake and its transformation in contaminated environments. Metal bonds tightly to soil particles or is present in less accessible chemical forms that may not be readily available for microbial remediation. It is also a matter of concern that relates to the long-term stability of bioremediation sites, environmental adaptation such as changes in soil chemistry, or changes in the microbial community, which can potentially immobilize the previously immobilized metal, posing a risk of secondary contamination. There are also technical and economic challenges in the microbial remediation of large and heavily polluted sites. Maintaining a consistent distribution and activity of microbes throughout a contaminated area can also be challenging. Maintaining and monitoring suitable conditions for microbial activity can be costly.

CONCLUSION

The study of microbial activity for the remediation of heavy metal contamination in soil shows a positive, promising, and eco-friendly approach. There is a possibility of reducing and removing the toxicity of toxic elements and mobility of harmful heavy metals from contaminated soil by using the natural process of microorganisms, and this method can be used to modify the environmental impact. However, this sustainable approach presents challenges, such as environmental variability, metal bioavailability, microbial toxicity, and long-term stability. These challenges are crucial to the widespread application of these techniques. Research is ongoing on the genetic and molecular mechanisms of microbial metal resistance and transformation, along with the development of innovative strategies to improve the efficiency and efficacy of microbial remediation, which will be essential to realize its potential fully.

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