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Review of Bioremediation and Phytoremediation Techniques for Heavy Metal Contamination in Mining Areas of Sulawesi, Indonesia

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ABSTRAK

Kegiatan pertambangan di Sulawesi, Indonesia, telah menyebabkan pencemaran logam berat yang meluas dan menimbulkan ancaman serius terhadap ekosistem, produktivitas pertanian, serta kesehatan masyarakat. Mengatasi permasalahan lingkungan ini memerlukan pendekatan remediasi yang berkelanjutan dan sesuai dengan kondisi ekologi setempat. Tinjauan ini mengevaluasi penerapan teknik bioremediasi dan fitoremediasi dalam penanganan kontaminasi logam berat di wilayah pertambangan Sulawesi, dengan penekanan pada mekanisme biologis, efektivitas, dan keterbatasannya. Literatur yang diterbitkan antara tahun 2015 hingga 2024 dikumpulkan dari basis data Scopus, ScienceDirect, SpringerLink, dan Google Scholar menggunakan kata kunci “bioremediation,” “phytoremediation,” “heavy metals,” dan “Sulawesi mining.” Studi-studi yang relevan dianalisis secara kualitatif untuk mengidentifikasi strategi remediasi utama, agen biologis yang terlibat, serta hasil lingkungan yang dilaporkan. Hasil telaah menunjukkan bahwa bioremediasi menggunakan strain mikroba lokal seperti *Bacillus* dan *Pseudomonas*, serta fitoremediasi dengan tanaman hiperakumulator seperti *Pteris vitata* dan *Eichhornia crassipes*, mampu menurunkan konsentrasi logam Hg, Pb, Cd, dan Cr secara signifikan pada tanah dan air tercemar. Sistem kombinasi tanaman–mikroba menunjukkan efek sinergis yang meningkatkan efisiensi penyerapan dan stabilisasi logam, meskipun penerapan dalam skala besar masih menghadapi tantangan akibat variabilitas lingkungan dan biaya pemeliharaan. Secara keseluruhan, kedua pendekatan ini menawarkan alternatif yang ramah lingkungan dan berbiaya rendah untuk mengurangi pencemaran akibat kegiatan pertambangan di Sulawesi. Penelitian lanjutan perlu difokuskan pada penerapan skala percontohan, adaptasi spesies lokal, serta integrasi pendekatan ini ke dalam kebijakan restorasi lingkungan daerah guna mendukung pemulihan ekosistem yang berkelanjutan.

Kata kunci: bioremediasi, logam berat, pertambangan, fitoremediasi, pencemaran

ABSTRACT

Mining activities in Sulawesi, Indonesia, have caused extensive heavy metal contamination, posing serious threats to ecosystems, agricultural productivity, and public health. Addressing these environmental challenges requires remediation approaches that are both sustainable and compatible with local ecological conditions. This review evaluates the application of bioremediation and phytoremediation techniques for managing heavy metal contamination in Sulawesi’s mining areas, emphasizing their underlying biological mechanisms, efficiency, and limitations. Literature published between 2015 and 2024 was gathered from Scopus, ScienceDirect, SpringerLink, and Google Scholar using the keywords “bioremediation,” “phytoremediation,” “heavy metals,” and “Sulawesi mining.” The selected studies were qualitatively analyzed to identify the major remediation strategies, the biological agents involved, and the reported environmental outcomes. Findings indicate that bioremediation using indigenous microbial strains such as *Bacillus* and *Pseudomonas* and phytoremediation employing hyperaccumulator plants, including *Pteris vitata* and *Eichhornia crassipes*, have achieved considerable reductions in Hg, Pb, Cd, and Cr concentrations in soil and water. Combined plant–microbe systems exhibited synergistic effects that enhanced both metal uptake and stabilization efficiency, though challenges remain for large-scale implementation due to environmental variability and maintenance costs. Overall, both techniques offer environmentally friendly and cost-effective alternatives for reducing mining-related pollution in Sulawesi. Future studies should focus on pilot-scale applications, adaptation of native species, and integration of these approaches into regional environmental restoration policies to support sustainable ecosystem recovery.

***Keywords*:** bioremediation, heavy metals, mining, phytoremediation, pollution

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1. INTRODUCTION

The environment is an essential resource that supports human life and sustainability (Pajarina, 2023). However, anthropogenic activities that disregard ecological consequences have led to a decline in environmental quality worldwide. Pollution resulting from human actions manifests in various forms, including air, water, and soil contamination, as well as deforestation, climate change, and other environmental disturbances (c). Among these, mining has been identified as one of the most damaging activities to the environment. Mining operations cause ecosystem destruction, contamination of terrestrial and aquatic systems, alteration of soil properties, and significant biodiversity loss (Ojo et al., 2023). Globally, mining has left a legacy of hazardous mine wastes containing heavy metals and metalloids (Newsome & Falagán, 2021). Heavy metal pollution is now recognized as a global environmental issue (Selvi et al., 2019). Studies have reported that mining activities in Bolivia (Alvizuri-Tintaya et al., 2022) and Ghana (Akoto et al., 2023) have resulted in heavy metal concentrations in water and soil that exceed safe limits. These findings highlight the persistent nature of metal pollution and the urgent need for sustainable remediation approaches.

Indonesia ranks among the world's largest nickel producers, particularly in the Sulawesi and North Maluku regions. The Ministry of Energy and Mineral Resources (Kementerian ESDM RI, 2020) estimates national nickel reserves at 72 million tons, or about 52% of global reserves. Mining activities in South, Central, and Southeast Sulawesi have been rapidly expanding, with Southeast Sulawesi alone hosting 138 mining companies (BPS, 2022). Nickel extraction processes often release associated metals such as arsenic (As), copper (Cu), platinum (Pt), and iron (Fe) into surrounding environments (Syarifuddin, 2022). These metals can accumulate in rivers and coastal ecosystems, posing toxicological risks to aquatic organisms and local communities (Rumbia et al., 2023).

Heavy metals are particularly concerning because of their persistence and bioaccumulation potential. Certain metals, such as lead (Pb), mercury (Hg), chromium (Cr), and cadmium (Cd), are highly toxic. In contrast, others such as nickel (Ni), iron (Fe), copper (Cu), zinc (Zn), and cobalt (Co) are essential at trace levels but harmful in excess (Audu et al., 2020). Once introduced into the food chain, these pollutants can accumulate in living organisms, leading to severe health effects (Zhang et al., 2024; Ojo et al., 2023). Therefore, effective soil and water remediation strategies are urgently needed to mitigate heavy metal contamination (Sharma et al., 2023).

Remediation techniques generally include physical, chemical, and biological methods (Praveen & Nagalakshmi, 2022). Among them, bioremediation and phytoremediation have emerged as eco-friendly and cost-effective approaches. Bioremediation employs microorganisms such as bacteria, fungi, and algae to transform, immobilize, or detoxify contaminants (Hussein et al., 2024; Schommer et al., 2023). Phytoremediation, on the other hand, uses plants and their rhizosphere microbial communities to absorb, degrade, or stabilize pollutants in soils and waters (Gani et al., 2024; Praveen & Nagalakshmi, 2022). These biological interactions facilitate the breakdown of pollutants and the uptake of metals through processes such as phytoextraction, rhizofiltration, and phytostabilization.

Both bioremediation and phytoremediation have been widely applied globally, yet their implementation in Sulawesi's mining regions remains underexplored. A synthesis of existing findings is essential to identify the most effective techniques, species, and microbial strains suitable for local conditions.

Therefore, this review aims to analyze and summarize the application of bioremediation and phytoremediation techniques for heavy metal contamination in mining areas of Sulawesi, Indonesia, highlighting their mechanisms, effectiveness, challenges, and implications for sustainable remediation policies.

2. METHODOLOGY

This study employs a narrative literature review to comprehensively examine bioremediation and phytoremediation techniques for managing heavy metal contamination in mining areas, with particular emphasis on Sulawesi, Indonesia. The review was designed to synthesize current scientific knowledge, identify effective remediation strategies, and provide practical insights applicable to tropical mining contexts.

Literature was collected from multiple reputable academic databases, including Springer Link, Google Scholar, ScienceDirect, MDPI (Multidisciplinary Digital Publishing Institute), and Web of Science. The search strategy used various combinations of keywords, including "bioremediation," "phytoremediation," "heavy metals," and "Sulawesi mining," along with specific terms related to microorganisms (bacteria, fungi, algae) and plants (hyperaccumulators, phytoextraction). Boolean operators (AND, OR) were employed to refine search results and ensure comprehensive coverage of relevant literature.

Articles were selected based on several inclusion criteria. First, publications were restricted to peer-reviewed research articles published between 2015 and 2024 to ensure the inclusion of recent advances in the field. Second, selected studies were required to focus on heavy metal bioremediation or phytoremediation and to provide quantitative data on remediation efficiency, metal accumulation capacity, or removal rates. Third, preference was given to studies reporting on mining-related contamination, conducted in tropical or Southeast Asian contexts, and with clear methodological descriptions. Articles published before 2015, non-peer-reviewed publications, studies lacking experimental data, and those focusing solely on chemical or physical remediation methods were excluded from the review.

After applying these criteria, 93 peer-reviewed research articles were identified as the primary analytical framework for this comprehensive review. Table 1 shows how these articles are distributed by research focus. The complete reference list contains 101 sources: 93 are core peer-reviewed research papers, and eight are supporting materials, including government statistical reports (n=2), academic book chapters (n=4), and institutional research documents (n=2). The temporal distribution shows that researchers have consistently been interested in this area during the review period, with publications fairly evenly spread across 2015-2024. This suggests that scientists are still focusing on heavy metal remediation technologies.

The extraction of data from the chosen articles concentrated on several critical parameters necessary for thorough analysis. These encompassed the categories of heavy metals examined (including nickel, mercury, lead, cadmium, and chromium), the particular remediation strategy implemented (bioremediation or phytoremediation), the biological organisms employed (bacterial species, fungal strains, algal species, or plant varieties), quantitative indicators of remediation efficacy represented as percentage removal or accumulation capacity, experimental conditions and methodological specifics, and key findings along with their prospective applications. This systematic extraction facilitated the comparative analysis of diverse remediation strategies and their efficacy across various contamination scenarios.

This review covers several important aspects of cleaning up heavy metals in mining settings. First, it provides a thorough overview of the levels of heavy metal pollution in Sulawesi's mining areas, including the types and amounts of metals present and their effects on the environment. Second, it examines how microorganisms, such as bacteria, fungi, and algae, can clean up the environment by altering and removing metals through their metabolic pathways. Third, it examines phytoremediation methods that use plants, including how they take up, transport, and store metals. Fourth, it compares different remediation methods by examining their pros and cons and how well they work. Lastly, it discusses real-world uses and ways to put them into practice, specifically with the mining industry in Sulawesi, taking into account the area's environmental conditions and available resources.

Table 1. Distribution of Reviewed Articles by Research Focus

Research Focus	Number of Articles	Percentage (%)	Explanation	Representative References
Heavy metal contamination in Sulawesi/Indonesia	8	8.6	Studies documenting heavy metal pollution levels, sources, and environmental impacts specifically in Sulawesi mining regions	Ramadhoni et al., 2020; Rumbia et al., 2023; Adidharma et al., 2020; Utomo et al., 2021; Syarifuddin, 2022; Sihombing et al., 2024; Suparman et al., 2023; Neneng et al., 2020
Bacterial bioremediation	15	16.1	Research on bacterial species and strains capable of heavy metal removal through biosorption, bioaccumulation, biotransformation, and other bacterial mechanisms	Rengarajan et al., 2024; Tariq et al., 2019; Ameen et al., 2020; Bai et al., 2021; Khadim et al., 2019; Latif et al., 2023; Gao et al., 2017; Vega-Páez et al., 2019; Nanda et al., 2019
Fungal bioremediation (mycoremediation)	13	14	Studies investigating fungal species for heavy metal remediation through biosorption and bioaccumulation in fungal biomass	Zhang et al., 2020; Manguilimotan & Bitacura, 2018; Albert et al., 2018; Li et al., 2018; Gola et al., 2016; Alothman et al., 2020; Bano et al., 2018; Karimah, 2023; Haya, 2023
Algal bioremediation	11	11.8	Research on microalgae and macroalgae species for heavy metal uptake and removal from aquatic environments	Vela-García et al., 2019; León-Vaz et al., 2021; Santos et al., 2019; Sarangi & Rajkumar, 2024; Abomohra et al., 2021; Ibrahim et al., 2018; Alavi et al., 2018; Balaji et al., 2016
Phytoremediation mechanisms and applications	14	15.1	Studies on hyperaccumulator plants, metal uptake mechanisms, translocation, and phytoremediation techniques including phytoextraction and phytostabilization	Herlina et al., 2020; Rai, 2019; Cui et al., 2023; Chauhan et al., 2020; Alcantara et al., 2017; Dulanlebit et al., 2021; Innah & Umar, 2023; Yan et al., 2020; Shah & Daverey, 2020
Bioremediation mechanisms and concepts	18	19.4	Theoretical and mechanistic studies on biosorption, bioaccumulation, biotransformation, bioleaching, and fundamental bioremediation principles	Zhou et al., 2023; Kapahi & Sachdeva, 2019; Priyadarshanee & Das, 2021; Pande et al., 2022; Sarkodie et al., 2022; Abo-Alkasem et al., 2023; Hussein et al., 2024; Liu et al., 2023
Remediation methods (in situ and ex situ)	10	10.7	Technical approaches and methodologies including bioventing, biosparging, biostimulation, bioaugmentation, biopiles, composting, and bioreactors	Brown et al., 2017; Tribedi et al., 2018; Scalvenzi, 2018; Lin et al., 2022; Nivetha et al., 2023; Nwankwegu et al., 2022; Saravanan et al., 2024; Setianingsih & Titah, 2020

This review offers extensive insights into biological remediation strategies suitable for tropical mining environments by integrating findings from laboratory studies, field trials, and case reports within the selected literature. The narrative synthesis method enables the integration of diverse research findings, identification of knowledge gaps, and formulation of recommendations for future research and practical applications to manage heavy metal contamination in Sulawesi's mining areas.

3. DISCUSSION

3.1. Heavy Metal Contamination in Mining Areas of Sulawesi

Several studies have highlighted heavy metal contamination in mining areas, particularly in the Sulawesi region. The rapid expansion of nickel mining activities along the coastal waters of Morowali has raised concerns about heavy metal contamination. Analysis using the geoaccumulation index (I geo) revealed that Morowali water sediments are contaminated with the heavy metal nickel (Ni), with concentrations ranging from 192.01 to 202.09 mg kg^{-1} (Ramadhoni et al., 2020). Moreover, fish from Weda and Morowali contained Cr, Fe, Cd, and Cu levels exceeding safety thresholds, rendering them unsafe for consumption (Utomo et al., 2021).

In the South Konawe Regency, Southeast Sulawesi Province, X-Ray Fluorescence (XRF) tests indicated elevated concentrations of heavy metals—nickel (Ni), cobalt (Co), copper (Cu), and iron (Fe) — in bottom sediments, exceeding established thresholds. Sediment quality along the Puuwiau watershed was categorized as ranging from low contamination (for Cu and Zn) to very high contamination (for Co) based on contamination factor calculations (Rumbia et al., 2023).

Similarly, mining areas in North Konawe reported moderately polluted sediment concentrations of nickel and other heavy metals, ranging from 3.922 to 34.08 mg kg^{-1}, according to US EPA-2004 standards (Adidharma et al., 2020). Therefore, adopting safe disposal methods and developing efficient remediation strategies is crucial (Praveen & Nagalakshmi, 2022). Bioremediation and phytoremediation are viable approaches for reducing heavy metal concentrations. Strategic measures must be implemented to eliminate the adverse effects of heavy metals on ecology and human health in areas affected by mining.

3.2. Bioremediation

Bioremediation involves using biological organisms (fungi, algae, and bacteria) to eliminate or neutralize environmental pollutants through their metabolic activities (Sharma, 2020). Microorganisms are essential to bioremediation because they can decompose contaminants, namely heavy metals, hydrocarbons, and pesticides. Through a variety of metabolic pathways, microorganisms can degrade complex pollutants into less harmful forms (Hussein et al., 2024).

Bioremediation methods encompass two primary approaches: ex situ and in situ (Praveen & Nagalakshmi, 2022). In situ targets the original contaminated land, treating waterlogged soil and underground water directly on-site. This approach entails providing nutrients and oxygen to the contaminated site to promote microbial growth and accelerate biodegradation (Saravanan et al., 2024). In situ extraction is a method that helps cleanse contaminated sites using treatment mechanisms without excavating or removing them from their current positions. Three general techniques are employed: soil vapour extraction (venting), air sparging, and in situ natural attenuation monitoring. Air, oxygen, and nutrients are applied to the polluted soil or water to boost microbial action, quickly breaking down pollutants (Hussein et al., 2024). Common in situ bioremediation methods encompass Biostimulation, bioaugmentation, bioventing, and Biosparging.

One bioremediation technique, bioaugmentation, uses specific microbial strains to accelerate the breakdown of contaminants. It works well when the local microbial population cannot sufficiently or at all break down the related pollutants. Bioaugmentation can remove heavy metals, chlorinated solvents, and hydrocarbons. (Nwankwegu et al., 2022).

Figure 1. Condition of the River Due to Nickel Mining Activities in Morowali (Walhi, 2024)

Enhancing aerobic biodegradation in contaminated soil by injecting air or pure oxygen into the unsaturated zone is known as bioventing. Because of this, aerobic bacteria can use organic pollutants as a source of energy for their natural breakdown. Bioventing is suitable for dense petroleum products like diesel and aviation gasoline because it frequently uses low airflow rates to lessen the volatilization of contaminants, particularly hydrocarbons. This technique is recognized as one of the most efficient and cost-effective options for in situ bioremediation of contaminated soils (Brown et al., 2017).

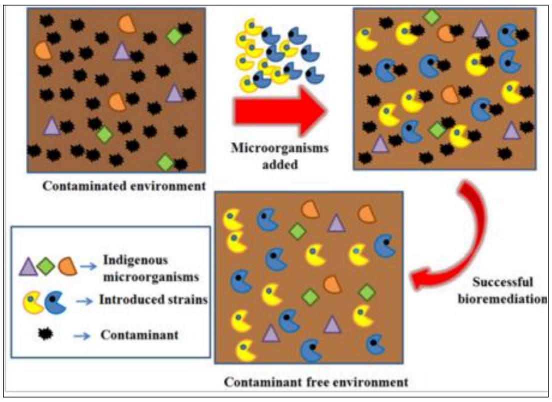


Figure 2. Bioaugmentation System (Tribedi et al., 2018)

Biostimulation is considered an effective, cost-effective, and environmentally friendly remediation technology. It involves adding rate-limiting substrates (e.g., nitrogen, phosphorus, oxygen, and electron donors) to heavily contaminated sites. This supplement helps the existing bacteria degrade extremely hazardous and toxic environmental pollutants (Tribedi et al., 2018).

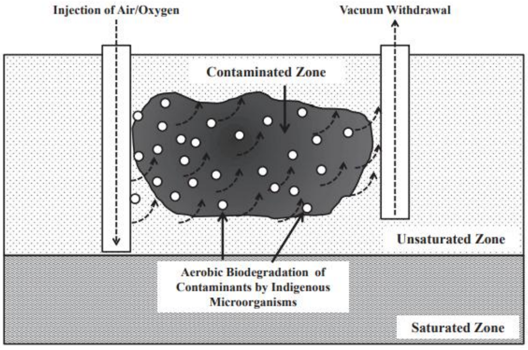


Figure 3. Bioventing System (Brown et al., 2017)

Biosparging is a method that involves injecting a highly pressurized gas, such as air or oxygen, into soil contaminated with pollutants. The injected gas forms an inverted cone around the injection point, effectively pushing contaminants out of the soil and promoting their aerobic biodegradation by microorganisms (Eslami & Joodat, 2018). Both bioventing and biosparging techniques are often employed simultaneously to establish efficient removal of soil pollutants, particularly in challenging conditions.

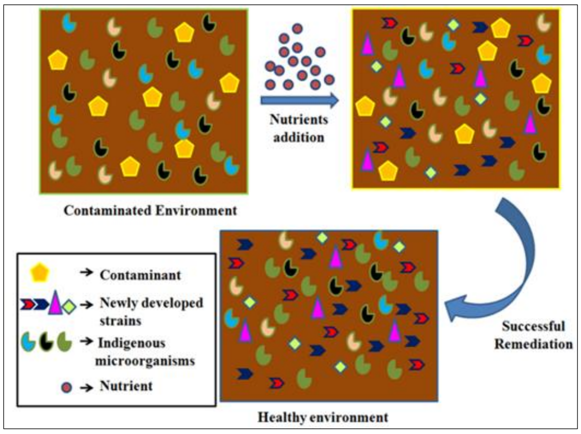


Figure 4. Biostimulation System (Tribedi et al., 2018)

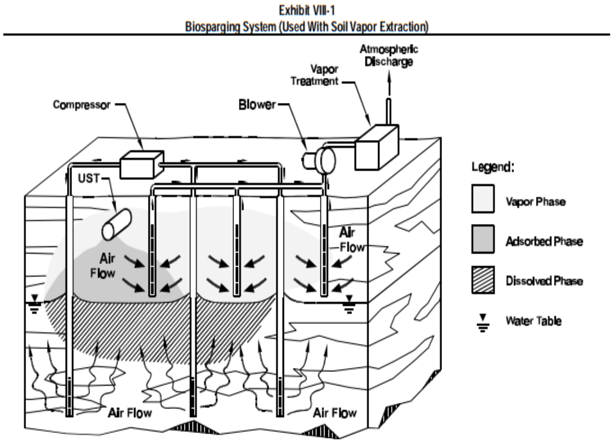


Figure 5. Biosparging System (Sharma, 2019)

Biosparging can be used to remediate soil and groundwater. It can combine with soil in the capillary fringe and below the water table, lowering the amount of dissolved oil compounds in groundwater. This strategy is affordable, flexible in its application, and rather easy to implement (Sayqal & Ahmed, 2023).

In ex situ bioremediation processes, contaminated water or soil is removed from its original location and treated elsewhere using biological organisms (Ali et al., 2019). These methods involve using bioreactors, aeration, steam regulation, and increasing the addition of supplementary nutrients to enhance the rate of pollutant degradation. Examples of ex situ processes include land biopiles, farming, and composting (Nivetha et al., 2023). Landfarming is a straightforward, cost-effective technique in which polluted soil is spread over a support layer above the ground surface, allowing native microorganisms to degrade pollutants aerobically. Processes such as tillage, fertilizer application, and irrigation are typically involved (Scalvenzi, 2018). Composting is a biological process used for managing organic waste, with the resulting compost serving as a soil conditioner and organic fertilizer (Lin et al., 2022). This technique offers various benefits, including low capital and operational costs and straightforward and efficient implementation. During composting, polluted soil is mixed with biodegradable organic matter to provide nutrients that stimulate the activity of hydrocarbon-degrading microorganisms. Consequently, composting can also enhance soil quality (Setianingsih & Titah, 2020).

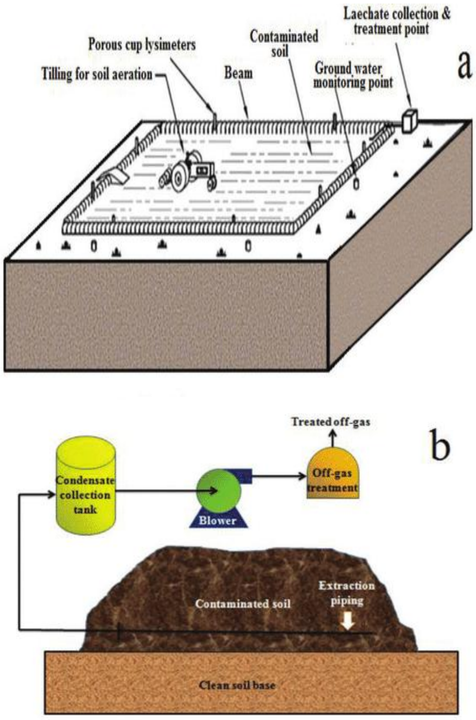


Figure 6. *Ex Situ* Bioremediation Method (a) Agricultural Land, (b) Biopile (Scalvenzi, 2018)

Biopiles combine landfarming and composting methods designed to function as aerated compost chambers. Primarily used for the remediation of surface contamination caused by petroleum hydrocarbons, they offer an improved landfarming technique to reduce the physical loss of toxins through volatilization and percolation. By establishing a favorable environment for anaerobic microorganisms, biopiles facilitate the degradation of contaminants (Nandini et al., 2019). A bioreactor serves as a container in which pollutants undergo specific biological transformations. Bioreactor operation encompasses several modes: fed-batch, batch sequencing, batch, continuous, and multistage. Contaminated samples may be placed into the reactor in solid or slurry form. Notably, bioreactor-based bioremediation offers significant advantages, including precise control over bioprocess parameters — such as pH, stirring, temperature, and aeration rates —as well as inoculum concentration and substrate. Additionally, bioreactors can treat both contaminated water and soil. However, bioreactor-based bioremediation has not been widely adopted due to high costs, challenges in controlling diverse bioprocess parameters, and varying pollutant responses across bioreactor types (Scalvenzi, 2018).

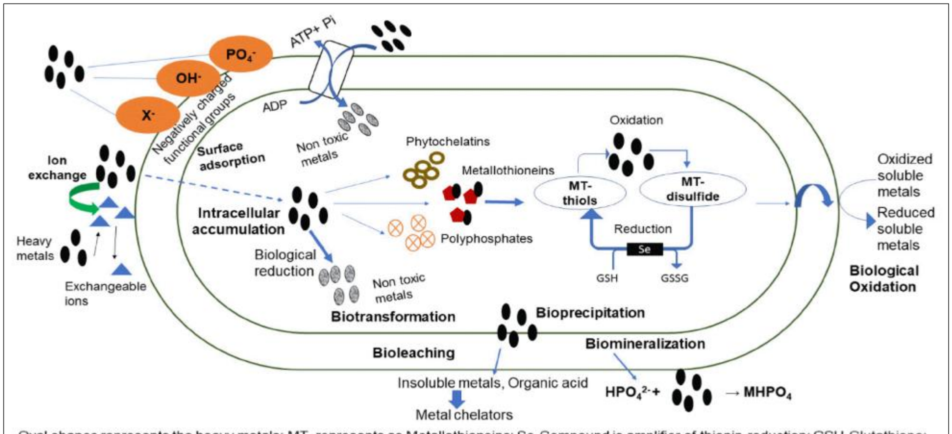
3.2.1. Mechanism of Bioremediation

Microorganisms employ various processes, including biosorption, bioleaching, bioaccumulation, and biotransformation, to decrease the negative effects of heavy metals and ensure their survival (Zhou et al., 2023). In such a toxic environment, they become accustomed to and survive exposure to heavy metals. Different extracellular polymeric substances located on biomass cell walls can remove heavy metals from solution by proton exchange or metal microprecipitation. Another feature of biomass surfaces is the presence of negative charge due to carboxyl, phosphoryl, amino, and sulfo groups, which serve as potential ion-exchange sites and metal reservoirs (Kapahi & Sachdeva, 2019).

Biosorption involves a series of processes in which metal ions are removed from solution by biosorbents. Natural resources, including algal biomass, fungi, bacteria, and trollops that grow on garbage, plants, or industrial waste, can be used as biosorbents. Biosorption is mostly used to detoxify cells or dead bioassimilators, removing heavy metal pollutants at parts-per-billion concentrations. Usually, live cell mass is absent, but in some cases it is actively used for biosorption of heavy metals (Priyadarshanee & Das, 2021). Biosorption involves organisms binding with metals to form complexes with non-toxic properties (Abo-Alkasem et al., 2023). This process commonly involves various forms of dead biomass, including agro-waste, microalgae, plant waste, agricultural residues and microbial biomass (Zhou et al., 2023).

In biosorption, heavy metal ions generally bind to the biomass surface via functional groups on its surface. Biosorption can also transpire with living cell biomass. Living microbial cells exhibit a significant capacity to bind heavy metal ions to their surfaces via passive adsorption and complexation mechanisms (Kanamarlapudi, 2018). Biosorption, a phenomenon of considerable interest to researchers, entails the attachment of heavy metal ions to surface functional groups such as amide, imidazole, amino, carboxyl, and sulfonate (Priyadarshanee & Das, 2021).

Meanwhile, bioaccumulation is the uptake of toxic chemicals only by living cells. The toxin is transported across the cell membrane directly into the cytoplasm and accumulates intracellularly. In contrast to biosorption, which involves adsorption on the external surface of microbial cells, bioaccumulation refers to the adsorption and retention of toxic metal ions within living cells in a medium (Timková et al., 2018).



Oval shapes represents the heavy metals; MT- represents as Metallothioneins; Se-Compound is amplifier of thionin-reduction; GSH-Glutathione; GSSG-Glutathione disulfide

Figure 7. Mechanism of Microorganism Bioremediation (Jeyakumar et al., 2023)

Bioprecipitation is the microbial process of converting soluble metal species and metalloids into insoluble forms, such as sulfides, phosphates, hydroxides, and carbonates. This conversion is often initiated by microbial activity that generates organic acids or enzymes capable of precipitating heavy metal ions. Although bioprecipitation does not depend on metabolic activity in a consistent manner, microbial-induced environmental alterations are essential for precipitation. Changes in pH levels and redox potential in the extracellular environment facilitate the precipitation of heavy metals and improve their stability. *Klebsiella planticola* and *Pseudomonas aeruginosa* are recognized for inducing the precipitation of cadmium ions (Kapahi & Sachdeva, 2019)

Biotransformation involves modifying the structure of a chemical compound, resulting in more polar molecules. The interaction between metals and microbes transforms hazardous metals and organic molecules into substantially less harmful forms (Pande et al., 2022). This mechanism is vital for microorganisms to adapt to heavy metals (Ojuederie & Babalola, 2017). It's important to note that microbial transformation can occur through diverse methods, including isomerization, carbon bond formation, introduction of functional groups, reduction, condensation, oxidation, methylation, and hydrolysis, demethylation (Singh, 2017).

Bioleaching involves the release of low-molecular-weight compounds that facilitate the conversion of toxic metal forms into non-toxic forms through precipitation or dissolution (Abo-Alkasem et al., 2023). It is a microbial-driven process that relies on the ability of various microorganisms to transform fractions of heavy metals into soluble, extractable compounds that can be leached (Sarkodie et al., 2022). Bioleaching — the reduction of metal, with ease in microbial response, is used to extract and recover heavy metals. The efficiency of the separation process (recovery) is highly affected by microorganisms' ability to convert insoluble chemicals in contaminated soil (such as metals) into soluble compounds that are more readily extracted and recovered, given that metal resources are limited and non-renewable (Zhou et al., 2023).

3.2.2. Bioremediation with Bacteria

Bacteria are distinguished by their robustness, extensive surface area, rapid growth rate, and greater resistance to toxic heavy metals than other microbial forms (Nanda et al., 2019). Comprehensive studies have concentrated on the bioremediation of heavy metal ions utilizing bacterial agents. Bacterial biomass rapidly eliminates metals, including Cr, Cu, Pb, Cd, and Zn (Kapahi & Sachdeva, 2019). Bacteria do not decompose heavy metals; they convert them into non-toxic forms by modifying their physical and chemical properties (Dhaliwal et al., 2020). Functional groups such as phosphonate, amine, carboxyl, and hydroxyl are on the bacterial cell wall (Kapahi & Sachdeva, 2019).

Bacteria are categorized as gram-negative or gram-positive depending on their cell wall composition. The capacity of gram-positive bacteria to bind metals arises from the anionic functional groups present in their cell wall constituents, including teichoic acid, peptidoglycan, and teichuronic acid. Gram-negative bacteria's anionic characteristics and metal-binding capacity mainly stem from lipopolysaccharides and phospholipids (Karn et al., 2021). Metal binding via precipitation occurs when metal ions react with functional groups on the bacterial surface. This leads to insoluble organic metal deposits that remain attached to microbial cells. This process involves an ion exchange mechanism where binary metal cations are exchanged with counter ions on the biosorbent surface (Jeyakumar et al., 2023). Biosorption is exhibited in bacteria that can eliminate heavy metals such as Pb, Cd, and Cr. *Aeromonas* sequesters metals utilizing negatively charged groups on its cell wall, *Bacillus* adsorbs metals through chitin, teichoic acid, and carboxyl groups. *Pseudomonas* binds metals via polysaccharides on its cell surface (Liu et al., 2023). Several bacteria are employed in the remediation process, including *Alcaligenes faecalis*, *Brevibacterium iodinium*, *Bacillus cereus, Bacillus subtilis, Enterobacteria cloacae*, *Pseudomonas putida,* and *Pseudomonas aeruginosa* (Karn et al., 2021). Here are some studies on bioremediation with bacteria (Table 2).

3.2.3. Bioremediation with Fungi

Fungi have emerged as significant players in bioremediation endeavors. They represent a specialized group of saprophytic macrofungi, characterized by distinct fruiting bodies, with a remarkable ability to degrade specific organic waste like lignocellulosic materials and engage in the biosorption of heavy metals (Woldemariam, 2019). Certain wild edible fungi varieties can accumulate heavy metals, sometimes exceeding their original concentrations (Kapahi & Sachdeva, 2019). Utilizing fungi for bioremediation offers numerous advantages, including their ability to be cultivated on a large scale using cost-effective growth media, their rapid multiplication phase, and their high biomass yield. Among the fungi commonly employed in bioremediation efforts are *Rhizopus oryzae, Aspergillus niger, Aspergillus awamori*, *Penicillium chrysogenum*, and *Coprinopsis atramentaria*, and (Karn et al., 2021). Biosorption entails multiple constituents of fungal cell walls, including proteins, chitin, glucans, lipids, polysaccharides, pigments, and functional groups such as phosphate, hydroxyl, amino, carboxyl, or sulphate. Biosorption is mediated by interactions such as adsorption, ion exchange, and complexation, which efficiently sequester heavy metals (Ojuederie & Babalola, 2017). This phenomenon occurs through electrostatic Van Der Waals forces between positively charged dissolved metal particles and negatively charged fungal cell surfaces (Aznur et al., 2022).

Penicillium, Cephalosporium, Aspergillus, and *Rhizopus* are among the fungal genera extensively researched for their potential in mitigating heavy metal contamination, particularly by removing ions like Pb^{2+} and Zn^{2+} from water and soil solutions (Abo-Alkasem et al., 2023). Various fungal species, including wood decay fungi (white and brown rot fungi), mushrooms, and others, are employed in mycoremediation due to their ability to uptake heavy metals into their fruiting bodies. Some wild edible mushroom species are known to accumulate significant amounts of heavy metals. Notably, *Pleurotus ostreatus* and *Termitomyces clypeatus*, both white-rot fungi, have demonstrated the ability to degrade persistent pollutants, such as heavy metals (Jeyakumar et al., 2023). Here are some studies on bioremediation with fungi (Table 3).

3.2.4. Bioremediation with Algae

Brown algae, belonging to the *Phaeophyta* group, exhibit superior biosorption capacity compared to other algae groups like *Rhodophyta* (red algae) and *Chlorophyta* (green algae) (Kapahi & Sachdeva, 2019). The efficacy of metal ion biosorption is contingent upon aspects including the type and composition of algal biomass, alongside the charge and chemical properties of the heavy metal ions. Microalgae include reactive groups with active binding sites that can create complexes with pollutants, such as heavy metals, in wastewater, resulting in flocculation and a subsequent decrease in total dissolved and suspended solids concentrations (Balaji et al., 2016). Generally, the means of physical heavy metal removal by microalgae are two-stage systems. This involves two stages: a rapid extracellular passive adsorption and the slower second stage resulting from intracellular diffusion and uptake. The microalgal cell wall, which is made primarily of polysaccharides (alginate and cellulose), organic proteins and lipids, possesses many functional groups (such as amino, hydroxyl, imidazole, carboxyl, sulfonate, phosphate, thiol) that can bind heavy metals. Furthermore, cellular polymeric compounds such as peptides and extracellular polymeric substances (EPS) with uronate groups enhance the binding capacity of microalgae for heavy metals (Priatni et al., 2018).

Table 2. Bioremediation Studies with Bacteria

Bacteria	Heavy Metal	Reference
Bacillus cereus+Biocar	As, Cd, Pb, Cr, Cu, Zn, Ni, Cl^-, SO_4^{2-}, and Hg	(Rengarajan et al., 2024)
Pseudomonas aeruginosa	As	(Tariq et al., 2019)
Rhodopseudomonas palustris	Co	(Gao et al., 2017)
Lysinibacillus sphaericus	Hg	(Vega-Pez et al., 2019)
Exiguobacterium sp	Pb^{2+}	(Bai et al., 2021)
Lactobacillus plantarum	Ni^{2+}, Cr^{2+}, Cd^{2+}, Pb^{2+}	(Ameen et al., 2020)
Bacillus amyloliquefaciens	Cd^{2+}	(Khadim et al., 2019)
Bacillus aryabhattai	Ni^{2+}	
Exiguobacterium indicum	Cr	(Maslan, 2022)
Bacillus mobilis	Cr	(Maslan, 2022)
Alcaligenes faecalis	Cu	(Latif et al., 2023)
Pseudomonas sp	Hg	(Sihombing et al., 2024) (Suparman et al., 2023)
Proteus (PSAA1)	Cr	(Suparman et al., 2023)
Proteus (SMCS21)	Cr	(Suparman et al., 2023)
Micrococcus (PSAA8)	Cr	(Neneng et al., 2020)
Pseudomonas sp.	Hg	

Table 3. Bioremediation Studies with Fungi

Fungi	Heavy Metal	Reference
Trichoderma brevicompactum	Pb, Cu, Cr, Cd, Zn	(Zhang et al., 2020)
Aspergillus sp	Cd	(Manguilimotan & Bitacura, 2018)
Penicillium sp	Cd	(Manguilimotan & Bitacura, 2018)
Absidia cylindrospora	Cd, Cu, Pb	(Albert et al., 2018)
Flammulina velutipes	Cu^{2+}, Zn^{2+}, Hg^{2+}	(Li et al., 2018)
Beauveria bassiana	Zn, Cu, Cd, Cr, Ni	(Gola et al., 2016)
Penicillium chrysogenum	Cd, Cu, Pb	(Alothman et al., 2020)
Aspergillus ustus	Cd, Cu, Pb	(Alothman et al., 2020)
Sterigmatomyces halophilus	Cd, Cu, Fe, Pb, Zn, Mn	(Bano et al., 2018)
Aspergillus flavus	Cd, Cu, Fe, Pb, Zn, Mn	(Bano et al., 2018)
Penicilium	Cd	(Karimah, 2023)
Monila	Cd	(Karimah, 2023)
Curvularia	Cd	(Haya, 2023)
Penicillium	Pb	(Haya, 2023)
Monilia	Pb	(Haya, 2023)
Curvularia	Pb	

Table 4. Bioremediation Studies with Algae

Algae	Heavy Metal	Reference
Pleurococcus sp.	Hg	(Vela-García et al., 2019)
Chlorella sp.	Hg	(Vela-García et al., 2019)
Scenedesmus sp.	Hg	(Vela-García et al., 2019)
Chlorella sorokiniana	Cd	(León-Vaz et al., 2021)
Chlorella vulgaris	Cd, Zn	(Santos et al., 2019)
Stoechospermum marginatum	As, Zn, Cr, Pb	(Sarangi & Rajkumar, 2024)
Gracilaria sp	Cu	(Abomohra et al., 2021)
Sargassum sp.	Cu	(Abomohra et al., 2021)
Ulva sp.	Cu	(Abomohra et al., 2021)
Jania rubens	Pb^{+2}, Cd^{+2}, Ni^{+2}	(Ibrahim et al., 2018)
Colpomenia sinosa	Pb^{+2}, Cd^{+2}, Ni^{+2}	(Ibrahim et al., 2018)
Ulva lactuca	Pb^{+2}, Cd^{+2}, Ni^{+2}	(Ibrahim et al., 2018)
Nizimuddinia zanardini	Pb(II), Cd(II), Cr(VI)	(Alavi et al., 2018)
Stoechospermum marginatum	Pb(II), Cd(II), Cr(VI)	(Alavi et al., 2018)
Chlorella sp.	Hg	(Neneng et al., 2020)

The process of heavy metal cleanup by algae involves two phases: biosorption and bioaccumulation. Initially, heavy metals are deposited onto the cellular surface (biosorption). At this point, algae serve as prospective biosorbents owing to the availability of several functional groups on their cell surfaces. Algal biosorption encompasses two pathways: the exchange of metal ions with calcium, sodium, magnesium, or potassium ions at the algal cell surface, or the formation of complexes with functional groups on the cell surface (Shamim, 2018). During the second stage, heavy metals are translocated across the cell membrane into the cytoplasm or other organelles. This facilitates the accumulation of heavy metals within the algal cell, a process known as bioaccumulation (Aznur et al., 2022). Some studies on bioremediation using algae are shown in Table 4.

3.3. Phytoremediation

Phytoremediation uses plants to absorb heavy metals and mitigate their harmful environmental effects (Bhat et al., 2022). Plants can take ionic substances from the soil, even at low concentrations, via their roots. They develop root systems that penetrate the soil and create rhizosphere ecosystems to sequester heavy metals and modulate their availability, therefore facilitating the remediation of contaminated soil and preserving its fertility (Geetha et al., 2022). The first and most straightforward method for effective heavy metal phytoremediation is the identification of efficient hyperaccumulating plants. Over 450 plant species, encompassing at least 45 angiosperm categories, annual herbs, perennial shrubs, and trees, have been recognized as metal hyperaccumulators. These include *Brassicaceae*, *Fabaceae*, *Euphorbiaceae*, *Asteraceae*, *Lamiaceae*, and *Scrophulariaceae*. Certain species, like *Sedum alfredo*, can accumulate various elements, including Zn, Cd, and Pb (Yan et al., 2020). Studies about it in Table 5.

3.3.1. Uptake, Translocation and Detoxification of Heavy Metals in Plants

Heavy metal accumulation in plants involves several mechanisms of mobilization, root uptake, xylem loading, root-to-bud transit, cellular compartmentalization, and sequestration. Heavy metals are typically present in soil as insoluble species and are unavailable to plants. By excreting various root-signalling molecules, plants can modulate rhizosphere pH and enhance the biotransformation of heavy metals into forms accessible to plants (Yan et al., 2020). Plants absorb heavy metals from the soil through root-to-shoot transport, where roots uptake metals either via symplastic transport (through the plasma membrane of root endodermal cells) or apoplastic transport (movement through free spaces between cell walls). In apoplastic transport, heavy metals infiltrate via the intercellular space, whereas in symplastic transport they traverse designated ion channels or carriers (Shah & Daverey, 2020). Upon entering root cells, heavy metal ions can bind to diverse chelators, including organic acids, forming complexes that can form carbonate, sulfate, and phosphate deposits. These complexes are immobilized in extracellular areas (apoplastic cell walls) or intracellular spaces (symplastic compartments, such as vacuoles). Metal ions sequestered in vacuoles may be conveyed into the stele and later integrated into the xylem stream via root symplasm (Yan et al., 2020). This process enables the transfer of heavy metals within the plant.

The movement of heavy metals within plants is facilitated by vascular tissues (xylem and phloem) and is closely linked to water transport (transpiration). The transfer of heavy metals through xylem sap from roots to shoots is primarily governed by root hydraulic conductance and leaf transpiration. Hyperaccumulator plants can accumulate heavy metals, transport them, and distribute them within roots and shoots. The primary aim of phytoremediation is to facilitate the transfer of heavy metals from roots to shoots for elimination (Nedjimi, 2021). During xylem loading, metal ions must navigate a water-impermeable barrier called the Casparian strip. This barrier facilitates the symplast pathway for the effective translocation of metal ions to the aerial portions of the plant. It obstructs apoplastic transport of metal ions from the basolateral side of root cortices to steles, necessitating simple symplastic transport to traverse this barrier and access xylem vessels. Xylem loading is a precisely regulated process controlled by membrane proteins, including P-type ATPases, heavy-metal-transporting ATPases, MATE (Multidrug and Toxin Extrusion protein), and oligopeptide transporter proteins (Shah & Daverey, 2020).

Plant heavy metal detoxification involves removing heavy metals from the cell or sequestering them within the vacuole, followed by detoxification once they enter the cytosol—a process known as sequestration/detoxification. This mechanism stops heavy metals from disrupting essential metabolic pathways, enabling plants to thrive in metal-contaminated environments without toxic effects (Ejaz et al., 2023). Hyperaccumulator plants exhibit remarkable detoxification abilities and can sequester substantial amounts of heavy metals in their aerial parts without causing phytotoxicity. Hyperaccumulators sequester hazardous heavy metals predominantly in aerial plant tissues, such as leaf cell vacuoles, whereas non-hyperaccumulators store them in subterranean plant tissues, like root vacuoles. Locations for detoxification and sequestration of heavy metals are generally selected to reduce harm to photosynthetic structures, including trichomes, epidermis, and the cuticle (Shah & Daverey, 2020).

Plants primarily employ avoidance and tolerance as their principal defensive strategies against heavy metal toxicity. Plants are the initial defence against heavy metals at the extracellular level by restricting their absorption and inhibiting their infiltration into plant tissues via root cells. This occurs through root absorption, metal ion precipitation, and metal exclusion. Heavy metals are present in plants as soil constituents, and when exposure occurs, they are initially immobilized—for example, by altering metal ions or by absorbing them through roots. Different root exudates, such as organic and amino acids, could bind heavy metals that pool in the rhizosphere through stable complex formation. Root exudates from certain species alter rhizosphere pH, promoting the immobilization and precipitation of heavy metals, thereby decreasing their availability and toxicity (Yan et al., 2020). Plants employ tolerance mechanisms, including inactivation, metal chelation, and heavy metal compartmentalization, to mitigate the toxicity of heavy metal ions that infiltrate the cytosol. Through categorization, various organic and inorganic ligands in the cytoplasm bind heavy metals, reducing their concentration. After classification, inactive compartments, such as vacuoles, petioles, leaf sheaths, trichomes, bind heavy metal-ligand complexes and securely sequester them (Sabreena et al., 2022).

Table 5. Research on Phytoremediation

Plants	Heavy Metal	Reference
Pelargonium hortorum	Pb, Cd	(Gul et al., 2019)
Pelargonium zonale	Pb, Cd	(Gul et al., 2019)
Pistia stratiotes	Fe, Cu, Cr, Cd, Ni, Zn, As	(Rai, 2019)
Pirodela polyrhiza	Fe, Cu, Cr, Cd, Ni, Zn, As	(Rai, 2019)
Eichhornia crassipes	Fe, Cu, Cr, Cd, Ni, Zn, As	(Rai, 2019)
Cordyline fruticose	Pb	(Herlina et al., 2020)
Cardamine violifolia	Hg	(Cui et al., 2023)
Helianthus annuus L	Pb	(Chauhan et al., 2020)
Manihot esculenta Crantz	Hg, Au	(Alcantara et al., 2017)
Pteris vitata	Hg	(Dulanlebit et al., 2021)
Amaranthus spinosus	Hg	(Dulanlebit et al., 2021)
Ipomoea reptanspoir	Hg	(Dulanlebit et al., 2021)
Impatiens balsamina L.	Hg	(Innah & Umar, 2023)
Zinnia Elegans Jacq.	Hg	(Innah & Umar, 2023)

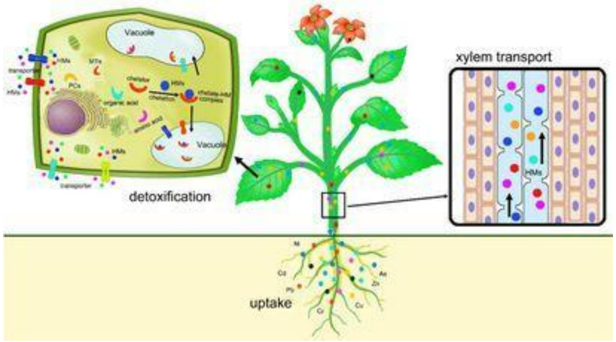


Figure 8. Translocation Uptake, Metal Detoxification (Yan et al., 2020)

Plants can purify contaminated environments through various processes, such as phytoextraction, phytofiltration, phytovolation, phytodegradation, and phyodesalinization (Khilji et al., 2024).

3.3.2. Phytoextraction

Phytoextraction, or phytoaccumulation, refers to the translocation of toxic chemicals from contaminated soil to different plant tissues via the root system, ultimately reaching the aerial shoot system (Praveen & Nagalakshmi, 2022). Heavy metal cations are mobilized in the rhizosphere and subsequently absorbed and translocated from the roots to the aerial portions of the plant. This results in the deposition and compartmentalization of heavy metal ions in plant tissues. The stages comprise the phytoextraction process for heavy metals. High-biomass species, including *Zea mays, Cannabis sativa, Nicotiana tabacum,* and *Helianthus annuus*, have proven effective in phytoextraction of heavy metals from polluted soil (Yan et al., 2020). The principal factors affecting a plant species' effectiveness in phytoextraction are its capacity to collect heavy metals and its above-ground biomass. Thus, plants that exhibit substantial aboveground biomass production and notable heavy metal accumulation in their aerial components are selected for phytoextraction applications (Sabreena et al., 2022).

3.3.3. Phytostabilization

Phytostabilization is an approach to immobilize heavy metals in soil by using metal-tolerant plant species to bind them and reduce their bioavailability. This approach traps the metals within an inorganic matrix, preventing them from entering the food chain (Yan et al., 2020). Phytostabilization can be absorbed and incorporated into sequestered root tissues. It can also be sorbed in root cell walls or precipitate, reducing excessive metal valence in the rhizosphere. Heavy metals immobilized in the amphibious rhizosphere may not pose a harmful risk through groundwater leaching, thereby reducing heavy metal movement to some extent, avoiding environmental pollution, and enhancing ecosystem security (Montreemuk et al., 2024).

3.3.4. Phytovolatilization

Phytovolatilization is a phytoremediation approach that uses plants to absorb contaminants from the soil, convert hazardous elements into a more volatile form, and subsequently release them into the atmosphere through transpiration via the foliage or leaf system. This technique effectively detoxifies heavy metals such as Se, As, and Hg, as well as organic pollutants (Yan et al., 2020). Commonly used plants for phytovolatilization include *Crinum americanum*, *Nicotiana tabacum, Bacopa monnieri, Triticum aestivum,* and *Trifolium repens* (Dhaliwal et al., 2020).

3.3.5. Pitodegradation

The process of breaking down pollutants absorbed by plants through metabolic pathways is termed phytodegradation or phytotransformation, while pollutants external to the plant are broken down by enzymes produced in the roots (Schnoo R). Several enzymes facilitate the degradation of pollutants, including phosphatase, peroxidase, nitroreductase, nitrilase, and dehalogenase (Deng & Cao, 2017). Genetically modified *Liriodendron tulipifera*, or yellow poplar, plants have been engineered to thrive in tissue culture under elevated mercury concentrations and to convert the mercury from its highly toxic form, Hg^{2+}, to a much less harmful form, Hg^0 (Nedjimi, 2021).

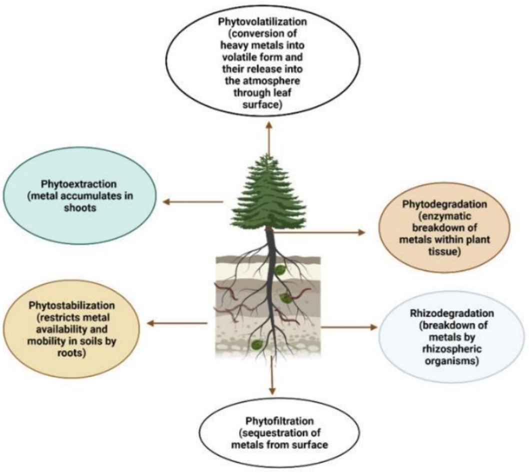


Figure 9. Phytoremediation Mechanism (Sabreena et al., 2022)

3.4. Comparative Evaluation and Critical Analysis

3.4.1. Comparative Effectiveness of Remediation Methods

When using bioremediation and phytoremediation to clean up heavy metal pollution in mining areas, one needs to carefully consider how well they work, how much they cost to implement, the technical requirements they entail, and their limitations. Table 6 gives a complete comparison of the primary remediation methods discussed in this review. It combines results from several studies to help people decide how to use them in the Sulawesi mining context.

Table 6. Comparative Analysis of Bioremediation and Phytoremediation Techniques for Heavy Metal Contamination

Method	Organisms/ Plants	Time Required	Cost	Advantages	Limitations	Applicability to Sulawesi
Bacterial Bioremediation	*Bacillus*, *Pseudomonas*, *Alcaligenes*	Weeks to months	Low-Moderate	High adaptability; Multiple mechanisms; Indigenous species available	Sensitive to pH and temperature; Requires optimization	**High** - Indigenous bacteria identified; Suitable for tropical conditions
Fungal Bioremediation	*Aspergillus*, *Penicillium*, *Trichoderma*	Weeks to months	Low-Moderate	High biosorption capacity; Produces extracellular enzymes	Slower than bacteria; Requires specific growth conditions	**Moderate** - Local strains available; Needs further screening
Algal Bioremediation	*Chlorella*, *Sargassum*, *Ulva*	Days to weeks	Moderate	Fast growth; Dual function (remediation + biomass); CO_2 sequestration	Requires water bodies; Light dependent; Harvesting needed	**Moderate** - Coastal mining areas suitable; Marine algae abundant
Phytoextraction	*Cordyline fruticosa*, *Eichhornia crassipes*	Months to years	Low	Long-term solution; Eco-friendly; Metal recovery possible	Slow process; Requires large area; Disposal of biomass	**High** - Native hyperaccumulators identified; Suitable climate
Phytostabilization	Metal-tolerant plants	Months to years	Low	Prevents metal spread; Low maintenance	No metal removal; Long-term monitoring needed	**Moderate** - Useful for large contaminated areas
In situ Bioremediation	Mixed microbial consortia	Months	Low	Treats contamination on-site; Minimal excavation	Environmental factors affect efficiency; Monitoring required	**High** - Cost-effective; Minimal disruption
Ex situ Bioremediation	Optimized cultures	Weeks to months	Moderate-High	Controlled conditions; Faster; Predictable	Requires excavation; Higher operational cost	**Moderate** - Suitable for high-value contaminated sites

The comparative analysis indicates that bacterial bioremediation is the most adaptable method, achieving removal efficiencies of 20%-100%, depending on bacterial species, metal type, and environmental conditions. Research conducted in mining regions of Sulawesi has identified indigenous bacterial strains proficient in the remediation of mercury and chromium (Sihombing et al., 2024; Suparman et al., 2023; Neneng et al., 2020), indicating significant potential for local application. Bacterial bioremediation is particularly well-suited for widespread use in Sulawesi because it is inexpensive and can be used in tropical climates.

Phytoremediation, especially phytoextraction with native hyperaccumulator plants, works just as well as other methods, with removal rates of 42% to 95% for different heavy metals. The discovery that *Cordyline fruticosa* is an effective lead accumulator with 82.8–95% efficiency (Herlina et al., 2020) is important for local use because this ornamental plant is common in Indonesia and grows well in tropical climates. *Eichhornia crassipes* (water hyacinth) also has great potential; in Indonesian waters, it could be used for beneficial remediation (Rai, 2019).

3.4.2 Critical Evaluation of Research Gaps

Even though there is increasing research on bioremediation and phytoremediation, there are still significant gaps in our knowledge that make it difficult to deploy these technologies on a large scale right away in Sulawesi mining areas. First, although laboratory and small-scale studies yield encouraging outcomes, there is a significant lack of field-scale validation studies performed in authentic Sulawesi mining environments. The intricate interplay among tropical soil attributes, seasonal climatic fluctuations, and native microbial populations necessitates site-specific investigation to enhance remediation parameters.

Second, most studies to date focus on single-metal contamination cases, whereas mining areas in Sulawesi typically exhibit mixed-metal contamination (Ni, Co, Cu, Fe, Cr, Cd) at varying levels. There is still little research on microbial consortia and plant species that can remove multiple heavy metals simultaneously. The synergistic or antagonistic effects of metal mixtures on remediation efficiency necessitate further investigation.

Third, the long-term viability and ecological consequences of integrating hyperaccumulator plants or enhanced microbial populations into Sulawesi ecosystems remain inadequately evaluated. Native species like *Cordyline fruticosa* do not pose much of a threat to the environment, but using non-native hyperaccumulators could harm the environment, so we need to be very careful. Likewise, the fate of metal-laden plant biomass post-phytoextraction—whether through secure disposal, metal recovery, or energy production—remains an unresolved practical challenge that necessitates comprehensive waste management strategies.

Fourth, there is a lack of research on how to integrate bioremediation and phytoremediation with ongoing mining. Most studies focus on what will happen after mining is over, but rehabilitating while mining is still underway could yield significant environmental and economic benefits. Creating ways to clean up that work with mining operations is an important area of research.

Fifth, socio-economic factors influencing technology adoption are still inadequately researched. Biological remediation has technical and economic benefits, but it needs community involvement, capacity building, and compliance with local rules to work. Research on technology transfer, training requirements, and community engagement strategies would enhance practical implementation in Sulawesi.

3.4.3. Recommended Organisms and Approaches for Sulawesi Context

A thorough review of the literature and an analysis of conditions specific to Sulawesi reveal several organisms and methodologies that are especially promising for local implementation:

Prioriy microorganisms

1. Indigenous bacterial strains already found in Sulawesi mining areas, such as *Pseudomonas* sp. (22.54% removal of mercury; Sihombing et al., 2024), *Proteus strains* (18.44-21.54% removal of chromium; Suparman et al., 2023), and *Micrococcus* strains. These organisms can adapt to their surroundings and can be used right away with little concern about safety.
2. Well-known bacterial species that can remove metals, such as *Bacillus cereus* (removal efficiency: 19–36% for multiple metals; Rengarajan et al., 2024), *Pseudomonas aeruginosa* (arsenic removal: 98%; Tariq et al., 2019), and *Alcaligenes faecalis* (copper removal: 74%; Latif et al., 2023). These species exhibit strong performance and may be isolated from local ecosystems or introduced safely.
3. Indigenous fungal species isolated from Sulawesi soils, including *Aspergillus* sp. and *Penicillium* sp., identified from TPA Piyungan (Karimah, 2023; Haya, 2023), which exhibit cadmium and lead remediation capabilities.

Plants that are most important for phytoremediation:

1. *Cordyline fruticosa* (removing lead: 82.8–95%; Herlina et al., 2020). This ornamental plant is native to Southeast Asia, manageable to find, and well-suited to tropical conditions. It also has a fantastic ability to absorb lead, making it perfect for lead-contaminated mining sites in Sulawesi.
2. *Eichhornia crassipes* (water hyacinth) multi-metal removal: 63-83%; Rai, 2019). This plant is invasive, but its fast growth and ability to absorb multiple metals could be used strategically to clean up polluted water bodies near mining operations. It also has the added benefit of controlling biomass.
3. Indigenous wetland species for phytofiltration of mining effluents, necessitating additional screening and characterization from Sulawesi's varied tropical flora.

Recommended Integrated Approach:

For the best results in cleaning up mining areas in Sulawesi, it is best to use a combination of different methods:

1. Phase 1 (Immediate/Short-term): Using native or well-known strains of bacteria to quickly lower the levels of highly toxic metals (Hg, Cr, As) in areas that are heavily contaminated. In situ methods, such as biostimulation and bioaugmentation, reduce costs and disruptions.
2. Phase 2 (Medium-term): Setting up phytoremediation systems that use *Cordyline fruticosa* for soils that have lead in them and *Eichhornia crassipes* for water bodies that are dirty. These systems will continue removing metals while improving the landscape and providing ecosystem services.
3. Phase 3 (Long-term): Create phytostabilization strategies that use native plants that can handle metals to clean up large areas of contamination where complete removal is not possible. This will prevent metals from moving around and allow the ecosystem to slowly recover.
4. Continuous monitoring: Setting up regular monitoring programs to check on the progress of remediation, change treatment plans, and look at signs of ecological recovery.

This integrated approach leverages the strengths of different remediation methods to address the various types of contamination that can occur in Sulawesi mining areas. Focusing on native plants and animals maximizes ecological compatibility and economic viability while also supporting local capacity building and longterm environmental management.

4. CONCLUSION

Studies on heavy metal pollution in Sulawesi mining areas show that pollutant levels often exceed safe levels, indicating that mining is destructive to the environment around it, including soil and water systems. This review shows that bioremediation and phytoremediation are both cost-effective and environmentally friendly approaches to addressing this pollution.

Bioremediation uses microorganisms to clean up polluted areas by biosorption, bioaccumulation, biotransformation, and bioleaching. Bacterial species such as *Bacillus*, *Pseudomonas*, and *Alcaligenes* exhibit removal efficiencies ranging from 20% to 100%, with native Sulawesi strains demonstrating notable potential (*Pseudomonas* sp.: 22.54% Hg removal; *Proteus* spp.: 18.44–21.54% Cr removal). Fungal systems utilizing *Aspergillus*, *Penicillium*, and *Trichoderma* exhibit 10–97% efficacy, whereas algal bioremediation achieves 45–92% removal in aquatic ecosystems. In situ methods (bioventing, biosparging, biostimulation, bioaugmentation) treat contamination directly on-site, while ex situ methods (landfarming, biopiles, composting, bioreactors) involve removing material for treatment. For large-scale uses, in situ methods usually work better because they are cheaper and cause less trouble.

Plants are used in phytoremediation to remove heavy metals by moving them through the soil, taking them up through their roots, loading them into their xylem, and storing them in vacuoles. Phytoextraction (metal accumulation in harvestable biomass), phytofiltration (aquatic removal), phytovolatilization (volatile conversion), phytodegradation (enzymatic breakdown), and phytostabilization (soil immobilization) are all important methods. Native hyperaccumulator species show great promise: *Cordyline fruticosa* removes 82.8–95% of lead, *Eichhornia crassipes* removes 63–83% of multiple metals (Fe, Cu, Cr, Cd, Ni, Zn, As), and *Pteris vitata, Amaranthus spinosus*, and *Ipomoea reptans* accumulate 21–61% of mercury. Species adapted to the area are suitable for cleanup because they do not harm the environment or spread.

A comparative analysis shows that the best results come from combining microbial bioremediation to quickly reduce toxicity with phytoremediation to maintain optimal results over time. Plant–microbe consortia exhibit synergistic effects, in which rhizosphere microorganisms augment metal mobilization and plant uptake beyond their individual capacities.

Significant knowledge deficiencies hinder extensive implementation, notably the absence of field-scale validation in genuine Sulawesi mining contexts, inadequate research on multi-metal contamination scenarios, insufficient long-term ecological evaluations, a lack of integration strategies with ongoing mining operations, and limited exploration of socio-economic adoption factors. Subsequent research should emphasize field-scale pilots in representative locations (Morowali, Konawe, Bombana), examine indigenous plant–microbe consortia, formulate biomass management protocols, and establish long-term monitoring initiatives. Policymakers should make biological remediation a requirement in mine closure plans, offer financial incentives, establish demonstration sites, and invest in building capacity. Mining companies should include cleanup from the start of a project, work with researchers, and work with communities as partners.

Sulawesi can develop sustainable remediation models for all tropical mining areas by prioritizing native organisms, adapting methods to local conditions, filling gaps through targeted research, and encouraging collaboration across groups. These models will balance resource extraction with environmental protection and help Indonesia achieve its sustainable development goals.

AUTHOR DISTRIBUTIONS

Fitria Azis, Nurfadini, Amalyah Febryanti, Sappewali, Dian Fitrah Ardita R., Nur Asmi have conducted a literature survey on environmental bioremediation and phytoremediation in mining areas. Ahyar Ahmad and Harningsih Karim contributed to manuscript corrections and reviews to enhance the completeness of the review article.

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