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Eco-Friendly Solutions to Heavy Metal Pollution: The Role of Microbial Bioremediation — A Mini Review

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ABSTRACT

The accumulation of heavy metals in the environment is a grave threat and is the result of mining, agricultural, and industrial activities. This review article examines eco-friendly processes, including microbial bioremediation, to mitigate heavy metal contamination. Heavy metals have been present in the environment since the beginning of time. Their concentrations are rising due to anthropogenic factors and are contributing to several neurological, cardiovascular, and renal diseases, highlighting the urgency for effective remediation techniques. Microbial bioremediation utilizes the inherent capabilities of microorganisms to detoxify heavy metals through various processes such as bioaccumulation, biosorption, and biotransformation. These processes immobilize or convert heavy metals into less toxic forms. It offers a sustainable alternative to conventional chemical and physical remediation techniques, which are costly and often result in the production of harmful byproducts. This review discusses the complex processes involved in microbial bioremediation, the types of microorganisms used, and the relative benefits of microbial bioremediation over traditional techniques. Furthermore, biotechnological advances such as genetic engineering and the formation of microbial consortia, which improve the effectiveness of bioremediation initiatives, are also discussed. Despite the potential of microbial solutions, several issues exist that necessitate further investigation into the integration of recent advancements and modern applications to enhance the efficacy and efficiency of bioremediation methods, ultimately prioritizing environmental sustainability.

INTRODUCTION

Heavy metals are transition elements classified as essential (e.g., molybdenum, manganese, copper, iron, nickel, and zinc) and non-essential (e.g., Arsenic, Cadmium, Lead, and Mercury) [1]. Heavy metals have been naturally present on Earth since its formation. However, their levels are increasing in both aquatic and terrestrial environments due to human activities such as mining, smelting, and agriculture, as well as natural processes like erosion and weathering [2]. Non-point sources of pollution, including industrial and agricultural activities without a single identified source, are the primary contributors to heavy metal emissions in the atmosphere [3]. Modern environmental challenges, including mining, industrial processes, and agriculture, contribute to toxic metal accumulation, with short-term remediation methods being costly, resource-intensive, and potentially causing secondary pollution. Bioremediation is a sustainable method of mitigating heavy metal pollution, utilizing various microbes to degrade, immobilize, or convert heavy metals into less toxic forms. It offers a long-term solution to heavy metal pollution. Some chemical methods for removing

heavy metals exist, but the use of harsh chemicals generates toxic byproducts that disrupt natural microbial communities and may lead to long-term ecological damage. Physical methods (e.g., soil excavation and water filtration) used for the removal of heavy metals are also costly and less efficient. Microbial bioremediation is a sustainable and cost-effective alternative to both and reduces contamination without the use of harmful chemicals. Genetically engineered microorganisms enhance the efficiency of these processes.

The silent threat: heavy metal contamination and its consequences

Identifying the effects of heavy metals poses a significant challenge to environmental science due to their multifaceted impact on the climate and the continually deteriorating ecosystem. Persistent pollutants, such as mercury, lead, arsenic, and cadmium, are causing severe long-term damage; therefore, it is crucial to design effective bioremediation strategies. The widespread and long-lasting damage caused by the metals released from industries, mines, and farms contaminates soil, water, and sediments. This disruption of ecosystems harms plants

and animals and reduces biodiversity. The accumulation of cadmium in plants reduces their growth, resulting in a decline in crop yield, which, on a large scale, impacts wildlife and local agriculture. Heavy metals, in addition to harming agricultural productivity, exert toxic effects on soil microorganisms, where they play vital roles in nutrient cycling and sustaining soil fertility. The disruption in the microbial community can lead to imbalances in the existing decomposition process. This further influences the health of terrestrial ecosystems.

Beyond the immediate ecosystem, these toxic elements often find their way into the food chain. Once in the chain, they pose significant health risks to both humans and animals. Chronic exposure to heavy metals has been linked to diseases. Heavy metals can lead to neurological disorders, kidney damage, and various forms of cancer in humans. It is documented that aquatic life is especially vulnerable, as contaminated waters impair fish reproduction and development. This impacts and threatens both biodiversity and the stability of food webs. There is an escalating use of industrial chemicals and improper waste management, with the scope of heavy metal contamination continuing to expand. Hence, making proactive prevention, monitoring, and innovative clean-up strategies are more urgently needed than ever before.

Effect on the environment

Heavy metals naturally occur in the environment and are detrimental to both humans and their environment. Heavy metals like cadmium, nickel, mercury, arsenic, copper, chromium, and lead pollute the environment [4]. They are the main reason for water pollution. Industries discharge polluted water containing heavy metals into the environment, either by direct release into water bodies or indirectly through leakage, leading to severe water contamination. Soil pollution by heavy metals is caused by various anthropogenic activities, including agricultural methods, the automobile sector, the mining of metallic ores, and the leaching of metals from landfills. [5]. Heavy metals affect the soil by altering its properties, including color, porosity, pH, natural chemistry, and quality [2]. Heavy metals cause air pollution in the form of vehicle emissions, coal burning, and biomass combustion [6]

Health impacts of heavy metal pollution

Heavy metals have adverse effects on humans. These metals are known to disrupt metabolism within the human body, accumulate in the main body organs, and cause severe neurological, cardiovascular, and renal diseases. For instance, lead affects the brain negatively, an effect that can lead to developmental difficulties and behavioral disorders in children. Other toxic effects of heavy metals are associated with health problems like skin lesions, kidney dysfunction and immune system disorders, gastrointestinal problems, neurological disorders, vascular damage, birth defects, cancer, etc [7]. Lead, copper, and zinc cause health problems like nephrotoxicity, carcinogenicity, neurotoxicity, and sexual gland dysfunction [5] while cadmium, mercury, and nickel cause cardiac failure, kidney damage, Alzheimer's disease, lung issues, and brain damage [8]. At first glance, one might think that the dangers attributed to the aforementioned metals are only suffered by industrial workers, but the general population is also at risk.

Economic and social impacts

There are many harmful economic and social impacts of heavy metal pollution. On a local level, pollution primarily affects sectors such as agriculture and fisheries, which rely heavily on the quality of water and soil. Pesticides, chemical fertilizers, and heavy metals in crops, fish, and other water-inhabiting organisms

lead to low yields and income, as well as high costs for remediation and medical treatments. The cleaning up of affected ecosystems is also a costly process, which entails the use of capital-intensive physical and chemical technologies. Social conflicts such as displacement or living in compromised housing due to proximity to industrial sites or mining operations are often found in communities' living standards, thereby increasing the level of poverty. However, as the number of people affected by illnesses associated with heavy metals ceases to rise, the workload of countries' healthcare facilities increases, the cost of health insurance soars, and the overall efficiency of employees decreases. These impacts exacerbate injustice, particularly for vulnerable groups of people, who often reside in areas where these industries are established and cannot afford to mitigate the effects of pollution.

Processes involved in microbial bioremediation

Unlike conventional methods, microbial bioremediation is natural and economical. Its application in countering heavy metal pollution mainly involves using naturally occurring and artificially engineered microorganisms to detoxify ecosystems contaminated with heavy metals, such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr). The innate capability of microorganisms to transform, immobilize, or eliminate toxic substances is harnessed in these processes. Detoxification of metals is accomplished by various techniques, including intracellular accumulation, extracellular binding, and transformation, each of which contributes uniquely to metal detoxification.

These mechanisms include microbial degradation, biotransformation, bioaccumulation, and mineralization, and are explained below. Several microbial strategies, which can also work in concert, form the backbone of bioremediation successes. Microbes may actively uptake and sequester metal ions within their cells, which effectively reduces the bioavailability of toxic agents. Microorganisms can directly adsorb metals to cell surfaces or excrete compounds that cause metals to precipitate out of solution. These processes limit the mobility of heavy metals in the environment. Genetically engineered strains of microorganisms, using conventional technology such as CRISPR or "clustered regularly interspaced short palindromic repeats," can be tailored for maximum efficiency and offer promising results in targeted applications.

Microbial bioremediation adaptability is its beauty: microbial communities can adjust to changing contamination profiles and environmental conditions. This adaptation makes the process resilient and self-sustaining over time. Ongoing research focuses on understanding inter-microbial interactions to harness the full potential of microbial cooperation. Optimizing growth conditions and integrating bioremediation with monitoring systems to ensure long-term success in contaminated ecosystems is urgently needed.

Bioaccumulation

Bioaccumulation of heavy metals is a highly efficient process whereby microorganisms actively take up heavy metals from their environment into their cells. By intracellular sequestration, the metals are prevented from interacting with and attacking other organisms in the ecosystem. *Pseudomonas aeruginosa* and *Saccharomyces cerevisiae* are engineered to increase their metal uptake capacity by the overexpression of metal-binding proteins. The mechanisms of uptake include active transport systems driven by ion gradients and metal-specific proteins, such as metallothioneins. Bioaccumulation is particularly effective for highly soluble metals, such as cadmium and mercury, and can

substantially decrease the bioavailability of metals in water systems [9].

Biosorption

Biosorption is complementary to bioaccumulation. In this process, heavy metals bind to cellular surfaces as a result of their physicochemical attraction to the functional groups (carboxyl, hydroxyl, and phosphate) present on microbial cell walls. The binding capacity for metals, such as lead and chromium, has been more extensively studied, particularly in organisms like *Bacillus subtilis* and *Aspergillus niger*. This process is energy-independent and thus very useful for treating larger volumes of wastewater [10].

Biotransformation

This is a process in microbial bioremediation, in which heavy metals that cannot be degraded chemically or physically are transformed into less toxic or water-soluble chemical products with the help of microbial enzymes or metabolites. These enzymes and metabolites are potential agents used to alter the properties of metals [11]. For instance, microbes like *Pseudomonas* can reduce hexavalent chromium (Cr(VI)), an extremely detrimental and soluble form of chromium, to trivalent chromium (Cr(III)), a less toxic form that precipitates out of solution. It significantly mitigates the detrimental effects of chromium on the environment. Consequently, biotransformation plays an essential role in the detoxification of contaminated ecosystems [10].

Mineralization

Mineralization involves the long-term immobilization of heavy metals by converting them into stable mineral forms. *Desulfovibrio* is a sulfate-reducing bacterium that precipitates metals like sulfides. This ultimately prevents their environmental spread by assimilating the pollutants into nonmobile mineral matrices. In addition to it, microbial-induced precipitation and mineralization of cadmium (Cd) are used to mitigate soil contamination. Cd precipitation through carbonate, phosphate, and sulfide formation is aided by microorganisms, rendering the metal less toxic and less able to enter the environment [12].

Biofilms

Microbial cells in extracellular polymeric substances (EPS) constitute biofilms. By the biosorption and bioaccumulation of heavy metals, biofilms greatly reduce heavy metal pollution. Since metal ions are positively charged, they bond to the negatively charged EPS. The high microbial density in biofilms, along with this bonding, improves the efficacy of biofilms and consequently reduces heavy metal toxicity [13].

Microbial Degradation

Generally thought to be associated with organic contaminants, biodegradation can also play a supplementary role in heavy metal bioremediation by breaking down the organometallic complexes and releasing the metals for binding and transformation. For example, the microorganisms that can degrade methylmercury can limit its bioaccumulation in aquatic food chains.

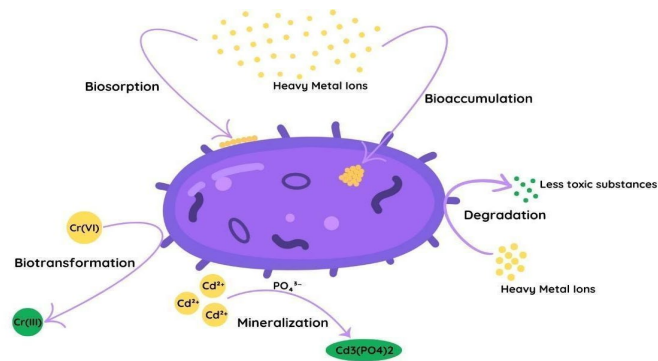


Figure 1. Mechanisms of microbial bioremediation of heavy metals. Microorganisms mitigate heavy metal toxicity through several processes, including biosorption of metal ions onto cell surfaces, bioaccumulation within intracellular compartments, enzymatic degradation into less toxic forms, biotransformation of toxic species (e.g., reduction of Cr(VI) to Cr(III)), and mineralization processes that convert soluble metal ions into insoluble precipitates (e.g., $\text{Cd}_3(\text{PO}_4)_2$). These pathways collectively reduce the mobility, bioavailability, and toxicity of heavy metals in contaminated environments.

Microorganisms Used in Bioremediation

Microorganisms, including algae, fungi, and bacteria, play a crucial role in bioremediation processes, as they can degrade, transform, and immobilize various heavy metals. The selection of microbes for a particular process depends on several factors, such as the type of pollutant and environmental conditions. Some bacteria, such as *Pseudomonas* species, possess unique detoxification systems that enable them to reduce harmful metals like chromium and copper [14]. Other bacterial species, such as *Geobacter*, can eliminate uranium, iron, and cadmium [15].

Fungal species such as *Penicillium* and *Aspergillus* can also be employed in bioremediation techniques, as they can break down organic pollutants. Moreover, owing to its exceptionally high tolerance to cadmium, *Aspergillus* proves to be the best choice for the bioaccumulation of cadmium [16]. Other microbes, particularly green algae, also possess bioremediation capacity due to their ability to effectively absorb and sequester heavy metals, such as lead, cadmium, and mercury, from contaminated water. They are effective in dealing with polluted aquatic ecosystems.

Comparative Analysis

Chemical remediation of heavy metals involves the usage of chemicals (e.g., sodium hydroxide or lime) to remove or precipitate heavy metals. These processes produce toxic byproducts, ultimately leading to secondary pollution and reduced efficacy. Physical remediation employs processes like adsorption, filtration, and ion exchange, which are less efficient and have high initial and operational costs. Whereas microbial bioremediation utilizes microbes and their abilities, offering a sustainable and cost-effective solution to heavy metal pollution. A comparison of the three types highlights their advantages and limitations in relation to one another, as illustrated in the table.

Table 1. Comparative analysis of microbial, chemical and physical remediation.

Feature	Microbial Bioremediation	Chemical Remediation	Physical Remediation
Cost	Generally low initial and operational costs since naturally occurring or specially cultivated microorganisms can be used on-site with minimal infrastructure. It may become higher in challenging conditions. Particularly effective at breaking down or transforming a broad range of organic contaminants (e.g., oil spills, pesticides). Often less efficient for heavy metals unless specific microbes are employed. Results can be slower and require specific environmental conditions.	Usually involves high costs because specialty chemicals and trained personnel are required for application and monitoring. Costs can also increase due to the purchase, transport, and safe disposal of chemicals.	High costs stem from the need for advanced equipment, specialized maintenance, and often large energy inputs. Examples include pumps, excavators, or filtration units, which require significant investment and ongoing maintenance.
Efficiency	Minimally invasive, as introduced or stimulated microbes are generally safe, and byproducts are often non-toxic. However, microbial imbalance or unintended spread can occasionally disrupt local ecosystems. Bioremediation is typically a slow to moderate process, as microbes need time to adapt, multiply, and perform biochemical breakdown. Speed increases with optimized conditions but remains slower than alternatives.	Highly efficient for targeted pollutants such as heavy metals, industrial chemicals, or pesticides. Clean-up is often rapid, but chemical selectivity can leave some contaminants unaffected.	It can rapidly remove or isolate a variety of pollutants such as sediments, debris, or some metals. However, efficacy varies based on method (e.g., filtration vs. soil vapor extraction) and site-specific conditions. Usually does not address chemical transformation of pollutants.
Impact on Environment	Bioremediation is typically a slow to moderate process, as microbes need time to adapt, multiply, and perform biochemical breakdown. Speed increases with optimized conditions but remains slower than alternatives.	Chemical use can create secondary pollution through runoff or toxic byproducts. Chemical residues may persist in the environment, affecting local plants, animals, and soil health. Residual toxicity requires further management.	Physical disruption, such as excavation or dredging, can destroy habitats and cause soil erosion. Energy intensive procedures increase carbon footprint. Waste generated may need further treatment before disposal.
Speed	Highly sustainable, particularly when indigenous microbes are used and not genetically engineered. Promotes restoration of natural balance. Can be repeated with minimal resource input.	Offers a rapid response, often suitable for emergency spills or high-risk contamination. Chemicals act quickly but may require repeated applications for thorough remediation.	Provides fast and immediate removal or containment of pollutants, making it suitable for acute or large-scale contamination events. No lag phase; however, only addresses physical presence, not chemical transformation.
Sustainability		Less sustainable as it depends on ongoing chemical production, transport, and disposal. Repeated treatments increase environmental burden, and chemicals are largely non-renewable.	Generally not sustainable due to energy demand, resource consumption, and production of secondary wastes (e.g., filters, polluted barriers). Limited long-term ecosystem recovery.

Biotechnological Advancements

The effectiveness of microbial bioremediation has increased due to recent advancements in biotechnology. Genetic engineering has significantly contributed to this increase by improving the capacity of microorganisms to effectively break down pollutants. Due to the introduction of specific protein-encoding genes, genetically modified microbes can more effectively and efficiently tolerate, transform, and remove heavy metals from contaminated environments. Additionally, multi-functional, genetically engineered microorganisms (MFGEMs) have been developed that can target multiple contaminants simultaneously, thereby enhancing the remediation results. These microbes are a valuable asset, as they offer a more economical and environmentally friendly solution while also mitigating the drawbacks of natural microbes [17].

Furthermore, the formation of microbial consortia enhances the efficacy of bioremediation by utilizing a variety of microorganisms that work concertedly to break down or immobilize heavy metals. To target a greater variety of pollutants and enhance resistance to toxic metals, they employ corresponding metabolic pathways, which ultimately increase efficiency. Additionally, the integration of state-of-the-art technologies, such as metabolomics, genomics, and bioinformatics, has enhanced our understanding of microbial

interactions and their potential applications in environmental remediation [18].

CONCLUSION

One of the most urgent environmental issues today is heavy metal pollution. It causes adverse effects on human health and is a threat to ecosystems and socioeconomic stability. Although successful in some situations, traditional remediation techniques frequently require a lot of resources and produce secondary pollution. Microbial bioremediation offers an environmentally friendly, cost-effective, and sustainable solution to heavy metal pollution. It harnesses the natural capabilities of microbes such as fungi, algae, and bacteria to transform, remove, and immobilize toxic metals. The effectiveness and reach of microbial solutions have been enhanced by advancements in biotechnology, including genetic engineering and microbial consortia. Microbial bioremediation holds enormous potential as a key component of future pollution management strategies, despite ongoing challenges with process optimization, scalability, and ecological safety. To enhance its efficiency and protect human and environmental health, continued research, the incorporation of contemporary technologies, and policy support will be necessary.

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