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Mycoremediation of Mercury: Investigating Detoxification Mechanisms in Selected Fungal Species

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Abstract
Mercury (Hg) contamination poses a critical threat to environmental and human health due to its toxicity, persistence, and bioaccumulative nature. Understanding microbial mechanisms for mercury detoxification is essential for developing sustainable bioremediation strategies. This review highlights key mechanisms employed by fungi to mitigate mercury toxicity, including resistance, bioaccumulation, and biosorption. Resistance mechanisms are primarily mediated by the mer operon, with enzymes like MerA and MerB facilitating mercury reduction and detoxification. Fungi also bioaccumulate mercury through passive and active transport systems, binding it to intracellular proteins such as metallothioneins. Additionally, fungal biomass live or dead—can effectively adsorb mercury via cell wall functional groups through biosorption. Fungal metabolites, particularly low molecular mass organic acids, further influence mercury mobility and sequestration in the environment. The effectiveness of bioremediation is influenced by numerous factors, including environmental conditions such as pH, oxygen, and water availability, microbial community characteristics, and nutrient availability. Fungi demonstrate notable advantages in bioremediation due to their tolerance to harsh conditions, extensive hyphal growth, and secretion of extracellular enzymes. In Nigeria, multiple studies have demonstrated the bioremediation potential of fungi and other microbes for petroleum hydrocarbons and heavy metals, including mercury, in contaminated environments. The findings underscore the promising role of fungal-based biotechnologies in addressing environmental pollution, particularly in regions heavily impacted by industrial activities.

Keywords: Mercury (Hg) contamination, Toxicity, Bioaccumulation, Bioremediation, metallothioneins

Introduction

Mercury (Hg) contamination is a important environmental issue, posing severe risks to both human health and ecosystems worldwide (Charkiewicz et al., 2025). This heavy metal is released into the environment through industrial activities such as mining, agriculture, and the manufacturing of various goods (Mae et al., 2025). Due to its toxicity, persistence, and bioaccumulative properties, mercury contamination can cause long-lasting environmental damage and severe health complications, including neurological disorders and kidney damage in humans. The management of mercury pollution has become increasingly urgent, prompting the search for sustainable, cost-effective methods of removing mercury from contaminated environments (Thakur et al., 2025). One of the promising solutions lies in the field of mycoremediation, where fungi are harnessed to detoxify harmful substances (Periakaruppan et al., 2025). Fungi are highly adaptable organisms capable of thriving in a variety of harsh environmental conditions, making them particularly suitable for bioremediation (Venâncio, 2025). These microorganisms employ diverse mechanisms to combat mercury toxicity, including resistance through the mer operon, bioaccumulation, and biosorption (Sarkar and Bhattacharjee, 2025). These processes enable fungi to either transform mercury into less harmful forms, concentrate it within their cells, or bind it to their biomass, thus removing it from contaminated environments (Periakaruppan et al., 2025). Furthermore, the production of organic acids and other metabolites by fungi can enhance mercury mobility, providing additional means for its detoxification (Anas et al., 2025).

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Understanding these mechanisms and their usefulness for extensive environmental cleanup has become a more prominent area of research in recent years. The ability of fungi to clean up contaminated areas is greatly enhanced by their large hyphal growth, high biomass production, and extracellular enzyme secretion (Parida, 2025). The success of fungal bioremediation initiatives is also greatly influenced by variables like microbial community characteristics, nutrient availability, and environmental conditions (Kebede et al., 2021).
This paper analyzes the potential of fungus in the detoxification of mercury, highlighting the important processes of resistance, bioaccumulation, and biosorption that fungi exploit to minimize mercury toxicity. It also examines the factors that influence the efficiency of mycoremediation and discusses the promising role of fungal-based biotechnologies in addressing mercury contamination, particularly in regions such as Nigeria, where industrial activities have exacerbated environmental pollution. By optimizing these processes, mycoremediation can become an effective, sustainable solution for reducing mercury contamination and its harmful effects on both the environment and human health.

Mechanisms Of Mercury Detoxification
One hazardous heavy metal that seriously endangers both human health and the environment is mercury (Hg) (Kim et al., 2016). Due to its persistence and ability to bioaccumulate, understanding the mechanisms of mercury detoxification is crucial for developing effective bioremediation strategies (Kumar et al., 2023). Various microorganisms, particularly fungi, have evolved diverse mechanisms to cope with mercury toxicity, which can be broadly categorized into resistance, bioaccumulation, and biosorption (Durand et al., 2020).

Mercury Resistance Mechanisms in Microorganisms
Microbial resistance to mercury often involves enzymatic detoxification processes, most notably the mer operon (Nascimento et al., 2003). This genetic system, which genes for proteins that change poisonous ionic mercury (Hg^{2+}) into less hazardous elemental mercury (Hg^0), which is volatile and can exit the cell, is found in many bacteria and certain fungi. Important enzymes in this system include mercuric reductase (MerA), which catalyzes the NADPH-dependent reduction of Hg^{2+}, and organomercurial lyase (MerB), which breaks down carbon-mercury bonds in organomercury compounds, releasing Hg^{2+} for MerA to reduce. Studies that have isolated mercury-resistant fungi from contaminated soils provide evidence for the presence and activity of such resistance mechanisms (Nascimento et al., 2003). A novel Hg-volatilizing Lecythophora sp. fungus (DC-F1) has the ability to bioremediate mercury-contaminated soil (Chang et al., 2019). A novel species of the fungus Penicillium is also present. According to Chang et al. (2020), DC-F11 that was isolated from contaminated soil also showed mechanisms resistant to mercury (II).

Bioaccumulation of Mercury by Microorganisms:
Bioaccumulation refers to the uptake and accumulation of substances, such as mercury, within an organism. Fungi can accumulate mercury through both energy-dependent active transport systems and passive uptake mechanisms. In order to counteract the harmful consequences of the accumulating mercury, it can be sequestered inside the fungal cells and frequently bound to cellular components such metallothioneins and other metal-binding proteins (Davidova et al., 2024). There are differences in the ability of different fungus species to bioaccumulate mercury. According to Kapoor et al. (1999), Aspergillus niger has demonstrated the ability to bioremove heavy metals. From cold sulfidic spring water biofilms, a novel strain of Mucor hiemalis (EH8) that accumulates mercury was also identified (Hoque and Fritscher, 2016).

Biosorption of Mercury by Fungal Biomass
Mercury and other contaminants attach to the surface of microbial cells or their constituents by a process known as biosorption, which is metabolism-independent (Priya et al., 2022). Fungal cell walls, which are composed of chitin, glucans, and other polysaccharides, contain functional groups that effectively bind metal ions through processes such as ion exchange, complexation, and adsorption. Using both live and dead fungal biomass, biosorption is a useful and affordable technique for removing mercury from contaminated soil and water (Ayele et al., 2021). It has been investigated how mercury (II) biosorbs onto fungal biomass from various species. The process by which Aspergillus versicolor biomass adsorbs mercury has been investigated. Additionally, immobilized fungal residues have demonstrated mercury (II) adsorption properties (Li et al, 2018).

Role of Fungal Metabolites:
The dynamics of mercury in the environment can be influenced by the many organic acids and other metabolites that fungi can create (Liu et al., 2018). The leaching and mobilization of mercury from solid matrices may be aided by the fungus's synthesis of low molecular mass organic acids (LMMOAs). Conversely, fungal exudates might also play a role in complexing or immobilizing mercury, thereby reducing its bioavailability (Ash et al., 2016).

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Factors Affecting Bioremediation Efficiency
A complex interaction of different factors determines the effectiveness of bioremediation, a vital technology for the breakdown or conversion of pollutants into less hazardous substances. These elements can be broadly divided into three categories: the microbial community's characteristics, environmental conditions, and the accessibility of necessary nutrients and amendments.
Environmental Conditions
A contaminated site's physical and chemical conditions have a big impact on how well bioremediation works (Kebede et al., 2021). Water availability is a fundamental requirement for microbial metabolic activities involved in pollutant breakdown. Similarly, oxygen availability is critical for aerobic bioremediation processes, where it acts as an electron acceptor (Fragkou et al., 2021). However, anaerobic bioremediation occurs under oxygen-limited conditions (Domingues et al., 2017). pH is another crucial factor affecting microbial activity and enzyme function. Studies have indicated that slightly acidic conditions can be favourable for bioremediation. For instance, a bioremediation study of refinery effluent observed a pH range of 6.56 – 6.903 (Kumar et al., 2022). Similarly, Govarthanan et al. (2016) reported that an optimized pH of 6.0 – 7.0 greatly influenced bioremediation efficiency. This study also found correlations between pH and parameters such as CO_2 evolution (positive), oil and grease (negative), lead (negative), and nickel (negative) (Yusuf et al., 2024). In contrast to bacteria, fungi are notably better able to flourish in environmentally stressful situations such as low pH and inadequate nutritional status.

Characteristics of the Microbial Community
Effective bioremediation depends on the existence and activity of microorganisms that can break down the particular pollutants (Ahmad et al., 2023). The outcomes of bioremediation may be better when several bacterial strains are employed rather than simply one. Because of their rapid development, increased biomass output, and extensive hyphal reach in the environment, fungi have also shown increased efficacy in bioremediation (Pande et al., 2020).
Filamentous fungi's high surface-to-cell ratio makes them great degraders in certain environments. A crucial component of bioremediation is the local microflora's capacity to generate extra enzymes that aid in the breakdown of contaminants in a contaminated environment (Bhandari et al., 2021). The capacity of fungi to produce a range of extracellular enzymes that are necessary for bioremediation—a process that is accelerated in the absence of nourishment—makes them special. Another element affecting the procedure's speed and efficiency is the microorganisms' rate of growth.
Methods like bioaugmentation, which introduces cultured microorganisms to the contaminated area, can increase the catabolic potential of the local microbial community. Biological agents such as termites, algae, fungi, bacteria, and plants are necessary for bioremediation. In particular, Mycoremediation uses technology based on fungi to disinfect.

Nutrient Availability and Amendments
Essential nutrients are necessary for microorganisms' development and metabolic processes. A competent bacterium must have access to sources of nitrogen and phosphorus in order to degrade a polluted carbon source (Singh et al., 2022). If these nutrients are lacking, the remediation process can be rendered ineffective. Strategies such as biostimulation, which involves modifying environmental conditions to stimulate existing microorganisms, often include the addition of nutrients to enhance microbial activity (Goswami et al., 2018). Certain nutrients and seeded cultures can increase the effectiveness of pollutant decomposition. Enhancing the indigenous microflora's capacity to proliferate by providing them with more food is the basic objective of bioremediation (Abatenh et al., 2017).

Previous Studies On Bioremediation In Nigeria
Nigeria has faced significant environmental pollution challenges due to industrial activities, particularly in the petroleum sector and other industries. Consequently, numerous studies have investigated the potential and application of bioremediation techniques to address these issues. This review highlights some of the previous studies on bioremediation conducted in Nigeria, drawing on the provided sources (Mafiana et al., 2021; Ite et al., 2016).

Many studies have focused on the bioremediation of petroleum hydrocarbon-contaminated soil and water. Offiong et al. (2019) looked into the use of particular organic wastes for the bioremediation of hydrocarbon-contaminated soil. Ubogu et al. (2019) investigated the rhizoremediation of a swamp contaminated by crude oil using Phragmites australis and Eichhornia crassipes, and they found that the quantities of total petroleum

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hydrocarbons (TPH) in the rhizospheres of these species decreased. Obire et al. (2008) looked for saprophytic and crude oil-degrading fungi in cow dung and chicken droppings as potential bioremediating agents.

Furthermore, Ekundayo et al. (2012) looked at the biodegradation of Bonny light crude oil by locally isolated fungus from oil-contaminated soils in Akure, Ondo State. The application of bioaugmentation in the bioremediation of gasoline-contaminated agricultural soil was examined by Nwankwegu and Onwosi (2017). Smith et al. (2015) evaluated bioslurry and biopiling techniques for hydrocarbon-contaminated soils in dry environments. Vanishree et al. (2014) investigated the biodegradation of gasoline using Aspergillus species. The effects of Penicillium Sp. and Mortierella Sp., which were isolated from oil-contaminated soil in car repair shops, biodegraded crude oil, refinery effluent, and specific petroleum components, were examined by Okougbo et al. (2016). Ariyo and Obire (2016) investigated the microbial community and hydrocarbon-using microorganisms from abattoir soils in the Niger Delta.

The bioremediation of heavy metal contamination has also been the subject of research in Nigeria. When Mshelia et al. (2022) bioremediated soil contaminated with zinc and cadmium using microflora from abattoir effluent, they discovered that both metals were considerably reduced over the course of three weeks. Their study revealed that these heavy metals might be extracted from polluted soil by the microorganisms present in abattoir wastewater. Alori et al. (2018) looked at the bioremediation potential of sunflower and Pseudomonas species in soil contaminated with lead and zinc. Nwagwu et al. (2017) identified, characterized, and assessed the bioremediation capability of heavy metal-tolerant bacteria from the Panteka stream in Kaduna, Nigeria.

A study in Kaduna that also screened fungus isolates from refinery effluent and the Romi River for bioremediation potential found that Chrysosporium tropicum, Aspergillus flavus, Aspergillus niger, and Rhizopus oryzae were viable possibilities. The amounts of lead, phenol, cadmium, nickel, and oil and grease in refinery effluent were successfully reduced by a combination of these fungi (Obukohwo et al., 2020). Ezeonuegbu et al. (2016) assessed the capacity of fungal species isolated from refinery effluent to extract and bioaccumulate lead, nickel, and cadmium from refinery waste. Doku and Belford (2012) looked on the capacity of Aspergillus niger and Aspergillus flavus to bioaccumulate heavy metals from wastewater from paper mills. Atikpo and Michael (2018) assessed six microorganisms' efficacy in treating agricultural soil tainted with lead.
Phytoremediation, which uses plants to clean up contaminated regions, is also being studied. Ubogu et al. (2019) demonstrated the rhizoremediation of crude oil using Phragmites australis and Eichhornia crassipes. Ugya et al. (2015) examined the efficacy of Pistia stratiotes in phytoremediation after the Kaduna Refinery and Petrochemical Company contaminated Romi Stream. Ajibade et al. (2013) evaluated the efficacy of water hyacinth phytoremediation in removing heavy metals from domestic sewage. Akinbile et al. (2019) assessed the efficacy of Azolla pinnata in a variety of wastewater treatment procedures for agricultural reuse. Akinbile et al. (2016) studied the phytoremediation of domestic wastewaters in wetlands formed on the surface of free water using Azolla pinnata.

Research has also been done on the effects of abattoir effluents and associated contaminants; the results may influence bioremediation strategies. Adesemoye et al. (2006) examined the microbial makeup of the contaminated soil and abattoir wastewater in Lagos, Nigeria. Adesina et al. (2018) assessed the impact of Kara Abattoir effluent on the Ogun River's water quality in Nigeria. Atuanya et al. (2018) examined the antibiotic resistance and plasmid profiles of bacteria isolated from abattoir effluents along the Ikpoba River in Benin City, Nigeria. Joseph et al. carried out a microbiological evaluation of the effluents from particular slaughterhouses in adjacent water bodies in Kaduna Metropolis in 2021. These earlier studies demonstrate a keen interest in exploring different bioremediation methods for Nigerian pollution types that use indigenous plant and microbial species. The findings of these studies offer crucial information for developing cost-effective and ecologically friendly bioremediation methods for Nigerian environmental management.

Conclusion

Mercury detoxification by fungi offers great potential for bioremediation, leveraging mechanisms like enzymatic resistance, bioaccumulation, biosorption, and metabolite production, with effectiveness influenced by environmental conditions and nutrient availability.

Recommendation

To enhance mercury bioremediation, it is recommended to utilize mercury-resistant fungal species, optimize environmental conditions, integrate fungal methods with other techniques, develop sustainable strategies, expand research on fungal metabolites, and implement supportive policies and regulations for effective environmental management.

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