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Lactic Acid Bacteria: Heavy Metal Remediation, Mechanism, Current Status and Future Prospects

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Abstract

Heavy metal (HM) pollution is a critical issue worldwide. The use of microorganisms, especially lactic acid bacteria (LAB), to address HM contamination is gaining attention due to its mild operating conditions, low costs, and minimal environmental impact. This review consolidates recent findings on the potential of LAB as biosorbents for HMs. LAB, being a food-safe probiotic, offers dual applications in soil and wastewater treatment as well as food-based metal removal. The primary mechanisms of HM removal by LAB include extracellular adsorption, intracellular accumulation, and lactic acid (LA) fermentation, particularly valuable in the food industry. Key factors affecting LAB's bioremediation efficiency are pH, temperature, biomass, ion concentration, and adsorption time. While laboratory studies demonstrate LAB's theoretical feasibility, its practical application remains constrained by limited Efficiency. This review also highlights methods for enhancing LAB's adsorption efficiency, such as pretreatment and mixed cultivation, and outlines future research directions to support the practical implementation of LAB in HM bioremediation.

INTRODUCTION

The rapid pace of urbanization and industrialization has led to a significant rise in heavy metal (HM) levels in soils, rivers, oceans, and food (Hao et al., 2024; Sudharshan Reddy and Sunitha, 2023). These toxic metals can disrupt proteins and enzymes in humans and animals, leading to toxicity and adverse health effects (Le and Nguyen, 2024). Unlike pollution from organic compounds, which can often be reduced or eliminated by natural or biological processes, HMs are persistent and accumulate in living organisms without degrading (Sodhi et al., 2022).

Microbial remediation has gained global interest due to its low cost, mild operating conditions, and minimal secondary pollution (Chen et al., 2020; Hussein et al., 2024). This technology leverages microorganisms' unique chemical structures and metabolic activities to decrease HM activity in contaminated environments. Research highlights that bacterium (Hu et al., 2024), fungi (Dhami et al., 2017), yeast (Ben Said et al., 2019), and algae (Amal Raj et al., 2024) possess strong HM adsorption and accumulation abilities. However, fungi and algae may sometimes overgrow and disrupt native microorganisms in contaminated environments, especially in nutrient-rich polluted waters.

Lactic acid bacteria (LAB) are Gram-positive, facultatively anaerobic bacteria that ferment carbohydrates to produce lactic acid (Ahmad et al., 2020; Perczak et al., 2018). Found abundantly in nature, LAB are safe, non-toxic, and widely used in food products like yoghurt, pastries, and health foods. Studies have shown that LAB can support digestive health, promote nutrient absorption, relieve constipation, and help maintain gut flora balance. LAB can also enhance plant growth (Murindangabo et al., 2023). Recent research indicates LAB's capability to adsorb HMs, with common HM-adsorbing LAB strains including Lactobacillus, Bacillus, Enterococcus, Streptococcus, and Pediococcus.

MECHANISMS

HM remediation by microorganisms primarily involves several processes, including surface adsorption, physical deposition, ion exchange, and cell membrane penetration (Wu et al., 2021). In practice, these mechanisms often work together to facilitate comprehensive metal removal. Metal ion adsorption in LAB can occur both on the cell surface and within the cell. External polymers like proteins and sugars on the cell surface, as well as intracellular metal-binding proteins, interact with metal ions to immobilize them. Biotransformation occurs inside the cell, where LAB can modify the valence states of HMs through redox reactions, methylation, and similar processes, thereby reducing toxicity and mobility (Lin et al., 2019).

Compared to physical and chemical methods, microbial remediation tends to have lower efficiency. However, LAB offers distinct advantages due to its rapid growth, resilience in harsh conditions, and the ability to utilize organic matter in nutrient-poor environments. LAB can remain active in pH levels of 4.0–8.0 and temperatures of 5–45°C, demonstrating high HM tolerance (Ma et al., 2023). Additionally, LAB's probiotic nature makes it suitable for HM remediation in food and water (Li et al., 2020; Shu et al., 2021).

The LAB cell wall, composed of negatively charged substances like peptidoglycan, glucan, and proteins, effectively binds positively charged metal ions. When HM ions encounter cell wall functional groups (e.g., -COOH, -OH, -SH), they may form coordination complexes, which can reduce HM toxicity. For example, Yi et al. (2017) observed that functional groups such as -OH, -CONH, and -COOH were involved in the Pb adsorption process by *Leuconostoc mesenteroides*. LAB's cell surface polysaccharides also help adsorb HM ions via carboxyl and phosphate groups. Additionally, organic acids and other byproducts from microbial metabolism can interact with HMs, affecting their migration and bioavailability.

Intracellularly, LAB can absorb HMs through a slower, energy-intensive process that relies on cellular metabolism. Transporter proteins facilitate HM movement into the cell, where they accumulate. Internal processes, such as redox reactions and methylation, help reduce HM toxicity. This active uptake process depends on various transport and hydrolytic enzymes. LAB's HM adsorption mechanisms are intricate and involve a combination of extracellular binding and intracellular processing.

Several factors influence LAB's HM adsorption efficiency, including cell condition and adsorption environment. Cell factors include age, physiological status, and nutrient availability, though these are difficult to control experimentally. Environmental conditions, such as pH, temperature, metal ion concentration, and biomass levels, are more easily adjusted to enhance adsorption efficiency. Each condition's impact on HM adsorption is therefore carefully considered to optimize the process.

APPLICATION IN FOOD INDUSTRY

Safe, non-toxic food is essential for survival; however, various natural and human-made pollutants are increasingly entering the environment and contaminating food. Conventional HM removal methods, such as washing, soaking, and heating, are commonly applied. Despite their use, these methods have limitations, including restricted effectiveness for inorganic metal ions, low removal efficiency, high costs for equipment and reagents, the need for trained personnel, and the generation of hazardous wastewater. Research has shown that microorganisms, including bacteria, algae, fungi, and yeasts, can effectively adsorb or accumulate HMs, whether active or inactive (Kuanar et al., 2022). Biological adsorption offers advantages over physical and chemical methods, such as reduced chemical requirements, high efficiency, selectivity for specific HMs, and minimal waste. Additionally, bio-adsorbents can often be recycled and reused.

Lactic acid bacteria (LAB) are particularly suited for HM removal in food due to their high safety profile and widespread use in food processing. LAB are especially valuable in the production of fermented foods, like rice products, where HM removal must align with quality and flavour standards. As probiotics, LAB also supports digestive health and promotes balanced intestinal microbiota (Bendali et al., 2011; Petrova et al., 2022). Utilizing LAB for HM remediation in food could, therefore, indirectly benefit human health. Table 1 summarizes studies exploring LAB's role in HM removal from food. In these studies, LAB mechanisms for removing HMs include conventional biosorption and bioaccumulation; lactic acid (LA), a primary metabolite, may also contribute. Research has shown that cadmium removal from rice is associated with LA, which interacts with cadmium-binding sites on proteins, breaking bonds to release cadmium ions (Zhai et al., 2019).

CHALLENGES AND FUTURE PERSPECTIVES

The primary challenge in using LAB for heavy metal (HM) remediation is their relatively low adsorption capacity. Beyond traditional techniques discussed earlier, methods like genetic engineering, LAB immobilization, and integration with nanomaterials show promise for enhancing adsorption efficiency, improving strain stability, reducing costs, and maximizing environmental impact.

CONCLUSION AND LIMITATIONS

With rising HM levels, urban areas must develop innovative, cost-effective solutions for metal treatment. Advances in microbial remediation, particularly LAB-based methods, are proving more effective than many conventional approaches. LAB offers a safe, reliable, and effective HM adsorbent due to its growth resilience, stability, and health benefits. This review highlights recent findings on LAB in HM remediation, noting LAB's dual function of adsorption and bioaccumulation to remove or transform metals in contaminated environments. Additionally, LAB metabolites, including lactic and acetic acids, can increase the bioavailability and mobility of HMs, allowing for more efficient capture of metal ions.

The current limitation to broader application remains LAB's low adsorption efficiency. Established methods to improve this efficiency include LAB pre-treatment, mixed cultivation with other strains, and introducing co-existing ions. Emerging approaches like genetic engineering, nanomaterial integration, and bacterial immobilization are gaining interest as well. Expanding our understanding of LAB's role in HM adsorption could significantly improve HM removal from food and environmental sources, advancing environmental management and food safety.

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