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Bacterial Bisorption as an Approach for the Bioremediation of Chromium Contaminated Soils: An Overview

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Abstract

Chromium possesses detrimental effects on the health of both plants and animals. Biosorption is a process where biological materials (bacteria, fungi, algae, or agricultural waste) are used to remove pollutants from contaminated sites. Conventional methods of remediating heavy metal-contaminated soils, such as excavation and chemical treatment, are expensive and disruptive, making them less desirable. Factors influencing bacterial biosorption efficiency are promising approaches involving bacteria to remove heavy metals such as Chromium, lead, nickel, cadmium, arsenic, etc., from contaminated soil. Some bacterial genera involved in biosorption include Alcaligens, Achromobacter, Acinetobacter, Alteromonas, Arthrobacter, Burkholderia, Bacillus, Enterobacter, Flavobacterium, and Pseudomonas. These bacteria can adsorb heavy metals such as Chromium and biotransform them into less toxic forms. Some factors influencing bacteria biosorption efficiency include pH, temperature, concentration, bacterial surface compositions, metal ion characteristics, and soil composition. Challenges associated with using bacteria for biosorption, as outlined in previous literature, include the slowness of the process and the fact that it may not be suitable for large-scale application, even though many other authors have proven its applicability on a large scale. Also, the key quality needed from the bacterial biosorbent must be tolerating the heavy metals. Another area of focus in current research is optimizing environmental conditions, such as temperature, pH, and nutrient availability, to achieve a more efficient biosorption at a larger scale. This overview highlighted the roles of bacteria in the biosorption of chromium heavy metal as a strategy for the bioremediation of Chromium contaminated soil. Conclusively, bacterial biosorption has a great potential for use in Chromium- contaminated soil remediation, and more research is needed to fully realize this potential, especially in biotechnology and molecular engineering.

Keywords: Bacteria, Biosorption, Chromium, contaminated soil, Heavy metals

INTRODUCTION

Heavy metals are naturally occurring elements with high atomic weights and densities (Edo *et al.*, 2024). They include lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), Chromium (Cr), and others, which are ubiquitous in the environment and can have detrimental effects on human health and ecosystems (Singh *et al.*, 2023; Uddin *et al.*, 2023). Among toxic heavy metals, Chromium is among the top sixteen toxic contaminants that adversely affect human health (Ayele and Godeto, 2021).

Chromium has diverse industrial applications but can pose environmental risks and cause health issues, including kidney damage, lung cancer, and skin irritation, particularly in its hexavalent form (Sharma *et al.*, 2022). This is because Chromium (VI) is highly toxic and carcinogenic, capable of penetrating cell membranes and causing DNA damage. Additionally, excessive intake of chromium(III) picolinate may lead to disorders such as gastrointestinal irritation, kidney damage, and allergic reactions (Sawicka *et al.*, 2021). Chromium contamination in soil occurs primarily due to anthropogenic activities such as industrial processes, improper waste disposal, and agricultural practices (Mohanty *et al.*, 2023), and this is alarming as chromium-contaminated soils pose risks to human health, ecosystems, and agricultural productivity (Amuah *et al.*, 2024).

Bioremediation of chromium-contaminated soil includes using bacteria to metabolize or transform chromium compounds into less toxic forms (Kumar and Saini, 2024). Certain bacteria, such as *Enterobacter*, *Pseudomonas*, *Bacillus*, and *Arthrobacter*, are effective in this process (Vincze *et al.*, 2024). These bacteria can either directly reduce hexavalent Chromium (Cr(VI)) to trivalent Chromium (Cr(III)), which is less toxic, or they can bind chromium ions onto their cell surfaces, effectively removing them from the soil environment (Min *et al.*, 2024). Bioremediation is a promising and environmentally friendly approach for cleaning chromium-contaminated soil (Liu *et al.*, 2024).

By interacting with the target contaminants on their cell surfaces, bacteria can bind and extract heavy metals and other pollutants from solutions, and this process is known as bacterial biosorption (Priyadarshanee and Das, 2021). It has vast applications, including water treatment, bioremediation, resource recovery, and medicine. (Selvasembian and Singh, 2022). This overview aimed to highlight the roles of bacteria in biosoption of chromium heavy metal as a strategy that can be used in the bioremediation of Chromium contaminated soils.

HEAVY METALS

Heavy metals are metals and metalloids with an atomic density greater than 4g/cm3, which is four times greater than the density of water (1g/cm^3) (Dimkpa *et al.*, 2023). Various industrial manufacturing or catalytic processes can release heavy metals like lead (Pb), Chromium (Cr), zinc (Zn), cadmium (Cd), iron (Fe), copper (Cu), manganese (Mn), and nickel (Ni) into wastewater or solid waste discharges (Singh *et al.*, 2023). Due to their non-biodegradable or non-destroyable nature and ongoing accumulation in the food chain, these toxic metals pose a serious risk to human health and the environment, making them persistent environmental pollutants (Priyadarshanee and Das, 2021).

In addition to being naturally occurring environmental components, food, air, and water all contain trace levels of heavy metals that enter the biological system and eventually cause bioaccumulation (Data *et al.*, 2024). Certain heavy metals, such as Cu2+, Zn2+, Fe2+/Fe3+, etc., are necessary in minute levels for a number of essential biological processes in human physiology, yet even at slightly elevated concentrations of these metals, toxicological manifestations occur in humans (Sabol and Otřísal, 2024).

The toxicity of heavy metals is influenced by various factors, particularly the dose, route of exposure, chemical species of the heavy metal, and the age, gender, genetics, and nutritional status of the exposed individuals (Guatam *et al.*, 2024). Toxic heavy metals that induce a range of ailments include Chromium (Cr), cadmium (Cd), lead (Pb), mercury (Hg), zinc (Zn), copper (Cu), and aluminum (Al). Hemoglobinuria, stomatitis tremor, diarrhea, short-term memory loss, mental retardation, and gastrointestinal problems are among the ailments associated with these metals (Priyadarshanee and Das, 2021).

CHROMIUM

Chromium (Cr) is a transition metal with the atomic number 24 and mass number 51.9. It is found in the earth's crust, commonly occurring in minerals such as chromite (Ali *et al.*, 2020). It is characterized by its hard, lustrous, and silvery appearance and high corrosion resistance (Yin *et al.*, 2020). Chromium is widely used in various industries due to its unique properties, but it also poses environmental and health risks, particularly in its hexavalent form, necessitating devising effective strategies for their remediation (Kumar and Saini, 2024).

Tannery waste is considered one of the major contributors to chromium cycling in soil and water environments (Tirkey *et al.*, 2023). The role of tannery waste as a major contributor to chromium cycling in both soil and water is illustrated in Figure 1.

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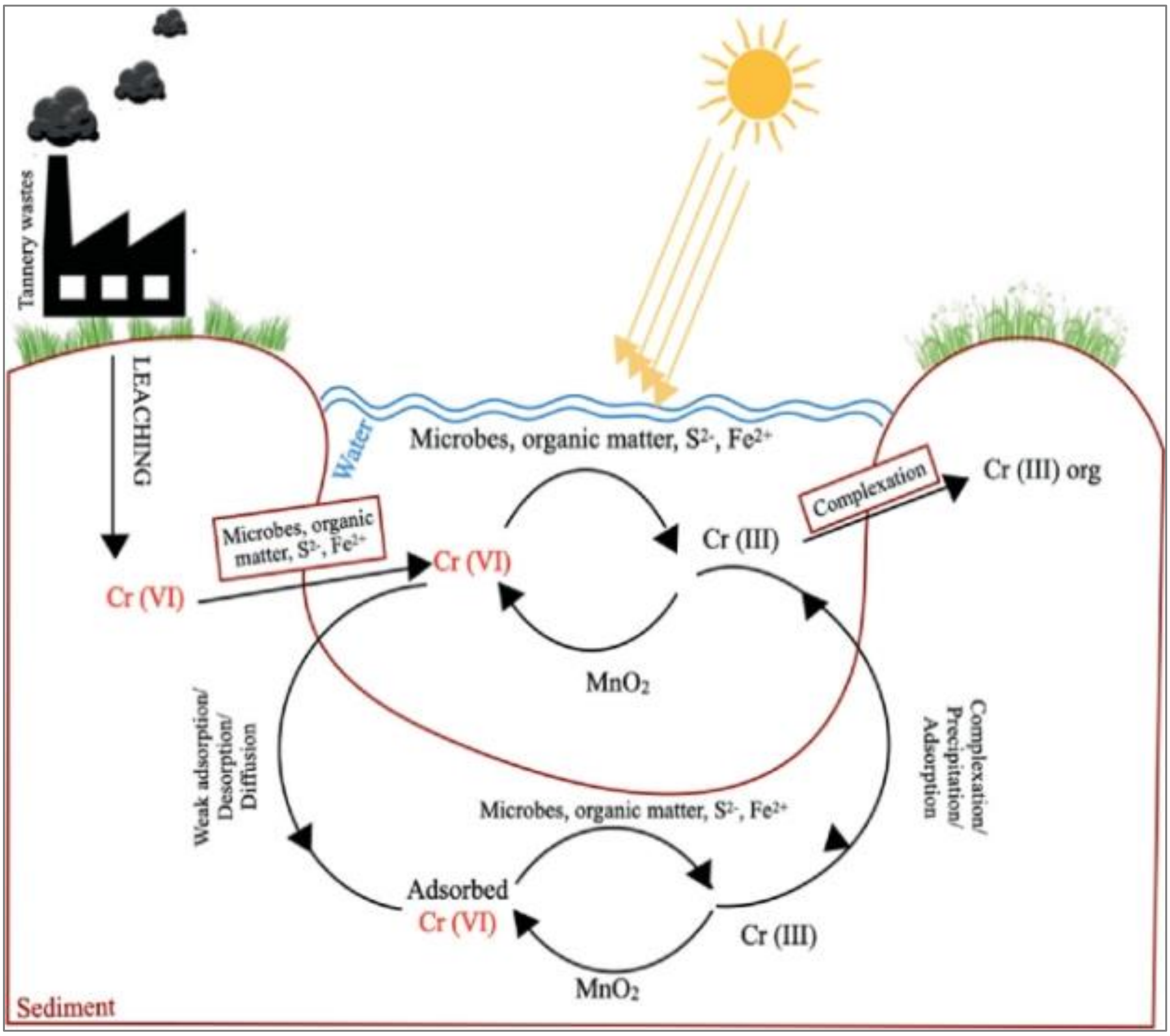

Figure 1: Tannery Waste as a Major Contributor to Chromium Cycling in both Soil and Water Environments. **Source:** Tirkey *et al.* (2023).

Physicochemical Properties of Chromium

Chromium is a hard and brittle metal with a melting point of approximately 1,857°C and a boiling point of 2,671°C (Czelusniak *et al.*, 2019). It exhibits high resistance to corrosion, making it suitable for use in stainless steel production and other high-temperature applications (Fedorov *et al.*, 2024). Chromium exhibits multiple oxidation states, with the most stable forms being Chromium (III) and Chromium (VI). Cr (III) compounds are typically insoluble and less toxic, while Cr (VI) compounds are highly soluble and toxic, posing significant environmental and health risks (Han *et al.*, 2024).

Effects of Chromium

Chromium, particularly in its hexavalent form (Cr (VI)), can have several negative effects on both the environment and human health (Rani *et al.*, 2024). Hexavalent Chromium can cause pollution of the whole ecosystem as it contaminates the soil, water bodies, and the atmosphere when released through industrial activities such as electroplating, welding, leather tanning, and chromate production (Kumar and Saini, 2024). Prolonged exposure to Cr(VI) can increase the risk of lung cancer, irritate the respiratory tract, cause skin irritation, and lead to the development of symptoms such as coughing, wheezing, shortness of breath, rashes, itching, and blistering of the skin, particularly among workers in industries where chromium exposure is common.

Aerobic and anaerobic microbes can employ different mechanisms in reducing Chromium five to Chromium three, as illustrated in Figure 2.

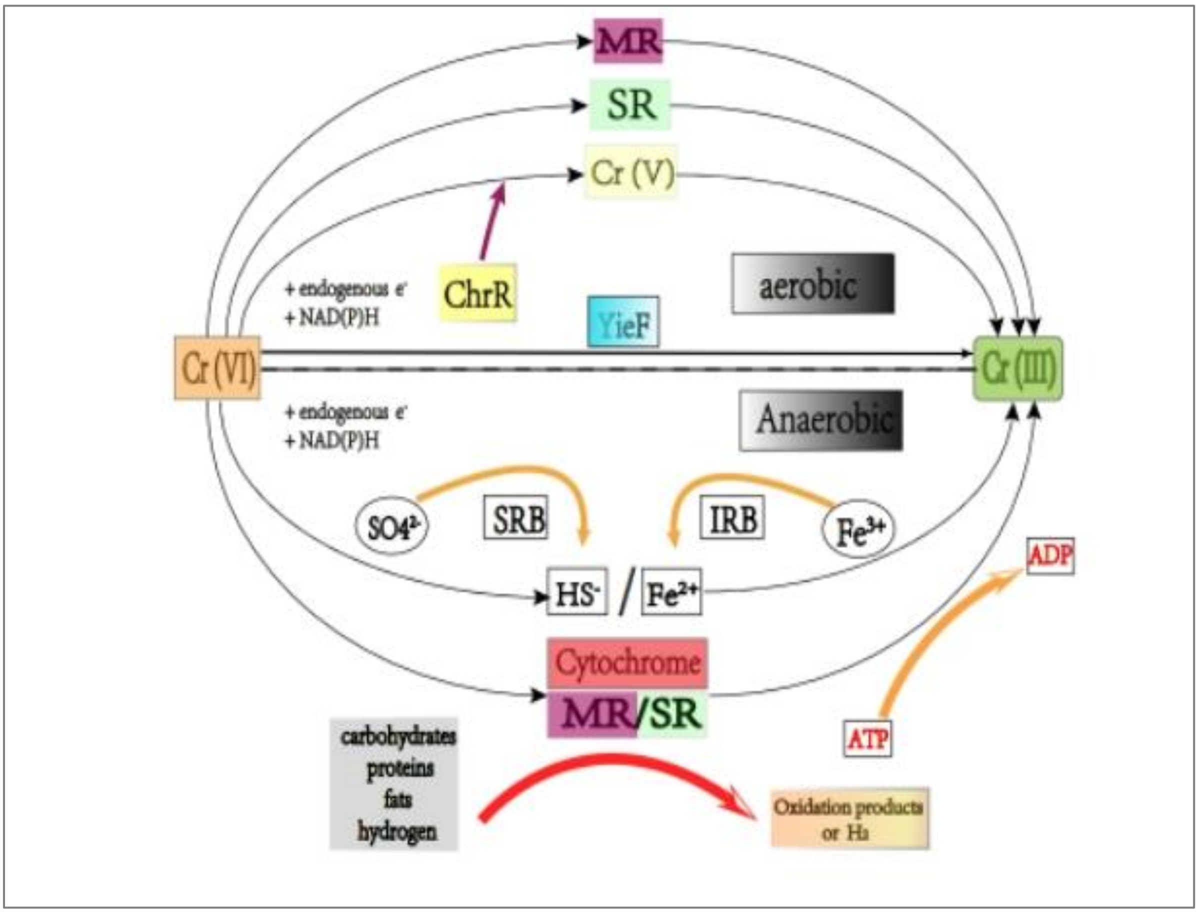

Figure 2: Mechanisms for the reduction of Chromium (VI) to Chromium (III) by aerobic and anaerobic microbes. **Source**: Chen and Tian (2021).

Chromium Contaminated Soil

Chromium-contaminated soil refers to soil that has been polluted or contaminated with Chromium, typically in hexavalent Chromium six (Cr(VI)) form, although trivalent chromium (Cr(III)) contamination can also occur (Montes *et al.*, 2024). Anthropogenic activities can also lead to the accumulation of Chromium in the soil, as illustrated in Figure 3.

Figure 3: Soil and Water Body Contaminated by Chromium Due to Man-made Excavation. **Source:** Gao and Xia (2011).

Sources of Chromium Contamination

Industrial activities that utilize chromium compounds, such as electroplating, metal finishing, and stainless steel production, can release Chromium into the environment through wastewater discharges, air emissions, and solid waste disposal, leading to degradation of the soil structure, loss of soil fertility and reduction of microbial activities in the soil (Rahman *et al.*,2024; Zhang *et al.*, 2024). Improper disposal of industrial wastes containing chromium compounds, such as chromate salts and chromium-contaminated sludge, can lead to soil contamination in landfill sites, waste disposal areas, and abandoned industrial sites, which can pose risks to drinking water supplies and aquatic ecosystems downstream (Prasad *et al.*, 2021).

In agriculture, chromium-containing fertilizers, pesticides, and soil amendments can also contribute to chromium accumulation in soil, inhibiting plant growth, reducing crop yield, and disrupting soil ecosystems (Zulfuqar *et al.*, 2023).

Strategies for Remediating Chromium-Contaminated Soils

The following can serve as strategies for remediating Chromium contaminated soils:

i. Soil Washing

Physical techniques such as soil washing or flushing can remove chromium contaminants from the soil by washing the soil with water or chemical solutions and then treating the wastewater generated (Yuan *et al.*, 2024).

ii. Bioremediation

Bioremediation techniques, including bacterial biosorption and phytoremediation, involve using microorganisms or plants to degrade, immobilize, or absorb chromium contaminants in soil and convert them into less toxic or less mobile forms (Waoo, 2024).

iii. Chemical Remediation

Chemical treatments such as reduction-oxidation (redox) reactions, precipitation, and ion exchange can be employed to convert hexavalent to trivalent, and the trivalent is less soluble and less toxic. These treatments facilitate chromium removal or immobilization in soil (Li *et al.*, 2024).

BIOSORPTION

Biosorption is a cost-effective, versatile, and environmentally friendly process that utilizes biological materials, such as bacteria, fungi, algae, and agricultural wastes, to remove pollutants from contaminated sites (Jamir *et al.*, 2024). It offers a promising alternative to conventional treatment methods for soil, wastewater remediation, and environmental protection (Alkhanjaf *et al.*, 2024).

Biosorption involves the passive binding of pollutants to the surface of biological materials, primarily through physical and chemical interactions, including surface binding, ion exchange, electrostatic attraction, and complexation (Jamir *et al.*, 2024). Natural and modified biomaterials, such as agricultural residues, bacterial biomass, algal biomass, and fungal mycelia, serve as biosorbents for removing a wide range of pollutants, including heavy metals, organic compounds, dyes, and pharmaceuticals from solutions (Singh and Vijayan, 2024).

Several factors influence the efficiency of biosorption, including the characteristics of biosorbents (e.g., surface area, functional groups, and cell wall composition), properties of pollutants (e.g., concentration, speciation, and ionic strength), solution conditions (e.g., pH, temperature, and agitation), and process parameters (e.g., contact time and biomass dosage) (Ullah *et al.*, 2023).

BACTERIAL BIOSORPTION

Bacterial biosorption is a bioremediation technique that harnesses the ability of certain bacteria to adsorb heavy metals, including Chromium, onto their cell surfaces or extracellular polymeric substances (EPS) (Omer and Shanmugam, 2024). Unlike traditional remediation methods that involve physical or chemical processes, bacterial biosorption relies on the metabolic activities of bacteria to sequester and immobilize contaminants (Thakur and Kumar, 2024).

Various bacterial species capable of biosorbing chromium ions from contaminated environments have been identified. These include species from the genera *Pseudomonas*, *Bacillus*, *Achromobacter*, *Acinetobacter*, *Alteromonas*, *Arthrobacter*, *Burkholderia*, *Enterobacter*, *Flavobacterium*, *Escherichia coli*, and*Shewanella*species, which exhibit varying degrees of chromium tolerance and biosorption efficiency (Vincze *et al.*, 2024). These bacteria can biosorb Chromium and other heavy metals through their cell wall, cell membranes, and cytoplasm, as illustrated in Figure 4.

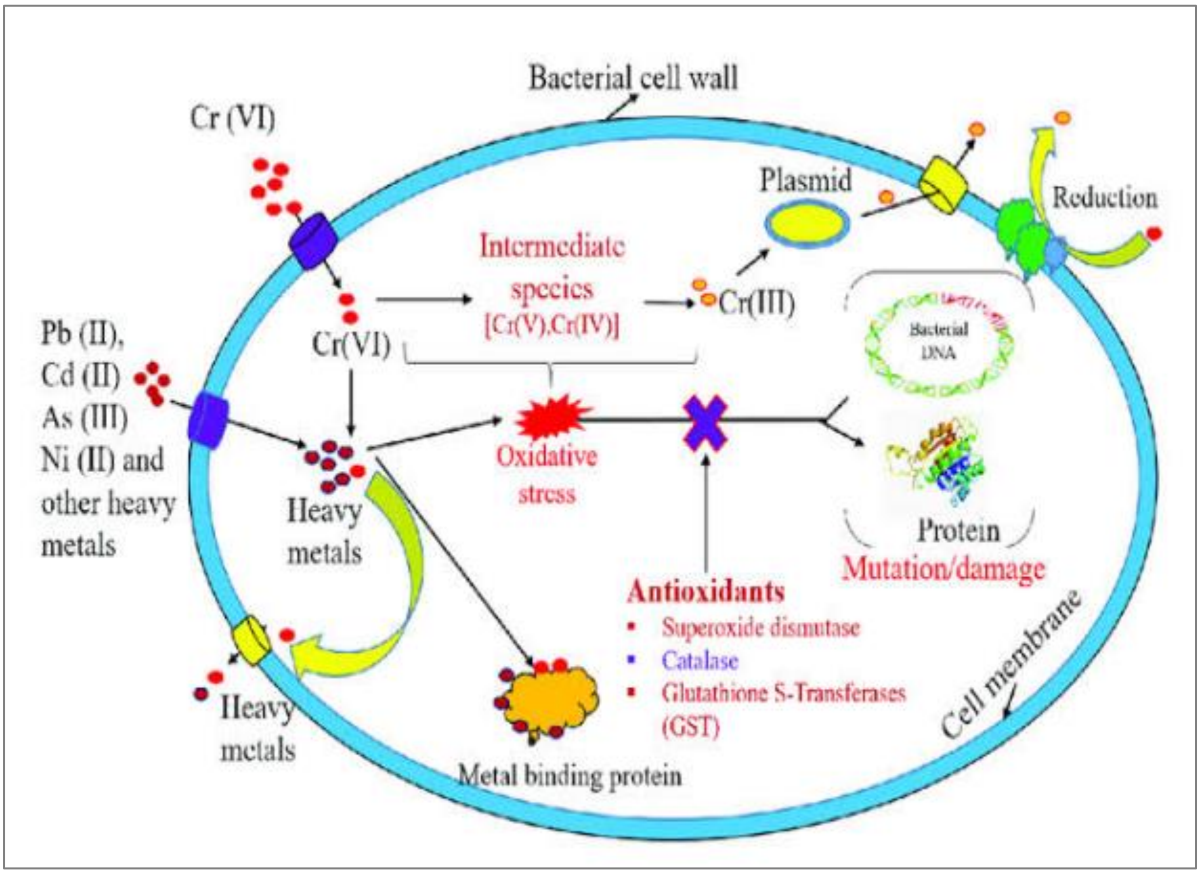

Figure 4: The Reduction of Chromium (VI) to Chromium (III) by Bacterial Cell. Source: Zhang *et al.* (2023).

Mechanisms of Bacterial Biosorption in Bioremediation of Chromium-Contaminated Soil

Bacterial biosorption of Chromium in contaminated soil involves various mechanisms by which bacteria bind and immobilize chromium ions, particularly hexavalent chromium [Cr(VI)], which is highly toxic and mobile (Pallavi *et al.*, 2024). Some of the mechanisms include the following:

i. Physical Adsorption

Bacterial cell surfaces possess functional groups such as carboxyl, hydroxyl, and amino groups, which can interact with chromium ions through physical adsorption mechanisms (Priyadarshanee and Das, 2024), Van der Waals forces, hydrogen bonding, and electrostatic interactions, which enable the attachment of chromium ions to the cell surface (Madhogaria *et al.*, 2024). This process is rapid but reversible, allowing for the temporary binding of chromium ions (Kumari *et al.*, 2024).

ii. Chemical Adsorption

Chemical adsorption involves the formation of strong bonds between chromium ions and functional groups on the bacterial cell surface through covalent or ionic interactions (Ravishankar *et al.*, 2024). Chromium ions can form complexes with carboxyl and hydroxyl groups, leading to their immobilization on the cell surface (Priyadarshanee and Das, 2024).

iii. Reduction

Some bacterial species possess enzymatic systems, such as chromate reductases, capable of reducing toxic Cr(VI) to the less toxic and less mobile trivalent Chromium [Cr(III)] (Wani*et al.*, 2024). Cr(III) ions have lower solubility and are more likely to precipitate or remain bound to bacterial cell surfaces (Wu *et al.*, 2024).

iv. Complexation

Bacteria may produce extracellular polymeric substances (EPS) or exopolysaccharides containing ligands capable of forming stable complexes with chromium ions (Priyadarshanee and Das, 2024). These EPS act as binding agents, facilitating the sequestration of chromium ions from the soil matrix (Priyadarshanee and Das, 2024). Complexation enhances chromium uptake and retention by bacteria, reducing its mobility and potential for leaching into the groundwater (Huang *et al.*, 2024).

v. Ion Exchange

Bacterial cell walls contain ion exchange sites, such as negatively charged sites associated with functional groups like carboxyl and phosphate (Namdeti, 2023). Chromium ions in the soil solution can exchange with ions at these sites, leading to their immobilization on the cell surface (Pallavi *et al.*, 2024).

vi. Metabolic Adaptation

Bacteria can adapt to chromium-contaminated environments through genetic mutations or metabolic adjustments that enhance their ability to biosorb chromium ions (Liu *et al.*, 2024). Upregulation of metal transporters, efflux pumps, or enzymes involved in chromium reduction and detoxification allows bacteria to thrive in chromium-rich soils and effectively mitigate chromium toxicity (Ali *et al.*, 2023). Figure 5 highlights different mechanisms of bacterial biosorption.

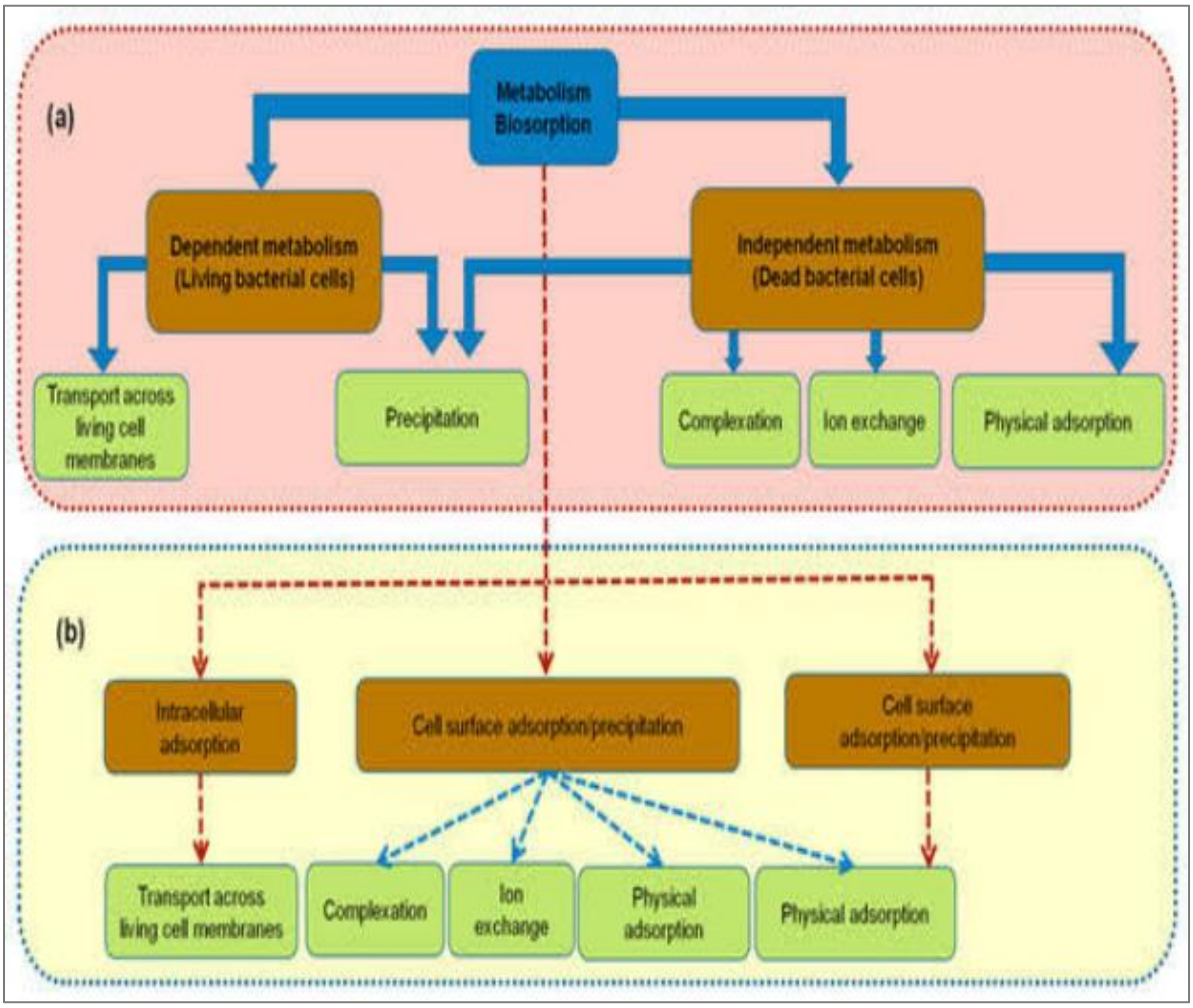

Figure 5: Mechanisms of bacterial biosorption. **Source:** Pham *et al.* (2022).

Factors Influencing Bacterial Biosorption

Several factors influence the efficiency of bacterial biosorption, including the type of bacterial species acting as the biosorbent, biomass concentration, pH, temperature, chromium concentration, and presence of competing ions (Liu *et al.*, 2024). Thus, optimal conditions for biosorption may vary depending on the specific characteristics of the bacterial strain and the physicochemical properties of the contaminated environment (Sun *et al.*, 2024).

Advantages of Bacterial Biosorption

Bacterial biosorption offers several advantages over conventional remediation methods as outlined by Khan *et al.* (2024) as follows:

i. High Specificity of Bacteria for Chromium Ions
Some bacterial strains exhibit high specificity for chromium ions, minimizing interference from other contaminants. Certain bacterial species possess surface functional groups such as carboxyl, hydroxyl, and amino, exhibiting a strong affinity for Cr ions. These functional groups form coordinate complexes with Cr ions, facilitating their immobilization and subsequent removal from contaminated sites.

ii. Environmental Friendly
Biosorption processes are often environmentally friendly, relying on natural microbial activity to remove contaminants. Unlike conventional chemical treatments, bacterial biosorption operates under mild conditions and does not require the addition of harsh chemicals, which may lead to the generation of toxic sludge. Thus biosorption process minimizes secondary pollution and reduces energy generation.

iii. Cost-effectiveness

Bacterial biosorption can be a cost-effective remediation option, particularly for large-scale applications with relatively low biomass production costs. The cost-effectiveness of bacterial biosorption for Cr removal positions it as a competitive and sustainable alternative to traditional treatment methods. By leveraging low-cost biomass production, minimal chemical requirements, biomass regeneration, and energy efficiency, biosorption offers a financially viable solution for mitigating chromium contamination in various industrial and environmental settings.

Applications of Bacterial Biosorption

Bacterial biosorption has been successfully applied in various environmental settings for the remediation of chromium-contaminated soils, sediments, wastewater, and industrial effluents (Hashem *et al.*, 2024). A successful and faster bioremediation can be achieved by employing bioaugmentation or inoculation techniques to introduce chromium-tolerant bacterial strains into the contaminated soil. *In-situ* bioremediation using indigenous bacterial strains is also a key factor employed in the bioremediation of chromium-contaminated soil. During the *in-situ* implementation of bioremediation strategies for chromium-contaminated soil, activities such as bioventing, bioaugmentation, or natural attenuation are applied to remediate the soil directly at the contaminated site while minimizing disturbance to the surrounding environment help in achieving success (Cui *et al.*, 2023). On the other hand, *Ex-situ* treatment of chromium-contaminated soil or wastewater is best been achieved using engineered bacterial species (Kamarudheen et al., 2020).

Pilot-scale demonstration projects of bacterial biosorption technologies in industrial settings help achieve a large-scale bioremediation project of chromium-contaminated soil (Cui *et al.*, 2023). During the *ex-situ* bioremediation approaches, activities such as land farming, biopiles, or bioreactors help in faster bioremediation of the excavated contaminated soil, normally in controlled environments (Hashem *et al.*, 2024). Numerous bacteria are essential to the health of an ecosystem, particularly when it comes to the biogeochemical cycling of heavy metals, which involves biosorption of heavy metals from the surrounding environment, and a bacterium can have the ability to biosorpt individual or groups of the metals as reported, by Fardami *et al.* (2023). Bacterial biosorption ability to biosorpt an individual or some groups of heavy metals was presented in Table 1 below as reported by different researchers.

Table 1: Heavy Metals Biosorption Ability of Common Bacterial Biosorbents

Heavy metal	Bacteria	Reference
Cr, Cu, Co, Ni, Zn, Cd and Pb	*Pseudomonas aeruginosa* ASU 6a	Zhang *et al.* (2014)
Cr, Zn, Cu, and Pb	*Streptomyces* *Amycolatopsis*	Prabhakaran *et al.* (2016)
Cr, Ag, and Hg	*Bacillus* sp.	Zhang *et al.* (2014)
Pb, Cu, and Cd	*Bacillus megaterium* X4	Velusamy *et al.* (2011)
Pb, Zn and Cd	*Arthrobacter* sp.	Nosalova*et al.* (2023)
As and Pb	*Pseudomonas aeruginosa*	Ibrahim *et al.* (2022)
As and Hg	*Enterobacteriaceae* strain *Pseudomonas putida* *Cupriavidusnecator* *Exiguobacterium* sp. *Bacillus aquimaris* *Bacillus cereus* *Alcaligenes* sp.	Prabhakaran *et al.* (2016)
Hg	*Bacillus* sp.	Prabhakaran *et al.* (2016)
As	*Acinetobacterlwoffii*, *Enterobacteragglomerans*	Hamzah *et al.* (2013)
Cu	*Sphingomonas* sp. *Stenotrophomonas* sp.	Altimira *et al.* (2012)
Pb	*Alcaligenesfaecalis* strain UBI	Ibrahim *et al.* (2022)

CONCLUSION

Chromium contamination in soils is a serious environmental issue with widespread implications for ecosystems and human health. Bacterial biosorption offers a promising approach for the bioremediation of Chromium-contaminated soil. This process can be achieved by utilizing natural microbial processes to remove and detoxify chromium ions through a better understanding the different mechanisms involved, such as physical adsorption, chemical adsorption, reduction, complexation, ion exchange, and metabolic adaptation.

RECOMMENDATIONS

The following recommendations are proffered for improving bacterial biosorption processes for the remediation of Chromium contaminated soils.

i. Comprehensive characterization of chromium-contaminated soils to understand the extent of contamination based on chromium speciation, soil properties, and potential impacts on the environment and human health. This will help guide the application of suitable bacterial strains in the bioremediation of Chromium contaminated soils.

ii. Identifying and selecting bacterial strains with high chromium tolerance, surface binding capacity, and/or enzymatic capability for efficient chromium reduction and successful bioremediation of Chromium contaminated soil.

iii. By considering indigenous bacterial populations adapted to specific Chromium-contaminated soil conditions, better and enhanced bioremediation of Chromium-contaminated soils will be achieved using autochthonous bacteria.

iv. Optimizing environmental conditions such as pH, temperature, moisture content, and nutrient availability to maximize bacterial biosorption activity and enhance the efficiency of chromium bioremoval.

v. Local communities, stakeholders, and regulatory agencies should be included in the bioremediation process to add transparency, enhance communication and better collaboration, and ensure successful outcomes in large-scale bioremediation processes.

vi. Ensuring compliance with regulatory standards and guidelines for soil bioremediation, microbial biotechnology, occupational health, and safety will help in successfully bioremediation of Chromium contaminated soils.

By implementing the above recommendations, stakeholders can effectively ensure the success of large-scale bioremediation projects on Chromium contaminated soils while minimizing environmental impacts and ensuring regulatory compliance.

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