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BIOSURFACTANT PROPERTIES AND ITS APPLICATION IN CHROMIUM REMOVAL: A REVIEW

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ABSTRACT

Chromium contamination primarily originates from anthropogenic activities such as industrial discharges, mining operations, and the improper disposal of chromium-containing products, leading to its infiltration into soil and groundwater. The persistence of chromium in the environment poses severe ecological and health risks, including bioaccumulation in aquatic organisms and adverse effects on plant growth and soil microbes. Human exposure to chromium through contaminated water or occupational settings is linked to respiratory problems, skin disorders, and heightened cancer risk. Addressing these challenges necessitates sustainable remediation approaches, highlighting the potential of biosurfactants as eco-friendly alternatives to conventional methods. This review was aimed to provide an overview on different properties of biosurfactants and its application in chromium removal, covering key aspects from introduction to future perspectives. Biosurfactants as microbial-derived surface-active agents, exhibit properties that make them highly effective in reducing chromium contamination. Their biodegradability, low toxicity, and renewable production ensure minimal environmental impact. Moreover, their amphiphilic nature enhances chromium bioavailability, facilitating microbial uptake and reduction. Certain biosurfactants chelate metal ions, preventing chromium migration and secondary contamination, while their synergistic interactions with microorganisms improve remediation efficiency. Future research on biosurfactants for chromium removal should focus on optimizing microbial production for higher yield and cost efficiency. Exploring the molecular mechanisms of chromium interaction with biosurfactants can enhance their application in diverse environmental conditions. Additionally, scaling up processes for industrial applications and evaluating long-term environmental impacts are critical for practical implementation.

Keywords: Biosurfactant, Properties, Chromium-reduction, Chromium-removal

INTRODUCTION

Biosurfactants are diverse and heterogeneous group of microbial metabolites produced by certain bacteria and fungi that have both hydrophilic and hydrophobic components (Fardami *et al.,* 2022a). They are naturally produced as surface-active molecules by microorganisms that can play a significant role in the bioremediation of heavy metal contaminants, including chromium (Parades-Aguilar *et al.*, 2025; Verma *et al.*, 2025). These compounds possess unique amphiphilic properties, enabling them to reduce surface tension, emulsify hydrophobic substances, and enhance the bioavailability of contaminants (Lawal *et al.*, 2022). In the context of chromium reduction, biosurfactants aid in mobilizing and solubilizing chromium compounds, thereby facilitating their interaction with microbial cells or reactive agents (Parades-Aguilar *et al.*, 2025). This is particularly crucial in chromium-contaminated environments where the metal often exists in complex forms that are less accessible for microbial reduction processes (Tiwari and Tripathy, 2023). By increasing the bioavailability of chromium, biosurfactants effectively enhance the efficiency of microbial and enzymatic reduction mechanisms (Selva Filho *et al.*, 2023).

Chromium exists in two primary oxidation states in the environment: trivalent chromium (Cr (III)) and hexavalent chromium (Cr (VI)) (Liang *et al.*, 2021; Fardami and Abdullahi, 2024; Gusau *et al.*, 2024). While Cr (III) is relatively stable and less toxic, Cr (VI) is highly toxic, carcinogenic, and more soluble, making its reduction to Cr (III) a critical step in remediation efforts (Xia *et al.*, 2019; Gusau *et al.*, 2024). Biosurfactants contribute to this reduction process by altering the physicochemical properties of chromium and the surrounding environment (Gusau *et al.*, 2024). They can form stable complexes with Cr (VI), facilitating its uptake by chromium-reducing bacteria or bringing it into close proximity with reducing agents - (Malaviya and Singh, 2016). Additionally, biosurfactants can enhance the hydrophobicity of microbial cell membranes, increasing the contact between bacteria and chromium ions, which is essential for efficient reduction (Sarubbo *et al.*, 2015).

Microorganisms such as Pseudomonas sp., Bacillus subtilis, and Rhodococcus sp. are known to produce biosurfactants while also exhibiting chromium-reducing capabilities (Fardami, 2021). The dual function of these microorganisms allows them to thrive in chromium-contaminated environments and actively participate in its detoxification (Fardami and Abdullahi, 2024). Biosurfactants produced by these microbes not only improve the solubilization and sequestration of chromium but also stabilize Cr (III) in non-toxic forms, preventing its reoxidation to Cr (VI) (Fardami, 2021). Furthermore, the production of biosurfactants can stimulate microbial growth and metabolic activity in harsh environments, enabling sustained chromium reduction even under adverse conditions such as high salinity, low pH, or the presence of other heavy metals (Gusau *et al.*, 2024).

The application of biosurfactants in chromium bioremediation holds significant potential for sustainable environmental management. Strategies combining biosurfactant-producing microorganisms with other remediation techniques, such as phytoremediation or chemical reduction, can further enhance chromium detoxification (Mulligan, 2017). Moreover, biosurfactants are environmentally friendly and biodegradable, making them a safer alternative to synthetic surfactants (Fardami 2021). Research into optimizing biosurfactant production, improving their stability under environmental conditions, and scaling up their use in contaminated sites is ongoing (Fardami *et al.,* 2022a). With advancements in biotechnology and microbial engineering, biosurfactants are poised to become a cornerstone in the development of efficient, eco-friendly solutions for chromium reduction and the remediation of contaminated ecosystems (Fardami, 2021; Mulligan, 2017).

Chromium contamination has become a pressing environmental concern due to its widespread presence and detrimental effects on ecosystems and human health (Akbar *et al.,* 2024; Changotra *et al.,* 2024; Fardami and Abdullahi, 2024; Rahman *et al.,* 2024; Sharma *et al.,* 2024). The metal exists in various oxidation states, with hexavalent chromium (Cr (VI)) being particularly hazardous (Rani *et al.,* 2024). Sources of chromium pollution include industrial discharges, mining activities, and improper disposal of waste (Mansor *et al.,* 2024). The urgency to mitigate the impact of chromium contamination has spurred research into innovative and sustainable remediation strategies (Fardami and Abdulllahi, 2024; Sharma *et al.,* 2024).

Biosurfactants, a class of microbial-derived surface-active molecules, have emerged as promising agents for environmental applications (Venkataraman *et al.,* 2024). Unlike chemical surfactants, biosurfactants are biodegradable, environmentally friendly, and can be produce d from renewable resources (Gayathiri *et al.,* 2022). Certain bacteria and fungi produce a broad and varied class of microbial metabolites called biosurfactants, which contain both hydrophilic and hydrophobic components (Fardami *et al.,* 2022a). Their unique properties make them suitable for a range of applications, including the reduction of toxic metals like chromium (Gayathiri *et al.,* 2022).

Considering the relationship between biosurfactants and chromium based on bioremediation approach, it becomes evident that harnessing the unique qualities of these biological molecules holds promise for sustainable and effective remediation strategies (Karnwal *et al.,* 2024). This exploration is not merely about addressing a pollution challenge but also about embracing innovative, nature-inspired solutions that align with the principles of environmental stewardship and conservation (Hussain *et al.,* 2024).

The interaction between biosurfactants and chromium compounds can lead to the formation of stable complexes, which may mitigate the toxicity associated with chromium (Otzen, 2017). For example, certain biosurfactants can bind to hexavalent chromium (Cr (VI)), a highly toxic and soluble form of chromium, converting it into less toxic forms, such as trivalent chromium (Cr (III)) (Simões *et al.,* 2024). This transformation is particularly important, as Cr (III) is significantly less soluble and poses a lower risk to human health and the environment (Zha *et al.,* 2024). The mechanisms behind this transformation often involve electrostatic interactions, hydrophobic interactions, and coordination bonds between the biosurfactant molecules and chromium ions, showcasing the complex nature of these biochemical interactions (Otzen, 2017).

Furthermore, the effectiveness of biosurfactants in mediating chromium interactions is influenced by various factors, including the type of biosurfactant, environmental conditions (such as pH, temperature, and ionic strength), and the concentration of chromium compounds (Zha *et al.,* 2024). For instance, rhamnolipids produced by *Pseudomonas aeruginosa* have been shown to effectively mobilize Cr (VI) from contaminated soils, while also promoting the growth of chromium-resistant microorganisms (Simões *et al.,* 2024). While many studies highlight the potential of biosurfactants in heavy metal remediation, the precise mechanisms underlying chromium interaction remain poorly understood. Limited research is available on the role of biosurfactant applications, structure, such as hydrophobicity, in enhancing chromium removal. The existing literature lacks in-depth analysis of properties, mechanism and application of biosurfactants. This review aimed to provide an overview on biosurfactant properties and its application in chromium removal.

Scope and categorization of the reviewed research

The scope of this review encompasses a comprehensive analysis of relevant studies sourced from databases such as Research gate,Web of Science, and Google Scholar. Keywords used included "biosurfactants," "chromium removal," "biosurfactant properties," "heavy metal remediation," and "bioremediation of chromium." Inclusion criteria for cited studies involved peer-reviewed articles published in English, focusing on biosurfactant properties such as surface activity and emulsification capacity, their mechanisms of chromium removal, and experimental or real-world applications. Studies addressing the removal of chromium (both Cr(III) and Cr(VI)) using biosurfactants and those discussing challenges and future prospects were prioritized.

The reviewed literature was analyzed and categorized through a structured approach, By Identification and Selection of Relevant studies which were identified based on their focus on biosurfactants, their physicochemical properties, and their specific application in chromium removal. Selection criteria included the publication's relevance, scientific quality, and alignment with the topic. It was categorized by Property-Based Categorization in which Literature was categorized based on key biosurfactant properties, such as surface activity, emulsification capacity, and biodegradability, as these directly influence their effectiveness in chromium removal. Studies were further categorized by their application, including mechanisms of chromium removal (e.g., adsorption, chelation, or complexation), the types of chromium addressed (Cr (III) or Cr(VI)).

Detrimental Effect of Chromium as Environmental Contaminant

Chromium, a transition metal found in various natural compounds, is essential in trace amounts for living organisms. However, human activities have significantly increased the release of chromium into the environment, leading to widespread contamination (Kapoor *et al.,* 2022). Among the various oxidation states of chromium, hexavalent chromium (Cr (VI)) is of particular concern due to its high toxicity and mobility in the environment (Saha *et al.,* 2011). Plants and animals are negatively affected by chromium contamination in soil and water bodies (Fardami and Abdullahi, 2024). There are many processes that can remediate chromium contamination in both soil and water bodies (Fardami, 2021). Traditional techniques for cleaning up heavy metal-contaminated soils, like chemical treatment and excavation, are costly and time-consuming, which makes them less appealing. Using biological materials like bacteria, fungi, algae, or agricultural waste is now becoming more promising than the conventional methods (Fardami and Abdullahi, 2024).

Chromium, particularly in its hexavalent form (Cr (VI)), is a significant environmental contaminant that poses serious health risks to humans and ecosystems (Zha *et al.,* 2024). Often released into the environment through industrial activities such as electroplating, leather tanning, and wood preservation, chromium can infiltrate soil and water systems, leading to widespread contamination. Cr(VI) is highly soluble in water, making it readily bioavailable and easily absorbed by living organisms (Zha *et al.,* 2024) This bioavailability enhances its toxicological effects, as chromium can enter the food chain, affecting not only aquatic life but also terrestrial organisms and ultimately humans (Rahman *et al.,* 2024). The presence of chromium in the environment is not just a localized issue; it can persist for long periods, accumulating in sediments and posing long-term risks to environmental and public health (Singh *et al.,* 2024).

The toxicological effects of chromium exposure are well-documented, with significant implications for human health (Dehkordi *et al.,* 2024). Cr (VI) is classified as a human carcinogen, and exposure has been linked to various forms of cancer, particularly lung cancer, among workers in chromate-producing industries (Ayejoto and Egbueri, 2024; Meaza *et al.,* 2024). Additionally, chromium can cause a range of non-carcinogenic health issues, including respiratory problems, skin ulcers, and gastrointestinal distress (Lu *et al.,* 2024). Chronic exposure to chromium can lead to systemic toxicity, impacting organs such as the liver and kidneys (Meaza *et al.,* 2024). Vulnerable populations, including children and individuals with pre-existing health conditions, are particularly at risk. Furthermore, studies have shown that pregnant women exposed to high levels of chromium can experience adverse reproductive outcomes, raising concerns about its impact on future generations (Baig *et al.,* 2024).

The environmental impact of chromium contamination extends beyond human health. Aquatic ecosystems are particularly susceptible to chromium toxicity, as elevated levels can lead to bioaccumulation in fish and other aquatic organisms (Fulke *et al.,* 2024)). This bioaccumulation can disrupt food webs and diminish biodiversity, as sensitive species may be unable to survive in contaminated habitats (Roy, 2024). Chromium can also impair the physiological functions of aquatic life, causing oxidative stress, reduced reproductive success, and increased mortality rates (Pereira, *et al.,* 2021). In terrestrial ecosystems, chromium can affect soil microbiota and plant health, inhibiting growth and nutrient uptake (Ao *et al.,* 2022). The alteration of these ecosystems can have cascading effects, leading to a decline in ecosystem services such as clean water provision, soil fertility, and carbon storage (David Raj *et al.,* 2024).

Efforts to mitigate the detrimental effects of chromium as an environmental contaminant are essential but challenging (Xie, 2024). Remediation strategies often involve removing or stabilizing chromium from contaminated sites, utilizing various approaches such as phytoremediation, chemical reduction, and bioremediation (Pandey *et al.,* 2024). However, these methods must be carefully designed to avoid further environmental disruption and to ensure the safety of surrounding communities (Bibri *et al.,* 2024). Moreover, monitoring and regulatory frameworks are necessary to assess chromium levels in the environment and enforce compliance with safety standards (Vaiopoulou, and Gikas, 2020). Public awareness and community involvement in addressing chromium contamination are also vital, as informed citizens can advocate for cleaner industrial practices and support local remediation efforts (Ogbeide, and Henry, 2024). The complexities of chromium contamination demand a comprehensive and multidisciplinary approach, emphasizing the need for ongoing research and collaboration among scientists, policymakers, and communities to safeguard health and the environment Khorram-Manesh, *et al.,* 2024).

The Need to Address Chromium Pollution

Addressing chromium pollution has become a critical imperative for several reasons (Mohanty and Selvaraj, 2024). First and foremost, chromium contamination poses severe risks to human health. Prolonged exposure to Cr (VI) is associated with a range of health issues, including respiratory problems, skin irritation, and an increased risk of lung cancer (Mohanty and Selvaraj, 2024). Industrial workers, communities residing near industrial sites, and those relying on contaminated water sources are particularly vulnerable. Recognizing and mitigating these health risks is essential for safeguarding public well-being (Awogbami *et al.,* 2024).

Furthermore, chromium pollution exerts detrimental effects on ecosystems. Aquatic life, in particular, is highly sensitive to changes in chromium levels (Hu *et al.,* 2024). The metal can accumulate in sediments, affecting the benthic community and, consequently, disrupting the entire aquatic food chain (Babaniyi *et al.,* 2025). The ecological repercussions extend to terrestrial ecosystems, impacting plant growth and the animals that depend on these plants for sustenance (Babaniyi *et al.,* 2025). The global nature of chromium pollution adds another layer of complexity to its management. Chromium does not adhere to geopolitical boundaries, and contamination in one region can have far-reaching consequences (Igelle *et al.,* 2024).

Collaborative efforts on an international and local scale are imperative to develop effective strategies for monitoring, controlling, and remediating chromium pollution (Onyedikachi, and Mukah, 2024). The capacity of microorganisms to exhibit remarkable promise in absorbing heavy metals is one of their wonderful ability in adapting extreme environment. Many researchers have reported heavy metals, and their findings have made it possible to reveal a microbe with the capacity to absorb heavy metals in heavy metal bioremediation using the biosorption concept in a variety of environmental settings in most cases, leading to impressive outcomes. *Alcaligenes faecalis* strain U.B.I., a bacterium isolated from a mining site in Zamfara state, Nigeria, was reported by Ibrahim et al. (2023) to have good potential in the biosoption of heavy metals. This emphasizes the need for innovative and sustainable approaches that can be applied universally to address chromium contamination in different environmental settings (Onyedikachi, and Mukah, 2024). *Alcaligenes faecalis* strain U.B.I was reported to withstand heavy metals under a variety of environmental circumstances. It has been observed that the bacterium *Alcaligenes faecalis* strain U.B.I. has an ideal capability for chromium (Cr+) absorption of 93.0% as reported by Ibrahim et al. (2023).

Biosurfanctant

Biosurfactants exhibit a diverse range of chemical structures, comprising lipopeptides, glycolipids, phospholipids, and polymeric surfactants (Fardami *et al.,* 2022b). These molecules are synthesized by bacteria, yeast, fungi, and even some plants, showcasing the adaptability and ubiquity of these natural compounds (Kubicki *et al.,* 2019). Unlike conventional chemical surfactants, biosurfactants are biodegradable and often exhibit low toxicity, making them environmentally benign and well-suited for applications in ecological restoration (Johnson *et al.,* 2021).

The unique amphiphilic nature of biosurfactants imparts them with the ability to interact with both hydrophobic and hydrophilic substances, facilitating the emulsification and solubilization of organic and inorganic compounds (Yesankar *et al.,* 2023). The possession of hydrophilic and hydrophobic head and tail respectively is presented in Figure 1 A and the two micelle formations are also presented in Figure 1 B and 1 C (Figure 1). This property is particularly relevant in the context of chromium reduction, where effective interaction with the metal ions is crucial for remediation success. Biosurfactants can enhance the bioavailability of chromium, promoting its microbial reduction and subsequent immobilization (Mishra *et al.,* 2021).

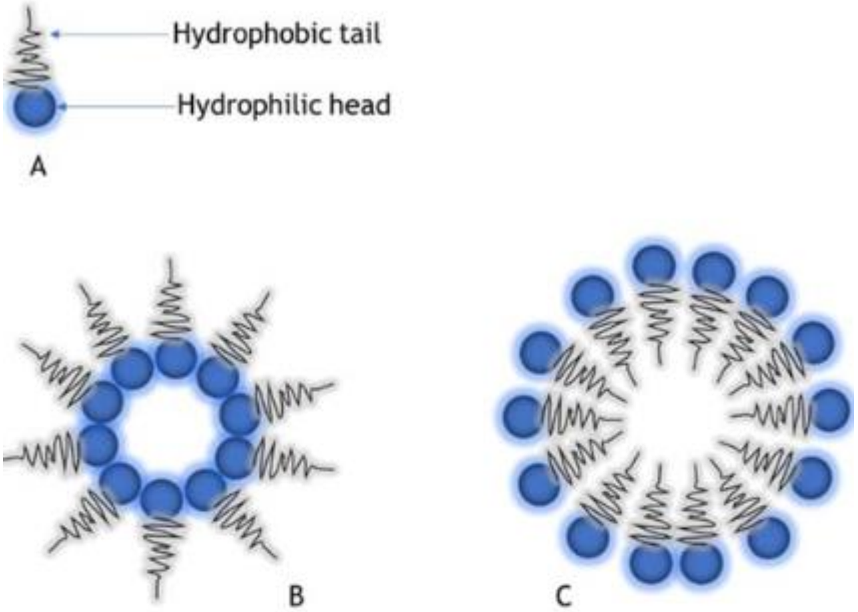

Figure 1: Amphiphatic Nature and Micelle Formation of Biosurfactant (The possession of hydrophilic and hydrophobic head and tail respectively is presented in Figure 1 A and the two micelle formations are also presented in Figure 1 B and 1 C.
Source:(Sanches *et al.,* 2021)

Moreover, the microbial production of biosurfactants aligns with the principles of green chemistry, emphasizing sustainability and reduced environmental impact (Fardami *et al.,* 2022c). The renewable nature of the raw materials used in biosurfactant production further underscores their eco-friendly credentials (Dalbanjan *et al.,* 2024). As the world seeks innovative strategies to address environmental challenges, biosurfactants stand out as a bioinspired solution that not only aids in pollution control but also aligns with broader goals of ecological sustainability (Nawaz *et al.,* 2024). By understanding the fundamentals of biosurfactants and their role in environmental remediation, its potential is always been exposed as tool to be used in reshaping the landscape of sustainable technology and contributing to a cleaner, healthier planet (Sharma, 2022).

Characteristics of Biosurfactants

Biosurfactants, as microbial-derived surface-active molecules, possess a distinctive set of characteristics that make them particularly appealing for environmental applications, including the reduction of chromium contamination (Selva *et al.,* 2023). Understanding these unique properties is essential for elucidating how biosurfactants interact with chromium compounds and contribute to effective remediation strategies (Mishra *et al.,* 2024). Below are some of the general characteristics of biosurfactants:

Biodegradability

One of the key advantages of biosurfactants is their biodegradability. Unlike synthetic surfactants, which often persist in the environment and contribute to pollution, biosurfactants are naturally broken down by microorganisms (Johnson *et al.,* 2021). This characteristic aligns with the principles of green chemistry, emphasizing the importance of sustainable and eco-friendly solutions in environmental remediation efforts (Johnson *et al.,* 2021). The search for hydrocarbon has been of great priority for alternative source of energy and economy to many countries (Allamin *et al.,* 2020). This search for energy has become a contributor to hydrocarbon contamination of different environment within down and upstream sectors of petroleum industries (Johnston *et al.,* 2019). Microorganism producing biosurfactants are found to be the best candidate that biodegrade hydrocarbon contaminated environment (Fardami *et al.,* 2022b). Surface-active biomolecules called biosurfactants are created by microbes and have a variety of uses in addressing various environmental issues both hydrophilic and hydrophobic substances (Fardami *et al.,* 2022c).

Low Toxicity

Biosurfactants generally exhibit low toxicity, reducing their impact on ecosystems and making them safer alternatives to chemical surfactants (Johnson *et al.,* 2021). This characteristic is crucial in applications where minimizing harm to the environment and non-target organisms is a priority (Das *et al.,* 2021). The use of biosurfactants in chromium reduction aims to mitigate the ecological impact associated with traditional remediation methods (Singh *et al.,* 2021).

Versatility in Structure

The structural diversity of biosurfactants is a notable feature (Kubicki *et al.,* 2019). These molecules can vary widely in composition, including lipopeptides, glycolipids, phospholipids, and polymeric surfactants (Sałek *et al.,* 2022). This diversity allows for tailored approaches, as different biosurfactants types may exhibit varying affinities and efficiencies in interacting with chromium species (Simões *et al.,* 2024).

Surface Activity and Emulsification

Biosurfactants are characterized by their amphiphilic nature, enabling them to interact with both hydrophobic and hydrophilic substances (Otzen, 2017). This property facilitates the emulsification and solubilization of a wide range of organic and inorganic compounds, including chromium (Otzen, 2017). The ability to modify the surface tension of aqueous solutions enhances the bioavailability of contaminants, promoting their interaction with microbial communities (Kaczorek *et al.,* 2018).

Amphiphilic nature of biosurfactant also made it an excellent antimicrobial as reported by many researchers. Lawal et al. (2022) reported that biosurfactants can destroy the virus's envelope and the viral membrane's structures by operating based on principle that biosurfactant’s anti-viral property is due to the hydrophilic properties that are within the acetyl groups. Additionally, the hydrophobic properties of biosurfactant are also important in making it to have antiviral activity. These activities of biosurfactants against viruses make it to be potential anti-viral agents against Covid-19 (Lawal *et al.,* 2022).

Renewable Production Sources

Biosurfactants are produced by microorganisms, including bacteria, yeast, and fungi, often utilizing renewable resources as substrates. This aspect makes biosurfactant production more sustainable compared to the production of synthetic surfactants derived from petrochemicals (Sarubbo *et al.,* 2022). The use of renewable resources aligns with the global shift towards greener and more sustainable technologies (Gielen *et al.,* 2019).

Understanding these characteristics provides a foundation for exploring the application of biosurfactants in chromium reduction (Mat *et al.,* 2024). The biodegradability, low toxicity, structural versatility, and renewable production sources collectively contribute to the appeal of biosurfactants as environmentally friendly tools for addressing the complex challenges posed by chromium contamination (Thakur *et al.,* 2024). In the following sections, we will delve into how these characteristics translate into effective mechanisms for chromium reduction and explore the potential of biosurfactants in real-world applications (Nadar, and Khan, 2024).

Application of Biosurfactants in Chromium Reduction

The application of biosurfactants in chromium reduction is highly needed due to the versatile function of biosurfactant in different aspects and it becomes clear that addressing chromium pollution is not only a scientific challenge but a multidimensional imperative (Come, 2019). Biosurfactants, amphiphilic compounds produced by microorganisms, play a crucial role in the bioremediation of heavy metals such as chromium (Mishra *et al.,* 2021). Chromium, particularly in its hexavalent form (Cr (VI)), is highly toxic and carcinogenic, making its reduction to the less harmful trivalent form (Cr (III) essential for environmental cleanup (Sharma *et al.,* 2022). The importance of mitigating chromium contamination extends beyond the laboratory, touching on issues of public health, environmental conservation, and global cooperation (Ongong, 2022). Biosurfactants, with their eco-friendly properties, present a promising avenue for tackling chromium pollution while aligning with broader sustainability goals (Thakur *et al.,* 2024).

In the pursuit of sustainable solutions for environmental challenges, biosurfactants have emerged as versatile and eco-friendly agents, holding significant promise in various applications, including the reduction of chromium pollution (Markam *et al.,* 2024). Biosurfactants are amphiphilic molecules produced by microorganisms, displaying unique surface-active properties that distinguish them from their synthetic counterparts (Dini *et al.,* 2024).

Multiples Oxidation States of Chromium

Chromium, a transition metal with diverse oxidation states, plays a critical role in various industrial processes, including metallurgy, leather tanning, and electroplating (Grace *et al.,* 2019). However, the improper disposal of industrial effluents and waste products has led to the widespread contamination of soil and water by chromium compounds, posing serious threats to both the environment and human health (Mishra *et al.,* 2019). Understanding the background of chromium contamination is crucial for appreciating the necessity and significance of remediation strategies such as the use of biosurfactants (Ara, 2007).

Chromium exists in multiple oxidation states as Cr (VI), Cr (V), Cr (IV), Cr (III) and Cr (II) (See Figure 1) with hexavalent chromium (Cr (VI)) and trivalent chromium (Cr (III)) being the most prevalent and environmentally relevant (Liang, *et al.,* 2021). Cr (VI) is highly soluble, mobile, and toxic, making it a particularly challenging contaminant to manage. On the other hand, Cr (III) tends to form less soluble compounds, exhibiting lower mobility but still contributing to environmental concerns (Liang, *et al.,* 2021).

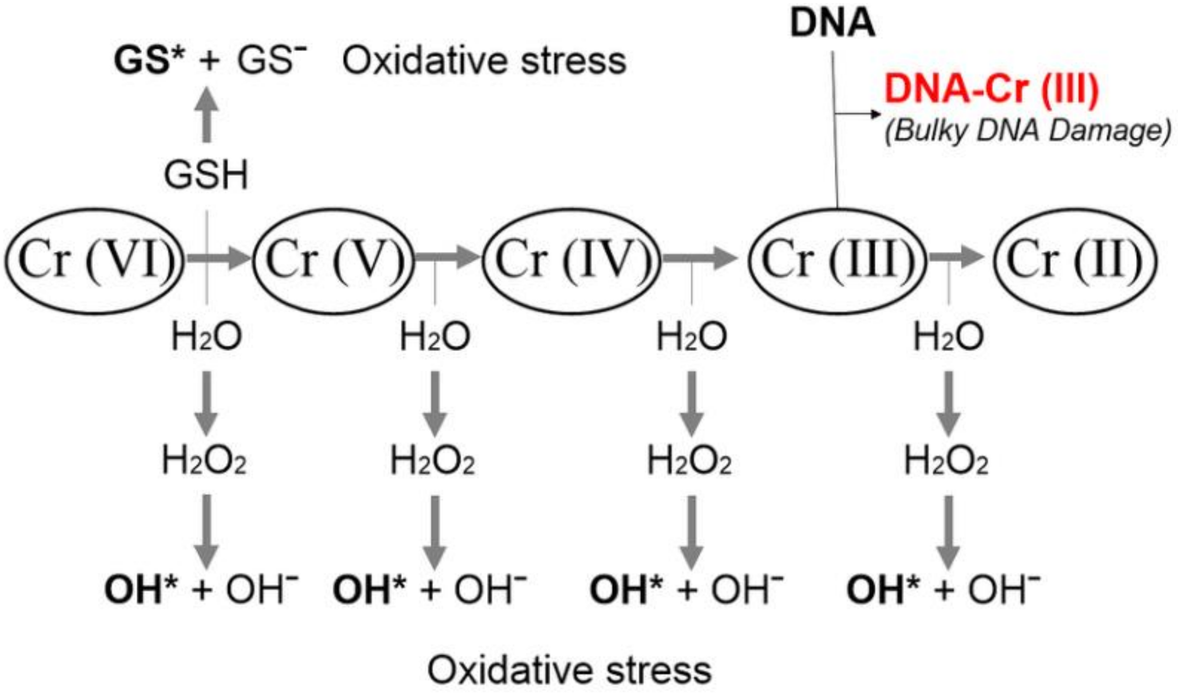

Figure 2: Multiple Oxidation States or Forms of Chromium
Source: Achmad and Auerkari (2017).

Sources of Chromium Contamination

Anthropogenic activities, such as industrial discharges, mining operations, and the disposal of chromium-containing products, are primary sources of chromium pollution (Tumolo *et al.,* 2020). These anthropogenic activities may also include an extensive usage of metals in a variety of human endeavors which is also contributing to an increase in heavy metal contamination as reported by Fardami et al. (2022d). Industrial effluents containing Cr (VI) can infiltrate soil and groundwater, leading to the wide dispersal of chromium in the environment. Additionally, inadequate waste management practices contribute to the release of chromium into ecosystems (Prasad *et al.,* 2021).

Tannery effluents are a significant environmental concern, particularly due to the high levels of chromium they release into water bodies and soils (Nur-E-Alam *et al.,* 2020; Singh *et al.,* 2023). Chromium, a heavy metal commonly used in the tanning process to improve leather durability and resistance, is often discharged in large quantities through untreated or inadequately treated effluents (Kalsoom and Batool, 2020). The tanning process involves converting animal hides into leather using chromium salts, primarily in the form of chromium (III). However, improper handling, disposal, and leakage of these effluents lead to contamination of nearby ecosystems (Buljan and Rajamani, 2024; Fardami and Abdullahi, 2024). Chromium, once in the environment, can undergo oxidation to its more toxic and mobile form, chromium(VI), which poses serious threats to aquatic and terrestrial life as well as human health (Buljan and Rajamani, 2024).

In water bodies, chromium contamination disrupts aquatic ecosystems by affecting the growth, reproduction, and survival of aquatic organisms (Fardami, 2021). Chromium (VI) is highly soluble in water and can accumulate in aquatic organisms, entering the food chain and leading to biomagnification (Bakshi and Panigrahi, 2018). This contamination not only compromises the health of aquatic species but also poses risks to human populations relying on these water sources for drinking, agriculture, and fishing (Fardami, 2021). Industrial areas with large-scale tannery operations often report elevated chromium levels in rivers, lakes, and groundwater, leading to long-term ecological degradation (Gusau *et al.,* 2024). Additionally, the chemical's persistence in water bodies makes it a challenge to remediate, further exacerbating its environmental impact (Kapoor *et al.,* 2022).

The contamination of soils by tannery effluents is another critical issue (Ilango and Sridharan, 2025). When effluents are discharged into open fields or used as irrigation water, chromium accumulates in the soil, altering its physicochemical properties. High concentrations of chromium can lead to soil toxicity, reducing its fertility and affecting plant growth (Musah, 2025). Chromium uptake by plants not only stunts their development but also introduces the toxic metal into the terrestrial food chain (Ilango and Sridharan, 2025). Furthermore, chromium binds strongly to soil particles, making it difficult to remove through natural processes, leading to long-term soil contamination (Gusau *et al.,* 2024). This accumulation negatively impacts agricultural productivity and biodiversity in affected areas, making it a pressing environmental concern (Ilango and Sridharan, 2025).

Environmental and Health Impacts of Chromium

The consequences of chromium contamination are far-reaching. In aquatic environments, it can lead to the bioaccumulation of chromium in fish and other organisms, posing risks to both aquatic life and those consuming contaminated seafood (Ray, and Vashishth, 2024). In soils, chromium can persist for extended periods, affecting plant growth and soil microbial communities (Ren *et al.,* 2024). Human exposure to chromium, either through contaminated water sources or occupational settings, has been linked to respiratory issues, skin disorders, and an increased risk of cancer (Sazakli, 2024).

Recognizing the complex nature of chromium contamination is imperative for developing effective remediation strategies (Zha *et al.,* 2024). While various technologies exist for chromium removal, the drawbacks of conventional methods, such as high costs and potential secondary pollution, necessitate the exploration of alternative, sustainable approaches (Xie, 2024). This background sets the stage for a comprehensive examination of biosurfactants applications in chromium reduction, offering a contextual understanding of the challenges at hand and the need for innovative solutions (Xie, 2024).

Specific Properties that Make Biosurfactants Suitable for Environmental Applications

The application of biosurfactants in environmental contexts, particularly in the reduction of chromium contamination, is underpinned by a distinctive set of properties that render these microbial-derived molecules highly effective and sustainable (Jain, 2022). This section delves into the key properties that make biosurfactants well-suited for addressing environmental challenges, emphasizing their relevance in the realm of chromium reduction (Shahwar *et al.,* 2024).

Enhanced Bioavailability

Biosurfactants possess the unique ability to enhance the bioavailability of hydrophobic compounds, including chromium. Their amphiphilic nature enables them to interact with and solubilize otherwise sparingly soluble contaminants, making them more accessible to microbial activity (Pacwa-Płociniczak *et al.,* 2011). This property is crucial in the context of chromium reduction, where increasing the bioavailability of the metal facilitates its microbial transformation and immobilization (Zha *et al.,* 2024).

Microbial Interactions

Biosurfactants play a pivotal role in microbial interactions with contaminants. By modifying the surface properties of cells and creating favorable conditions, biosurfactants enhance microbial adherence to chromium compounds (Sarubbo *et al.,* 2015). This facilitates the reduction of toxic Cr (VI) to less harmful Cr (III) through microbial metabolism, contributing to the overall effectiveness of remediation efforts (Xia *et al.,* 2019).

Metal Chelation and Complexation

Certain types of biosurfactants exhibit metal-binding capabilities, forming stable complexes with metal ions. In the case of biosurfactants can chelate with Cr (III) ions, aiding in their sequestration and preventing their migration in the environment (Gupta *et al.,* 2024). This property adds an extra layer of control to the remediation process, reducing the risk of leaching and secondary contamination (Rajendran *et al.,* 2022).

Synergistic Action with Microorganisms

Biosurfactants often act synergistically with microorganisms present in contaminated environments. As microbial production of biosurfactants coincides with microbial growth, the introduction of biosurfactants can enhance the overall microbial activity (Domingues *et al.,* 2017). This collaborative action creates a conducive environment for the reduction of toxic Cr(VI) to less harmful forms, promoting the success of chromium remediation strategies (Dubey *et al.,* 2024).

Environmental Compatibility

The inherent biodegradability and low toxicity of biosurfactants contribute to their environmental compatibility (Hogan *et al.,* 2019). When applied for chromium reduction, biosurfactants offer a sustainable alternative to traditional remediation methods that may involve the use of harsh chemicals. The reduced environmental impact aligns with the broader goals of minimizing ecological harm during remediation efforts (Selva Filho *et al.,* 2023).

Understanding these properties illuminates the multifaceted role of biosurfactants in addressing chromium pollution. Their capacity to enhance bioavailability, interact with microorganisms, chelate metal ions, and demonstrate environmental compatibility positions biosurfactants as valuable tools in the pursuit of sustainable and effective solutions for chromium reduction (Singh *et al.,* 2021). In the subsequent sections, we will explore these properties in action, examining laboratory studies and real-world applications that showcase the potential of biosurfactants in mitigating the impact of chromium contamination (Dubey *et al.,* 2024).

Mechanisms of Chromium Removal by Biosurfactants and a whole microbial cell

The mechanisms by which biosurfactants facilitate chromium removal involve a complex interplay of physical, chemical, and biological processes. One of the primary mechanisms is the alteration of chromium's bioavailability (Shahwar *et al.,* 2024). Biosurfactants can form micelles that encapsulate chromium ions, rendering them more accessible to microbial cells. This increased bioavailability enhances the uptake of chromium by microorganisms that possess reductive capabilities, leading to more efficient bioremediation (Mishra *et al.,* 2024).

In addition to improving bioavailability, biosurfactants can also directly influence the redox state of chromium ions (Shahwar *et al.,* 2024). Certain microbial strains produce biosurfactants that contain functional groups capable of donating electrons. These electron-donating properties facilitate the reduction of Cr (VI) to Cr (III) through biochemical pathways involving electron transport chains (Fardami and Abdullahi, 2024). The reduction process is often mediated by specific enzymes, such as chromate reductases, which are up regulated in the presence of biosurfactants (Shahwar *et al.,* 2024). Chromium enters bacterial cell as chromium VI and leaves the cell as chromium III as illustrated in Figure 1. This enzymatic activity is crucial for the detoxification of chromium, as the reduction not only converts toxic Cr (VI) into less harmful Cr (III) but can also lead to the precipitation of chromium as insoluble compounds, further enhancing its removal from contaminated sites (Otzen, 2017). The sequential steps involved in bioreduction of Cr (VI) to Cr (III) within a microbial cell based on active uptake and active expulsion is presentenced in Figure 3 below.

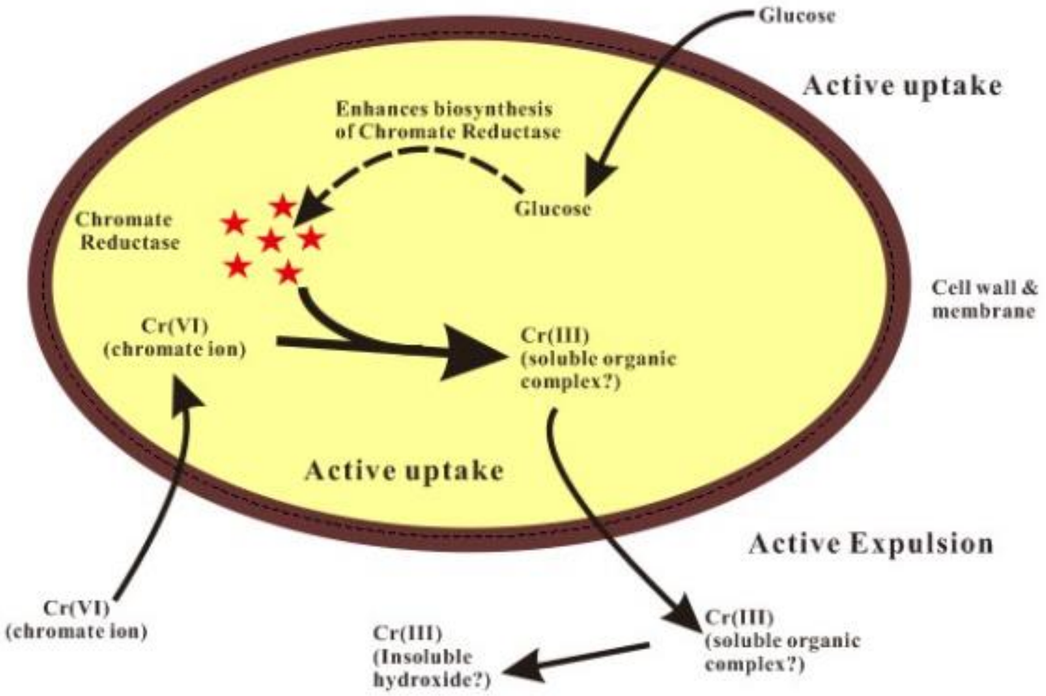

Figure 3: Bioreduction of Cr (VI) to Cr (III) within a microbial cell based on active uptake and active expulsion
Source: Nguema *et al.* (2014).

Another significant mechanism is the role of biosurfactants in mobilizing and stabilizing chromium complexes within the microbial ecosystem (Otzen, 2017). Through their surface-active properties, biosurfactants can solubilize metal complexes, thereby preventing the precipitation of chromium in its toxic form (Shahwar *et al.,* 2024)\.

This solubilization allows for a more homogeneous distribution of chromium in the contaminated environment, which can facilitate its uptake by microorganisms (Fardami and Abdullahi, 2024). Furthermore, some biosurfactants exhibit chelating properties, binding to chromium and forming stable complexes that can be metabolized by microbial communities (Otzen, 2017) This chelation not only assists in the detoxification process but also enhances the overall effectiveness of bioremediation efforts by promoting microbial growth and activity in chromium-rich environments (Otzen, 2017).

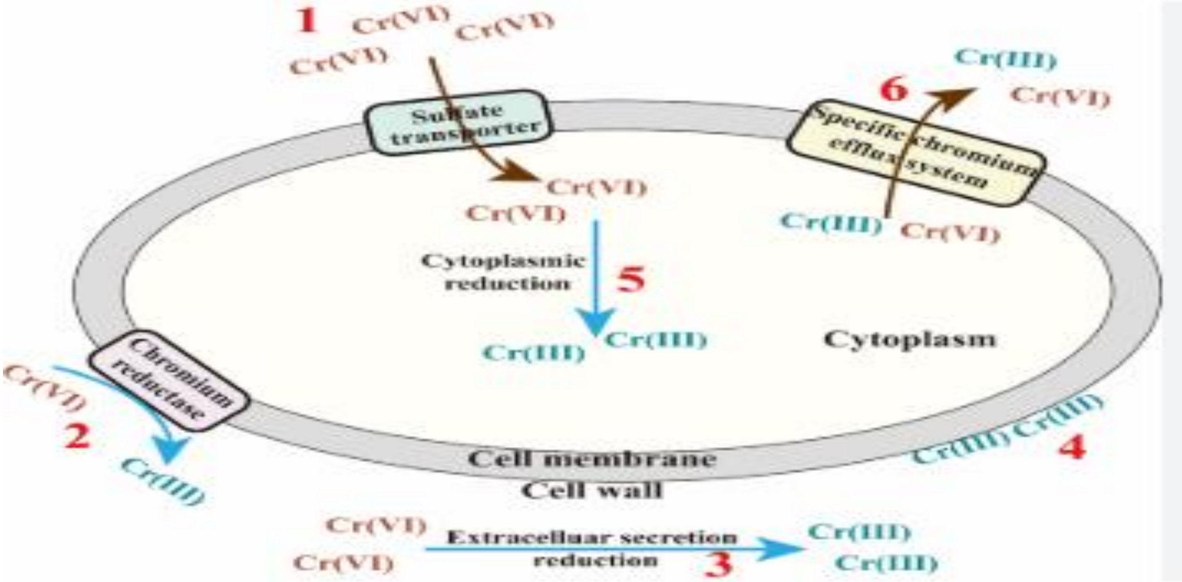

Figure 4: Reduction of Cr (VI) to Cr (III) within microbial cell membrane and cytoplasm
Source: Shan, *et al.,* (2022).

The synergistic interactions between biosurfactants and microbial communities are also pivotal in the chromium reduction process (Simões *et al.,* 2024). Biosurfactants can enhance the growth and activity of chromium-reducing bacteria by providing a favorable microenvironment. This enhanced microbial activity leads to a more significant reduction of chromium, as these specific bacteria can utilize the biosurfactants as carbon sources or as electron donors (Shahwar *et al.,* 2024). Additionally, the presence of biosurfactants can stimulate the expression of genes involved in chromium reduction pathways, further boosting the metabolic capabilities of the microbial population. As a result, the combined effects of biosurfactants and microbial activity not only improve the efficiency of chromium detoxification but also contribute to the overall sustainability of bioremediation practices. Through these multifaceted mechanisms, biosurfactants emerge as vital tools in the environmental management of chromium contamination, showcasing the potential of biological approaches in addressing heavy metal pollution (Shahwar *et al.,* 2024).

Biosurfactants are surface-active substances produced by microorganisms that have gained significant attention due to their unique properties and potential applications in bioremediation, particularly in the removal of heavy metals such as chromium. These compounds are amphiphilic, meaning they possess both hydrophilic and hydrophobic properties, allowing them to interact with various environmental pollutants. When biosurfactants come into contact with chromium compounds, they can alter the physicochemical properties of the chromium species, enhancing their solubility and bioavailability (Simões *et al.,* 2024). This interaction is crucial in contaminated environments, where the mobilization of chromium from solid to liquid phases can facilitate its bioavailability for microbial uptake and subsequent detoxification (Simões *et al.,* 2024).

This synergy between biosurfactants and microbial communities enhances the overall bioremediation process, as these microorganisms can further degrade organic pollutants and immobilize heavy metals, creating a more sustainable approach to environmental cleanup (Shahwar *et al.,* 2024)

In addition to their role in bioremediation, the interaction between biosurfactants and chromium compounds has implications for industrial applications, such as in wastewater treatment and metal recovery processes (Zha *et al.,* 2024). By harnessing the properties of biosurfactants, industries can develop more efficient methods for chromium removal from effluents, reducing the reliance on harsh chemicals and minimizing environmental impacts (Zha *et al.,* 2024). The ongoing research in this area aims to optimize the use of biosurfactants, exploring their potential to enhance the efficiency of bioremediation strategies and contribute to a circular economy where waste materials are transformed into valuable resources. Overall, understanding the dynamics of biosurfactant-chromium interactions is crucial for advancing both environmental remediation and industrial applications (Singh *et al.,* 2021; Shahwar *et al.,* 2024).

Microorganisms play a key role in ecosystem functioning, particularly in the biogeochemical cycling of heavy metals, by removing them from the environment (Fardami *et al.,* 2023). Gusau et al. (2024) has reported that different bacterial have the ability to biosorb heavy metals like chromium. Fardami (2021) also reported the removal of chromium, lead, nickel, copper and cadmium from contaminated water within a range of 59 to 64 percentage removal. Heavy metal removal of copper, lead, nickel and cadmium by rhamnolipid biosurfactant was also reported by Fardami et al. (2022d) within a range of 61 to 69 percentage removal. Microbes typically achieve heavy metal resistance through both passive and active mechanisms, including sequestration, efflux, and transformation within the microbial cell. During the efflux process, membrane proteins actively expel heavy metal ions from the cell using energy, which is essential for metal removal (Fardami *et al.,* 2023). Biosurfactants are utilized in decontaminating organic compounds, such as hydrocarbons, by enhancing their bioavailability or facilitating their removal through processes like pseudo-solubilization and emulsification during cleaning treatments (Fardami, 2021; Mulligan, 2017). For inorganic compounds, biosurfactants aid in their recovery by chelating metal ions and removing them during cleaning, achieved through interactions between the amphipathic compounds and the ions. In heavy metal remediation like chromium, biosurfactants offer significant advantages (Yagnik *et al.,* 2023). Unlike the whole microorganisms, which may struggle to survive in metal-contaminated soils, biosurfactants function effectively but require consistent replenishment. They help solubilize, disperse, and desorb contaminants in soil, enabling land reuse (Yagnik *et al.,* 2023).

Primary Methods for Soil Remediation with Biosurfactants

There are two primary methods for soil remediation with biosurfactants as outlined by Fardami (2021).

i. *Ex* situ treatment

Contaminated soil is excavated, placed in a glass column, and washed with a biosurfactant solution.

ii. *In* situ treatment

Biosurfactant solutions are introduced into the soil using drainage tubes and trenches. Another *in* situ treatment approach involves treating smaller soil volumes in cement mixers, where biosurfactants bind metals to form complexes that are removed during washing. The soil is returned to its original location, while the biosurfactant-metal complex undergoes treatment to separate the biosurfactant from the metal. This process relies on the strong bonds formed between positively charged metals and negatively charged biosurfactants, enabling effective metal removal during washing (Fardami, 2021).

Removal of Heavy Metal by Biosurfactant through Chelation Mechanism

The chelation property of biosurfactants plays a critical role in the removal of heavy metals from contaminated environments (Sarubbo *et al.,* 2015). Biosurfactants, especially those with anionic functional groups, form stable complexes with heavy metal ions through ionic bonds (Fardami, 2021). This chelation process occurs because the negatively charged biosurfactant molecules attract and bind to the positively charged metal ions, creating a strong interaction (Sarubbo *et al.,* 2015).

Biosurfactants can remove heavy metal by forming strong ionic bonds with metals, which are more robust than the metal-soil bonds. This facilitates desorption of the metal-biosurfactant complex into the soil solution by reducing interfacial tension. Cationic biosurfactants may also displace similarly charged ions through competition or ion exchange (Sarubbo *et al.,* 2015). Additionally, biosurfactant micelles can capture metal ions, further aiding removal. The process follows these steps:

i. Sorption of biosurfactant molecules to soil surface and forming a complexation with a heavy metal.
ii. Desorption of metal-biosurfactant complexes and incorporation of the metal into micelle.
iii. Precipitation of biosurfactant out of the complex (See Figure 4).

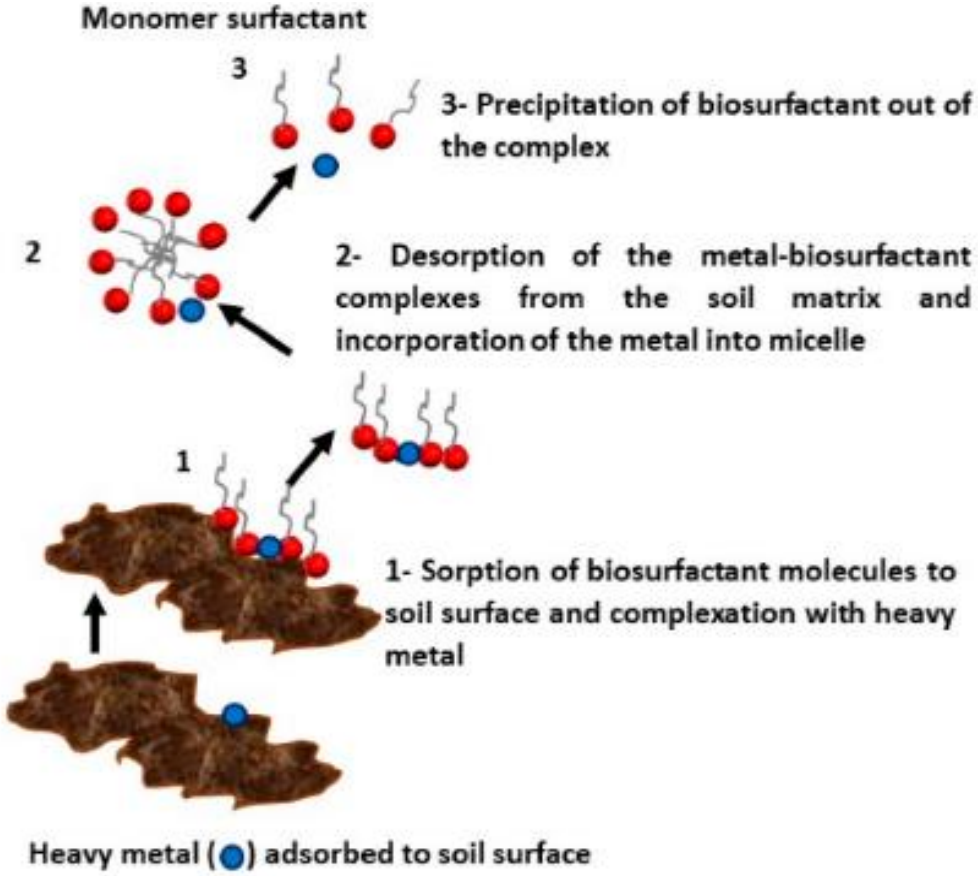

Figure 4: A display of Chelation Property by biosurfactants in making Complex with Chromium Heavy Metal.
Source: Sarubbo et al. (2015).

The key mechanisms in chelation for heavy metal removal was also summarized by Fardami (2021) as follows:

Metal Complex Formation
Anionic biosurfactants bind to metal ions through ionic bonds, resulting in the formation of stable metal-biosurfactant complexes.
Desorption from Soil
The chelated metal ions are detached from the soil matrix as the biosurfactant reduces the interfacial tension, allowing the metals to enter the soil solution.
Micelle Adsorption
Once in the solution, the chelated metal ions are adsorbed onto the micelles of the biosurfactant, where electrostatic interactions further stabilize the complexes.

Removal
These complexes are removed from the soil via washing or separation techniques, such as membrane filtration or precipitation.
Electrostatic interactions help attach heavy metals to the micelles, and membrane separation methods are used to recover them. While synthetic surfactants have been tested for decontamination, growing interest in natural alternatives has driven research into biosurfactants (Sarubbo *et al.,* 2015). Examples include rhamnolipids and surfactin from bacteria, and sophorolipids from yeasts, all of which show great promise in bioremediati5on (Sarubbo *et al.,* 2015; Fardami, 2021). To develop effective remediation strategies for heavy metal-contaminated sites, it is crucial to understand the environmental physicochemical parameters, microbial community structure and diversity, and the type and concentration of heavy metals present is highly needed (Fardami, 2021).

CONCLUSION

Biosurfactant, a microbial-derived amphiphilic molecule, exhibit unique properties that make it effective and eco-friendly tool for environmental remediation, including chromium removal and reduction. Their key characteristics include biodegradability, ensuring minimal environmental persistence; low toxicity, making them safer for ecosystems compared to chemical alternatives; and structural diversity, which allows tailored applications for specific contaminants. Their amphiphilic nature enhances the solubilization and bioavailability of hydrophobic and hydrophilic substances like chromium, facilitating microbial interaction and transformation. Furthermore, biosurfactants are sustainably produced using renewable resources, aligning with global goals for green technologies. These attributes, combined with their ability to chelate metals and support microbial chromium reduction, underscore their potential in mitigating chromium contamination sustainably and effectively. While biosurfactants demonstrate significant potential in chromium removal through their unique surface-active properties, future research should focus on optimizing large-scale production methods to reduce costs, exploring genetically engineered microorganisms for enhanced biosurfactant yields, and investigating the long-term environmental impacts of biosurfactant application. Additionally, more studies are needed on the performance of biosurfactants in complex, real-world wastewater systems and on developing hybrid technologies that combine biosurfactants with other remediation methods to improve efficiency and sustainability.

RECOMMENDATIONS

Here are some actionable recommendations for improving the application of biosurfactants in chromium reduction and by addressing these recommendations, biosurfactants can become a more effective, sustainable, and widely adopted tool for chromium reduction in environmental remediation.

By utilization of low-cost substrates that will help in exploring agricultural, industrial, and food waste as feedstock to reduce production costs while promoting sustainability.

By enhancing strain efficiency where the use of genetic engineering or adaptive laboratory evolution to improve microbial strains for higher biosurfactant yield and chromium-specific activity will be adopted.

By scaling-up the processes used in biosurfactant production to develop efficient bioreactors and scalable fermentation techniques in order to meet industrial demands.

By modifications of chemical structures or enzymes in order to enhance biosurfactant stability, selectivity, and binding affinity for chromium ions.

By adding of Synergistic Additives in order to combine biosurfactants with other agents, such as chelators, nanoparticles, or enzymes, to improve chromium reduction efficiency.

By designing biosurfactant formulations that will be tailored for specific environmental conditions, such as varying pH, temperature, or salinity.

By pairing biosurfactants producing microbes as chromium-reducing microbial consortia to boost overall remediation efficiency.

By Enhancing Bioavailability of biosurfactants in order to solubilize and mobilize chromium, making it more accessible for microbial uptake and reduction.

By optimizing process of remediation that will Fine-tune environmental parameters, such as nutrient availability and aeration, to maximize the synergistic effects of biosurfactants and microorganisms.

By applying site-specific approaches that will tailor biosurfactant applications to the unique characteristics of contaminated sites (e.g., soil type, chromium concentration, co-contaminants).

By conducting long-yerm monitoring in order to establish protocols for assessing the stability and effectiveness of biosurfactants over extended periods.

By using nanotechnology integration that will use biosurfactant-coated nanoparticles for targeted chromium removal and enhanced reactivity.

By developing circular economy models that will incorporate biosurfactants production into waste management systems to create a closed-loop process.

By establishing regulatory support that will work with policy makers to establish guidelines for using biosurfactants in chromium remediation.

By advancing characterization of biosurfactants by combining the mass spectral fragmentation patterns, which are indicative of a compound's chemical structures, with the relative gas chromatographic retention times and elution patterns of mixture components with application of gas chromatography–mass spectrometry (GC–MS) to identify compounds in order to have better understanding of biosurfactant interactions with chromium at molecular and nano-scale levels.

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