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## HEAVY METALS FROM TANNERY WASTE: FOCUS ON CHROMIUM POLLUTION AND BIOREMEDIATION TECHNOLOGIES

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### Abstract

Human health has been known to be adversely affected by heavy metals (including chromium), while anthropogenic and industrial activities had increased exposure to these metals. This study determined the toxicological effects of heavy metals, particularly chromium from tannery discharge and highlight the role of microorganisms in mitigating these pollutants. Tannery industries has been known to be one of the world's oldest industry in human civilization. In the past, these industries were majorly set up to satisfy the need for leather and musical instruments. Tanneries are essential part of the leather production chain because they use variety of chemical and mechanical processes to turn raw hides and skins into finished leather goods. Chromium derivatives are among the most important chemicals employed by these

industries, thereby causing release of heavy metals into the environment through waste discharge. Due to the hazardous, non-biodegradable and poisonous properties of these metals, they usually pose risk to both the environment and living species. In order to bioremediate these toxic effluents, indigenous (autochthonous) organisms are thus widely employed. Microorganisms including *Aspergillus*, *Bacillus*, *Brevibacillus*, *Burkholderia* and *Pseudomonas* species have been found to possess the potential of removing, detoxifying and remediating some of these waste constituents. Bio-augmentation, biostimulation, phytoremediation, bioreduction and biosorption are among the routine approaches employed by these organisms in order to create a safe, less toxic and eco-friendly environments. Further explorations by researchers are therefore

needed to fully harness the mechanisms employed by microorganisms in the bioremediation of chromium contaminants from tannery discharge.

## Introduction

An early use of the term "heavy metal" was dated back to 1817, when a German chemist Leopold Gmelin divided the elements into heavy metals, light metals and nonmetals (Koduru *et al.*, 2017). Light metals had densities ranging from 0.860 to 5.0g/cm<sup>3</sup>, while heavy metals had 5.308–22.0g/cm<sup>3</sup> (Shukla, 2021). The term "heavy metals" are later referred to elements having high atomic weight or atomic number (Ibrahim *et al.*, 2023). Dimkpa *et al.* (2023) defined heavy metals as the group of metals with an atomic density of more than 4g/cm<sup>3</sup>, which is five times higher than the density of water. In the Periodic Table, heavy metals primarily belong to the transition element (Alotaibi *et al.*, 2021). Heavy metals can be classified as non-essential (like cadmium, chromium, arsenic, mercury, and lead) and essential (like manganese, copper, nickel, iron, and zinc) (Mansor *et al.*, 2024). Essential metals help the body's metabolism function. For example, copper (Cu) is needed for the production of hemoglobin and the metabolism of carbohydrates (Waqas *et al.*, 2024). Similar to this, a lot of heavy metals are also necessary

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for plants because they function as cofactors, and initiate enzyme reactions (Thakur *et al.*, 2022). However, essential heavy metals exhibit toxicity if present in excess of the necessary concentration (Jomova *et al.*, 2022). Since non-essential metals are neither biodegraded in the environment nor are they metabolized in other intermediate compounds, they exhibit toxicity even at low concentrations (Briffa *et al.*, 2020).

Human health had been known to be adversely affected by heavy metals, while industrialization and anthropogenic activities had increased exposure to these metals (Subhanullah *et al.*, 2024). Many industries, including those involved in water treatment, metal molding, nuclear energy production, and leather production, releases heavy metals into the water supply (Jagaba *et al.*, 2024). Heavy metals pose a threat to the environment because they are hazardous and poisonous. Because these hazardous metals are neither biodegradable nor destroyable, they pose a serious risk to both human health and the environment (Fardami and Abdullahi, 2024). Plants and other living things can accumulate heavy metal ions in their organs when exposed

to heavy metal-polluted environment (Asiminicesei *et al.*, 2024). Another risk to human and animal health is heavy metal contamination of food (Munir *et al.*, 2021). Naturally, very small amounts of heavy metals are required by living things for internal metabolism. Humans will therefore inevitably come into contact with these metals (Ohiagu *et al.*, 2022). Deficiencies resulting from heavy metal accumulation by living organisms include growth retardation, cancerous growth, organ damage, impaired nervous system function, and in more extreme cases, death (Ungureanu and Mustatea, 2022). Heavy metals have a number of toxic acute and chronic effects on various body organs. The toxic effects of heavy metals can lead to various complications such as vascular damage, cancer, neurological disorders, gastrointestinal and kidney dysfunction, and birth defects (Waqas *et al.*, 2024). Arsenic and chromium are examples of carcinogenic metals that can interfere with DNA synthesis and repair (Budi *et al.*, 2024).

### **Chromium: An Important Source of Contamination**

According to Ali *et al.* (2020), chromium is a transition metal that is commonly found in minerals like chromite. Its atomic number is 24 and its mass is 51.9961g/mol. It's hard, shiny

appearance and strong resistances to corrosion are its defining characteristics. It's melting and boiling points are 1,907 and 2,672, respectively, and its density is 7.19 g/cm<sup>3</sup> at 20°C. Chromium is the first element of group 6 in the modern periodic table. It is a d-block element with an electronic configuration of [Ar] 3d<sup>5</sup> 4s<sup>1</sup> and corresponds to period 4 (Ayele and Godeto, 2021). Its distinctive properties include a strong resistance to corrosion and a hard, silvery appearance (Kumar and Saini, 2024).

Chromium may exist in several oxidation states, ranging from -2 to +6, but its most prevalent stable forms are trivalent (III) and hexavalent (VI) (Liang *et al.*, 2021). The properties of chromium metal vary depending on its oxidation state. The three stable isotopes of naturally occurring chromium are <sup>52</sup>Cr, <sup>53</sup>Cr, and <sup>54</sup>Cr. Of these, <sup>52</sup>Cr has the highest natural abundance (83.789%), making it the 21st most common element in the Earth's crust at about 100 ppm (Ayele and Godeto, 2021). Cr (VI) is linked to several diseases and pathologies, while trace amounts of Cr (III) are required for proper lipid and protein metabolism. Human exposure to Cr (VI) has been linked to an increased risk of death and an increased incidence of certain cancers, including those of the lung, kidney, and bone (Balali-Mood *et al.*, 2021; Pathak *et al.*, 2023).

Chromium is widely used in many industrial applications including tanneries due to its unique properties; however, remediation techniques need to be used carefully because of the risks it poses to human health and the environment, particularly when it is in its hexavalent form (Kumar and Saini, 2024).

### Sources of Chromium

As outlined by Tumolo *et al.* (2020), the two main sources of chromium are natural and anthropogenic source.

#### i. Natural Sources

Between the two most stable oxidation states of chromium ( Cr(III) and Cr(VI) ), the trivalent form is found in nature in a complex form with chromite ore ( $\text{FeCr}_2\text{O}_4$ ) which is a mineral found in mafic and ultramafic rocks. Through microbial intervention and geochemical processes, the naturally released Cr (III) ion most likely has the potential to oxidize into a highly toxic form (Cr (VI)) (Kumar and Saini, 2024). Additionally, the most significant natural source of chromium pollution in the environment is volcanoes and geologic parent materials. Chromium is typically a dispersed geochemical component found in mineral soils, and rocks. In trace amounts, chromium is also found in a variety

of environmental components such as soil, water, and air (Tumolo *et al.*, 2020).

#### ii. Anthropogenic Sources

In addition to the current natural processes, a number of industrial activities release chromium into soil and water bodies. This poses a serious risk to both aquatic and terrestrial life and has long been a source of concern for researchers across the globe. Industrial sectors that use chromium in varying quantities for different purposes include mining, chemicals, and tanning industries (Kumar and Saini, 2024). Over the last few centuries, there has been a significant increase in the concentration of Cr (VI) which is one of the most prevalent oxidation states in both marine and terrestrial ecosystems. Its primary sources are tanning leather, photography, electroplating, textiles, and dyeing (Dongre, 2021). Effluents from tannery industries has been an influential contributor to the cycling of chromium in the soil and water environments (Tirkey *et al.*, 2023; Gusau and Fardami, 2025).

### Toxic Effects of Chromium

Chromium, particularly in its hexavalent form can pose detrimental impacts on human health, plants, microorganisms and soil, thereby posing threat on ecosystem (Tirkey *et al.*,

2023). The following are some living organisms and environment that can be affected by chromium contamination.

### **i. On Humans**

The International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) categorized Cr (VI) compounds as group one human carcinogens with multiple complex mechanisms of action based on epidemiological studies (Wise Jr *et al.*, 2022). Exposure of humans to Cr (VI) can result in lung cancer, allergies, irritations, eczema, ulceration, and skin irritations. In addition to oxidative protein changes, exposure to Cr (VI) may cause DNA mutations, chromosomal damage at various stages, cytotoxicity, and carcinogenicity of compounds containing Cr (VI) (Pathak *et al.*, 2023). Furthermore, breathing in high concentration of hexavalent chromium can lead to respiratory issues like wheezing, coughing, nasal blockage, and facial erythema, and ulcers in the small intestine and stomach (Hossini *et al.*, 2022).

### **ii. On Microorganisms**

Chromium ions play a crucial role in electron transport reactions in biological systems, making them essential nutrients for life. But just like humans, microbes are also extremely sensitive to chromium and its compounds, both

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in excess and in deficiency. The genetic makeup, diversity, and size of microbial populations are all impacted by chromium toxicity (Kumar and Saini, 2024). Cr (VI) exposure in microbes can change the morphology of both Gram-positive and Gram-negative bacteria. Cell growth inhibition can also be caused by chromium, which also causes bacterial cell elongation and enlargement and inhibits cell division. In general, microorganisms can suffer from either excess or deficiency of chromium, which can lead to retarded cell functions and growth disruption (Sharma *et al.*, 2022).

### **iii. On Plants**

Different flora that grows in the soil has been continuously exposed to chromium compounds released naturally through various anthropogenic activities (Prasad *et al.*, 2021). Chromium compounds are extremely toxic to most plants and detrimental to their growth and productivity, even though low concentrations, chromium do not harm some crops. However, even at concentrations as low as 5 mg/kg in soil and 0.5 mg/L in solution, Cr (VI) can be extremely toxic to plants. Cr (VI) is also associated with decreased nutrient uptake and photosynthesis, both of which slow down plant growth (Genchi *et al.*, 2021). Plant cells produce reactive oxygen species due to a

number of physiological and biochemical processes that are severely disturbed. Plant necrosis and chlorosis are symptoms of chromium toxicity (Srivastava *et al.*, 2021).

#### iv. On Soils

Chromium-contaminated soil refers to soil that has been polluted or contaminated with chromium, typically in the form of hexavalent

chromium (Cr (VI)), although trivalent chromium (Cr (III)) contamination can also occur (Montes-Robledo *et al.*, 2024). The deposition of these chromium compounds into the environment can pose negative impacts on living organisms inhabiting the soil (Prasad *et al.*, 2021). Anthropogenic activities can also lead to accumulation of chromium in the soil as illustrated in Figure 1.



**Figure 1: Chromium Pollution of Environment due to improper Deposition of Effluents from Tannery Industry (Nur-E-Alam *et al.*, 2020)**

#### Tannery

One of the world's oldest industry is tanning. In the past, tanning operations were set up to satisfy the local need for musical instruments and leather footwear (Kenea, 2022). Tannery handles the processing of animal hides or skins to create leather, a material that finds application in a wide range of sectors including fashion, furnishings, and accessories.

Tanneries are essential part of the leather production chain because they use a variety of chemical and mechanical processes to turn raw hides and skins into finished leather goods (Ahmed *et al.*, 2021).

The two commonly used techniques for tanning raw hides includes chrome tanning and vegetable tanning. Chrome tanning contains chromium and is used for light leather, while

vegetable tanning which does not contain chromium, and are used for heavy leather items such as shoe soles, handbags, and belts (Ahmed *et al.*, 2021; Teklemedhin *et al.*, 2023). Four categories describe the production processes in tannery as finishing operations, post-tanning operations, beam house operations, and tanyard operations. The tanyard is where the leathers are actually made, but the beam house is where the processes leading up to tanning are monitored. These procedures are all carried out in tanneries (Hossain, 2023).

### **Tannery Effluent**

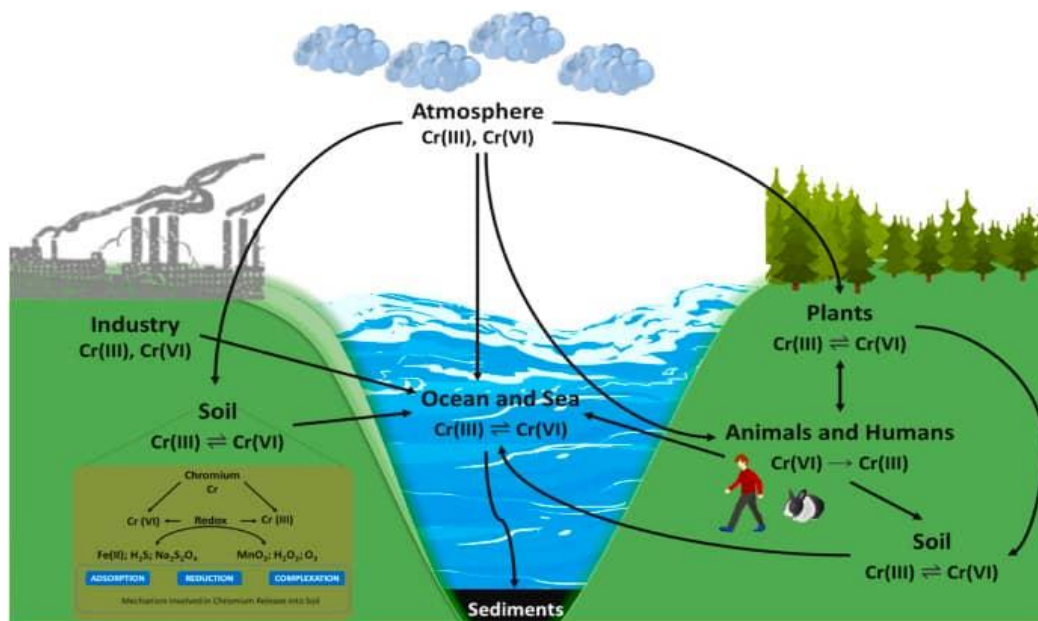
Wastes from the tanning process have a major negative influence on the environment, especially in nations with lax environmental laws. When these wastes are released into soil and water bodies, they pose impact on the physical, chemical, and biological properties of soil and water (Chowdhary *et al.*, 2020). Worldwide, leather industries produce enormous amounts of tannery effluent during the tanning process. In addition to being highly toxic to plants, animals, and microbes, it is regarded as one of the most contaminated industrial wastes. Fewer than 5% of industries worldwide have implemented appropriate effluent treatment measures, with the majority ignoring them due to financial concerns (Mao

*et al.*, 2022). Soil fertility is compromised when tannery wastewater enters agricultural areas or used to irrigate such areas. Furthermore, it has been documented that plants absorb metals from tannery wastes, such as chromium, which is then available in their roots, shoots, leaves, flowers, and fruits. There have been reports of organisms in tannery effluents acquiring adaptations that allow them to tolerate and make use of the hazardous components of the effluent (Tirkey *et al.*, 2023).

For the treatment of tannery effluent, indigenous organisms are thus widely used. However, a variety of extremophilic microbial flora that exhibit remarkable flexibility and adaptation to survive in the harsh tannery environment can be found in tannery effluent. Microorganisms including *Pseudomonas*, *Bacillus*, *Brevibacillus* and *Aspergillus* species have the potential to remove some of the waste constituents (Kajla *et al.*, 2021). But temperature, pH, availability of nutrients, and concentration can all affect these processes. Through a variety of processes, including methylation, oxidation, reduction, and adsorption uptake, these microorganisms are able to defend themselves against the toxicity of heavy metals found in the effluent (Deng *et al.*, 2021). Tannery waste has been known as one of the major substances which contributes

to the cycling of chromium in both water and soil environments (Tirkey *et al.*, 2023). Their

role as major chromium cyler in such environment is illustrated in Figure 2.



**Figure 2:** Tannery Industry as a Major Contributor to Chromium Cycling in both Terrestrial and Aquatic Environments (Singh *et al.*, 2022)

### Characterization of Tannery Effluent Generation

Depending on the size of the tannery, the chemicals used for a particular process, the amount of water used, and the type of final product produced, the characteristics of tannery effluents differ significantly between tanneries (Sodhi *et al.*, 2021). Characteristics like suspended solids (SS), heavy metals, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) can be used to describe the pollution of tannery effluent. The high toxic interferences of chromium, sulphide, chloride, and other elements had already caused number

of issues during the biological treatment of tannery wastewater (Ake *et al.*, 2022). Consequently, the effluent quality becomes undesirable with respect to chromium, sulfide, etc. Disposal of such effluent into soil and water bodies may cause adverse environmental effects (Chowdhary *et al.*, 2020).

### Methods of Tannery Effluents Treatment

Dhaliwal *et al.* (2020) reported that tannery effluent pollutants are being removed from contaminated sites using variety of techniques. Heavy metals as an example of tannery product can be eliminated from contaminated areas like soil and wastewater through a variety of

traditional physicochemical techniques like membrane filtration, reverse osmosis, adsorption, chemical precipitation, electrolysis, and coagulation. Alkhanjaf *et al.* (2024) emphasized that such conventional methods of removing pollutants are very expensive and also ineffective when reducing heavy metals at very low concentrations of 10–100mg/L. Furthermore, a lot of secondary waste and other hazardous products are produced by these traditional methods, which may call for the use of alternative technologies to transform them into nontoxic, and environmentally friendly forms. As a result, Singh *et al.* (2022) noted that attention has shifted to biological remediation techniques, which are less expensive, more environmentally friendly, and have a relatively high removal efficiency.

The capabilities of microorganisms or plants to adsorb, convert or transform pollutants in tanneries are one of the widely used technologies for bioremediation. Utilizing biological pollutants removal technologies can economically, safely, and easily remove pollutants from contaminated sites (Sharma *et al.*, 2022). Some biological techniques that have been used to remove and detoxify these substances from tannery effluents contaminated environments include biosorption, bioreduction, bioleaching, and phytoremediation (Dhaliwal *et al.*, 2020). Even **Abdullahi et al.**,

though a variety of chemical and physical techniques have been used for their removal, the biological remedy utilizing microorganisms has gained attention because it is simple, effective, and produces little to no-secondary waste (Babi *et al.*, 2023).

Jamir *et al.* (2024) defined biological treatment as a cost-effective, versatile and environmental friendly approach that utilize biological materials, such as bacteria, fungi, algae, and agricultural wastes, to remove pollutants from contaminated site. It offers a promising alternative to conventional treatment methods for soil and wastewater remediation to enhance environmental protection (Alkhanjaf *et al.*, 2024). The biological method of heavy metals including chromium removal uses the biomass of living or dead microorganisms (such as bacteria, fungi, algae, and yeast) to reduce toxic chromium ions to relatively less or nontoxic forms (Qin *et al.*, 2020). The biological reduction of Cr (VI) to Cr (III) represents a potentially valuable approach for the bioremediation of contaminated waste and detoxification of chromium contamination (Sharma *et al.*, 2022). Microbial species have the potential to remove chromium, which is a healthy and environmental beneficial sustainable development solution. One potential substitute for the current standard techniques for industrial wastewater

detoxification is the biosorption of Cr (VI) using microbial biomass (Qin *et al.*, 2020). Ayele and Godeto (2021) reported that, various microbial remediation methods, including biosorption, bioaccumulation, biotransformation, and bioleaching, are usually used to eliminate heavy metals, including chromium, from industrial wastewaters.

### **Bioremediation Strategies of Heavy Metals in Industrial Effluent**

The most significant sources of hazardous pollutants in the environment are industrial effluents including tanneries. The rate of urbanization and industrialization has increased the amount of organic pollutants in the environment. The novel method of bioremediation involves employing living organisms to detoxify or reduce tannery pollutants into less dangerous forms by means of the actions of microbes (Islam *et al.*, 2022). Bacteria showed enormous potentials when applied to soil contaminated by industrial effluents. Microbes are used extensively in tannery sectors for heavy metal remediation, and this approach is a compelling substitute for the physical and chemical methods (Singh *et al.*, 2022). The process of bioremediation is used to recover or remove heavy metals from contaminated environments (Medfu Tarekegn *et al.*, 2020). Compared to conventional

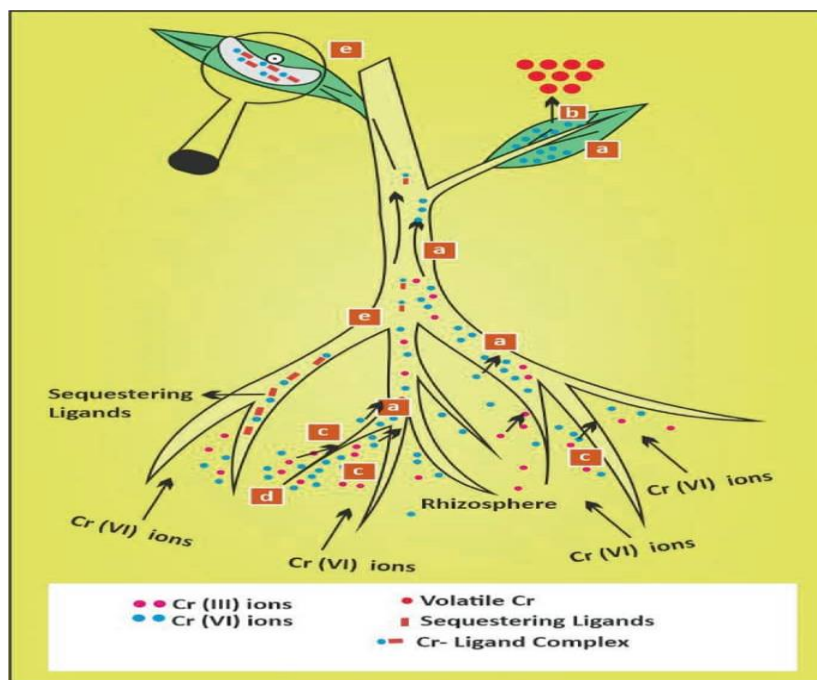
chemical and physical techniques which are frequently more expensive and ineffective, it is an environmentally friendly and economical method for the removal or recovery of heavy metals (Singh *et al.*, 2022). Only when microorganisms can grow and function in their environment will bioremediation be effective (Ramli *et al.*, 2023).

Microorganisms have amazing metabolic pathways that use a variety of toxic substances as an energy source for respiration and metabolism in order to support growth and development (Singh *et al.*, 2022). Microorganisms have developed a variety of survival strategies to survive in environments contaminated with heavy metals, including bioaccumulation, bio-mineralization, biosorption, and biotransformation. These mechanisms are used for remediation, either *ex-situ* (treating the pollutants away from the contaminated site) or *in-situ* (treating the contamination at the site) (Nivetha *et al.*, 2023). These properties have made them useful as biosorbents for the removal of heavy metals. It has been reported that various species of *Aspergillus*, *Pseudomonas*, *Bacillus*, and *Burkholderia* are effective reducers of heavy metals (Ramli *et al.*, 2023). Some major effective strategies include;

### i. Phytoremediation

Phytoremediation has emerged as a highly sustainable and eco-friendly strategy for the removal of chromium from tannery effluents through the use of metal-tolerant plants that can extract, stabilize, or transform chromium in contaminated soils and water bodies (Islam *et al.*, 2022; Pandey *et al.*, 2024). Plants such as *Brassica juncea*, *Vetiveria zizanioides*, and *Phragmites australis* have demonstrated significant ability to absorb and accumulate chromium in their roots and aerial tissues, thereby reducing its mobility and bioavailability in the environment. Phytoremediation involves a combination of

rhizofiltration, where plant roots absorb and adsorb chromium from effluents; phytoextraction, in which chromium is translocated and stored in plant biomass; and phytostabilization, where chromium is immobilized in the rhizosphere through root exudates and microbial interactions (Islam *et al.*, 2022). The rhizosphere plays a crucial role by hosting plant-growth-promoting rhizobacteria (PGPR) that enhance metal tolerance, increase chromium solubilization, and promote plant health under metal stress (Gupta *et al.*, 2024). Figure 3 highlights the phytoremediation uptake of chromium contaminants from the environment.



**Figure 3:** Phytoremediation of Chromium by Plant (Kaur *et al.*, 2022)

## ii. Bio-augmentation and Biostimulation

The process of bio-augmentation involves adding pre-grown microorganisms that have been carefully chosen to break down contaminants (Muter, 2023). Improving the microbial population at a location helps to clean up contaminants by guaranteeing that there are enough microorganisms in the soil to finish the bioremediation process, thereby rendering the chromium to be less toxic to the environment (Nivetha *et al.*, 2023). On the other hand, bio-stimulation involve the process of altering contaminated materials and locations to promote the growth of naturally occurring microbes. Nutrients such as nitrogen, phosphorous and potassium derivatives may be used in an effort to stimulate the microorganism's action. This approach indicates the presence of the right microbe. The bio-stimulation of microbiological processes at the sites (*in-situ*) when dealing with pollutants such as chromium is an important aspect for the bioremediation of such pollutants (Nivetha *et al.*, 2023).

## iii. Bacterial Reduction of Cr (VI) to Cr (III)

Microbial reduction of toxic Cr<sup>6+</sup> to the less toxic and less mobile trivalent chromium (Cr<sup>3+</sup>), mainly by bacteria such as

*Pseudomonas*, *Bacillus*, and *Escherichia coli*. As mentioned in previous sections, hexavalent chromium are more harmful to microorganisms, plants, and animals than trivalent species (Elahi *et al.*, 2020). Therefore, different processes under varied conditions can convert the more toxic Cr (VI) species to the less toxic ones. Apart from its extracellular adsorption and intracellular accumulation, chromium reductase enzyme plays a significant role in converting Cr (VI) into less toxic Cr (III) (Tang *et al.*, 2021). Significantly, at acidic pH, the biomass surface containing electron-donating agents like hydroxyl, amine, and secondary alcohol groups interacts favorably with Cr (VI) and is reduce to Cr (III) (Rahman and Thomas, 2021).

## iv. Biosorption of Chromium

Use of microbial biomass (bacteria, fungi, algae, or yeast) to passively bind and accumulate chromium ions on their cell surfaces through functional groups such as carboxyl, hydroxyl, amino, and phosphate. The process of biosorption, which occurs quickly, independently, and without metabolic energy, is what allow dead or inactive biomaterials to sequester specific heavy metal ions (Yaashikaa *et al.*, 2021; Fardami and Abdullahi, 2024). As the chromium ions enter

the cells during biosorption, it attach extracellularly to the cell walls and intracellularly to proteins like metallothionein. There is always a solid phase in the biosorption process that acts as the biosorbent (Deng *et al.*, 2021). The removal of Cr (VI) from microorganisms usually occurs in three steps: chromium binding to the cell surface, chromium translocation into the cell, and reduction of Cr (VI) to Cr (III) (Pal *et al.*, 2022). In general, bacteria can reduce Cr (VI) directly through chromate reductase enzymes or indirectly through metabolite reduction of Cr (VI) on the cell surface, outside or inside the cell (Sharma *et al.*, 2022).

#### **v. Bioaccumulation**

Bioaccumulation is a key bioremediation strategy employed in the detoxification of chromium from tannery effluents, which are often characterized by extremely high levels of hexavalent chromium due to its widespread use in leather tanning processes (Das *et al.*, 2025; Harshan Gandhi *et al.*, 2025). This process involves the uptake and intracellular sequestration of chromium ions by microorganisms such as bacteria, fungi, and algae, which possess highly efficient metal-binding proteins and transport systems. The cellular mechanisms rely on surface adsorption to the cell wall followed by active transport

into the cytoplasm, where chromium is either stored in vacuoles or bound to metallothioneins, peptides, and organic acids (Chugh *et al.*, 2022). Over time, these microbial cells act as natural biosorbents, progressively concentrating chromium in their biomass and thereby reducing its bioavailability and toxicity in the environment. Bioaccumulation offers a cost-effective and environmentally sustainable alternative to conventional chemical treatments, as it harnesses the metabolic potential of naturally occurring or engineered microbes that can withstand high metal concentrations (Das *et al.*, 2025). Furthermore, the biomass accumulated with chromium can be recovered and subjected to safe disposal or metal recovery techniques, closing the loop on waste minimization and resource recycling (Dey *et al.*, 2024).

#### **vi. Bioprecipitation and Biomineralization**

Bioprecipitation and biomineralization represent promising microbial strategies for immobilizing and detoxifying chromium in tannery effluents by converting soluble, toxic chromium species into stable, insoluble mineral complexes. In bioprecipitation, microorganisms induce chemical changes in their microenvironment by altering redox conditions or releasing metabolites such as

sulfides, carbonates, or phosphates that react with chromium ions to form insoluble precipitates (Raval *et al.*, 2025). Biomineralization goes a step further, whereby microbial enzymes catalyze the transformation of chromium into mineral forms such as chromium hydroxides, oxides, or phosphates, which can be permanently sequestered in sediments or microbial matrices (Ehrlich *et al.*, 2021). For instance, sulfate-reducing bacteria generate hydrogen sulfide that reacts with chromium to form chromium sulfide precipitates, while phosphate-solubilizing microbes facilitate the precipitation of chromium-phosphate complexes (Ou *et al.*, 2023). These processes not only reduce the toxicity of soluble hexavalent chromium but also prevent its re-entry into aquatic systems, thereby providing long-term stabilization. Additionally, biomineralization is seen as a natural analogue to geochemical immobilization processes, making it ecologically safer and more sustainable for long-term chromium remediation in tannery-contaminated sites (Deo *et al.*, 2024).

#### **vii. Biofilm-Mediated Removal**

In this strategy, microorganisms such as *Pseudomonas*, *Bacillus*, and *Aspergillus* species grow as biofilms, producing extracellular polymeric substances (EPS) that

provide abundant binding sites for chromium ions through functional groups like hydroxyl, carboxyl, and amino residues (Maurya *et al.*, 2022; Ebrahim *et al.*, 2025). The biofilm matrix not only enhances biosorption capacity but also protects the microbial cells from high concentrations of toxic hexavalent chromium, thereby enabling long-term survival and sustained remediation activity. Within biofilms, microenvironments with varying redox conditions promote the enzymatic reduction of Cr(VI) to the less toxic trivalent form [Cr(III)], which subsequently precipitates as insoluble complexes trapped in the EPS or bound to cell surfaces (Ebrahim *et al.*, 2025). Compared to planktonic cells, biofilm-forming microbes display greater resistance to toxic stress, higher tolerance to environmental fluctuations, and enhanced metabolic cooperation, all of which contribute to superior chromium detoxification performance. Biofilm-mediated removal can be applied in continuous flow bioreactors or constructed wetlands, where biofilms act as self-regenerating, low-cost filters that efficiently reduce chromium loads in wastewater (Singh *et al.*, 2021).

#### **viii. Enzyme-Mediated Detoxification**

The most critical enzymatic activity involved is chromate reductase, an NAD(P)H-

dependent enzyme widely distributed among chromium-resistant bacteria such as *Pseudomonas*, *Bacillus*, and *Enterobacter* species (Anand and Pandey, 2021). This enzyme catalyzes the reduction of hexavalent chromium [Cr(VI)], a highly soluble and carcinogenic form, to trivalent chromium [Cr(III)], which is less soluble, less mobile, and relatively non-toxic. Other enzymes such as oxidoreductases, dehydrogenases, and ligninolytic enzymes in fungi also contribute to chromium detoxification through direct reduction or by generating reactive metabolites that interact with chromium (Dubey *et al.*, 2024). Enzyme-mediated detoxification offers significant advantages over physical-chemical reduction methods, as it occurs under mild environmental conditions, avoids the generation of toxic byproducts, and can be fine-tuned through genetic engineering to enhance specificity and activity (Bilal *et al.*, 2021). Immobilization of chromate reductases on supports has further improved their stability and reusability in bioreactors for tannery wastewater treatment (Chaurasia and Kumar, 2022).

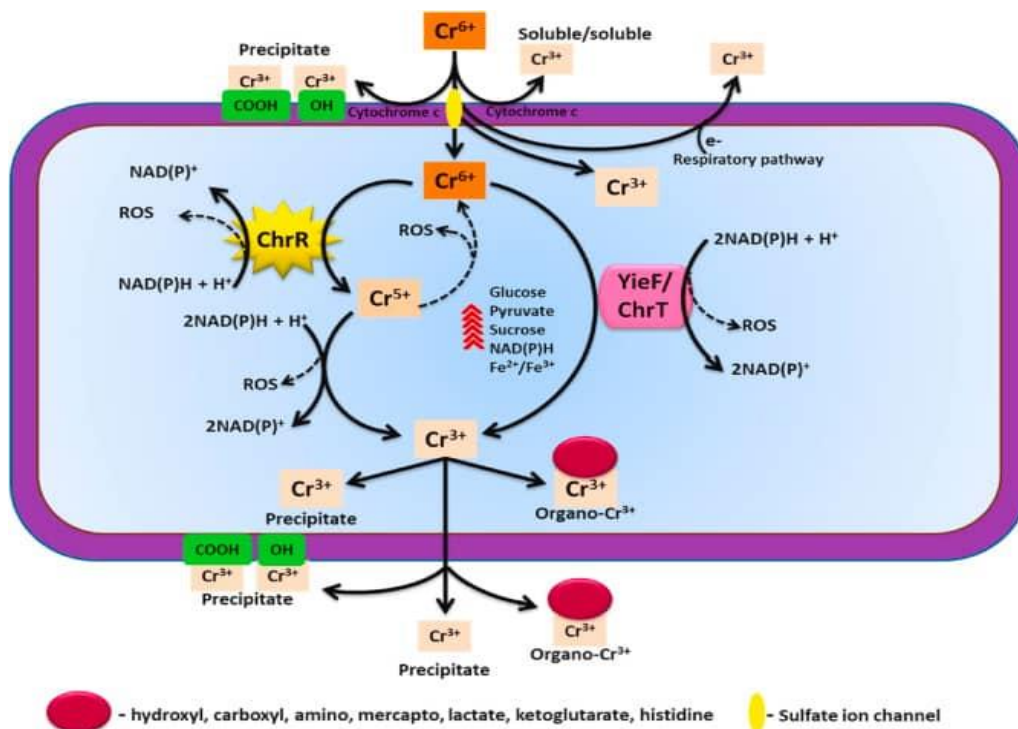
#### **ix. Consortium-Based Bioremediation**

Consortium-based bioremediation utilizes synergistic interactions among multiple microbial species to enhance the detoxification

of chromium from tannery effluents, providing a robust and versatile strategy compared to single-species approaches (Tyagi *et al.*, 2025). In such consortia, different microbial groups contribute complementary metabolic and physiological traits, including chromium reduction, bioaccumulation, biosorption, and precipitation, thereby improving the overall efficiency of bioremediation under fluctuating environmental conditions (Kuanar *et al.*, 2022). For example, sulfate-reducing bacteria can precipitate chromium as insoluble sulfides, while chromate-reducing bacteria simultaneously convert Cr(VI) to Cr(III), and biosorbent fungi immobilize the reduced species within their cell walls (Barman, 2024). The metabolic diversity within consortia also ensures resilience to high chromium loads and co-contaminants commonly found in tannery wastewater, such as organic matter, dyes, and sulfides. Consortium-based systems can establish self-sustaining biofilms in treatment reactors or natural systems, where extracellular polymeric substances (EPS) provide binding sites for chromium sequestration and create microenvironments that facilitate reduction and immobilization (Saini and Mishra, 2024). The use of microbial consortia not only accelerates the rate of chromium detoxification but also enhances adaptability across different effluent

compositions, making it suitable for real-world applications (Dubey *et al.*, 2024). Recent advances in metagenomics and synthetic biology have enabled the design of tailored microbial consortia with optimized chromium-remediation potential, offering promising

opportunities for eco-friendly treatment of tannery discharges at both laboratory and industrial scales (Dubey *et al.*, 2024; Kumar and Saini, 2024). The bioremediation strategies of toxic chromium by microbial biomass is illustrated in figure 4.



**Figure 4:** Bioremediation of Chromium using Microbial Biomass (Pushkar *et al.*, 2021)

### Conclusion

Effluents from tannery industries are composed of different toxic substances, some of which includes tannins and heavy metals. These heavy metals, particularly chromium, in its hexavalent form can cause detrimental effects on microbes, soil, plants, and human health, thereby posing threat on the ecosystem. The application of biological

agents (bioremediation) for detoxifying these heavy metals is considered as a promising approach for the mitigation of these pollutants. The technological strategies in bioremediation including biosorption, phytoremediation, bioaccumulation and bio-reduction among others are cost-effective, safe and eco-friendly approach for safer and cleaner environment.

## Recommendations

It is recommended that;

- i. More researches should be done to explore more novel biological agents for heavy metal bioremediation
- ii. The effluents from tannery industries should be treated first before disposing into the environment
- iii. General public, especially those residing in close proximity should be educated on the detrimental effects of prolonged exposure to heavy metal contaminants.
- iv. Researchers should make further researches to fully harness the mechanisms employed by microorganisms in the bioremediation of chromium contaminants from tannery discharge.

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