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BIOREMEDIATION: A SUPERIOR ALTERNATIVE FOR REMEDIATING TANNERY EFFLUENT-CONTAMINATED SOIL

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ABSTRACT

Tannery effluent poses significant risks to soil health, primarily through contamination with heavy metals like chromium, sulphides, and persistent organic pollutants (POPs). These toxic substances inhibit microbial activity, reducing nutrient cycling and organic matter decomposition essential for soil fertility. Beneficial microorganisms, including nitrogen-fixing bacteria, are particularly affected, leading to altered microbial communities dominated by less advantageous, metal-tolerant species. Accumulation of POPs and heavy metals disrupts soil enzymatic activities, interferes with plant root growth, and complicates remediation efforts due to pollutant migration to groundwater and potential entry into the food chain. Prolonged exposure to such contaminants diminishes soil fertility, reduces resilience, and disrupts ecosystem services, posing threats to agricultural productivity and environmental health. This review was aimed to outline what made bioremediation a superior treatment technology among other methods used in remediating tannery effluent contaminated soil. Efforts to mitigate tannery effluent impacts involve a combination of physical, chemical, and biological remediation technologies. Physical methods like soil washing, flushing, and thermal desorption focus on removing or isolating contaminants, while chemical approaches such as oxidation, reduction, and stabilization transform pollutants to less harmful forms or immobilize them. Biological remediation leverages microorganisms and plants to detoxify contaminants sustainably. Bioremediation strategies with aid of bioaugmentation and biostimulation do enhance microbial activity to address organic and inorganic pollutants effectively more than physical and chemical methods. Another excellent bioremediation technology called phytoremediation can also address organic and inorganic pollutants effectively, Achieving better remediation technique should be coupled with stringent industrial regulations, sustainable tanning methods, and stakeholder awareness.

Keywords: Soil washing, Thermal desorption, Bioremediation, Phytoremediation, Chromium, Persistent Organic Pollutants (POPs)

INTRODUCTION

Bioremediation is a sustainable and eco-friendly technology that employs living organisms, primarily microorganisms, to detoxify, degrade, or remove environmental contaminants from effluent contaminated soil (Sehrawat *et al.*, 2021). This approach capitalizes on the natural metabolic pathways of these organisms, which can transform hazardous substances into non-toxic or in a less harmful form (Sangeetha & Jagtap, 2024). The growing need for effective environmental management, driven by industrialization, urbanization, and agricultural activities, has intensified interest in bioremediation as a cost-effective alternative to conventional methods such as incineration, chemical treatment, and landfilling (Baskaran and Byun, 2024). While these traditional techniques often transfer contaminants to another medium or leave a secondary pollutant, bioremediation offers a holistic and integrative solution that promotes long-term ecosystem recovery (Kumar *et al.*, 2025).

Microorganisms, including bacteria, fungi, and archaea, are the primary agents of bioremediation due to their ability to metabolize a wide range of organic and inorganic pollutants (Mokrani *et al.*, 2024). These organisms break down contaminants as a source of carbon and energy or utilize them in their metabolic processes, ultimately reducing the concentration of harmful substances (Priya *et al.*, 2024). For instance, certain bacterial species can degrade hydrocarbons in oil spills, while others can immobilize heavy metals in contaminated soils by converting them into less soluble forms (Osadebe *et al.*, 2024). The versatility and adaptability of microorganisms have positioned them at the forefront of bioremediation research, with scientists continuously exploring novel species and genetic modifications to enhance their degradation capabilities (Contreras-Salgado, *et al.*, 2024).

Bioremediation techniques are broadly categorized into in situ and ex situ methods (Liu *et al.*, 2024). In situ bioremediation occurs directly at the contaminated site and includes techniques such as bioventing, bioaugmentation, and phytoremediation (Kuppusamy *et al.*, 2016). Bioventing involves supplying oxygen to stimulate the growth and activity of indigenous microorganisms, while bioaugmentation introduces specialized microbial strains to accelerate the degradation process (Saeed *et al.*, 2023). Phytoremediation, on the other hand, utilizes plants to extract, stabilize, or degrade pollutants in soils and water (Bhat *et al.*, 2022). Ex situ bioremediation involves the physical removal of contaminated material to a controlled environment, where conditions are optimized for microbial activity (Perez-Vazquez *et al.*, 2024). Techniques such as bio-piles, bioreactors, and land-farming exemplify as ex situ strategies each offering specific advantages depending on the nature and extent of contamination (Kaur and Sood, 2025).

The success of bioremediation is influenced by various environmental factors, including pH, temperature, oxygen availability, moisture content, and nutrient levels (Vasseghian *et al.*, 2024). Microbial activity is highly dependent on these conditions, as they directly impact the efficiency of contaminant degradation (Kiran *et al.*, 2024). For example, aerobic microorganisms require sufficient oxygen levels to metabolize organic pollutants effectively, while anaerobic conditions may be necessary for the degradation of certain compounds such as chlorinated hydrocarbons (Raj *et al.*, 2025). Similarly, temperature fluctuations can affect the enzymatic activities of microorganisms, thereby influencing the overall remediation process. Understanding and managing these factors are critical to optimizing bioremediation efforts (Narayanan *et al.*, 2023).

The integration of molecular biology and biotechnology has significantly advanced the field of bioremediation (Sharma *et al.*, 2024). Techniques such as metagenomics, transcriptomics, and proteomics enable researchers to identify and characterize microbial communities involved in contaminant degradation (Alidoosti *et al.*, 2024). Genetic engineering has also opened new possibilities for creating "designer microbes" with enhanced metabolic pathways, enabling them to degrade recalcitrant pollutants more efficiently (Ekpan *et al.*, 2024). Furthermore, bioinformatics tools are being employed to predict the behavior of microbial consortia under varying environmental conditions, facilitating the design of tailored bioremediation strategies (Pradhan and Kumar, 2024). This review was aimed to show case the concept of bioremediation as the best treatment among the treatment technologies used in remediating tannery effluent contaminated soil.

Tannery Industry

The tannery industry, a critical segment of the leather manufacturing sector, is one of the oldest industries globally, with historical significance dating back thousands of years (Henderson, 2024). Leather processing involves converting raw hides and skins, primarily sourced from livestock, into durable materials used in producing footwear, garments, furniture, and industrial goods (Priyadarshini *et al.*, 2024). Tanning techniques have evolved from traditional methods reliant on plant-based tannins to advanced chemical processes utilizing chromium salts and other synthetic compounds (Fraga-Corral *et al.*, 2020).

At the core of the tannery industry's environmental impact is its reliance on water and chemicals during processing (Marrucci *et al.*, 2022). The tanning process is inherently resource-intensive, with an average of 50 liters of water required per kilogram of raw hide processed (Ngobeni *et al.*, 2024). Chemicals, including sodium sulfide, lime, and chromium, are employed during dehairing, liming, and tanning, respectively (Rajendran *et al.*, 2024). The improper handling and disposal of these chemicals often lead to the generation of hazardous effluents (Pratap *et al.*, 2023). These effluents contain high concentrations of organic matter, salts, heavy metals, and synthetic dyes, which, if untreated, can severely harm ecosystems and human health (Khatun *et al.*, 2024). The complexity and variability of tannery effluents make their treatment a significant technical and financial challenge for stakeholders in the industry (Jaffari *et al.*, 2024).

One of the most pressing concerns associated with tannery effluents is the contamination of freshwater resources (Khatun *et al.*, 2024). Untreated or inadequately treated effluents are often discharged into nearby rivers, lakes, or groundwater systems, leading to elevated levels of biological oxygen demand (BOD) and chemical oxygen demand (COD) in aquatic environments (Wu *et al.*, 2024). This contamination disrupts aquatic ecosystems by depleting dissolved oxygen levels, rendering water bodies incapable of supporting aquatic life (Kumar *et al.*, 2021). Furthermore, tannery effluents often contain chromium in its toxic hexavalent form, which is not only harmful to aquatic organisms but also poses severe health risks to humans upon prolonged exposure, including skin diseases, respiratory issues, and even carcinogenic effects (Singh *et al.*, 2023).

The issue of solid waste management further complicates the environmental footprint of the tannery industry (Khatun *et al.*, 2024). Solid wastes, including fleshings, trimmings, and sludge from wastewater treatment plants, are often disposed of in landfills without adequate measures to prevent leachate contamination (Buljan and Rajamani, 2024). These wastes frequently contain residual chemicals and pathogens, posing risks of soil and groundwater pollution (Yadav *et al.*, 2020). In regions where informal leather processing thrives, the lack of proper waste management infrastructure exacerbates these issues, creating severe environmental degradation and public health crises (Agwu, 2024). The growing global demand for leather products further intensifies the generation of such wastes, necessitating urgent intervention (Dalbanjan *et al.*, 2024).

Addressing the challenges posed by tannery effluents requires a multifaceted approach encompassing technological, regulatory, and community-driven initiatives (Pundir *et al.*, 2024). Advanced effluent treatment technologies, such as membrane filtration, anaerobic digestion, and chemical precipitation, have shown promise in mitigating the environmental impact of tannery wastewater (Pundir *et al.*, 2024). However, the high costs associated with these technologies often deter their adoption, especially among small and medium-sized enterprises (SMEs) (Alengebawy *et al.*, 2024). Encouraging the development and deployment of cost-effective and scalable solutions, including phytoremediation and bioaugmentation, could play a pivotal role in enhancing effluent management across the industry (Kuppan *et al.*, 2024).

Regulatory frameworks and policy enforcement are equally critical in managing the environmental challenges of the tannery industry (Khan and Akond, 2024). The promotion of eco-friendly tanning methods, such as vegetable tanning and waterless processing technologies, can further reduce the environmental burden (Alemu *et al.*, 2024). Educational programs aimed at building awareness among tannery workers and local communities about the dangers of improper waste disposal are essential in fostering sustainable practices within the industry (Khan and Akond, 2024).

Tannery Effluent Contaminated Soil

Tannery effluent contaminated soil is a significant environmental concern, particularly in regions where the leather tanning industry thrives (Alam *et al.*, 2024). This contamination arises from the discharge of untreated or inadequately treated tannery wastewater, which contains high levels of organic and inorganic pollutants (Ethiraj *et al.*, 2024). The effluent often includes heavy metals such as chromium, lead, and cadmium; high concentrations of salts; and other hazardous chemicals like sulfides, phenols, and dyes (Bharti, 2024). These substances alter the physical, chemical, and biological properties of soil, leading to its degradation and posing risks to ecosystems and human health (Selvam *et al.*, 2024).

One prominent feature of tannery effluent contaminated soil is its elevated heavy metal content, particularly chromium, which is widely used in tanning processes to stabilize collagen fibers (Gendaszewska *et al.*, 2024). The effluents of tannery are always associated with contaminants like chromium, sulphides, and persistent organic pollutants (POPs). Hexavalent chromium (Cr (VI)) and trivalent chromium (Cr (III)) are the most common forms, with Cr (VI) being highly toxic, carcinogenic, and mobile in soil (Xie, 2024). Over time, these metals accumulate and bind to soil particles, making them persistent contaminants (Paul *et al.*, 2024). The bioavailability of heavy metals depends on factors such as soil pH, organic matter content, and cation exchange capacity (Zheng *et al.*, 2024). In contaminated soils, heavy metals can disrupt microbial activity and plant growth, affecting the overall soil ecosystem (Rizwan *et al.*, 2024).

The chemical composition of tannery effluent contaminated soils often includes high concentrations of salts and organic matter, leading to salinity and sodicity issues (Narayanan and Chellappan, 2024). The high salinity is due to the presence of chloride, sulfate, and sodium ions from tanning processes (Sahu *et al.*, 2024). Saline and sodic conditions degrade soil structure, reduce permeability, The accumulation of salts can also affect the soil's ability to support microbial diversity and impair water retention capacity (Xu *et al.*, 2024). Tannery effluent do negatively affect soil fertility and makes it challenging for plants to thrive because of the chemicals within the effluents (Zhang *et al.*, 2024).

Another critical aspect of these soils is their altered pH levels. Tannery effluent can render soils highly alkaline or acidic, depending on the chemicals used during tanning and the neutralization process (Hassan *et al.*, 2023). Extreme pH levels influence the solubility of heavy metals and other toxic elements, altering their bioavailability (Adamo *et al.*, 2024). Furthermore, altered pH conditions can suppress beneficial soil microorganisms, limiting essential processes such as nitrogen fixation and organic matter decomposition (Zhan, 2024).

The biological characteristics of tannery effluent contaminated soil are severely impacted due to the toxicity of pollutants (Dey *et al.*, 2024). Microbial diversity and population densities are often significantly reduced (Mo *et al.*, 2024). Beneficial microbes such as nitrogen-fixing bacteria and mycorrhizal fungi may be inhibited by heavy metals, phenols, and other toxic substances (Hnini *et al.*, 2024). The disruption of microbial communities adversely affects soil health and its ability to support vegetation (Pedrinho *et al.*, 2024). Additionally, bioaccumulation of toxic elements in soil organisms poses a risk to higher trophic levels, including humans, through food chain contamination (Saidon *et al.*, 2024).

Physically, tannery effluent contaminated soils often exhibit poor structural integrity (Jaffari *et al.*, 2024). The accumulation of organic matter and salts can lead to the formation of crusts on the soil surface, reducing aeration and water infiltration (Delgado and Gómez, 2024). The presence of organic pollutants can increase soil stickiness and reduce its porosity (Tadayoni *et al.*, 2024). Such physical changes not only degrade the soil's agricultural potential but also make it prone to erosion and compaction (Hasan and Tarannum, 2024). These conditions amplify the challenges of land restoration and sustainable use (Devendrapandi *et al.*, 2024).

Mitigating the impact of tannery effluent contamination on soil requires an integrated approach involving advanced treatment technologies, phytoremediation, and soil amendments (Mohanty *et al.*, 2024). Advanced oxidation processes, constructed wetlands, and bioreactors can help treat tannery wastewater before discharge (Kumar *et al.*, 2023). For existing contamination, phytoremediation using plants capable of heavy metal accumulation and salt tolerance can help rehabilitate the soil (Liu *et al.*, 2024). Additionally, the application of organic amendments such as compost and biochar can improve soil structure and fertility (Singh *et al.*, 2024). Research into microbial consortia capable of degrading organic pollutants and immobilizing heavy metals also shows promise in restoring contaminated soils (Tang *et al.*, 2024).

Impact of Tannery Effluent on Soil Properties

Tanneries, a critical sector in leather production, generate substantial quantities of wastewater, commonly known as tannery effluent (Buljan and Rajamani, 2024). This effluent contains various pollutants, including heavy metals, sulfides, and organic matter, which significantly impact soil properties when improperly managed (Khatun *et al.*, 2024). Soil contamination by tannery effluent poses severe environmental and agricultural challenges, altering the soil's physical, chemical, and biological characteristics (Tadesse *et al.*, 2017).

Impact of Tannery Effluent on Soil Physical Properties

One of the most evident effects of tannery effluent on soil is the alteration of its physical properties, such as texture, structure, and porosity (Islam et al., 2024). Effluent discharged onto land can lead to soil compaction, reducing its aeration and water-holding capacity (Khokhar et al., 2024). This phenomenon occurs due to the deposition of suspended solids and organic matter present in the wastewater, which clog soil pores (Abdalrahman et al., 2021). Additionally, the effluent's high salt content often leads to soil crusting, making the surface impervious to water infiltration and increasing surface runoff (Hagage et al., 2024). These changes adversely affect the soil's ability to support plant growth and reduce agricultural productivity (Su et al., 2024).

Impact of Tannery Effluent on Soil Chemical Properties

The chemical composition of soil is profoundly affected by the heavy metals and salts present in tannery effluent (Sinduja et al., 2022). Metals such as chromium, a key ingredient in leather tanning, accumulate in the soil and can exceed permissible levels, leading to toxicity Moreover, the tannery effluent's high sodium levels result in soil sodicity, disrupting the cation exchange balance and causing soil alkalinity (Selvam et al., 2024). Over time, these chemical imbalances can render the soil unsuitable for agriculture.

Impact of Tannery Effluent on Soil Biological Properties

Tannery effluent also has a detrimental impact on the biological activity within the soil (Dey et al., 2024). The presence of toxic substances, such as heavy metals and sulfides, inhibits microbial activity, which is crucial for nutrient cycling and organic matter decomposition (Zhang et al., 2024). Beneficial microorganisms, including nitrogen-fixing bacteria and decomposers, are particularly sensitive to such pollutants (Innocent et al., 2024).

The decline in microbial diversity and activity reduces the soil's fertility and its ability to support plant life (Pedrinho et al., 2024). Furthermore, prolonged exposure to these pollutants can alter the composition of microbial communities, favoring the growth of metal-tolerant but less beneficial species. Tannery effluents have detrimental effects on the biodiversity of microbial population because of the heavy metal residues such as chromium that inhibit microbial growth within contaminated soil environments or water bodies (Fardami and Abdullahi, 2024: Gusau et al., 2024).

Accumulation of Persistent Organic Pollutants (POPs)

Another concern is the accumulation of persistent organic pollutants (POPs) and other organic compounds in the soil due to tannery effluent (Iyiola et al., 2024). These compounds, often slow to degrade, can interfere with soil enzymatic activities and plant root growth (Devendrapandi et al., 2024). Additionally, they form complexes with heavy metals, influencing their mobility and bioavailability in the soil (Zhu et al., 2023). Such interactions complicate the remediation of contaminated soils, as the pollutants can migrate to groundwater or become bioavailable to crops, entering the food chain and posing risks to human and animal health (Masinga et al., 2024).

The long-term impacts of tannery effluent on soil extend beyond contamination, affecting the soil's resilience and ecosystem services (Dotaniya et al., 2024). Contaminated soils often exhibit reduced buffering capacities, making them more susceptible to further pollution and degradation (Dehkordi et al., 2024). The loss of soil fertility and productivity can lead to desertification in extreme cases, particularly in regions where agricultural practices heavily rely on soil quality (Alzahrani et al., 2024). Additionally, the loss of soil biodiversity disrupts ecological balances, affecting other ecosystem components, including water and air quality (Ekka et al., 2023).

Efforts to mitigate the impact of tannery effluent on soil properties require a multidisciplinary approach, combining sustainable industrial practices, stringent regulations, and effective remediation techniques (Aparicio et al., 2022). Pre-treatment of effluent to remove heavy metals and salts, the use of environmentally friendly tanning methods, and the adoption of bioremediation strategies are essential steps (Pundir et al., 2024). Additionally, raising awareness among stakeholders about the ecological consequences of improper effluent disposal can foster more responsible waste management practices (Dada et al., 2024). By addressing these issues, it is possible to minimize the adverse effects of tannery effluent and promote sustainable soil and environmental health (Jaffari et al., 2024). As soils are fundamental to ecosystems and human well-being, safeguarding their quality against industrial pollutants like tannery effluent is imperative for sustainable development and environmental conservation (Adepoju et al., 2024).

Physical, Chemical, and Biological Technologies in Mitigating Tannery Effluent Contaminated Soil

Tannery effluent, a by-product of the leather tanning process, contains a complex mix of organic and inorganic pollutants, including heavy metals, salts, and various organic compounds (Kolopajlo, 2024). The improper disposal of this waste can result in severe soil contamination, leading to degraded land, reduced agricultural productivity, and risks to human health (Choudhary *et al.*, 2024). Mitigating this contamination necessitates the implementation of advanced remediation technologies (Pundir *et al.*, 2024). Tannery effluent typically contains high concentrations of chromium, a heavy metal used in the tanning process, along with other contaminants like sulfides, chlorides, and organic matter (Mohanty *et al.*, 2024).

Physical Technologies for Soil Remediation

Physical remediation technologies focus on the removal, isolation, or containment of contaminated soil as reported by Alsakit et al. (2024). Below are some physical technologies for soil remediation:

Soil Washing and Flushing

Soil washing involves the use of aqueous solutions to extract contaminants from soil (Trellu *et al.*, 2021). This technique is particularly effective for removing heavy metals like chromium (Nur-E-Alam *et al.*, 2020). The process involves separating fine-grained, contaminant-laden particles from coarse-grained particles (Genske, 2024). Soil flushing, on the other hand, involves the in-situ application of water or chemical agents to leach contaminants into a collection system (Alsakit *et al.*, 2024). Both methods require proper treatment and disposal of the resulting effluent.

Electrokinetic Remediation

Electrokinetic remediation employs an electric field to mobilize contaminants in the soil (Sun *et al.*, 2023). Ions and charged particles migrate towards electrodes, where they can be collected or neutralized (Gidudu and Chirwa, 2022). This technique is highly effective for soils with low permeability, such as clayey soils often associated with tannery effluent contamination (Nasiri *et al.*, 2020).

Thermal Desorption

Thermal desorption involves heating contaminated soil to volatilize organic pollutants (Wang *et al.*, 2024). While primarily used for organic contaminants, it can also facilitate the removal of some heavy metals by altering their chemical state, making them more amenable to removal (Saini *et al.*, 2024). However, this method is energy-intensive and may not be cost-effective for large-scale applications (Pandit *et al.*, 2024).

Chemical Technologies for Soil Remediation

Chemical methods focus on transforming or immobilizing contaminants to reduce their toxicity and mobility in the soil (Hu *et al.*, 2024). These technologies often involve reagents that react with contaminants to produce less harmful compounds (Zhou *et al.*, 2024).

Chemical Oxidation and Reduction

Chemical oxidation involves the application of oxidizing agents such as hydrogen peroxide, potassium permanganate, or ozone to convert toxic Cr(VI) into the less toxic Cr(III) (Farhan *et al.*, 2023). Conversely, chemical reduction employs reducing agents like ferrous sulfate or sodium bisulfite for the same purpose (Nas, and Medina 2024). These methods are fast and effective but require precise control to prevent secondary pollution (Cao *et al.*, 2024).

Stabilization and Solidification

Stabilization and solidification (S/S) techniques involve adding binding agents like lime, cement, or fly ash to immobilize contaminants in soil (Yadav *et al.*, 2024). The contaminants are encapsulated within a solid matrix, reducing their leachability (Yeo *et al.*, 2024). This method is particularly effective for chromium-laden soils but may lead to long-term stability concerns (Yadav *et al.*, 2024).

Soil Amendment with Chelating Agents

Chelating agents, such as ethylenediaminetetraacetic acid (EDTA) or citric acid, are used to enhance the bioavailability of heavy metals, facilitating their removal (Saleem *et al.*, 2020). However, the persistence of synthetic chelating agents in the environment poses ecological risks, prompting interest in biodegradable alternatives (Khare *et al.*, 2024).

Biological Technologies for Soil Remediation (bioremediation)

Biological remediation, or bioremediation, leverages the metabolic capabilities of microorganisms, plants, or their enzymes to detoxify or remove contaminants from soil (Dervash *et al.*, 2024). These methods are often sustainable and cost-effective.

Microbial Bioremediation

Microorganisms, such as bacteria and fungi, play a pivotal role in degrading organic contaminants and transforming heavy metals (Zhang *et al.*, 2024). For example, certain bacteria can reduce Cr (VI) to Cr (III) under aerobic or anaerobic conditions (Chen *et al.*, 2024). Fungi like

Aspergillus and *Penicillium* can bioaccumulate heavy metals, reducing their mobility in soil (Dwivedi, 2023). Bioremediation by microbes can be carried out by either by indigenous or exogenous microbes or the use of both through careful monitoring by experts as well as through bioaugmentation and biostimulation. Microbes producing biosurfactants or a biomolecule of biosurfactant can be used to enhance the bioremediation process (Banat *et al.,* 2020; Bukar *et al*., 2025a). Biosurfactants, as microbially produced surface-active agents, have features that make them extremely effective at decreasing chromium contamination. Their biodegradability, low toxicity, and renewable production provide a low environmental impact. Furthermore, their amphiphilic character increases chromium bioavailability by enabling microbial uptake and reduction. Some biosurfactants chelate metal ions, which prevents chromium migration and secondary contamination (Bukar *et al.,* 2025a). Prospecting for microorganisms and substrates for the synthesis of considerable volumes of biosurfactants is becoming increasingly important due to the increased demand for these chemicals for usage in environmental and industrial applications (Bukar *et al*., 2025b). A better understanding of the environmental factor to achieve a successful bioremediation can also help as presented in Figure 1.

Figure 1: Understanding soil condition and application of exogenous oil degrading microbes in aiding better bioremediation process
Source: (Liu *et al.,* 2020).

Phytoremediation
Phytoremediation uses plants to extract, stabilize, or degrade contaminants in soil (Sharma *et al.*, 2023). Hyperaccumulator plants, such as *Brassica juncea* and *Helianthus annuus*, can absorb high concentrations of heavy metals (Pasricha *et al.*, 2023). Phytoremediation is eco-friendly but slow and limited by the bioavailability of contaminants (Lavanya *et al.*, 2024). Phytoremediation is one of the biological technologies for soil remediation within a capable plant through phytodegradation, phytovolatilization and phytoextraction that in most cases happen within the upper part of the plant. Phytofitlration, phytostabilization and phytostimulation are also mechanisms of phytoremediation that happen within plants roots as illustrated in Figure 2.

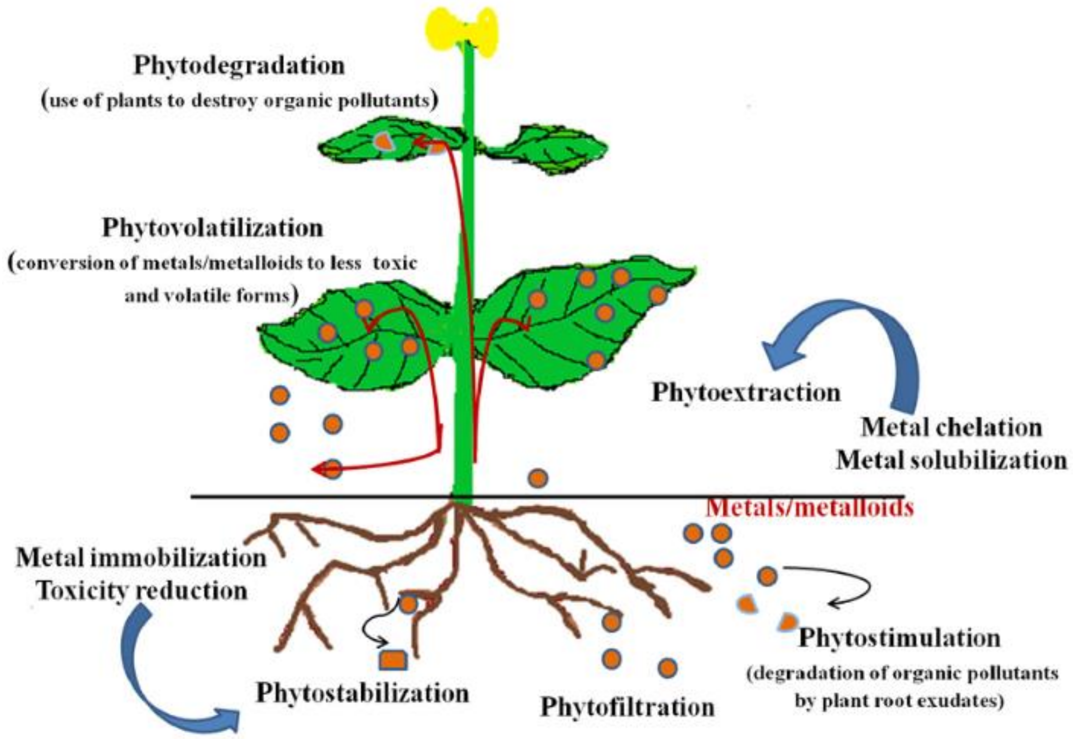

Figure 2: Mechanisms of phytoremediation of an effluent contaminated soil within upper and root parts of a plant
Source: (Ojuederie & Babalola, 2017).

These processes with regards to heavy metal contaminations are usually achieved through metal chelation, metal solubilisation and metal immobilization as reported by Fardami *et al.* (2023).The use of ocimum plant can also aid the phytoremediation of heavy metal within the heavy metal contaminated soil as presented in Figure 3 using chromium as example.

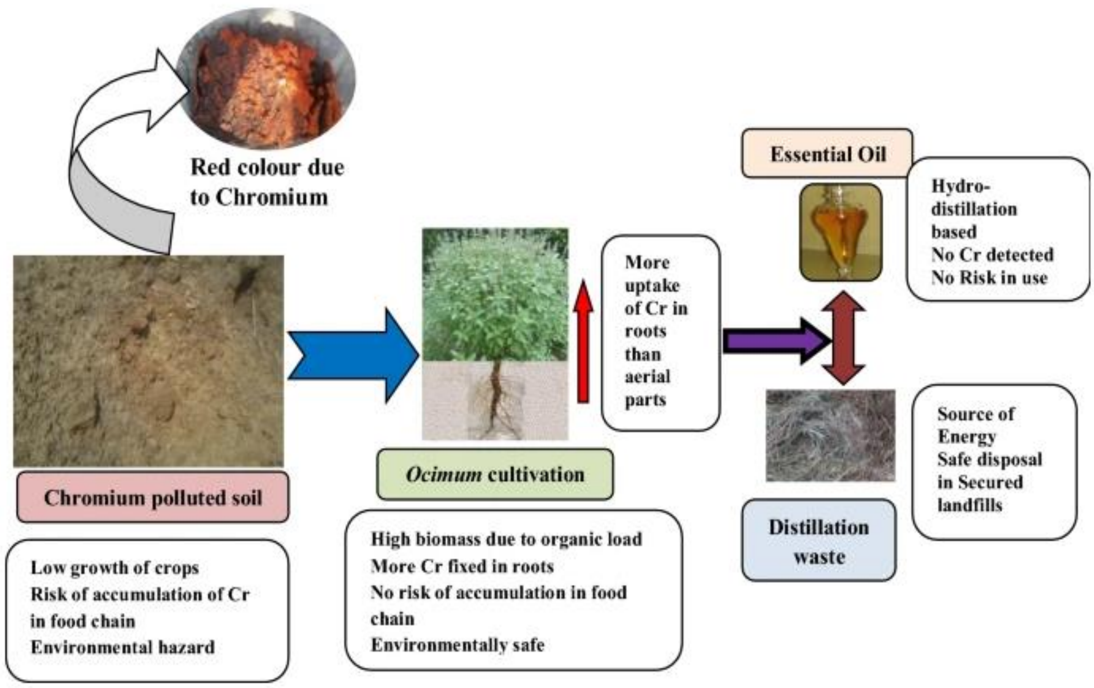

Figure 3: Phytoremediation of chromium heavy metal using ocimum plant cultivation
Source: (Gupta and Verma, 2022).

Enzymatic Remediation
Enzymatic approaches involve the use of microbial or plant-derived enzymes to degrade organic pollutants (Seth and Meena, 2024). Enzymes such as laccase and peroxidase have shown promise in breaking down tannery-derived organic contaminants (Thulasisingh *et al.*, 2024). However, their

application is limited by enzyme stability and cost. Enzymes such as chromate reductase and laccase, produced by bacteria and fungi, play a pivotal role in breaking down complex tannery pollutants (Shinde *et al.*, 2024). These enzymes can be isolated and applied directly to contaminated sites or used to enhance the activity of indigenous microbial populations (Ehis-Eriakha *et al.*, 2024). Enzymatic bioremediation has shown promise in accelerating the detoxification process, particularly in soils with high pollutant loads (Singh *et al.*, 2021). The use of enzymatic augmentation in the presence of a microbe can aid bioremediation as microbial or plant-derived enzymes are added in the site where tannery effluents, xenobiotics or hydrocarbon contaminants are needed to be removed as illustrated in Figure 4.

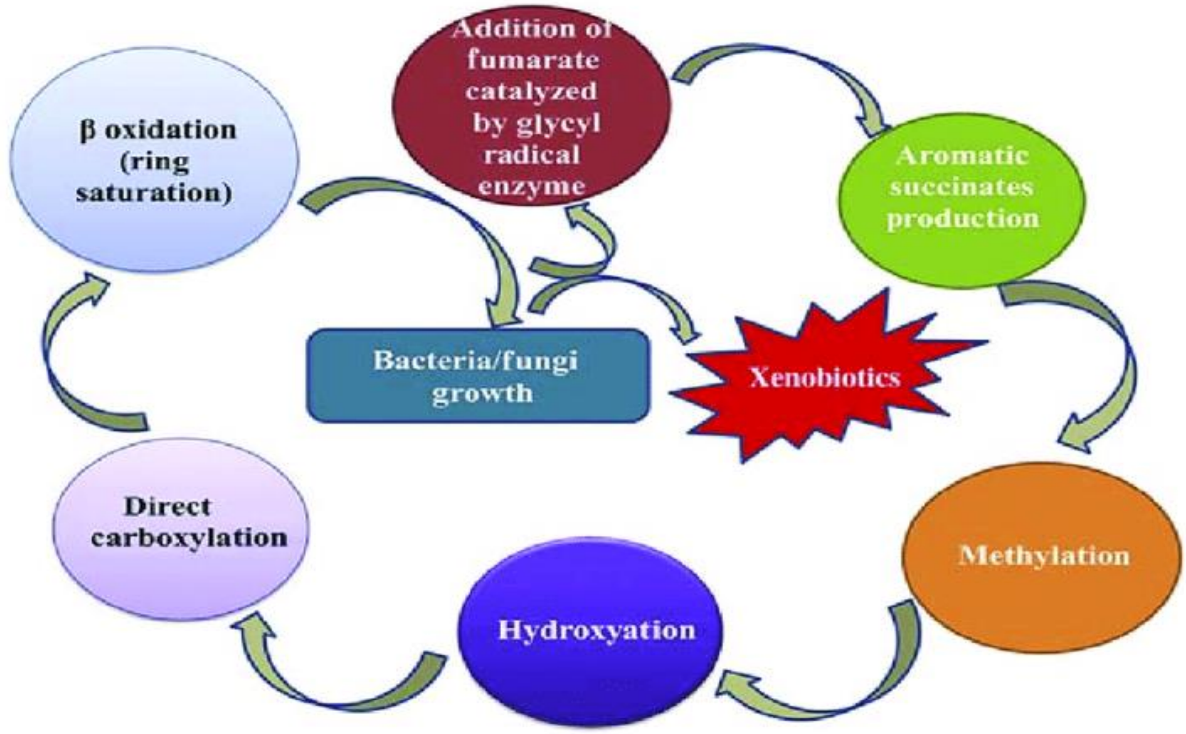

Figure 4: The use of enzymatic augmentation in the presence of a microbe to aid bioremediation
Source: (Gangola *et al.*, 2019)

Bioremediation: a Superior Alternative for Remediating Tannery Effluent-Contaminated Soil

Bioremediation is an environmentally friendly approach that leverages biological processes to remove or neutralize pollutants from contaminated environments, such as soil, water, and air (Kuppan *et al.*, 2024). This technology primarily employs microorganisms (bacteria, fungi,) or plants to metabolize and break down harmful substances into less toxic or non-toxic forms (Yaashikaa *et al.*, 2022). The benefits of bioremediation are vast and multidimensional, ranging from environmental restoration to economic savings (Kumar *et al.*, 2025). Its significance has grown as industries, governments, and environmentalists seek sustainable methods to mitigate pollution and rehabilitate ecosystems affected by human activities (Gelaye, 2024). One of the most notable benefits of bioremediation is its ability to restore ecosystems in a natural and sustainable manner (Sinam *et al.*, 2024). This is possible because a microbial cell do exhibit differents mechanisms to achieve a successful bioremediation such as biosorption, bioaccumulation, biotransformation, bioleaching, bio-precipitation bioprecipitation. Unlike traditional remediation techniques, which often involve physical excavation or chemical treatments that can further disrupt ecosystems, bioremediation works harmoniously with nature (Yang *et al.*, 2024).

Microorganisms naturally present in the environment or introduced in controlled amounts target pollutants while leaving native flora and fauna largely unaffected (Pathak *et al.*, 2022). This process not only addresses contamination but also helps maintain biodiversity and ecological balance, which are crucial for the health and resilience of ecosystems (Farias *et al.*, 2024). Bacterial cell can employ different mechanisms within and outside of the cell to achieve the concept of bioremediation as presented in Figure 5.

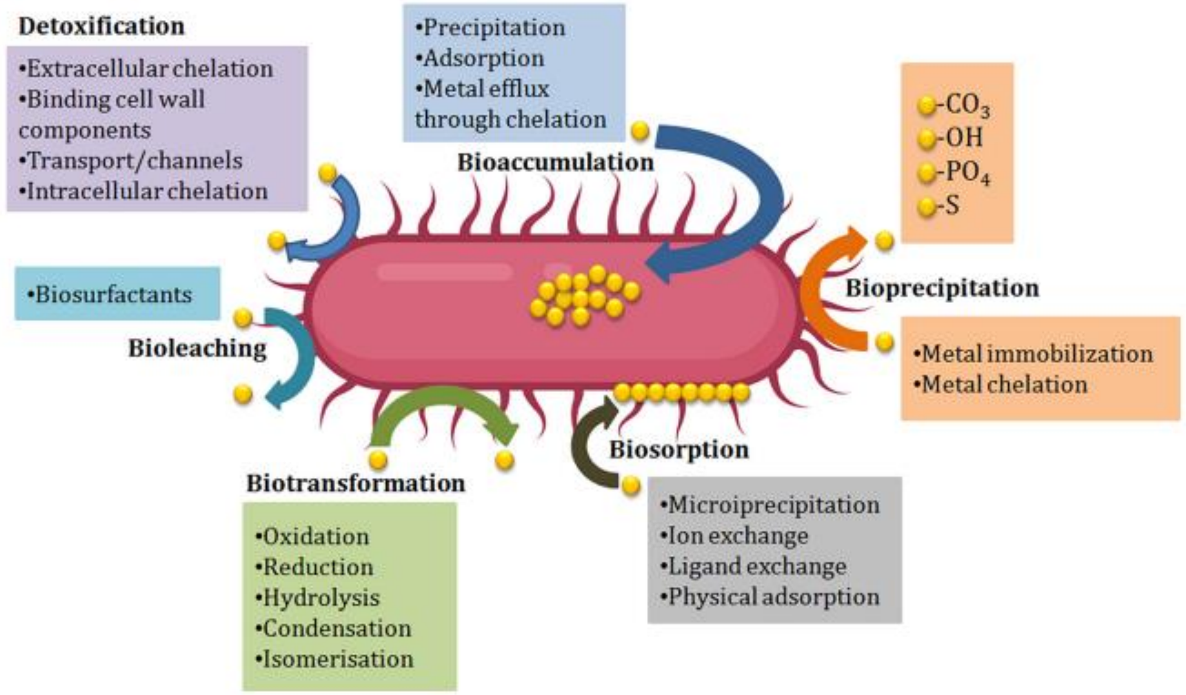

Figure 5: Different mechanisms that bacterial cell can employ within and outside of the cell to achieved bioremediation of a contaminant
Source: (Pande *et al.*, 2022)

Bioremediation is also highly versatile, capable of addressing a wide array of pollutants (Kour *et al.*, 2021). These include petroleum hydrocarbons, heavy metals, pesticides, and organic waste, among others (Tufail *et al.*, 2022). Technologies such as phytoremediation, mycoremediation, and bioaugmentation provide tailored solutions for different contamination scenarios (Thakur and Kumar, 2024). Another critical advantage of bioremediation is its cost- effectiveness compared to traditional methods (Kuppan *et al.*, 2024).
Chemical and physical remediation approaches often require significant financial investment due to the need for specialized equipment, labor-intensive processes, and waste disposal (Wong *et al.*, 2024). In contrast, bioremediation typically relies on naturally occurring organisms, minimizing costs associated with materials and waste management (Patel *et al.*, 2022). Moreover, it often requires less energy input, which further reduces operational expenses and aligns with global efforts to lower carbon footprints and adopt sustainable practices (Kumar *et al.*, 2025).
Bioremediation is inherently safer and less invasive than many conventional remediation methods (Bala *et al.*, 2022). Techniques such as excavation and incineration can release secondary pollutants into the air or disrupt surrounding areas (Siddiqua *et al.*, 2022). Chemical treatments might leave behind residues that could pose long-term environmental or health risks (Helwig *et al.*, 2024). In contrast, bioremediation reduces the likelihood of such adverse effects, as it often relies on in situ processes that treat contaminants directly in their natural locations (Nag *et al.*, 2024). This minimizes the risk of secondary pollution and ensures a more seamless integration of the cleanup process with the existing environment (Thakur and Kumar, 2024).
The long-term benefits of bioremediation extend beyond environmental restoration to encompass social and economic dimensions (Srivastava *et al.*, 2025). Clean, rehabilitated land can be repurposed for agriculture, urban development, or recreation, contributing to economic growth and improved quality of life for local communities (Fazia *et al.*, 2024).
Tannery effluents pose a significant environmental hazard due to their complex composition, including heavy metals such as chromium, high organic loads, and toxic substances (Buljan and Rajamani, 2024). Contaminated soils near tannery sites suffer from degradation in physical and chemical properties, including altered pH, reduced fertility, and loss of microbial diversity (Samanth, 2024).

Conversion of Cr VI into the Less Toxic Cr III by Microbial Cell
Microbial remediation is one of the most widely researched approaches in addressing tannery effluent contamination (Jaffari *et al.*, 2024). Microorganisms such as *Pseudomonas*, *Bacillus*, and *Aspergillus* species exhibit remarkable capabilities to degrade tannery pollutants, particularly chromium (Cr VI), a highly toxic and carcinogenic form of chromium (Kalsoom and Batool, 2020). These microbes employ enzymatic reduction processes to convert Cr VI into the less toxic Cr III, which is less soluble and easier to immobilize (Ma *et al.*, 2024). Figure 6 outlined an illustrated conversion of Cr VI into the less toxic Cr III by a bacterial cell.

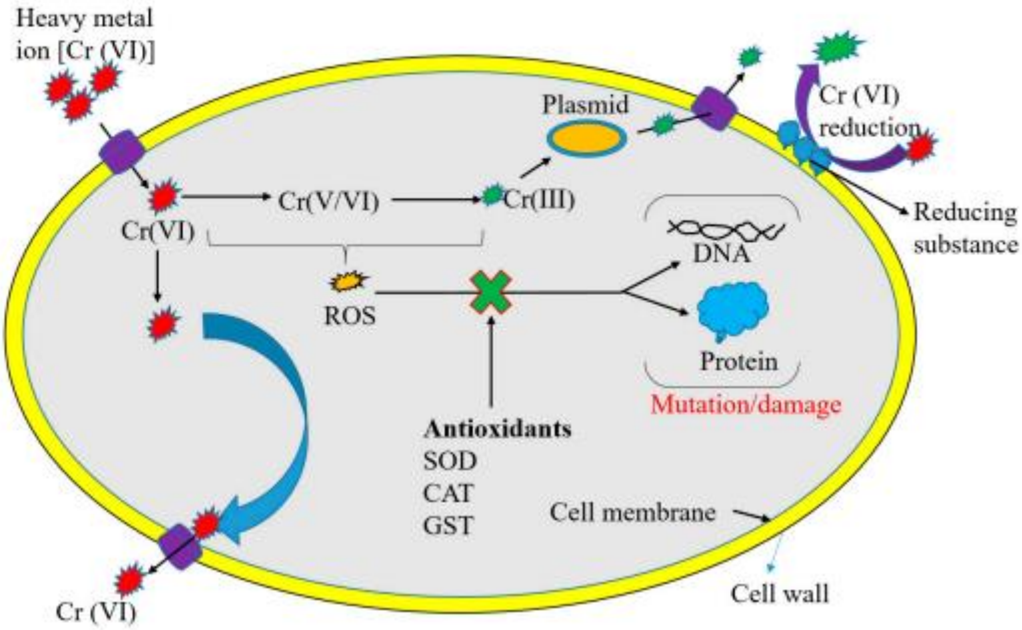

Figure 6: Conversion of Cr VI into the Less Toxic Cr III by Bacterial Cell
Source: (Zhou *et al.*, 2023).

Research has shown that microbial consortia, where multiple species work synergistically, can enhance degradation efficiencies as reported by Lü *et al.* (2024). Additionally, microbial biofilms, which provide protective environments for the microorganisms, further increase tolerance to high contaminant concentrations, making microbial remediation an effective tool for managing tannery effluent-laden soils (Upadhyay *et al.*, 2024).

CONCLUSION

Bioremediation offers an effective, adaptable, and sustainable solution to the challenges posed by environmental contamination. Its ability to restore ecosystems, reduce costs, ensure safety, and contribute to broader societal goals underscores its immense potential made it the better. As research continues to refine bioremediation technologies and expand their applications, this approach is likely to remain a cornerstone of global efforts to combat pollution and foster environmental sustainability. Bioremediation offers a viable and eco-friendly solution for treating tannery effluent-contaminated soils. While challenges persist, ongoing research and innovation are paving the way for more efficient and scalable applications. By embracing bioremediation, industries and policymakers can address environmental contamination while fostering sustainable development and restoring degraded ecosystems.

RECOMMENDATIONS

It can be recommended that:

Soils with extremely high levels of toxic pollutants may require pretreatment before bioremediation can be effectively implemented.

Continued research into optimizing conditions and developing robust microbial strains is essential in scaling up laboratory results and field applications should be properly understood because it remains a challenge due to the complexity of environmental systems.

Long-term evaluation and monitoring of bioremediated sites should be adhered because it is critical to ensure the stability of restored ecosystems and evaluation can be a better solution in addressing environmental pollution.

Integrating physical, chemical, and biological technologies should be enhanced so that the overall efficiency of remediation efforts such as electrokinetic remediation coupled with microbial bioremediation and soil washing can be combined with phytoremediation in order to treat the residual contamination.

Advancements in genetic engineering and nanotechnology should be ensured because it is now an essential tool in bioremediation as engineered microbes with enhanced degradation capabilities and stress tolerance are being developed day by day to tackle even the most recalcitrant pollutants.

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