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*Review article*

# Synergistic Methods for Chromium Cleanup Using Plant-Growth-Promoting Bacteria

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**ABSTRACT**
Chromium (Cr) pollution contributes a significant threat to environmental and human health due to its widespread industrial use and toxic effects. Among the various remediation strategies, the application of plant-growth-promoting bacteria (PGPB) has emerged as a promising approach. The article explores the synergistic potential of PGPB in enhancing plant-based remediation techniques for chromium cleanup. PGPBs enhance plant growth and stress tolerance through mechanisms such as hormone production, nitrogen fixation, and pathogen inhibition. Key strategies discussed include bioaugmentation, biostimulation, phytoextraction, and phytostabilization. These methods leverage the abilities of PGPB to promote plant growth, enhance chromium uptake, and immobilize chromium in the soil, thereby reducing its bioavailability and mobility. Case studies and experimental evidence highlight the effectiveness of PGPB in chromium-contaminated environments, demonstrating improved plant growth and metal accumulation. This review underscores the need for interdisciplinary collaboration, field-scale implementation, and ongoing research to harness the full potential of PGPB-mediated phytoremediation for sustainable chromium cleanup.

**Key words**: Chromium remediation, Plant-Growth-Promoting Bacteria (PGPB), phytoremediation, bioaugmentation, biostimulation, environmental pollution cleanup

## INTRODUCTION

The environment, comprising the biosphere, atmosphere, lithosphere, and hydrosphere layers sustains life in a delicate balance (Martin and Johnson 2012). The rapid industrialization over the last century has led to augmented exploitation of resources, triggering an increase in soil, water, air contamination, and subsequent environmental pollution. This phenomenon, largely driven by anthropogenic activities such as mining, smelting, metal-based industries, and foundries has resulted in widespread heavy metal pollution (Gautam et al. 2016). Additionally, leach from sources such as landfills, waste dumps, and agricultural applications including pesticides, insecticides, and fertilizers contribute to secondary sources of heavy metal contamination (Ahmed et al. 2021). Natural occurrences like volcanic activity, soil erosion, and metal corrosion, further exacerbate heavy metal pollution. Re-suspension of sediments, weathering of the earth's crust, and metal evaporation from soil and water also play significant roles in increasing heavy metal concentrations in the environment. Among the array of pollutants, heavy metals stand out as major contributors to environmental degradation (Briffa et al. 2020).

Chromium (Cr) is the prominent toxic heavy metal found naturally that has been extensively employed in industrial processes and gained significant attention in discussions regarding environmental pollution, owing to its distribution and detrimental impacts on both ecosystems and human health (Coetzee et al. 2020, Mitra et al. 2022, Sharma et al. 2022). Cr is a versatile element that can manifest in various oxidation states, including Cr (0), Cr(III), and Cr(VI). Among these, trivalent chromium [Cr(III)] is a significant element for living organisms, including humans. Its presence in adequate amounts is crucial for metabolic functions. Conversely, an imbalance, either deficiency or excess, can profoundly influence biological processes. In contrast, hexavalent chromium [Cr(VI)] presents a more concerning scenario (Coetzee et al. 2020). This highly soluble and mobile form of chromium is notorious for its toxicity, posing significant risks to both animals and humans. The Cr(VI) form exhibits detrimental effects on soil, plants, and microorganisms, disrupting ecosystem dynamics. In plants, this form disrupts essential metabolic functions, induces oxidative stress, and inhibits photosynthesis, leading to reduced yields and even plant death. Various crops, including cotton, peas, and maize, suffer from stunted growth, disrupted photosynthesis, and oxidative stress due to Cr(VI) contamination (Hasanuzzaman et al. 2020). Also, a high amount of Cr(VI) can harm soil microorganisms, disrupting ecosystem stability and function. Both Cr(III) and Cr(VI) present health risks to humans and animals, with chronic exposure leading to various complications. Cr induces endoplasmic reticulum (ER) stress, activating cell survival and apoptosis pathways. ER stress, autophagy, and apoptosis are interconnected processes implicated in Cr toxicity. Autophagy, triggered by Cr exposure, is a cellular mechanism to degrade damaged organelles, influencing cell survival under stress conditions. Long-term exposure to Cr(VI) elevates the risk of cancer in humans and animals, affecting organs such as the stomach, lungs, bladder, and pancreas. Furthermore, Cr compounds induce DNA damage, chromosomal aberrations, and mutagenesis, highlighting their genotoxic potential and long-term risks to exposed populations (Liu et al. 2020, Liu et al. 2022). Compared to Cr(III), Cr(VI) exerts more damaging and devastating effects on biological systems. The longevity of chromium in the environment, coupled with its capacity to bio-accumulate in the food chain, exacerbates its impact on public health and ecosystem integrity (DesMarias and Costa 2019).

The widespread pollution of chromium underscores the surging need for comprehensive regulatory measures and sustainable practices to safeguard environmental and human well-being. A range of remediation strategies are employed to address chromium pollution encompassing chemical, physical, and biological approaches (Oliveira 2012). Chemical techniques such as precipitation, electro-coagulation, and membrane filtration are utilized for Cr removal from contaminated sites. Physical barriers and nanotechnology-based adsorption (reverse osmosis, nanofiltration, ion exchange, biosorption, adsorption, and membrane filtration) processes offer additional means of remediation (Kumar et al. 2021). Biological remediation methods, including bioremediation and phytoremediation, leverage the capabilities of Cr-tolerant microorganisms and plants to convert toxic Cr(VI) into less harmful forms. Biosorption treatments, utilizing materials like acid-treated palm shell charcoal coated with chitosan, emerge as cost-effective and efficient options for Cr removal from sludge and effluents (Akunwa et al. 2014). Various factors such as temperature, pH, agitation, adsorbent dosage, effluent quantity, and contact time must be considered to ensure effectiveness during the remediation process (Yan et al. 2023). Among the currently known strategies, the application of Plant-growth-promoting bacteria (PGPB) is an effective approach for Cr cleanup.

## Chromium contamination

### *Sources*

Urbanization and industrialization have intensified human-induced heavy metal pollution, which significantly contributes to environmental degradation (Fig. 1). Chromium enters the environment specifically into the water bodies and soil sediment through multiple avenues such as agricultural runoff, industrial waste, solid waste dumps, acid mine drainage, acid rain, weathering, leaching, and more (Shimod et al. 2022).

Cr in the environment is mainly sourced by reducing chromium oxide, with major production countries like South Africa, Turkey, Kazakhstan, and India (Tumolo et al. 2020). The activities including mining, electroplating, leather-tanning, printing, and dyeing are significant contributors to chromium-releasing effluents and solid wastes with high Cr concentrations (Tang et al. 2021, Bandara et al. 2022). The releasing effluents and solid wastes containing Cr can undergo treatment using conventional methods like chemical reduction, ferrous sulfate treatment, alkaline precipitation, and removal of ion exchange, leading to the conversion of hexavalent to trivalent Cr and production of various toxic byproducts. These human-made sources add up to roughly 75,000 tons of chromium,

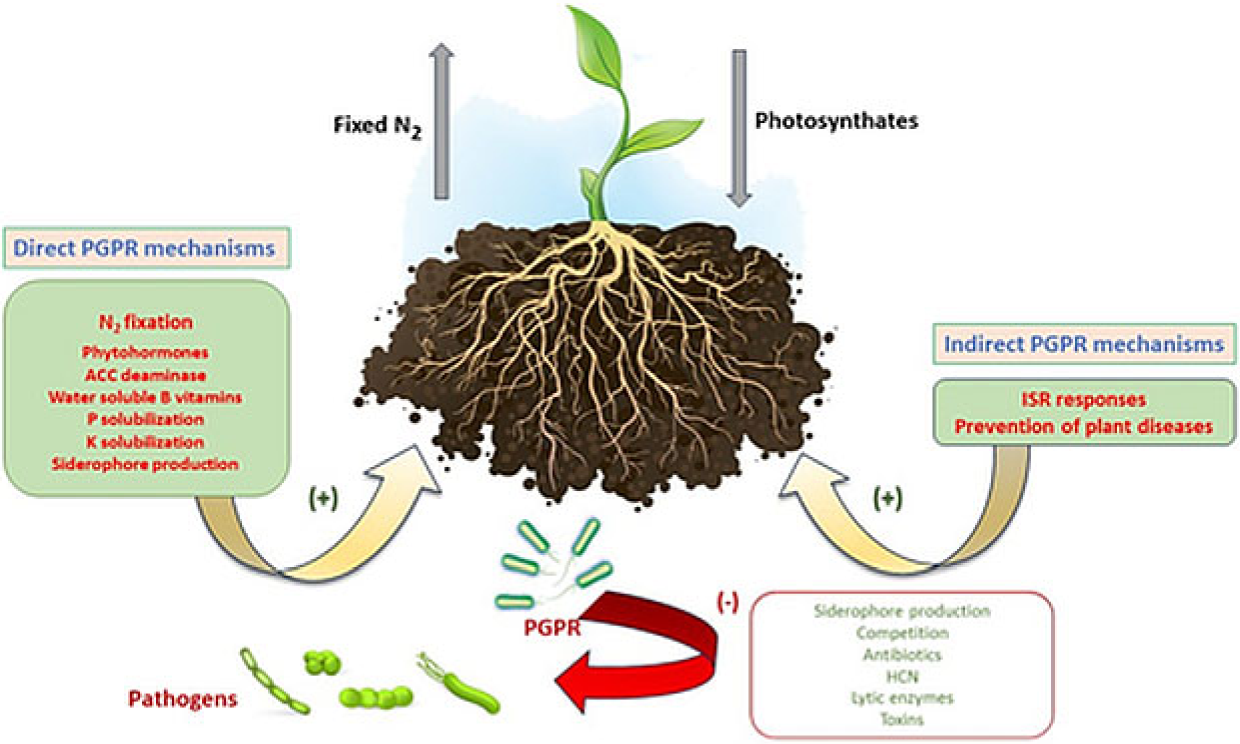


Figure 1. Mechanisms of action in plant growth promotion

with around 33% being in the form of toxic Cr(VI) (Coetzee et al. 2020). Landfilling of industrial waste exacerbates the issue, causing chromium to leach from soil into water bodies. The ferrochrome industry, particularly in South Africa, generates substantial waste materials with high chromium concentrations, further polluting the environment (Barnhart 1997). Tannery industries, in particular, contribute significantly to chromium inflow into the environment, with 40% of industrial usage accounting for chromium discharge. Effluents from tanneries, often untreated, elevate heavy metal concentrations in water bodies, posing health risks to aquatic life and surrounding flora and fauna (Nur-E-Alam et al. 2020). The eco-toxicity of chromium, especially in its hexavalent form, exacerbates environmental pollution and health concerns (Sharma et al. 2021).

*Environmental impact*

The uncontrolled release of toxic Cr(VI) poses a severe threat to the environment, with recent studies indicating a notable increase in its concentration in soil and ground waters, exceeding regulatory thresholds for freshwater, polluted water effluents, and soil quality standards. Chromium contamination adversely affects terrestrial vegetation, phytoplankton, and various organisms, with its environmental impact depending on atmospheric conditions and speciation (Sharma et al. 2022).

Chronic exposure to Cr(VI) has been discovered to possess sub-lethal effects on invertebrates, while fish exposed to chromium exhibit altered hatching times, DNA damage, and reduced survival rates (Bakshi and Panigrahi 2018). Cr(III) is considered more hazardous to fish than Cr(VI), with both forms posing risks to aquatic ecosystems. In soils, chromium accumulation reduces crop yields and grain quality, with significant buildup observed in industrial and cultivated soils (Singh et al. 2013). Chromium-induced toxicity in plants disrupts cellular function, seed germination, and overall productivity. Mining activities contribute to the contamination of nearby water bodies, endangering human health as local populations rely on contaminated water sources for daily activities. The presence of hexavalent chromium in rice plants indicates its potential to enter the food chain, posing further health risks to consumers. Environmental transformations such as oxidation, reduction, and sorption influence the fate of chromium in water and soil. While Cr(III) solubility depends on pH, Cr(VI) remains highly soluble across all pH levels. Despite being nonessential for plants, chromium uptake occurs passively for Cr(III) and through carriers of essential elements for Cr(VI) (Ali et al. 2023).

Phytoremediation strategies utilizing plants that hyperaccumulate chromium show promise for removing this metal from soil and water. However, adverse effects of Cr on plant physiology, including seed germination, photosynthesis, nutrient uptake, and enzymatic activities underscore the complexity of addressing chromium contamination in the environment (Oliveira 2012).

## CURRENT REMEDIATION METHODS AND THEIR LIMITATIONS

Chromium pollution poses significant environmental challenges due to its toxic nature and widespread occurrence. A range of remediation methods exist for addressing Cr pollution, but no single strategy offers a universal solution. Current remediation strategies employ a combination of biological and physico-chemical methods to mitigate Cr contamination in soil, water, and air. Chemical reduction methods, such as using Fe(0) and Fe(II) as reducing agents, have been extensively utilized to convert toxic Cr(VI) to less hazardous Cr(III). Nevertheless, a limitation of this approach is the possible assembling of nanoscale zerovalent iron (nZVI) particles, which reduces its efficacy. To address this issue, recent advancements involve incorporating nZVI into porous media like bentonite and sepiolite to enhance its remediation efficiency. Adsorption and ion exchange techniques offer promising avenues for Cr pollution remediation. Natural and manmade sorbents such as carbon nanotubes, activated carbon, modified clay, and sand, have been investigated for their ability to adsorb chromium from contaminated environments. Layered double hydroxides (LDHs) represent a category of anionic clay minerals with a high potential for chromium sorption. However, challenges remain in terms of efficient resin regeneration and waste minimization to enhance the overall performance and sustainability of ion exchange processes (Prasad et al. 2021).

Bacterial resistance, phytoremediation, electrocoagulation, biosorption, and bioaccumulation, are among the other remediation methods explored for Cr pollution mitigation. Each approach has its advantages and limitations, highlighting the importance of selecting optimal strategies based on site-specific conditions and cost-effectiveness. Physico-chemical methods exhibit high efficacy in removing Cr pollutants but often come with high implementation costs. In contrast, bioremediation approaches offer a more sustainable and environmentally friendly solution, albeit with limitations such as susceptibility to higher pollutant concentrations. Plant-growth-promoting bacteria (PGPB) have a key role in mitigating Cr contamination in soil and water environments.

Phytoremediation has gained attention as a nature-friendly approach for cleaning up contaminated sites using terrestrial and aquatic plant species. Despite the known toxicity of Cr to plants, several species have demonstrated the ability to remove chromium from the environment effectively. Moreover, Plant-based Microbial Fuel Cells (PMFCs) present a novel method for Cr removal from wastewater or soil, leveraging biological processes for electrochemical reduction. The effect of bioremediation methods relies on various criteria including the rate of plant growth, soil characteristics, and the concentration of pollutants.

### Plant-growth-promoting bacteria (PGPB)

Soil comprises of a diverse variety of microorganisms, with bacteria being the most prevalent, constituting approximately 95% of the total microbial population. The abundance and composition of these bacteria are influenced by various soil factors such as moisture level, temperature, salinity, and the existence of different plant species. Notably, bacteria are found in higher concentrations around plant roots, known as the rhizosphere, owing to the release of nutrients like amino acids, sugars, and organic acids secreted by plant roots. These bacteria interacted with plants in different mediums, either beneficially, harmfully, or neutrally, depending on environmental conditions and the specific bacterial species involved. Bacteria that promote plant growth, known as plant-growth-promoting bacteria (PGPB) are abundant in the rhizosphere and can enhance plant growth while mitigating stress caused by heavy metals like chromium. These bacteria stimulate plant growth through different processes, incorporating the secretion of growth-promoting substances like siderophores and indole-3-acetic acid, as well as phosphate solubilization and nitrogen fixation. The class encompasses various types, including symbiotic bacteria like *Frankia* spp. and *Rhizobia* spp., cyanobacteria, bacterial endophytes, and free-living bacteria. These PGPBs employ mechanisms to enhance plant growth by aiding in resource acquisition or modulating the amount of plant hormone. Also, they can indirectly benefit plants by mitigating the inhibitory effects of pathogens through biocontrol activities. Although extensively studied in the context of *Rhizobia* spp., PGPBs exhibit a wide range of mechanisms beyond nitrogen fixation, contributing to plant stress tolerance and overall health. In natural environments, plants and microorganisms coexist symbiotically, with PGPBs playing a crucial role in enhancing plant resilience to stressors by providing beneficial compounds and defending against diseases (Table 1). The application of PGPB formulations holds promise for promoting plant development and revitalizing degraded soils, offering a sustainable approach to land restoration and cultivation.

*Mechanisms of action in plant growth promotion*

The plant growth-promoting bacteria employ a range of mechanisms, both directly and indirectly to enhance plant growth (Boulé et al. 2011). Direct mechanisms involve bacterial traits that directly facilitate plant growth, such as the production of hormones like auxin, gibberellin, cytokinin, and ACC deaminase (Olanrewaju et al. 2017). Also, PGPB contributes to plant growth by fixing nitrogen, solubilizing phosphorus, and sequestering iron through bacterial siderophores. Indirect mechanisms entail bacterial traits that inhibit the growth of plant pathogens, including bacteria and fungi. These mechanisms include the production of antibiotics, hydrogen cyanide, induced systemic resistance, cell wall-degrading enzymes, siderophores and quorum quenching (Fig. 1). In addition to controlling phytopathogens, biocontrol of bacterial phytopathogens can be achieved through the selective use of bacteriophages. Various PGPBs possess one or more of these traits, and their effectiveness can vary depending on environmental and soil conditions. However, no single organism utilizes all available mechanisms for promoting plant growth (Olanrewaju et al. 2017).

One well-studied direct mechanism involves aiding resource acquisition by providing plants with essential nutrients such as iron, fixed nitrogen, and more. Many agricultural soils lack these nutrients, leading to suboptimal plant growth and increased reliance on chemical fertilizers. PGPBs, such as *Rhizobia* spp. and *Azospirillum* spp., can fix nitrogen and make it available to plants. Scientists have explored genetic approaches to increase nitrogen fixation, such as directing carbon resource bacteria towards oxidative phosphorylation rather than glycogen synthesis. Additionally, introducing bacterial hemoglobin genes can enhance respiratory rates in rhizobial cells, leading to increased nitrogenase activity and improved plant nitrogen content (Olanrewaju et al. 2017a).

PGPB can also influence plant ethylene levels, which possess a significant role in nodulation efficiency. Some rhizobial strains produce ACC deaminase, an enzyme that removes ACC, the immediate precursor to ethylene, thus increasing nodulation efficiency and plant biomass. While genetically engineered strains of Rhizobia hold promise for enhancing plant growth, regulatory constraints limit their field use in many jurisdictions. Despite these challenges, commercial inoculant producers continue to screen and test *Rhizobia* strains for active ACC deaminase, highlighting the ongoing efforts to leverage PGPB mechanisms for sustainable agriculture (Glick 2012).

*Role of PGPB in environmental remediation*

Plant-growth-promoting bacteria possess a significant role in environmental remediation, particularly by mitigating abiotic stresses that negatively affect agricultural productivity. Abiotic stresses such as heavy metal (HM) contamination, drought, salinity, extreme temperatures, and pH imbalances contribute to a substantial reduction in crop yields. PGPB, found abundantly in the rhizosphere, helps plants manage these stresses through various mechanisms, making them invaluable in transforming damaged and uncultivable land into fertile soil. One of the prominent functions of PGPB is in salinity tolerance. Up to 33% of agricultural land globally is affected by salinity, which disrupts plant growth by accumulating sodium in plant cells. PGPB enhances salinity tolerance by promoting the expression of genes associated with

Table 1. PGPB-assisted plant growth mechanisms for the phytoremediation of Chromium

| **Plant** | **Bacteria** | **Effect on plant** | **Reference** |
|---|---|---|---|
| *Lolium perenne* | *Bacillus proteolyticus* SES | Enhanced ryegrass growth and increases the . phytoextraction of Cr | Montreemuk et al. (2024) |
| *Pisum sativum* | *Microbacterium* sp. SUCR140 | Enhanced overall plant growth and reduced Cr(VI) toxicity to plants by lowering its soil bioavailability and uptake in SUCR140-inoculated plants. | Montreemuk et al. (2024) |
| Zea mays | Microbacterium sp. SUCR140 | Enhanced plant growth and decreased Cr(VI) toxicity by lowering its bioavailability in soil and plant uptake through the formation of a large number of mycorrhizal colonies. | Montreemuk et al. (2024) |
| *Zea mays* | *Providencia* sp. TCR05, *Proteus mirabilis* TCR20 | It increases the immobilization of Cr, boosts photosynthetic efficiency, and enhances plant growth. | Vishnupradeep et al. (2022) |
| *Cannabis sativa* | *Achromobacter denitrificans* MW886333, *Bacillus cereus* MW887524, *Bacillus subtilis* MW886231, *Bacillus thuringiensis* MW887525. | Increased metal accumulation in leaves, shoots, and roots, and enhanced phytoextraction efficacy. | Razzak et al. (2022) |
| *Medicago sativa* | *Pseudomonas* sp. | Increased biomass, promoted shoot and root growth, and chlorophyll levels, followed by a decrease in oxidative stress and an increase in Cr concentrations in roots. | Alves et al. (2022) |
| *Eruca sativa* | *Pseudomonas putida* (ATCC 39213) | There is an increase in Cr uptake. | Kamran et al. (2017) |
| *Hibiscus esculentus* L. | *Brucella* sp. K12 | Enhanced plant growth and yield with a substantial reduction in Cr (VI) concentration. | Maqbool et al. (2015) |
| *Lens esculenta* | *Ochrobactrum intermedium*, *Brevibacterium* sp., *Bacillus cereus* | Increased root length, shoot lengths, number/weight of grains and pods, and number/weight of grains and plants. | Ahemad (2015) |
| *Cicer arietinum* L. | *Paenibacillus lentimorbus* B-30488(r) | Promoted growth and decreased Cr(VI) uptake by plants | Ahemad (2015) |
| Alfalfa, clover | *Delftia* sp. JD2 | Enhance rhizobia performance | Ahemad (2015) |
| Chickpea (*Cicer arietinum*) | *Mesorhizobium* sp. RC3 | Increased accumulation of dry matter and enhancement in seed yield, number of nodules, and grain protein. | Ahemad (2015) |
| *Pisum sativum* | *Rhodococcus erythropolis* MTCC 7905 | Enhanced plant growth even at low temperatures | Ahemad (2015) |
| *Brassica juncea* | *Pseudomonas* sp. PsA4, *Bacillus* sp. Ba32 | Stimulated plant growth and lowers the Cr(VI) content | Rajkumar et al. (2006) |
| *Vigna radiata* | *Ochrobactrum* CrT-1, *Bacillus cereus* S6 | Decreases the toxicity of chromium in seedlings by converting Cr(VI) to Cr (III) | Ahemad (2015) |
| *Helianthus annuus* | *Brevibacterium* sp. | Increased auxin content, fresh weight, dry weight, plant height, and seedling growth | Ahemad (2015) |
| *Brassica juncea* | Rhizobacterial strains A3 and S32 | Increased plant growth | Ahemad (2015) |
| *Vigna mungo*, *Brassica juncea*, *Pennisetum glaucum* | *Pseudomonas* sp. RNP4 | Significant increase in plant growth | Ahemad (2015) |
| *Helianthus annuus* | *Ochrobactrum intermedium* C32413 | Increased fresh weight, dry weight, seedling length | Ahemad (2015) |
| Helianthus annuus | Ochrobactrum intermedium | Increased plant and seed germination height, decreased Cr(VI) uptake | Ahemad (2015) |

| Plant | Bacteria | Effect on plant | Reference |
|---|---|---|---|
| *Zea mays* | *Agrobacterium tumefaciens* | Increase plant biomass and Cr(VI) uptake | Rosariastuti et al. (2013) |
| *Glycine max* | *Bacillus subtilis* MAI3 | Increased the Cr (III) immobilization and decreased the Cr content in shoot tissues. | Oliveira (2012) |
| *Cicer arietinum* L. | *Bacillus* sp. PSB10 | Improve chlorophyll content, nodulation, leghemoglobin, seed yield, grain protein, and growth. Decreases the uptake of chromium in roots, shoots, and grains. | Wani and Khan (2010) |
| Chilli | *Cellulosimicrobium cellulans* KUCr3 | Increase growth parameters and reduced Cr uptake in plants | Chatterjee et al. (2009) |
| *Zea mays* | *Pseudomonas aeruginosa, Pseudomonas fluorescens*, *Ralstonia metallidurans* | Enhanced Cr uptake, facilitated soil metal mobilization, increased plant growth | Braud et al. (2009) |

the Salt Overly Sensitive (SOS) pathway, which helps in sodium sequestration (Ramakrishna et al. 2020). They also increase the activity of antioxidant enzymes and facilitate the production of phytohormones that activate stress response pathways. Additionally, PGPB produces ACC deaminase and exopolysaccharides, which further aid plants in coping with salinity by enhancing water retention and reducing ethylene levels that typically rise under stress (Orozco-Mosqueda et al. 2020).

PGPB also proves to be an effective agent of remediation in heavy metal-contaminated environments. Approximately 20 million hectares of land worldwide are affected by HM contamination (Li et al. 2020). PGPB can detoxify heavy metals by forming metal-protein complexes, biotransforming metals into less toxic forms, and promoting their accumulation in plant tissues. For instance, *Bacillus thuringiensis* enhances the removal of metals like zinc, copper, nickel, lead, arsenic, and cadmium in plants such as *Alnus firma,* while *Proteus mirabilis* reduces chromium toxicity in maize (Babu et al. 2013). These bacteria help in metal uptakes as well as increase the tolerance of plants to metal stress by regulating metal transporter genes. Moreover, PGPB assists plants in coping with drought stress, which affects over 160 million hectares of rain-fed land globally (Berger et al. 2016). Drought induces the aggregation of reactive oxygen species (ROS) in plants, leading to cell damage. PGPB helps mitigate this by enhancing the antioxidant defenses in enzymes like catalase, superoxide dismutase, and peroxidase (Tiepo et al. 2020). Studies have shown that PGPB can significantly boost chlorophyll content and overall plant health under drought conditions.

**Synergistic approaches: integrating PGPB for chromium cleanup**

The integration of growth-promoting bacteria with remedial strategies offers promising synergistic approaches for chromium cleanup. Bioaugmentation, Biostimulation, Phytoextraction, and Phytostabilization approaches underscore the multifaceted function of PGPB in combating chromium pollution.

*Bioaugmentation: Enhancing plant tolerance and chromium uptake*

Bioaugmentation enhances plant tolerance to heavy metals and promotes their uptake through the introduction of beneficial microbial communities into the soil. The indigenous microbial population in soil performs various soil functions, including nutrient recycling, pest control, and pollutant transformation, which can bolster phytoremediation efforts (Kour et al. 2021). PGPBs produce growth-promoting phytohormones, which enhance plant tolerance to heavy metals and promote their translocation within the plant (Manoj et al. 2020). Bioaugmentation techniques leverage these mechanisms to improve the phytoremediation capacity of plants for heavy metals. For instance, PGPB-producing indole-3-acetic acid (IAA) can stimulate lateral root development and root hair production, facilitating phytoremediation (DalCorso et al. 2019). Studies have demonstrated the effectiveness of PGPB in enhancing heavy metal phytostabilization, reducing the bioavailability of metals in soil, and promoting plant growth (Montreemuk et al. 2024). Co-inoculation of multiple microbial strains has been shown to further enhance stress tolerance and plant growth under adverse conditions (Orozco-Mosqueda et al. 2020).

*Biostimulation: Stimulating indigenous microbial communities for chromium reduction*

Biostimulation, the process of enhancing indigenous microbial communities, holds promise for efficient reduction of Cr(VI) contamination (Galani et al. 2022). This method can yield dual benefits - i) increasing the growth rates of native bacteria capable of directly reducing Cr(VI) through chromate reductase production and ii) fostering anaerobic environments conducive to the activity of iron-reducing bacteria, which chemically transform Cr(VI) into Cr(III) by generating $Fe^{2+}$. Through the continuous cycling of small quantities of iron, a substantial quantity of Cr(VI) has the potential to be converted into the less hazardous Cr(III) (Baldiris et al., 2018). Various organic electron donors, such as lactate, glucose, acetate, and yeast have been explored for their capacity to enhance Cr(VI) bioreduction. Among these, molasses, and emulsified vegetable oil (EVO) have emerged as viable options for in situ remediation of contaminated aquifers. Molasses, a by-product of sugarcane refining, has shown effectiveness in both chemical reduction of Cr(VI) at acidic pH and as a microbial nutrient at alkaline pH. EVO, while slower to dissolve, provides longevity to the remediation process. The colloidal nature of EVO can hinder effective distribution in porous materials (Yang et al. 2021). Biostimulation techniques, such as the addition of acetate, have demonstrated success in promoting anaerobic Cr(VI) treatment in diverse environments, including highly alkaline and saline soils and tannery sites. These approaches harness the potential of indigenous microbial communities to drive Cr(VI) reduction, offering a promising pathway for environmentally friendly and cost-effective bioremediation of polluted aquifers (Lara et al. 2017).

*Phytoextraction: Facilitating chromium accumulation in plants with PGPB assistance*

Phytoextraction, also termed phytosequestration or phytoaccumulation, offers an affordable, eco-friendly solution for extracting chromium (Cr) from polluted soil and wastewater using plants. This process involves the transportation of heavy metals from the soil or water into plants, where they are isolated in various plant tissues without altering soil properties (Bhat et al. 2022, Khan et al. 2022). The efficiency of phytoextraction depends on factors such as plant selection, soil characteristics, and bioavailability of heavy metals (Yan et al. 2020). Certain plants known as hyperaccumulators can store extensive rates of heavy metals without showing phytotoxicity, making them ideal candidates for phytoextraction. These plants can translocate huge quantities of heavy metals from roots to shoots and can detoxify and sequester metals effectively (Kafle et al. 2022). Specific plant species have been identified as efficient accumulators of heavy metals, further highlighting the potential of phytoextraction in remediation efforts. However, proper management of the biomass generated from phytoextraction is essential to prevent recontamination of the environment (Bortoloti and Baron 2022). Techniques such as combustion, compaction, composting, gasification, and phytomining can be employed to treat biomass effectively, ensuring minimal environmental impact (Suman et al. 2018, Baker 1981).

*Phytostabilization: Utilizing PGPB to immobilize chromium in soil matrices*

Phytostabilization involves restraining the distribution and bioabsorption of heavy metals by neutralizing them within the roots of metal-tolerant plants and the rhizosphere zone. This process curbs the mobility of heavy metals into the ecosystem; besides it prevents soil erosion and fosters an aerobic rhizosphere, promoting the accumulation of organic matter that aids in contaminant stabilization (Shackira and Puthur 2019). Through biochemical processes such as surface adsorption, precipitation, aggregation within roots, and transition by redox enzymes, plants can effectively stabilize metals like chromium. Specific plants along with some soil modifications enhance phytostabilization effectiveness. For instance, certain plant species like *Prosopis laevigata, Tagetes erecta*, and *Sedum alfredo* have been instrumental in minimizing the bioavailability of cadmium pollutants and strengthening phytostabilization efficacy (Thongchai et al. 2019). The addition of manures and biochar to contaminated soils has shown promise in reducing heavy metal concentrations, while amendments like dolomite and limestone have been effective in decreasing the bioavailability of metals like copper and nickel (Gul et al. 2015). Phytostabilization does not require further treatment or disposal of harmful substances; however, it is not regarded as a long-term remedy for heavy metal-polluted soil. Continuous monitoring of remediated sites is essential to mitigate the regeneration of heavy metals in nature and ensure sustainable environmental management practices (Bakshe and Jugade 2023).

## EXPERIMENTAL EVIDENCE

### Successful application of PGPB in Chromium-contaminated sites

In a study aimed to address chromium contamination in soils, plant growth-promoting bacteria were isolated from *Phaseolus lunatus* root nodules and evaluated for their tolerance to high Cr levels. The experiment encompasses the growing of these bacteria in Cr-contaminated soil amended with composted tannery sludge (CTS) at various rates. Results showed that 54 PGPB strains were isolated, with a higher proportion found in soils treated with lower CTS rates. Most isolates exhibited positive responses for catalase, phosphate, and urease solubilization, with some also positive for lipase, protease, and other traits. Despite a drop in the quantity of isolates tolerant to high Cr concentrations, three strains (UFPI-LCC87, UFPI-LCC61, and UFPI-LCC64,) showed significant Cr tolerance and biochemical capability. Notably, UFPI-LCC87 displayed high tolerance to the highest Cr concentration tested, indicating its potential for use in Cr-contaminated soils and plant growth promotion (Rocha et al. 2019).

### Experimental studies demonstrating the efficacy of synergistic strategies

Experimental studies investigating synergistic strategies for managing chromium-polluted soils have yielded promising results. One such study focused on identifying chromium-tolerant rhizobacteria and assessing their inoculation effects on *Lens culinaris* growth in chromium-polluted soils (Hadia-E-Fatima and Ahmed 2018). *Bacillus* species were found to significantly mitigate the adverse effects of Cr, promoting the growth of *L. culinaris* in contaminated environments (Huang et al. 2020). Another study isolated chromium resistant PGPB and tested their resistance to multiple heavy metals, including Cr. Among these bacteria, *Cellulosimicrobium* sp. NF2 demonstrated high heavy metal resistance, phosphate solubilization, and indole acetic acid production, promoting alfalfa growth in both control and heavy metal-spiked soils (Tirry et al. 2018, Ahemad 2015). Additionally, the inoculation of *Pseudomonas putida* enhanced *Eruca sativa* (Arugula) growth and Cr phytoextraction, mitigating the inhibitory effects of Cr and increasing plant metal uptake. Moreover, the combined application of PGPB and salicylic acid alleviated Cr toxicity in maize seedlings, reducing Cr accumulation and oxidative stress while enhancing plant growth and physiological responses (Kamran et al. 2017).

### Challenges and potential solutions in field-scale implementation

Field-scale implementation of strategies for mitigating heavy metal pollution has several challenges that need to be considered for successful execution. The major challenge is the variability in soil conditions and metal contamination levels across different sites, necessitating tailored approaches for each location. Additionally, the long-term effectiveness and sustainability of remediation methods need to be ensured, considering aspects such as organic matter content, soil pH, and microbial activity. Another hurdle is the scale-up of laboratory-tested techniques to field applications, which requires addressing logistical and operational constraints while maintaining efficacy. Moreover, the economic feasibility of large-scale implementation is crucial, as remediation costs can be substantial. To overcome these challenges, interdisciplinary collaboration among scientists, engineers, policymakers, and stakeholders is essential. Developing robust monitoring and assessment protocols to track remediation progress and environmental impacts is also critical. Furthermore, integrating innovative technologies such as remote sensing, machine learning, and bioremediation strategies can enhance the efficiency and cost-effectiveness of field-scale implementation efforts. Overall, addressing these challenges with systematic planning, flexible management, and stakeholder engagement can unlock the full potential of field-scale solutions for heavy metal pollution remediation.

## FUTURE PERSPECTIVES AND IMPLICATIONS

The future of PGPB-mediated chromium cleanup is promising, with emerging trends, commercialization potential, and significant environmental and socioeconomic benefits.

### Emerging trends in PGPB-mediated Chromium cleanup

The application of PGPB in phytoremediation offers a promising method for chromium cleanup. Recent advancements highlight several phytoremediation strategies, such as phytostabilization, phytodegradation, phytoextraction, phytovolatilization, phytofiltration, rhizodegradation, and phytodesalination, which are enhanced by PGPB (Poria et al. 2022). For instance, phytostabilization influences tolerant plants to trap heavy metals in the rhizosphere, reducing their motility and bioavailability. This approach is cost-effective and minimally invasive, making it suitable for stabilizing chromium in contaminated soils (Shackira and Puthur 2019). Phytodegradation utilizes plant enzymes and rhizosphere microorganisms to degrade contaminants, while phytoextraction involves the uptake and accumulation of metals in plant biomass, which can be harvested for disposal. Phytovolatilization and phytofiltration further contribute by transforming and removing contaminants via plant transpiration and root filtration, respectively (Zgorelec et al. 2020). The synergistic effects of PGPB in these processes enhance the efficiency and effectiveness of chromium remediation by promoting plant growth, increasing metal uptake, and facilitating microbial interactions that degrade or immobilize pollutants (Kafle et al. 2022a, Kotoky and Pandey 2020a,b, Nebeská et al. 2021).

### Potential for commercialization and large-scale deployment

The commercialization and large-scale deployment of PGPB-mediated phytoremediation are increasingly viable, driven by the successful application of microbial inoculants in agricultural and industrial settings. Studies have demonstrated that inoculation with specific PGPB strains, such as *Bacillus cereus* and *Pseudomonas citronellolis*, significantly improves plant growth and metal phytoextraction capabilities (Silambarasan et al. 2020, Bruno et al. 2021). The transition from laboratory to field applications is advancing, with pilot-scale studies showing promising results in containing and reducing Cr(VI) plumes using biobarriers and bioreactor systems (Ren et al. 2019). The development of commercial products like FZB24® TB and RhizoVital®, which utilize PGPB strains to mitigate environmental stress and promote plant growth, further exemplifies the market readiness of these technologies (Ngalimat et al. 2021). Additionally, the encapsulation of PGPB in carriers such as alginate hydrogels enhances their stability and efficacy, making them suitable for large-scale bioremediation projects (Ma et al. 2016).

### Environmental and socioeconomic implications of PGPB-based approaches

The implementation of PGPB-based phytoremediation holds significant environmental and socioeconomic implications. Environmentally, these approaches offer a sustainable and eco-friendly solution to chromium contamination, minimizing the need for chemical interventions and reducing the ecological footprint of remediation activities. By enhancing soil health and stabilizing contaminants, PGPB-mediated phytoremediation also promotes biodiversity and ecosystem resilience. Socioeconomically, the adoption of these technologies can lead to cost savings in remediation projects, provide opportunities for green job creation, and stimulate economic development in contaminated regions. Moreover, the successful commercialization of PGPB inoculants can drive innovation and investment in the biotechnology sector, fostering a market for sustainable environmental solutions. However, it is crucial to address potential risks such as the entry of contaminants into the food chain, and ensure that phytoremediation practices are designed to minimize adverse impacts on human health and the environment. Continued research, field trials, and collaborative efforts between scientists, policymakers, and industry stakeholders are essential to realize the full potential of these innovative bioremediation strategies.

## CONCLUSIONS

The integration of PGPBs with phytoremediation strategies offers a robust and sustainable solution for chromium pollution. PGPBs enhance plant resilience to chromium stress through various mechanisms, promoting growth and metal accumulation while reducing bioavailability. Synergistic approaches like bioaugmentation and biostimulation leverage these bacterial capabilities, improving the effectiveness of phytoremediation efforts. Case studies affirm the potential of PGPB in real-world scenarios, underscoring their role in transforming contaminated sites into productive landscapes. However, challenges such as site-specific variability, long-term sustainability, and economic feasibility must be addressed for large-scale implementation. Interdisciplinary collaboration, innovative technologies, and continuous monitoring are essential to optimize these strategies. PGPB-mediated phytoremediation not only provides environmental benefits but also offers socioeconomic advantages by reducing remediation costs and promoting green job creation. Continued research and field trials will be crucial in advancing these bioremediation techniques, ensuring a cleaner and healthier environment.

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## REFERENCES

Ahemad, M. 2015. Enhancing phytoremediation of chromium-stressed soils through plant-growth-promoting bacteria. Journal of Genetic Engineering and Biotechnology, 13(1), 51-58. https://doi.org/10.1016/j.jgeb.2015.02.001

Ahmed, A., Sara Taha, A. ., Sundas, R.Q. and Man-Qun, W. 2021. Heavy metals and pesticide toxicity in agricultural soil and plants: ecological risks and human health Implications. Toxics, 9, 42. https://doi.org/10.3390/toxics9030042

Akunwa, N.K., Muhammad, M.N. and Akunna, J.C. 2014. Treatment of metal-contaminated wastewater: A comparison of low-cost biosorbents. Journal of Environmental Management, 146, 517-523. https://doi.org/10.1016/j.jenvman.2014.08.014

Ali, S., Mir, R. A., Tyagi, A., Manzar, N., Kashyap, A. S., Mushtaq, M., Raina, A., Park, S., Sharma, S., Mir, Z.A., Lone, S.A., Bhat, A.A., Baba, U., Mahmoudi, H. and Bae, H. 2023. Chromium toxicity in plants: signaling, mitigation, and future perspectives. Plants, 12(7), 1502. https://doi.org/10.3390/plants12071502

Alves, A.R.A., Yin, Q., Oliveira, R.S., Silva, E.F. and Novo, L.A.B. 2022. Plant growth-promoting bacteria in phytoremediation of metal-polluted soils: Current knowledge and future directions. Science of the Total Environment, 838, 156435. https://doi.org/10.1016/j.scitotenv. 2022.156435

Babu, A.G., Kim, J.D. and Oh, B.T. 2013. Enhancement of heavy metal phytoremediation by Alnus firma with endophytic *Bacillus thuringiensis* GDB-1. Journal of Hazardous Materials, 250-251, 477-483. https://doi.org/10.1016/j.jhazmat.2013.02.014

Baker, A.J.M. 1981. Accumulation of heavy metals in soil and plants. Journal of Plant Nutrition, 3(1-4), 643-654. https://doi.org/10.1080/01904168109362867

Bakshe, P. and Jugade, R. 2023. Phytostabilization and rhizofiltration of toxic heavy metals by heavy metal accumulator plants for sustainable management of contaminated industrial sites: A comprehensive review. Journal of Hazardous Materials Advances, 10, 100293. https://doi.org/10.1016/j.hazadv.2023.100293

Bakshi, A. and Panigrahi, A.K. 2018. A comprehensive review on chromium induced alterations in fresh water fishes. Toxicology Reports, 5, 440-447. https://doi.org/10.1016/j.toxrep.2018.03.007

Baldiris, R., Acosta-Tapia, N., Montes, A., Hernández, J. and Vivas-Reyes, R. 2018. Reduction of hexavalent chromium and detection of chromate reductase (ChrR) in *Stenotrophomonas maltophilia*. Molecules, 23(2), 406. https://doi.org/10.3390/molecules23020406

Bandara, K.R.V., Manage, P.M., Bandara, K.R.V. and Manage, P.M. 2022. Heavy metal contamination in the coastal environment and trace level identification. In: Mancuso, M., Abbas, M.H.H., Bottari, T. and Abdelhafez, A.A. (Eds.). Marine Pollution - Recent Development, Intechopen. https://doi.org/10.5772/INTECHOPEN.106653

Barnhart, J. 1997. Occurrences, uses, and properties of Chromium. Regulatory Toxicology and Pharmacology, 26(1 I), 3-7. https://doi.org/10.1006/rtph.1997.1132

Berger, J., Palta, J. and Vadez, V. 2016. Review: An integrated framework for crop adaptation to dry environments: Responses to transient and terminal drought. Plant Science, 253, 58-67. https://doi.org/10.1016/j.plantsci.2016.09.007

Bhat, S.A., Bashir, O., Ul Haq, S.A., Amin, T., Rafiq, A., Ali, M., Américo-Pinheiro, J.H.P. and Sher, F. 2022. Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. Chemosphere, 303, 134788. https://doi.org/10.1016/j.chemosphere.2022.134788

Bortoloti, G.A. and Baron, D. 2022. Phytoremediation of toxic heavy metals by Brassica plants: A biochemical and physiological approach. Environmental Advances, 8, 100204. https://doi.org/10.1016/j.envadv.2022.100204

Boulé, J., Sholberg, P.L., Lehman, S.M., O'Gorman, D.T. and

Svircev, A.M. 2011. Isolation and characterization of eight bacteriophages infecting *Erwinia amylovora* and their potential as biological control agents in British Columbia, Canada. Canadian Journal of Plant Pathology, 33(3), 308-317. https://doi.org/10.1080/07060661.2011.588250

Braud, A., Jézéquel, K., Bazot, S. and Lebeau, T. 2009. Enhanced phytoextraction of an agricultural Cr- and Pb-contaminated soil by bioaugmentation with siderophore-producing bacteria. Chemosphere, 74(2), 280-286. https://doi.org/10.1016/j.chemosphere.2008.09.013

Briffa, J., Sinagra, E. and Blundell, R. 2020. Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon, 6(9), e04691. https://doi.org/10.1016/j.heliyon.2020.e04691

Bruno, L.B., Anbuganesan, V., Karthik, C., Tripti, Kumar, A., Banu, J.R., Freitas, H. and Rajkumar, M. 2021. Enhanced phytoextraction of multi-metal contaminated soils under increased atmospheric temperature by bioaugmentation with plant growth promoting *Bacillus cereus*. Journal of Environmental Management, 289, 112553. https://doi.org/10.1016/j.jenvman.2021.112553

Chatterjee, S., Sau, G.B. and Mukherjee, S.K. 2009. Plant growth promotion by a hexavalent chromium reducing bacterial strain, *Cellulosimicrobium cellulans* KUCr3. World Journal of Microbiology and Biotechnology, 25(10), 1829-1836. https://doi.org/10.1007/s11274-009-0084-5

Coetzee, J.J., Bansal, N. and Chirwa, E.M.N. 2020a. Chromium in environment, its toxic effect from chromite-mining and ferrochrome industries, and its possible bioremediation. Exposure and Health, 12(1), 51-62. https://doi.org/10.1007/S12403-018-0284-Z

DalCorso, G., Fasani, E., Manara, A., Visioli, G. and Furini, A. 2019. Heavy metal pollutions: state of the art and innovation in phytoremediation. International Journal of Molecular Sciences, 20(14), 3412. https://doi.org/10.3390/ijms20143412

DesMarias, T.L. and Costa, M. 2019. Mechanisms of chromium-induced toxicity. Current Opinion in Toxicology, 14(Vi), 1-7. https://doi.org/10.1016/j.cotox.2019.05.003

Galani, A., Mamais, D., Noutsopoulos, C., Anastopoulou, P., & Varouxaki, A. (2022). Biotic and abiotic biostimulation for the reduction of hexavalent chromium in contaminated aquifers. *Water (Switzerland)*, *14*(1). https://doi.org/10.3390/w14010089

Gautam, P.K., Gautam, R.K., Banerjee, S., Chattopadhyaya, M.C. and Pandey, J.D. 2016. Heavy metals in the environment: Fate, transport, toxicity and remediation technologies. pp. 101-130. In: Pathania, D. (Ed.) Heavy Metals: Sources, Toxicity and Remediation Techniques, Nova Scotia Publication, New Delhi.

Glick, B.R. 2012. Plant Growth-Promoting Bacteria: mechanisms and applications. Scientifica, 2012, 1-15. https://doi.org/10.6064/2012/963401

Gul, S., Naz, A., Fareed, I. and Irshad, M. 2015. Reducing heavy metals extraction from contaminated soils using organic and inorganic amendments – a review. Polish Journal of Environmental Studies, 24(3), 1423-1426. https://doi.org/10.15244/pjoes/26970

Hadia-E-Fatima. and Ahmed, A. 2018. Micro-remediation of chromium contaminated soils. Peer J, 2018(12), 6076. https://doi.org/10.7717/peerj.6076

Hasanuzzaman, M., Bhuyan, M.H.M.B., Parvin, K., Bhuiyan, T.F., Anee, T.I., Nahar, K., Hossen, M.S., Zulfiqar, F., Alam, M.M. and Fujita, M. 2020. Regulation of ROS metabolism in plants under environmental stress: A review of recent experimental evidence. International Journal of Molecular Sciences, 21(22), 1–44. https://doi.org/10.3390/ijms21228695

Huang, H., Zhao, Y., Fan, L., Jin, Q., Yang, G. and Xu, Z. 2020. Corrigendum to "Enhancement of heavy metal (Mn) phytoremediation by *Broussonetia papyrifera* with two Bacillus spp. Species". Chemosphere, 261, 128540. https://doi.org/10.1016/j.chemosphere.2020.128540

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A. and Aryal, N. 2022. Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. Environmental Advances, 8, 100203. https://doi.org/10.1016/j.envadv.2022.100203

Kamran, M.A., Bibi, S., Xu, R. kou, Hussain, S., Mehmood, K. and Chaudhary, H.J. 2017. Phyto-extraction of chromium and influence of plant growth promoting bacteria to enhance plant growth. Journal of Geochemical Exploration, 182, 269-274. https://doi.org/10.1016/j.gexplo.2016.09.005

Khan, A.U., Khan, A.N., Waris, A., Ilyas, M. and Zamel, D. 2022. Phytoremediation of pollutants from wastewater: A concise review. Open Life Sciences, 17(1), 488-496. https://doi.org/10.1515/biol-2022-0056

Kotoky, R. and Pandey, P. 2020a. Rhizosphere assisted biodegradation of benzo(a)pyrene by cadmium resistant plant-probiotic Serratia marcescens S2I7, and its genomic traits. Scientific Reports, 10(1), art 5279. https://doi.org/10.1038/s41598-020-62285-4

Kotoky, R. and Pandey, P. 2020b. Rhizosphere mediated biodegradation of benzo(A)pyrene by surfactin producing soil bacilli applied through *Melia azadirachta* rhizosphere. *International* Journal of Phytoremediation, 22(4), 363-372. https://doi.org/10.1080/15226514.2019.1663486

Kour, D., Kaur, T., Devi, R., Yadav, A., Singh, M., Joshi, D., Singh, J., Suyal, D.C., Kumar, A., Rajput, V.D., Yadav, A.N., Singh, K., Singh, J., Sayyed, R.Z., Arora, N.K. and Saxena, A.K. 2021. Beneficial microbiomes for bioremediation of diverse contaminated environments for environmental sustainability: present status and future challenges. Environmental Science and Pollution Research, 28(20), 24917-24939. https://doi.org/10.1007/s11356-021-13252-7

Kumar, M., Seth, A., Singh, A.K., Rajput, M.S. and Sikandar, M. 2021. Remediation strategies for heavy metals contaminated ecosystem: A review. Environmental and Sustainability Indicators, 12, 100155. https://doi.org/10.1016/j.indic.2021.100155

Lara, P., Morett, E. and Juárez, K. 2017. Acetate biostimulation as an effective treatment for cleaning up alkaline soil highly contaminated with Cr(VI). Environmental Science and

Pollution Research, 24(33), 25513-25521. https://doi.org/10.1007/s11356-016-7191-2

Li, Y., Lin, J., Huang, Y., Yao, Y., Wang, X., Liu, C., Liang, Y., Liu, K. and Yu, F. 2020. Bioaugmentation-assisted phytoremediation of manganese and cadmium co-contaminated soil by Polygonaceae plants (*Polygonum hydropiper* L. and *Polygonum lapathifolium* L.) and *Enterobacter* sp. FM-1. Plant and Soil, 448(1-2), 439-453. https://doi.org/10.1007/s11104-020-04447-x

Liu, K., Chen, P., Lu, J., Zhu, Y., Xu, Y., Liu, Y. and Liu, J. 2020. protective effect of purple tomato anthocyanidin on Chromium(VI)-induced autophagy in LMH Cells by inhibiting endoplasmic reticulum stress. Biological Trace Element Research, 194(2), 570–580. https://doi.org/10.1007/s12011-019-01795-3

Liu, K., Cui, Y., Li, H., Qi, C., Cheng, G., Gao, X., Zhang, Z., Liu, Y. and Liu, J. 2022. Hydrogen-rich medium regulates Cr(VI)-induced er stress and autophagy signalling in DF-1 cells. Biological Trace Element Research, 200(5), 2329-2337. https://doi.org/10.1007/s12011-021-02850-8

Ma, Y., Rajkumar, M., Zhang, C. and Freitas, H. 2016. The beneficial role of bacterial endophytes in heavy metal phytoremediation. Journal of Environmental Management, 174, 14-25. https://doi.org/10.1016/j.jenvman.2016.02.047

Manoj, S.R., Karthik, C., Kadirvelu, K., Arulselvi, P.I., Shanmugasundaram, T., Bruno, B. and Rajkumar, M. 2020. Understanding the molecular mechanisms for the enhanced phytoremediation of heavy metals through plant growth promoting rhizobacteria: A review. Journal of Environmental Management, 254, 109779. https://doi.org/10.1016/j.jenvman.2019.109779

Maqbool, Z., Asghar, H.N., Shahzad, T., Hussain, S., Riaz, M., Ali, S., Arif, M.S. and Maqsood, M. 2015. Isolating, screening and applying chromium reducing bacteria to promote growth and yield of okra (*Hibiscus esculentus* L.) in chromium contaminated soils. Ecotoxicology and Environmental Safety, 114, 343-349. https://doi.org/10.1016/j.ecoenv.2014.07.007

Martin, Y.E. and Johnson, E.A. 2012. Biogeosciences survey: studying interactions of the biosphere with the lithosphere, hydrosphere and atmosphere. Progress in Physical Geography, 36(6), 833-852. https://doi.org/10.1177/0309133312457107

Mitra, S., Chakraborty, A.J., Tareq, A.M., Bin, E.T., Nainu, F., Khusro, A., Idris, A.M., Khandaker, M.U., Osman, H., Alhumaydhi, F.A. and Simal-Gandara, J. 2022. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. Journal of King Saud University - Science, 34(3), 101865. https://doi.org/10.1016/j.jksus.2022.101865

Montreemuk, J., Stewart, T.N. and Prapagdee, B. 2024. Bacterial-assisted phytoremediation of heavy metals: Concepts, current knowledge, and future directions. Environmental Technology and Innovation, 33, 103488. https://doi.org/10.1016/j.eti.2023.103488

Nebeská, D., Trögl, J., Ševcù, A., Špánek, R., Marková, K., Davis, L., Burdová, H. and Pidlisnyuk, V. 2021. *Miscanthus x giganteus* role in phytodegradation and changes in bacterial community of soil contaminated by petroleum industry. Ecotoxicology and Environmental Safety, 224, 112630. https://doi.org/10.1016/j.ecoenv.2021.112630

Ngalimat, M.S., Yahaya, R.S.R., Baharudin, M.M.A.A., Yaminudin, S.M., Karim, M., Ahmad, S.A. and Sabri, S. 2021. A review on the biotechnological applications of the operational group *Bacillus amyloliquefaciens*. Microorganisms, 9(3), 614. https://doi.org/10.3390/microorganisms9030614

Nur-E-Alam, M., Mia, M.A.S., Ahmad, F. and Rahman, M.M. 2020. An overview of chromium removal techniques from tannery effluent. Applied Water Science, 10(9), art 205. https://doi.org/10.1007/s13201-020-01286-0

Olanrewaju, O.S., Glick, B.R. and Babalola, O.O. 2017. Mechanisms of action of plant growth promoting bacteria. World Journal of Microbiology and Biotechnology, 33(11), art 197. https://doi.org/10.1007/s11274-017-2364-9

Oliveira, H. 2012. Chromium as an environmental pollutant: insights on induced plant toxicity. Journal of Botany, 2012, 375843. https://doi.org/10.1155/2012/375843

Orozco-Mosqueda, M.D.C., Glick, B.R. and Santoyo, G. 2020. ACC deaminase in plant growth-promoting bacteria (PGPB): An efficient mechanism to counter salt stress in crops. Microbiological Research, 235, 126439. https://doi.org/10.1016/j.micres.2020.126439

Poria, V., Dêbiec-Andrzejewska, K., Fiodor, A., Lyzohub, M., Ajijah, N., Singh, S. and Pranaw, K. 2022. Plant growth-promoting bacteria (PGPB) integrated phytotechnology: A sustainable approach for remediation of marginal lands. Frontiers in Plant Science, 13, 999866. https://doi.org/10.3389/fpls.2022.999866

Prasad, S., Yadav, K.K., Kumar, S., Gupta, N., Cabral-Pinto, M.M.S., Rezania, S., Radwan, N. and Alam, J. 2021. Chromium contamination and effect on environmental health and its remediation: A sustainable approaches. Journal of Environmental Management, 285, 112174. https://doi.org/10.1016/j.jenvman.2021.112174

Rajkumar, M., Nagendran, R., Lee, K.J., Lee, W.H. and Kim, S.Z. 2006. Influence of plant growth promoting bacteria and $Cr^{6+}$ on the growth of Indian mustard. Chemosphere, 62(5), 741-748. https://doi.org/10.1016/j.chemosphere.2005.04.117

Ramakrishna, W., Rathore, P., Kumari, R. and Yadav, R. 2020. Brown gold of marginal soil: Plant growth promoting bacteria to overcome plant abiotic stress for agriculture, biofuels and carbon sequestration. Science of the Total Environment, 711, 135062. https://doi.org/10.1016/j.scitotenv.2019.135062

Razzak, S.A., Faruque, M.O., Alsheikh, Z., Alsheikhmohamad, L., Alkuroud, D., Alfayez, A., Hossain, S.M.Z. and Hossain, M.M. 2022. A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. Environmental Advances, 7, 100168. https://doi.org/10.1016/j.envadv.2022.100168

Ren, X.M., Guo, S.J., Tian, W., Chen, Y., Han, H., Chen, E., Li, B.L., Li, Y.Y. and Chen, Z.J. 2019. Effects of plant growth-promoting bacteria (PGPB) inoculation on the growth, antioxidant activity, Cu uptake, and bacterial community structure of rape (*Brassica napus* L.) grown in Cu-contaminated agricultural soil. Frontiers in Microbiology, 10, 01455. https://doi.org/10.3389/fmicb.2019.01455

Rocha, S.M.B., Antunes, J.E.L., Araujo, J.M.A., de Aquino, J.P.A., de Melo, W.J., Mendes, L.W. and de Araujo, A.S.F. 2019. Capability of plant growth-promoting bacteria in chromium-contaminated soil after application of composted tannery sludge. Annals of Microbiology, 69(6), 665-671. https://doi.org/10.1007/s13213-019-01455-w

Rosariastuti, R., Prijambada, I.D., Ngadiman., Prawidyarini, G.S. and Putri, A.R. 2013. Isolation and identification of plant growth promoting and chromium uptake enhancing bacteria from soil contaminated by leather tanning industrial waste. Journal of Basic & Applied Sciences, 9, 243-251. https://doi.org/10.6000/1927-5129.2013.09.32

Shackira, A.M. and Puthur, J.T. 2019. Phytostabilization of heavy metals: understanding of principles and practices. pp. 263-282. In: Srivastava, S., Srivastava, A. and Suprasanna, P. (Eds.) Plant-Metal Interactions. Springer, Cham. https://doi.org/10.1007/978-3-030-20732-8_13

Sharma, N., Sodhi, K.K., Kumar, M. and Singh, D.K. 2021. Heavy metal pollution: Insights into chromium eco-toxicity and recent advancement in its remediation. Environmental Nanotechnology, Monitoring and Management, 15, 100388. https://doi.org/10.1016/j.enmm.2020.100388

Sharma, P., Singh, S.P., Parakh, S.K. and Tong, Y.W. 2022. Health hazards of hexavalent chromium (Cr(VI)) and its microbial reduction. Bioengineered, 13(3), 4923-4938. https://doi.org/10.1080/21655979.2022.2037273

Shimod, K.P., Vineethkumar, V., Prasad, T.K. and Jayapal, G. 2022. Effect of urbanization on heavy metal contamination: a study on major townships of Kannur District in Kerala, India. Bulletin of the National Research Centre, 46(1), art 4. https://doi.org/10.1186/s42269-021-00691-y

Silambarasan, S., Logeswari, P., Valentine, A., Cornejo, P. and Kannan, V.R. 2020. *Pseudomonas citronellolis* strain SLP6 enhances the phytoremediation efficiency of *Helianthus annuus* in copper-contaminated soils under salinity stress. Plant and Soil, 457(1-2), 241-253. https://doi.org/10.1007/s11104-020-04734-7

Singh, H.P., Mahajan, P., Kaur, S., Batish, D.R. and Kohli, R.K. 2013. Chromium toxicity and tolerance in plants. Environmental Chemistry Letters, 11(3), 229-254. https://doi.org/10.1007/s10311-013-0407-5

Suman, J., Uhlik, O., Viktorova, J. and Macek, T. 2018. Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment? Frontiers in Plant Science, 871, 1476. https://doi.org/10.3389/fpls.2018.01476

Tang, X., Huang, Y., Li, Y., Wang, L., Pei, X., Zhou, D., He, P. and Hughes, S.S. 2021. Study on detoxification and removal mechanisms of hexavalent chromium by microorganisms. Ecotoxicology and Environmental Safety, 208, 111699. https://doi.org/10.1016/J.ECOENV.2020.111699

Thongchai, A., Meeinkuirt, W., Taeprayoon, P. and Pichtel, J. 2019. Soil amendments for cadmium phytostabilization by five marigold cultivars. Environmental Science and Pollution Research, 26(9), 8737-8747. https://doi.org/10.1007/s11356-019-04233-y

Tiepo, A.N., Constantino, L.V., Madeira, T.B., Gonçalves, L.S.A., Pimenta, J.A., Bianchini, E., de Oliveira, A.L.M., Oliveira, H.C. and Stolf-Moreira, R. 2020. Plant growth-promoting bacteria improve leaf antioxidant metabolism of drought-stressed Neotropical trees. Planta, 251(4), 83. https://doi.org/10.1007/s00425-020-03373-7

Tirry, N., Tahri Joutey, N., Sayel, H., Kouchou, A., Bahafid, W., Asri, M. and El Ghachtouli, N. 2018. Screening of plant growth promoting traits in heavy metals resistant bacteria: Prospects in phytoremediation. Journal of Genetic Engineering and Biotechnology, 16(2), 613-619. https://doi.org/10.1016/j.jgeb.2018.06.004

Tumolo, M., Ancona, V., De Paola, D., Losacco, D., Campanale, C., Massarelli, C. and Uricchio, V.F. 2020. Chromium pollution in European water, sources, health risk, and remediation strategies: An overview. International Journal of Environmental Research and Public Health, 17(15), 17155438. https://doi.org/10.3390/ijerph17155438

Vishnupradeep, R., Bruno, L. B., Taj, Z., Karthik, C., Challabathula, D., Tripti, Kumar, A., Freitas, H. and Rajkumar, M. 2022. Plant growth promoting bacteria improve growth and phytostabilization potential of *Zea mays* under chromium and drought stress by altering photosynthetic and antioxidant responses. Environmental Technology and Innovation, 25, 102154. https://doi.org/10.1016/j.eti.2021.102154

Wani, P.A. and Khan, M.S. 2010. *Bacillus* species enhance growth parameters of chickpea (*Cicer arietinum* L.) in chromium stressed soils. Food and Chemical Toxicology, 48(11), 3262-3267. https://doi.org/10.1016/j.fct.2010.08.035

Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S. and Chen, Z. 2020. Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. Frontiers in Plant Science, 11, 359. https://doi.org/10.3389/fpls.2020.00359

Yan, G., Gao, Y., Xue, K., Qi, Y., Fan, Y., Tian, X., Wang, J., Zhao, R., Zhang, P., Liu, Y. and Liu, J. 2023. Toxicity mechanisms and remediation strategies for chromium exposure in the environment. Frontiers in Environmental Science, 11, 1131204. https://doi.org/10.3389/fenvs.2023.1131204

Yang, X., Liu, P., Yao, M., Sun, H., Liu, R., Xie, J. and Zhao, Y. 2021. Mechanism and enhancement of Cr(VI) contaminated groundwater remediation by molasses. Science of the Total Environment, 780(2519), 146580. https://doi.org/10.1016/j.scitotenv.2021.146580

Zgorelec, Z., Bilandzija, N., Knez, K., Galic, M. and Zuzul, S. 2020. Cadmium and Mercury phytostabilization from soil using *Miscanthus* × *giganteus*. Scientific Reports, 10(1), 1-10. https://doi.org/10.1038/s41598-020-63488-5

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