Chapter 6
Employing Microbes for Cr Alleviation: A Reliant Harmless Approach

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Abstract Hexavalent chromium [Cr(VI)] is one of the toxic pollutants that creates a serious environmental issue. If Cr(VI) has been persisted to long period, healthy nature of the environment badly effects and makes a deadly impact to the living organisms. Due to extensive use of chromium related compounds by different industries are most responsible for such an environmental contamination. Since Cr(VI) is not easily biodegradable it poses to crucial health risks to wildlife and humans. Studies proven that Cr(VI) is mutagenic, genotoxic, and even carcinogenic. Hence, the concerns should be undertaken for an appropriate remediation for the Cr(VI) remediation/removal. However, currently, different physico-chemical methods are being carried out for Cr(VI) removal, nevertheless, are not environmentally friendly. Furthermore, traditional physico-chemical methods are needed large amount of chemicals that generates significant secondary pollution. To overcome this issue, the techniques with the use of microbes, such as bioaccumulation, biosorption, bio-reduction, bio-precipitation, subsequent bio-efflux have utilized different natural mechanisms to combat chromium toxicity. In this view, the chapter focuses one employing different microbes to respond for effective removal of chromium toxicity. In addition, the research issues and future prospects are also discussed to fill the gaps with respect to the problems associated with recent microbial remediation focusing to real-time applicability.

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6.1 Introduction

The element chromium(Cr) can be found in ash, boulders, and dirt from active volcanoes. Due to its strong redox potential, Cr can be found in a wide variety of oxidation states, from (II to IV). The two most stable forms of chromium are the trivalent [Cr(III)] and hexavalent [Chromium(VI)] forms (Sun, Brocato and Costa 2015). A great deal of difference exists between chromium (III) and (IV) in terms of their physical, chemical, and toxicological characteristics. The naturally occurring Cr(III) can be found in ores such ferrochromite, while the more poisonous Cr(VI) is typically produced by human activity. The Cr(III) cation dissolves in water to create the insoluble hydroxide cation, while the Chromium(VI) oxyanion species can exist as either the dichromate, divalent chromate, or monovalent chromate, depending on the pH (DesMarias and Costa 2019). The most mobile form of Chromium in water is Chromium(VI), which is more soluble in water. Since its discovery in 1797, chromium has been put to use in numerous industries due to its adaptability. Chrome plating, dye production, the textile industry, the aerospace sector, wood preservation, leather tanning, and mud drilling all make use of chromium compounds. Examples of chromium compounds with industrial relevance include dichromates, chromates, chromic sulphate, chromic acid, and chromic oxides. Most chemical compounds containing chromium are produced by smelting chromite ore. However, a significant amount of chromium-rich solid and liquid waste and air pollutants are generated throughout the mining and manufacturing processes (Vengosh et al. 2016). In addition to human activities like mining and manufacturing, natural rock formations like ultramafic and mafic rocks can leach Cr(VI) into groundwater. In Mexico, Brazil, Argentina, Italy, California, and Greece, ultramafic aquifers are linked to water storage reservoirs with high Cr(VI) concentrations. Some volcanic and meta-volcanic groundwater and aquifers linked with mixture or more felsic igneous and metamorphic forms in North Carolina display values of up to 25 g/L of Chromium(VI), making this state home to some of the highest Chromium(VI) concentrations in the world. Worldwide, Chromium(VI) pollution has become an urgent problem. In spite of the dangers to human health and environment, many industries throughout the world have illegally dumped hazardous waste or disposed of it in ways that benefit their bottom lines (Georgaki and Charalambous 2022). Chromium pollution and the long-term harm to groundwater are primarily attributable to dumping at these sites. Figure 6.1 illustrates the possible toxicological impacts of chromium on human. A one of the most frequent locales where Cr(VI) are listed below:

- All pigments based on chromates, including dyes, inks, paints, and polymers.
- As the name implies, chrome plating involves applying a thin layer of chromium metal to an object by dipping it in a chromic acid solution.

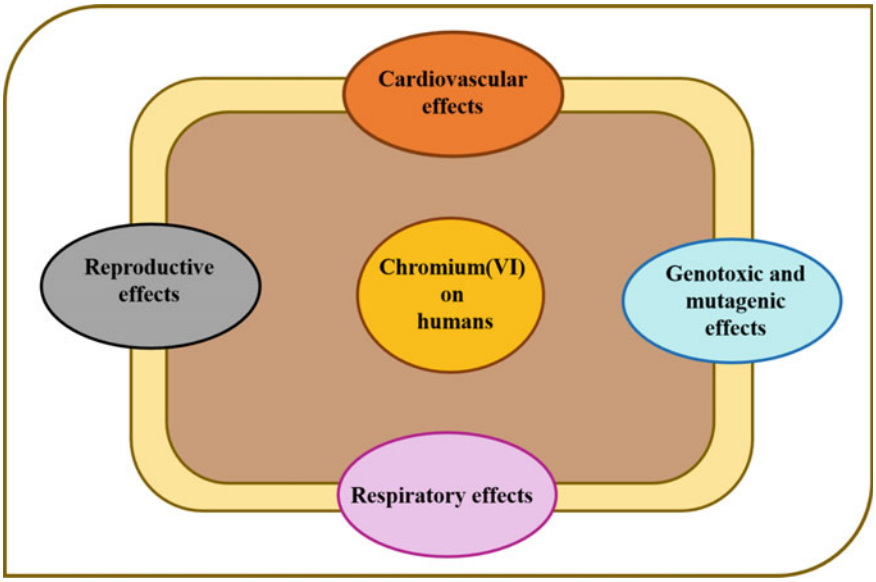

Fig. 6.1 The possible toxicological impacts of chromium(VI) on human

- Particles created during the process of smelting ferrochromium ore.
- Metal fumes produced during welding of nonferrous chromium alloys and stainless steel.

The World Health Organization (WHO) has designated chromium(VI) as a group I carcinogen. According to the guidelines for safe drinking water, chromium levels cannot exceed 50 ug/L. Between 0.2 and 2 g-Chromium(VI)/L is the typical range for Cr(VI) in North American drinking water (Monga et al. 2022). Even though the United States Environmental Protection Agency (EPA) recognizes Chromium(VI) as a toxic substance, it continues to be widely used in many industries. Drinking water is only allowed to have 100 g/L of total chromium [Cr(T)]. Figure 6.2 describes the spreading of chromium(VI) on human health and ecosystem.

To prevent the detrimental effects on human health, strict environmental controls must be imposed immediately on the amount of Chromium(VI) that can be emitted into the environment (Pavesi and Moreira 2020). Adsorption, ion exchange, chemical precipitation, membrane separation, electrocoagulation, and electrodialysis are only few of the methods that can be used to remove chromium(VI) from wastewater. To a large extent, Chromium(VI) is removed via chemical precipitation. Chromium(VI) can be eliminated through the use of chemical precipitators like $Ca(OH)_2$, MgO, NaOH, and calcium magnesium carbonate. The kind of precipitation agent, the volume of sludge, the agitation speed, the pH, the mixing time, and the presence of complexing agents are just few of the variables that might affect the outcome of the precipitation process. So far, it was proven that that the reverse osmosis, membrane filtration, electrocoagulation, ion exchange, and electrodialysis

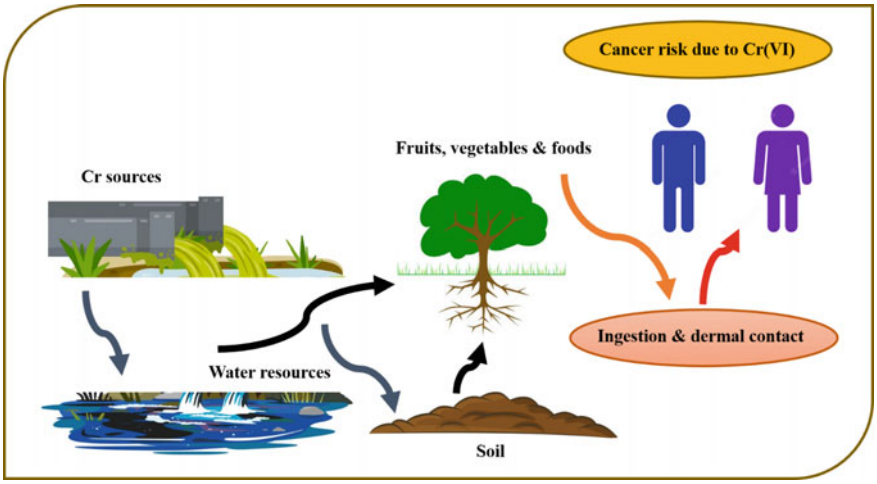

Fig. 6.2 Spreading of chromium(VI) on human health and ecosystem

are all effective methods for removing Chromium(VI), but each process has its own set of problems, such as high prices and concentrated wastes that must be dealt with afterward. Emerging as a potential effective technology for removing Cr(VI) from industrial effluents, bioremediation is on the rise. Bioremediation of chromium contamination by various fungi and bacteria has been demonstrated. Studies looking at the removal of Chromium(VI) from industrial effluent can be more promising while using different microbes, such as *Actinomycetes*, *Streptomyces rimosus*, and *Streptomyces griseus*. There are several examples of affordable agricultural wastes that have the adsorption potential to remove Chromium(VI) from waste-water. These include chitosan, rice husk, pomegranate husk, coconut shell, waste tea leaves, neem leaves, sawdust, watermelon rind, orange peel, and banana rachis. However, remediating chrome-polluted wastewater with microorganisms that are resistant to chromium has not been still thoroughly studied. The potential for hexavalent chromium to induce cancer, teratogenicity, and mutation has made it a widely recognized environmental hazard (Gad 1989). Using microorganisms that can metabolize and break down Chromium(VI) contaminants, this review intends to inform readers about the dangers caused by Chromium(VI) and the methods for eliminating it from polluted places.

6.2 Incidence of Hexavalent Cr(VI) on Human Health

Pollution from heavy metals is increasingly seen as an international environmental emergency. There is growing evidence that hexavalent chromium [Cr(VI)] is neurotoxic and should be treated as a global environmental pollutant. Many different plant

and microbial species are essential in the process of decontaminating polluted areas (Oliveira 2012). In humans, Cr(VI) and its metabolites, in particular chromates, enter the body via a unique pathway. Exposure to Cr(VI) typically occurs through inhalation, ingestion, or skin contact. Cr(VI) exposure is broken down into three distinct time periods: short-term (14 days), intermediate (75–364 days), and long-term (more than 364 days). There are a number of ways in which Cr(VI) poisoning can manifest. It is possible to cause modifications to the cellular structure, particularly in the membrane's lipoprotein region. Immune system activity or efficiency can be lowered; key enzymes like oxidative phosphorylation can be suppressed; and competition for cofactor fixation sites can diminish enzyme activity. Chromium(VI) binds to the DNA-polymerase enzyme and damages the molecule, leading to hypersensitivity reactions, nasal irritation, contact dermatitis, ulcers, emphysema, acute bronchitis, liver and kidney sickness, internal bleeding, lung and skin malignancies, and DNA damage. Despite the speed with which Chromium(VI) penetrates cells, it must undergo several modifications in the bloodstream before it can perform as Cr(III) in the tissues of the body (Iqbal, Ashraf and Ashraf 2009). While Chromium(VI) is eliminated from the body, chromate is taken into cells via a transport mechanism that also involves sulphate and phosphate ions. Ions of this type can cause cellular oxidative stress, which has been linked to multiple chronic diseases including cardiovascular disease and neurological disorders. The cellular damage caused by Cr(VI) includes oxidative stress elevation, DNA adduct formation, and chromosomal breakage. Given the substantial body of epidemiological evidence connecting Chromium(VI) to lung cancer, the WHO's International Agency for Research on Cancer (IARC) has classified compounds containing Chromium(VI) as group one human carcinogens with many complex mechanisms of action. Cr(VI) exposure has been associated to many adverse health effects in humans, including eardrum perforation, dermatitis, allergies, respiratory difficulties, ulcers, itchy skin, and even lung cancer. At different times, Cr(VI) radiation can cause oxidative protein alterations, chromosomal damage, and mutations in DNA. It can also cause carcinogenic effects of substances containing Cr(VI) (Sanz-Gallen et al. 2021). Damage to the nasal lining, inflammation, anaemia, stomach ulcers, and other respiratory issues such coughing, nasal blockage, wheezing, and facial erythema can result from inhaling significant amounts of hexavalent chromium. Workplace exposure to hexavalent chromium has the potential to cause the following health problems:

- Inhaling large amounts of hexavalent chromium can irritate or even damage the nasal passages, throat, and lungs (respiratory tract).
- Airborne hexavalent chromium causes lung cancer in workers.
- Hexavalent chromium may cause irritation or even damage to organs if it comes into contact with them in sufficient quantities.

6.3 Microbial Remediation

As can be shown in Table 6.1, many different types of microbes based on their functional groups have evolved in the resistances to Cr(VI). The most well-studied mechanism (Fig. 6.3) of this type of bioremediation is the microbial enzymatic conversion of Chromium(VI) to Chromium(III). Biodegradation of contaminated waste and elimination of Chromium(III) pollution via biological reduction of Chromium(VI) to Chromium hold promise (Song et al. 2016). Chromium-detouring microbes could one day provide a sustainable and green replacement for traditional manufacturing. Bacteria, fungus, and algae are only some of the microorganisms that can be used in these procedures. In place of using biomass (both living and nonliving cells) and biological and agricultural wastes in typical wastewater purification methods, biosorption of Chromium(VI) has been proposed. The bacteria that lead to or aid in the biological decline of Chromium(VI) to less mobile Chromium(VI) may be precipitated for use in cleaning up polluted areas (III). Metal ions can be extracted from the environment by bacteria and used as fuel before being converted to biomass through an enzyme-catalyzed, potentially hazardous chemical breakdown. Microbial remediation involves promoting the breakdown of potentially dangerous compounds in soil, subterranean materials, sludge, water, and leftover bacteria. Multiple bioremediation approaches, such as bioaccumulation, biotransformation, biosorption, and bioleaching, have been shown to be effective at removing Cr and other heavy metals from industrial pollution (Stoltidis et al. 2011). Hexavalent chromium [Cr(VI)] is only absorbed by living organisms through a process called bioaccumulation, which is reliant on the metabolism of these organisms to power the transcellular transit of this toxic metal. There are several stages involved in the bioaccumulation process in bacteria. Toxic heavy metal ions initially bind to a ligand on the cell's outer membrane. Transporter proteins are responsible for bringing the metal-ligand complex from the cell surface inside the cell. Phytochelatins and metallothionein are two types of metal-binding proteins that interact with complexes transported into the cell, triggering reactions like precipitation and methylation (Panda and Choudhury 2005). A larger concentration of metal renders the method ineffective against non-living cells and effectively halts the multiplication of microorganisms. Environmentally beneficial processes such as biosorption, biotransformation, and bioaccumulation degrade and eliminate toxic chromium ions from industrial effluent.

6.4 Biosorption of Chromium(VI)

In contrast to bioaccumulation, which only occurs in actively metabolic cells, biosorption can happen in both actively metabolic cells and decaying microbial biomass. Ion exchange, surface precipitation, or a rigorous manufacturing procedure are used to remove harmful ions like Cr(VI) from the bacterial cell wall. There is a wide variety in composition and organization in the cell walls of bacteria. Algae's cell

Table 6.1 Most studied microbes and responsible functional groups for chromium(VI) remediation

S. No	Microbes	Functional groups	References
1	*Aspergillus Niger*	$-NH_2$, $-OH$, and $-COOH$	Chhikara et al. (2010)
2	*Bacillus marisflavi*	Phosphate groups, OH, free phosphates, $-NH$ acetamido group, and $-CN$	Kim et al. (2022)
3	*Chlorella miniata*	$-CH_3$, O–H, C–H, P = O, COO−, C–O–, and N–H	Congeevaram et al. (2007)
4	*Klebsiella* sp.	O–H, $-NH_2$, $-COOH$, $-CONH-$, $-CH_2$, and C=C	Han et al. (2008)
5	*Pleurotus ostreatus*	COOH and NH	Pun, Raut and Pant (2013)
6	*Streptomyces werraensis*	N–H, O–H, C–O–, and C–H	Dadrasnia et al. (2015)
7	*Pseudomonas aeruginosa*	Carboxylic group, C–Cl, $-NH$, $-OH$, $-C-C-$, and S–	El-Naggar et al. (2020)
8	*Aspergillus foetidus*	C = O, N = C = S, C–O, PO_{4-3}, amine, and OH	Ahluwalia and Goyal (2010)
9	*Arthrinium malaysianum*	C–O, –OH, C_xOH, C = O, and $-NO_2$	Majumder et al. (no date)
10	*Scenedesmus sp.*	N–H, C–O, C–H, O–H, C–F, $-COOH$, C–Br, and C–Cl	Han et al. (2008)

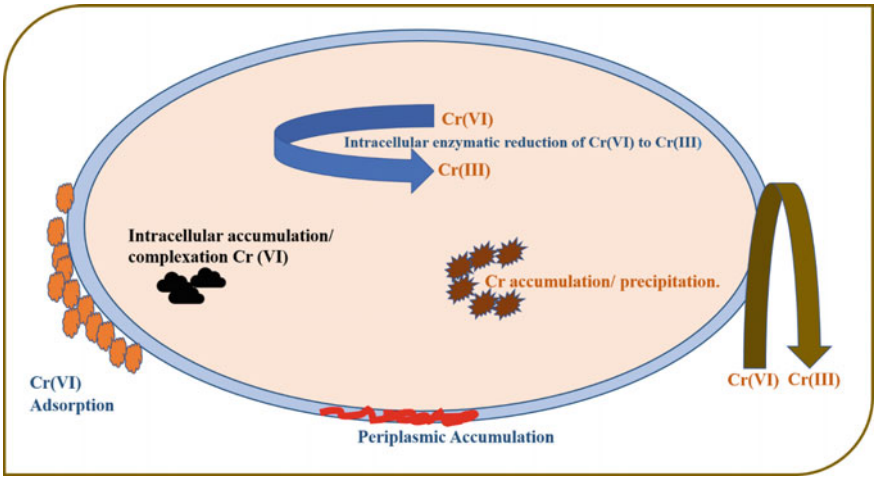

Fig. 6.3 The Microbial resistance mechanisms for Cr(VI)

walls are made up mostly of sulfonated polysaccharides, alginate, and mannans, as opposed to the fungal cell walls' glycoproteins, glucans, melanin, chitin, and peptidoglycan. Both the biomass used in biosorption and the functional groups in the microbial cell wall play significant roles in the biosorption process. For the removal

of harmful heavy metals from polluted environments, the biosorption approach is preferred over more traditional kinds of bioremediation. The production of multi-functional groups and the even distribution of binding sites across the cell surface are just two of the many advantages of the biosorption method. In addition to the bio-great sorbent's efficiency and renewability, there is also the potential for metal recovery (De Pauw and Van Vaerenbergh 1983). As a result of these and other advantages, research into the biosorption of heavy metals by diverse microorganisms, especially hexavalent chromium, has expanded. The ability of some organisms to take in heavy metals and then drive their transition into less dangerous forms has captivated environmental protection experts, engineers, and biotechnologists for decades. The Chromium(VI) ion is removed through ion exchange, surface precipitation, or a similar mechanism after it has bound extracellularly to different functional groups of the microbial cell wall. Organisms like microbes have had thousands of years to develop strategies for dealing with environmental pressures. Microorganisms' defense mechanisms against heavy metals are quite diverse. Methods include active transport of metal ions, metal ion reduction, and extracellular and intracellular sequestration are all at play. The metabolic state of the cell will determine which of two biological processes—biosorption or bioaccumulation—will be responsible for the removal of heavy metals. Increased membrane permeability plays a role in the metabolism-dependent process of heavy metal uptake by cells. This happens when metal ions accumulate inside a bio-cell and pollutants are taken up by the cell. Sorbent's Biosorption allows for the rapid, self-sufficient, metabolically passive sequestration of heavy metal ions by dead/inactive biomaterials. During biosorption, heavy metals adhere to the exterior of cells, while during bioaccumulation, they bind to inside proteins such metallothionein. These biosorption methods all require the use of a bio-sorbent that is solid at room temperature (Chen et al. 2023). The sorbate is drawn to the sorbent and attached to it in a number of ways due to the sorbent's stronger affinity for the sorbate species. Biosorption is the physicochemical reaction between metal species and the components of the cells of biological species. Many different mechanisms, such as accumulation, adsorption, oxidation, methylation, and reduction, allow them to survive in environments with high concentrations of hazardous Cr(III)(VI). These creatures have binding sites where heavy metal ions can become trapped and be taken up by the cell. Functional groups present in bio-sorbents include phosphates, imidazole, carboxyl, amino, thioether, hydroxyl, sulphate, amine, phenol, and sulfhydryl. Metal ions are utilized by microorganisms in a broad variety of ways, including as cell wall-associated metals, metal siderophores, intracellular accumulation, extracellular polymeric connections with extracellular mobilization or immobilization of metal ions, and transition and metal volatilization. Physicochemical interactions between ions in solution and the charged surface groups of microorganisms include ion exchange, adsorption, complexation, and microprecipitation. The bioaccumulation process begins with metal uptake and continues through metal binding to metallothionein, Cr localization inside cell component, extracellular precipitation, metal deposition, and complexation. There are three stages in the microbial removal of Chromium(VI): cellular translocation, surface binding, and intracellular reduction (III). Due to the activity of chromate reductase enzymes and the metabolism of

Chromium(VI) metabolites, microbes are able to decrease Chromium(VI) on their surface, in their extracellular and intracellular habitats, and in their food sources (Peng et al. 2023).

6.5 Hexavalent Chromium to Tetravalent Chromium Reduction

Effluents from the textile, galvanizing, leather, tannery, metallurgical, paint, electroplating, and metal processing and refining industries are a global and regional source of harmful metal ions. These companies harm the aquatic environment by discharging metal ions into nearby waterways and open pits. The most likely environmental effect of these metals would be a shift in the total amount of surface and groundwater. As well as posing a threat to human health, these contaminants also pose a risk to animal life (Peng et al. 2023). Discomfort in the body and potentially deadly diseases like kidney failure and cancer stem from this. As opposed to its divalent (Cr^{2+}) form, the trivalent (Cr^{3+}) form is more bioavailable, more stable, and less harmful to humans. EPA and EU regulations limit Cr discharge into surface water bodies to less than 0.05 mg/l and total Chromium output to less than 2 mg/l due to its high toxicity.

6.6 Factor Affecting Bioremediation

Biological therapy refers to the process by which microorganisms including bacteria, fungus, and plants break down, transform, immobilize, and remove several potentially harmful chemicals from the environment. Involving microbes in the process is advantageous because the enzymatic pathways within them work as biocatalysts, speeding up the rate at which biochemical reactions can happen and ultimately destroying the offending contaminant. Microbes can combat pollution because they have access to a wide variety of nutrients, energy sources, and building materials. The success of bioremediation depends on a variety of variables, such as the kind and concentration of contaminants, the state of the surrounding environment, and the existence of appropriate microorganisms (Zhou et al. 2018). Inhibiting interactions between bacteria and pollutants slows down degradation. In addition, bacteria and pollutants do not spread uniformly. Bioremediation processes are difficult to regulate and optimize for a number of reasons. Pollutants being accessible to microbes, and microbes being present that can break down hazardous pollutants.

6.6.1 Availability of Nutrients

The rate and efficiency of biodegradation, as well as microbial growth and reproduction, are all affected by the availability of nutrients. Changing the C:N:P ratio of bacteria, especially by adding essential nutrients like P and N, might enhance their degradation competence. Carbon, nitrogen, and phosphorus are only few of the nutrients that microorganisms need to live and keep reproducing (Xie et al. 2022). The degree to which hydrocarbons break down is also restricted at low concentrations. If the correct nutrients are added, metabolic activity of microorganisms and, thus, the rate of biodegradation, can be increased even in subfreezing conditions. In aquatic environments, biodegradation is hindered due to a lack of accessible nutrients. These nutrients exist in nature, but in minute quantities.

6.6.2 Environmental Factors

Interactions can be predicted during the process by utilizing the metabolic capability of the microorganisms and the physicochemical parameters of the targeted pollutants. However, contextual circumstances at the interaction site alter the interaction's actual success. Many environmental factors, including but not limited to temperature, site characteristics, water solubility, redox potential, pH, nutrients, moisture, oxygen concentration, soil structure, and temperature, affect the growth and activity of microorganisms. The rate of decay is dependent on the aforementioned factors (Xu et al. 2019). Bioremediation can take place in a variety of pH levels, although the optimal range for microbial decomposition in aquatic and terrestrial settings is 6.5–8.5. The rates of degradation of pollutants are affected by a wide variety of factors, including the pH of aquatic and terrestrial ecosystems, the types of soluble elements present, and the quantities of those materials. The survival of microbes and the amount of hydrocarbons present are most strongly influenced by temperature. Most oleophilic bacteria are metabolically quiescent because their cellular transport channels shut down or even freeze due to the extremely cold water in this location. There seems to be a sweet spot for the degradation process when the metabolic cycle of the associated biological enzymes is at its most potent. In addition, a particular temperature is required for the decomposition of a given material. The rate at which bioremediation proceeds is affected by temperature because it affects the physiological characteristics of the microbes involved. At the optimum temperature, microbial activity rates reach their maximum and then gradually decline. The rate of decline picked up speed as the temperature rose or fell, and it levelled off once it reached a certain threshold. Figure 6.4 presents a schematic flow of biosorption process for Cr(VI) by microorganisms.

The acidity, basicity, or alkalinity of a chemical influences the metabolic activity of microorganisms and the pace at which the chemical is removed. Soil pH is a good indicator of the soil's capacity for supporting microbial growth. Because of how pH

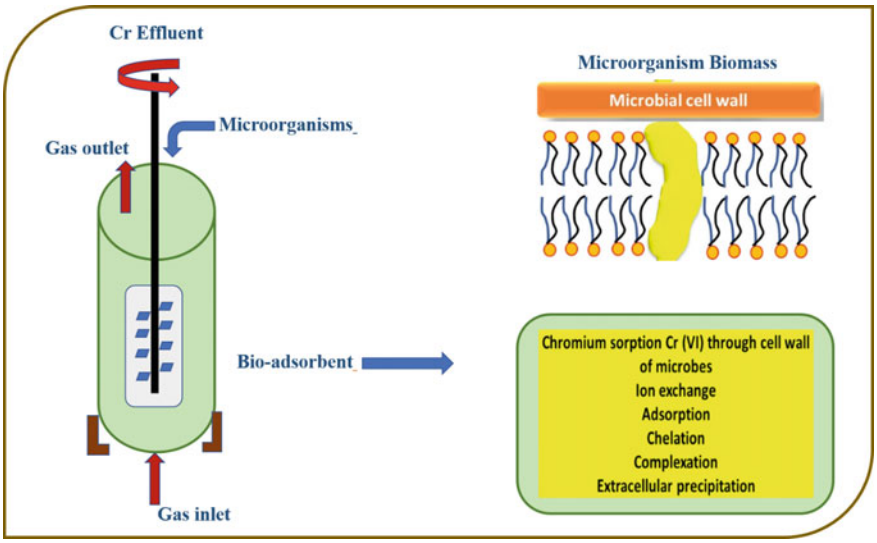

Fig. 6.4 A schematic flow of biosorption process for Cr(VI) by microorganisms

variations affect metabolic processes, the outcomes were unfavorable whether the pH was raised or lowered. Cleanup attempts could be hampered by the toxicity of certain contaminants at high quantities, which has an adverse effect on microorganisms. Toxicants, concentrations, and exposed microorganisms all have a role in determining the extent and mechanisms of toxicity. Specific forms of life are extremely sensitive to a wide variety of organic and inorganic substances (Xu et al. 2022). The different microbes that were reported in terms of their mechanisms, such as transformation, bioaccumulation, and biological removal are presented in Tables 6.2, 6.3 and 6.4.

6.7 Future Prospects

Numerous bioremediation procedures, in particular competent reduction approaches by bacteria, have been developed to tackle the difficult problem of eliminating Cr(VI) contaminants from the environment (Lin et al. 2003). Cleaning, managing, and repairing polluted ecosystems through bacterial metabolism is where microbial degradation shines as a technique. Microorganisms offer electrons to decrease Cr through either endogenous enzymes or externally introduced reducing chemicals (VI). However, the rate at which undesirable waste chemicals are degraded can be slowed by a number of factors, including the presence of competing biological agents, unfavorable external abiotic conditions (pH, moisture, aeration, temperature), a lack of food, and poor pollutant bioavailability. These features make natural biodegradation less effective, leading to unfavorable outcomes. Simply said, bioremediation

Table 6.2 Microbial species that have been reported for the transformation of Cr(VI) and optimal condition

Microorganisms	Optimal condition	Removal efficiency	Isolation source	Initial [Cr(VI)]	References
Bacillus sp.	Agitation: 100 rpm; Temp: 21 °C; pH: 6.9; with 0.5% glucose	100% in72 h	Tannery contaminated soil	10 mg L^{-1}	Zahoor and Rehman (2009)
Bacillus sphaericus	Temp: 25 °C; pH: 6.0; Agitation:120 rpm; with 1.0 g L^{-1} glucose	62% in 48 h	Contaminated soil	20 mg L^{-1}	Ibrahim et al. (2012)
Providencia sp.	Temp: 37 °C; pH: 7.0; Rotating speed: 200 rpm	100% in 96 h (200 mg L^{-1})	Contaminated soil	100, 200, 300 mg L^{-1} $K_2Cr_2O_7$	Thacker et al. (2006)
Acidithiobacillus thiooxidans	Temp: 30 °C; pH: 2.5; Rotating speed: 150 rpm; with Sulphur medium	100% in 1 d	–	2.5 mg L^{-1}	Bhattacharya et al. (2019)
Acinetobacter haemolyticus	Temp: 30 °C; pH: 5–7	100% in 36 h	Effluent from textile	50 mg L^{-1}	Zakaria et al. (2007)
Ochrobactrum sp. CSCr-3	Temp: 35 °C; pH: 10	80% in 30 h	Soil from chromium landfill	200 mg L^{-1}	Wang et al. (2019)
Serratia sp. Cr-10	Temp: 37 °C; pH: 7.0; 1% (w/v), With fructose	100% after 12 h	Soil from chromium contaminated area	10, 20 mg L^{-1}	Zhang et al. (2011)
Cellulosimicrobium sp. MWM81	Temp: 37 °C; pH: 7.0	45% in 48 h	Contaminated soil	10 mM	Zahoor and Rehman (2009)
Acinetobacter guillouiae SFC 500-1A	Temp: 28 ± 2 °C; pH: 8- 10 Agitation:150 rpm (phenol source)	~62% in 72 h	Sludge from tannery	10 mg L^{-1}	Vendruscolo et al. (2017)
Bacillus Subtilis MNU16	Temp: 30 °C; pH: 7.0	75% within 72 h	Soil obtained from coal mining	50 mg L^{-1}	Upadhyay et al. (2017)
Arthrobacter sp. LLW01	Temp: 22 °C; pH: 7–8; Rotation speed: 150 rpm; with 15 mM of glucose	50% in 144 h	Contaminated soil	50 μM	Li et al. (2021)

(continued)

Table 6.2 (continued)

Microorganisms	Optimal condition	Removal efficiency	Isolation source	Initial [Cr(VI)]	References
Penicillium oxalicum SL2	Temp: 30 °C; pH 5–7: Agitation speed: 200 rpm	100% within 144 h	Indoor air	1,000 mg L^{-1}	Yu et al. (2019)
Arthrobacter sp.	Temp: 21 °C; pH: 6.9; Agitation speed: 100 rpm; medium contains 0.5% glucose	100% in 46 h	Tannery contaminated soil	20 mg L^{-1}	Zahoor and Rehman (2009)
Bacillus atrophaeus MM20	Temp: 21 °C; pH: 6–7; Agitation speed:100 rpm	94% after 50 h	Tannery contaminated soil	10 mg L^{-1}	Patra et al. (2010)
Arthrobacter sp. SUK 1201	Temp: 35 °C; pH value: 7; Rotation speed:120 rpm; medium with1.0 g L^{-1} glucose	67% in 7 days	Overburden from chromite mine	2.0 mM	Dey and Paul (2012)
Aspergillus niger (CICC41115)	Temp: 37 °C; pH value: 7.0; roation speed: 150 rpm	100% in 84 h	Soil from commercial	50 mg L^{-1}	Fernández et al. (2018)
Pseudomonas sp. JF122	Temp: 30 °C; pH: 6.5; Agitation speed: 150 rpm	100% in 72 h	Contaminated site	2.0 mg L^{-1}	Islam et al. (2019)
Cellulosimicrobium sp. KX710177	Temp: 35 °C; pH: 6–7; Agitation speed: 120 rpm	62% after 96 h	Wastewater from tannery	300 mg L^{-1}	Bharagava and Mishra (2018)
Bacillus sp. SFC 500-1E	Temp: 28 °C; pH value: 7; Rotation speed:150 rpm	43% after 72 h	Tannery sediments	50 mg L^{-1}	Ahmed (2018)
Bacillus sp.	Temp: 35 °C; pH: 6–7; Agitation speed: 200 rpm;	> 95% for 72 h (40 mg L^{-1})	Soil from chromate pollutant	10, 40 mg L^{-1} $K_2Cr_2O_7$	Elangovan et al. (2006)
Acidithiobacillus ferooxidans	Temp: 30 °C; pH: 1.8; Agitation speed:150 rpm;	100% in 3 d	–	5.0 mg L^{-1}	Bhattacharya et al. (2019)
Burkholderia cepacia MCMB-21	Temp: 35 °C; pH: 9; 2% NaCl; 2% lactose	98% in 36 h	Alkaline crater lake	75 mg L^{-1}	Sanjay et al. (2017)
Pseudomonas sp. G1DM21	Temp: 37 °C; pH value: 7; Rotation speed: 150 rpm	99.7% in 48 h	Landfill from industrial contamination	500 μM	Das et al. (2021)
Bacillus sp. CSB-4	Temp: 35 °C; pH: 7.0; Agitation speed:100 rpm	>90% in 144 h	Soil from chromite mine	100 mg L^{-1}	Das et al. (2021)

Table 6.3 Involvement of microbes for the involvement of bioaccumulation for Cr(VI) and related conditions

Microbe	Optimum conditions	Source of isolation	Initial concentration of [Cr(VI)]	Efficiency of bioaccumulation & time	References
Streptomyces sp. MC1	Temp: 30 °C; agitation speed:220 rpm pH: 6–7	Sediment obtained from contaminated site	50 mg L^{-1}	52% for 72 h	Ahmed et al. (2016)
Acinetobacter sp. PD12S2	Temp: 37 °C; pH: 7.0; medium contains 4.0 g L^{-1} glucose	Tannery waste	8.86 mg L^{-1}	Uptake of 0.19 mg L^{-1} h^{-1}	Panda and Sarkar (2012)
Escherichia coli VITSUKMW3	Temp: 30 °C; pH: 7.5	Water outlet from chromite mining	20 mg L^{-1}	40% for 5 h	Upadhyay et al. (2017)
Arthrobacter sp. Sphe3	Temp: 30 °C; pH: 8.0;	-	45 mg L^{-1}	100% Accumulation	Ramrakhiani et al. (2011)
Baciilus circulans	–	Effluent from tannery	50 mg L^{-1}	Within 24 h	Shukla et al. (2012)
Exiguobacterium sp. ZM2	Temp: 28 °C; pH: 2.5	Contaminated site and tannery effluent	100 mg L^{-1}	29.9 mg g^{-1} for 120 min	Alam et al. (2011)
Acinetobacter sp. AB1	Temp: 30 °C; pH: 10	Tannery	50 mg L^{-1}	100% for 72 h	Essahale et al. (2012)
Enterobacter aerogenes T2	Temp: 37 °C; pH: 7.0; 4.0 g L^{-1} glucose	Effluent from tannery	8.86 mg L^{-1}	0.35 mg L^{-1} h^{-1} (uptake)	Panda and Sarkar (2012)
Bacillus subtilis VITSUKMW1	Temp: 30 °C; pH: 7.5;	Water outlet from chromite mining	20 mg L^{-1}	40% for 8 h	Upadhyay et al. (2017)
Acinetobacter sp. B9	Temp: 30 °C; pH 7.0; agitation speed: 200 rpm	Wastewater of chrome treatment plant	7.0 mg L^{-1}	67% for 24 h	Bhattacharya and Gupta (2013)
Enterobacter sp. DU17	Temp: 37 °C; pH: 7.0; agitation speed: 180 rpm; with 0.2% fructose	Waste dump from tannery	50 mg L^{-1}	Approximately 79%	Chen et al. (2022)

(continued)

Table 6.3 (continued)

Microbe	Optimum conditions	Source of isolation	Initial concentration of [Cr(VI)]	Efficiency of bioaccumulation & time	References
Streptomyces werraensis LD 22	Temp: 41 °C; pH: 7.0; agitation speed: 100 rpm	Residues from animal fecal	250 mg L^{-1}	51.7% for 7 d	Bhattacharya et al. (2019)
B. mycoides 200AsB1	Temp: 30 °C; pH 7.0; agitation speed:180 rpm	Rhizosphere obtained from Pteris vittata	25 mg L^{-1}	100% within 25 h	Bhattacharya et al. (2019)
Aspergillus sydowii	Temp: 28 °C; pH 5.0; agitation speed: 80 rpm	Sediment from Mangrove	50 mg L^{-1}	24.9% for 7 d	Bhattacharya et al. (2019)
Mixed culture	Temp: 20 °C; pH: 9.0; nutrient broth with 4% NaCl	Wastewater from industrial saline effluent	50 mg L^{-1}	89% for 5 d	Koçberber and Dönmez (2007)
Acinetobacter junii ITSUKMW2	Temp: 30 °C; pH: 7.5	Water outlet from chromite mining	20 mg L^{-1}	40% in 8 h	Upadhyay et al. (2017)
Exiguobacterium sp. KSKE41	Temp: 28 °C; pH: 7.0	Polluted soil	10 mM	35% for 48 h	Zahoor and Rehman (2009)
Bacillus subtilis	Temp: 37 °C; pH: 6–9; agitation speed: 180 rpm	Mining samples	0.2 mM	More than 90% within 48 h	Ni et al. (2020)
Saccharomyces cerevisiae	Temp: 25 °C; agitation speed: 100 rpm, pH 5.0	Polluted site	90 mg L^{-1}	99.66% for 3 h	Tang et al. (2021)

can only be effective if conditions are favorable for the growth and development of microorganisms. There have been numerous applications of bioremediation, each with a unique set of circumstances and results. Websites that employ this technique are becoming increasingly common since the benefits generally outweigh the hazards. Many species from many different regions are studied and found to have efficient regulatory processes (De Agostini et al. 2020). However, due to the widespread heavy metal contamination of agricultural land at present, it is imperative that future microbial remediation techniques also focus on the soil and environment,

Table 6.4 Microbe involved for treatment with respect to removal of Cr(VI) and optimal condition

Polluted wastewater	Microbe	Removal efficiency and initial Cr(VI) (mg L^{-1})	Optimal condition	Mode of the treatment	References
Electroplating	*P. aeruginosa A2Chr*	100% for 30 h, 15	Temp: 37 °C; pH: 7.2; agitation speed: 150 rpm	Batch	Chaturvedi (2011)
Electroplating	*P. aeruginosa* A2Chr	93% for 8 h, 10	Temp: 37 °C; pH: 7.2	Rotating bio-contactor using lab-scale	Satarupa and Amal (2010)
Electroplating	*Saccharomyces cerevisiae*	98% for 30 min, 18 ± 1.0	Temp: 25 °C; pH: 2.3; agitation speed: 150 rpm	Batch	Shahida et al. (2017)
Electroplating	(ChromeBac™ system) *Acinetobacter*	99%, 17–81	–	Bioreactor (Pilot scale)	Chen et al. (2022)
Tannery	*P. lilacinus*	100% for 48 h, 50	pH: 8.0	Batch	Wang et al. (2007)
Tannery	*E. aerogenes T2*	84% for 72 h, 1.3	–	Batch	Panda and Sarkar (2012)
Tannery	*B. cereus Cr 1*	73% for 48 h, 2.41	Temp: 35 °C, pH: 8.4; agitation seed: 120 rpm	Batch	Maurya et al. (2022)
Waste Leather Industry	*Arthrinium malaysianum*	30% for 24 h, 2.41	Temp: ambient, pH: 7.3 Shaking condition	Batch	Ramrakhiani et al. (2011)
Electroplating	*P. oxalicumstrain SL2*	100% for 96 h, 96.1	Temp: 30 °C; pH: 7.0	Batch	Fernández et al. (2018)

(continued)

Table 6.4 (continued)

Polluted wastewater	Microbe	Removal efficiency and initial Cr(VI) (mg L^{-1})	Optimal condition	Mode of the treatment	References
Tannery	*P. aeruginosa A2Chr*	60% for 35 h, 40	Temp: 37 °C; pH: 7.0; agitation speed: 150 rpm	Batch	Chaturvedi (2011)
Electroplating	*P. aeruginosa A2Chr*	76% for 4 h, 10	Temp: 37 °C; pH: 7.2	Bioreactor using dialysis	Kumar and Pandey (2006)
Tannery	*Aspergillus sp. FK1*	65% for 7 d, 557	Agitation: 250 rpm; pH: 5.0–55	Lab-scale bioreactor	Yoon et al. (2006)
Electroplating	*Candida lipolytica*	94–100%, 8–30	Temp: 25 °C, pH: 1.92–5.22	Bioreactor (lab-scale)	Konovalova et al. (2003)
Tannery	*Paecilomyces lilacinus*	100% for 18 h, 1.24	pH: 8.0	Batch	Garbisu et al. (1998)
Electroplating	*B. cereus IST105*	76% for 3d, 968	Temp: 30 °C, pH: 7.0	Batch	Ackerley et al. (2004)
Electroplating	*Acinetobacter* sp. B9	93% for 144 h, 30	Temp: 30 °C, pH: 7.0; agitation seed: 200 rpm	Batch	Viti et al. (2003)
Tannery	Fungal Consortia	100% in 36 h, 9.86	Temp: 28 °C, pH: 4.0	Stirred bioreactor	Kotaś and Stasicka (2000)
Electroplating	*Penicillium oxalicumstrain SL2*	100% for 48 h, 40.6	Temp: 30 °C; pH: 7.0; agitation seed: 200 rpm	Batch	Yoon et al. (2006)

as has been reported on bioremediation cutting-edge technologies. Following are some suggestions for addressing the identified gaps in the research:

(1) The complexity of natural environmental variables, especially soil, makes it challenging to achieve the goal of governance using entirely manufactured bacteria. Using a bacterial synergy, mixed cultures of microorganisms improve both environmental adaptability and treatment success.
(2) This is a suitable method for screening microorganisms for their ability to decrease or bind multiple hazardous metals, as polluted areas typically include more than one type of heavy metal.
(3) Bioremediation performs poorly and takes considerably more time than physical and chemical materials for removing heavy metals. The development of a consortia of microorganisms to enhance process efficiency should be the focus of future research.

6.8 Conclusion

This chapter analyzes the impact of metal accumulation pathways on metal removal as it relates to Cr(VI) bioremediation and biosorption by microorganisms. Reducing environmental Chromium(VI) levels with microbial treatment is one of the most effective and long-lasting methods. These bacteria' extraordinary homeostasis and tolerance of toxic metals systems are what have allowed them to thrive in such a harsh environment. Microbe-based technique, or biosorption, is a safe and inexpensive way to remove chromium from water. Furthermore, it shows great promise for future applications. Transport mechanisms such as precipitation, complexation, ion exchange, cell membrane, and physical adsorption are essential for biosorption. Several factors, including contact time, pH, temperature, biomass, and metal content, can drastically affect the efficiency of a bio-biosorption sorbent. Microbe-based technique, or biosorption, is a safe and inexpensive way to remove chromium from water. Furthermore, it shows great promise for future applications. Transport mechanisms such precipitation, cell membrane, ion exchange, complexation, and physical adsorption are essential for biosorption to occur. The effectiveness of a bio-biosorption sorbent is sensitive to a wide range of conditions, such as pH, temperature, biomass, contact time, and metal content. Removing many contaminants at once may be challenging in industrial wastewaters because, unlike laboratory solutions, they can contain dangerous heavy metals. As this review has shown, further study is needed to fully realize the potential of microbial biotechnology for environmental improvement.

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