Chapter 4
A Study on Different Bioremediation Approaches to Hexavalent Chromium

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Abstract Hexavalent chromium is a geochemical element and designated as priority pollutant. It has mutagenic and carcinogenic property and poses a serious threat to both humanity and ecosystem. Despite of toxicity, little dose of chromium acts as micronutrient in the diets of animals and humans and also helps in sugar, protein, and lipid metabolism in mammals. Chromium speciation exists in two states: hexavalent chromium and trivalent chromium, out of which the latter is nontoxic. Health problems associated with high dose of chromium are ulcers, diarrhea, irritation of skin, eye and lung carcinoma, dysfunction of kidney, birth defects, and reduced reproductive health. The lethal dose $(LD)_{50}$ value for oral toxicity in rats is 50–100 mg kg^{-1} and 1900–3000 mg kg^{-1} for Cr (VI) and Cr (III), respectively. Due to high toxicity of Cr (VI) compounds, there is multiplicity of treatment technologies including physico-chemical and biological methods. Physico-chemical methods are high energy demanding, have high operational cost, generate secondary pollutant, and sometimes have lesser efficiency due to high metal concentration and interferences. In contrast to physciochemical method, bioremediation of Cr (VI) reduction is operated at low cost, and less energy is required with high efficiency of reduction, no health and environmental hazards. Microorganisms involved in remediation metabolize the chemicals via enzyme-catalyzed pathway converting into harmless compounds and often use compounds as a source of their growth. Despite of all these methods, some green technologies and modification in these techniques also proved to be effective in chromium reduction. This chapter deals with occurrence and fate of chromium, speciation, various treatment technologies, mechanism of reduction and their advantages-disadvantages, pilot-scale studies, and future perspectives in remediating toxic hexavalent chromium.

Keywords Bioreduction · Biotransformation · Constructed wetlands

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4.1 Introduction

The seventh most abundant element and metal found in earth's crust is chromium (Cr) which is excavated as chromite ($FeCr_2O_4$) (Sultana et al. 2014). Being a geochemical element, its presence is found in rocks, fresh water, and mineral soils. Despite of several oxidation states, it is the most stable form, and trivalent chromium Cr (III) and hexavalent chromium Cr (VI) are prevalent in environment (Sultana et al. 2014; Fernandez et al. 2018). Chromium cycle mainly follows oxidation and reduction of its different form. Oxidation of Cr (III) into hexavalent form in sediments and soils occurs by manganese oxide while Cr (VI) is reduced to its trivalent form by soil compounds that are in reduced form. Hexavalent chromium has wide range of industrial application like chrome plating, leather tanning, electroplating, stainless steel industries, and wood preservation (Jobby et al. 2018). United States Environmental Protection Agency-USEPA has designated this element as priority pollutant as it becomes easy for the metal complexes to cross the membrane, thereby generating reactive oxygen species (ROS) which in turn alters cellular structure (Fernandez et al. 2018; Fedorovych et al. 2009; Juvera-Espinosa et al. 2006). Owing to toxicity of chromium element, hexavalent chromium is 1000 times mutagenic and 100 times lethal than trivalent state (Chojnacka 2010). Organisms come into contact with chromium via inhalation, oral digestion, or dermal contact. Cr (III) enters through digestive system, and if there enters Cr (VI), simultaneously most of them gets reduced to Cr (III) (Hamilton et al. 2018; Pechancova et al. 2019). Absorption of Cr in the gastrointestinal tract follows the unsaturated passive transport and is severely influenced by substances present in diet. The Cr species then travels in the bloodstream and gets accumulated in the deep organs like liver, kidney, and spleen and then excreted out via urine and negligible amount by bile or hair (Finley et al. 2017). Cr (III) is helpful in human metabolism like cholesterol and triglyceride levels, stability and amalgamation of proteins, nucleic acids, glucose maintenance, and stability of cell membrane (Di Bona et al. 2011; Frois et al. 2011; Fernandez et al. 2014). A study compared rats supplied with less content of Cr (III) and another provided with heavy amount of Cr (III) confirms that those having little amount of trivalent chromium had no adverse consequences and are not used as nutritional supplement. Higher dosing of trivalent chromium forms composite with organic compounds which interferes with metalloenzymatic process (Poljsak et al. 2010) and may cause lung cancers, decrease in reproductive health and birth deficiency (Fernandez et al. 2018).

These polluting agents are directly thrown into water and soil from various sources generates pollution, contamination and demolition of the ecosystem. For the treatment of chromium ions, various technologies have been developed till date from water, wastewater, and soil. Physico-chemical methods like use of activated carbon, chemical precipitation, reverse osmosis, ion exchange, membrane technologies, and adsorption (Krowiak 2013) have been extensively used but sometimes these processes are exceptionally expensive when the metal concentration varies from 1 to 100 mg/L. Another drawback of these techniques is they generate huge quantity of toxic chemical sludge which creates a serious concern for disposal. On the other side, microorganisms interact with chromium via biosorption, enzymatic reduction, and bioaccumulation is gaining grounds due to its low operationality and minimum chemical requirement. Use of scrap iron in reducing Cr (VI) is a promising and emerging technology because of its easy availability, faster reaction rate, and cost-effectiveness.

4.2 Chromium Toxicity and Contamination

Chromium is an essential micronutrient in the diets of humans and animals which is helpful in lipid, sugar and proteins metabolism, but in case of plants and microorganisms, there is no such known necessity of chromium in their metabolic pathways. However, chromium is toxic at high level depending upon its oxidation state. In between its two oxidation states (III) and (VI), hexavalent state is highly lethal, carcinogenic, and mutagenic and has effects on lowering reproductive capacity and birth defects as well. The casualty may occur due to large dosage of Cr (VI). The lethal dose $(LD)_{50}$ value for oral toxicity in rats is 50–100 mg kg^{-1} for Cr (VI), and for Cr (III), it is 1900–3000 mg kg^{-1} (Jobby et al. 2018). The other toxicity effects associated with chromium are that it reduces the plant's capacity to grow by decreasing uptake of nutrients and photosynthesis. The morphological, physiological, and biochemical processes of plants are rigorously affected by high dose of chromium which induces formation of reactive oxygen species. In plants, a phenomenon called chlorosis and necrosis indicates its toxicity.

Chromium has corrosion-resistant quality due to which it has been widely used in industrial processes like manufacturing of stainless steel, metallurgical, tanning, wood preservation, electroplating, pulp and paper, and production of paints. These industries generate huge amount of wastes in the environment. In many countries, the chromium contamination in surface water has crossed its permissible limits approximately 0.5–2 mg/L. (US Environmental Protection Agency 1987) and (Guidelines for drinking-water quality 1996) reported that the total chromium content of 84 mg/L and 0.2–44 mg/L has been found in the surface water of Central Canada and USA, respectively. The contamination to groundwater by Cr (VI) is due to leaching and seeping of dumped wastes as a filling material possess a great threat to health. Major source of Cr (VI) pollution are tannery industries where chromium compound has been used to tan hides. However, Cr is not completely used in the tanning process of leather, a large portion of it is discharged as it is in the effluent. Around the world, approximately 40 million tonnes of chromium waste is produced by tanning industries which is directly released into water and disposed of on land. It has been detected in India that around 2000–32,000 tonnes of elemental chromium are discharged annually by tannery industries in the environment having chromium concentration ranging between 2 and 5 g/L which is higher than the permissible limit.

4.3 Chromium Reduction by Different Methods

4.3.1 Physical and Chemical Methods

Physical methods of Cr (VI) reduction include membrane filtration, granular activated carbon, adsorption, photocatalysis, electrodialysis, soil washing (Wang et al. 2008), and chemical methods include use of chemicals like ferrous sulfate, sulfur dioxide, barium sulfite, sodium metabisulfite, lime and limestone, and sodium sulfite, for reduction of Cr(VI) to Cr(III). The disadvantages of these methods are high energy demand, high operational cost, generation of secondary pollutant and sometimes lesser efficiency due to high metal concentration and interferences (Zouboulis et al. 2004). A list of physico-chemical treatment technologies is discussed in Table 4.1.

4.3.2 Biological Methods

Bioremediation is one of the best approachs toward remediating heavy metal pollution. It is a phenomenon of transforming harmful pollutants into nontoxic compounds by involving living organisms (fungi, bacteria, plants, yeast, and algae). The advantage of this method is that there is low operational cost, less energy requirement, high efficiency, no health and environmental hazards, metal recovery and possibility to reuse. Microorganisms involved in remediation metabolize the chemicals via enzyme-catalyzed pathway converting into harmless compounds and often uses compounds as a source of their growth. Some of the parameters that affect the efficiency of the process are chemical nature of pollutants, structure of the compound, pH and temperature of the system, nutritional state, presence of microbial community and hydrogeology. Bioremediation approaches to heavy metal treatment are bioaccumulation, biosorption, and biotransformation.

4.3.2.1 Bioremediation by Fungi

Fungi has been well known for biosorption of Cr (VI). Several genera of fungi had been discovered in biosorption process such as *Aspergillus oryzae*, *Trichoderma* sp., *A. niger*, *Fusarium oxysporum*, *Trichoderma inhamatum*, *Hypocrea tawa*, *Fusarium oxysporum* NCBT-156, *Saccharomyces cerevisiae*, *Penicillium griseofulvum* MSR1, and *Acremonium* sp.. Cr (VI) biosorption by fungi can be accomplished by metabolism-dependent and independent pathway. The mechanism for Cr (VI) sorption involves adsorption of Cr (VI) on the cell surface of fungi by formation of a chemical bond that have some functional groups present. The presence of hydroxyl, carboxyl, amino, and carbonyl groups on the cell surface helps in attachement of Cr (VI) on the wall of fungal cell. Involvement of different

Table 4.1 Different physico-chemical methods of Cr (VI) removal

Materials applied	Mechanism of treatment	Cr (VI) concentration (mg/L)	Efficiency (%)	Advantages	Disadvantages	References
Mixed maghemite–magnetite		0.5–3.5	95	–	–	Chowdhury et al. (2012)
Activated carbon-coated α-Fe2O3 nanoparticles	Adsorption	25	94	Faster removal rate	Inhibition of Cr removal due to deprotonation of functional groups at high pH	Lia et al. (2019)
Nanoscale zero-valent metal by sodium borohydride reduction	Reductive immobilization	60	99.99	Faster reaction rate	Reduction efficiency decreased while increasing Cr concentration	Fang et al. (2011)
FeS-coated iron (Fe/FeS) magnetic nanoparticle	Adsorption, oxidation-redcution, precipitation	25	82.1	Aggregation of particles was prevented providing larger BET surface area and higher removal efficiency	Limitation of reactive sites with increase in Cr concentration	Gong et al. (2017)
Carboxymethyl cellulose (CMC) stabilized microscale iron sulfide (FeS)	Reduction	1407 mg/kg Cr (VI) spiked in soil	98	Higher removal and immobilization efficiency	–	Li et al. (2017)
Biochar-supported zero-valent iron nanoparticles		320 mg/kg Cr (VI) spiked soil	100	Enhanced immobilization and decreased migration of Cr, reduced bioavailability and bioaccumulation, improved soil fertility	–	Su et al. (2016)

(continued)

Table 4.1 (continued)

Materials applied	Mechanism of treatment	Cr (VI) concentration (mg/L)	Efficiency (%)	Advantages	Disadvantages	References
Graphene oxide incorporate mixed matrix membrane (MMM) hollow fibers	Adsorption	10, 25, 50, 100, 250, 500	88	–	–	Mukherjee et al. (2014)
Iron electrodes	Electrocoagulation	49.96	100	–	–	Khan et al. (2019)
MIL-53(Fe) as positive photoelectrode and active carbon as negative electrode	Photocatalysis and capacitive deionization	50	81.6	Visible light absorption capacity was good, bigger surface area, rich metal-containing catalytically active sites, and desirable pores	MIL-53(Fe) does not fit for practical application	Houa et al. (2018)
TiO2 P25	Photocatalysis	10–200	79	–	–	Sanea et al. (2018)
Powdered activated carbon (PAC)	Adsorption	50	>80	High adsorption rate	Quick saturation with time	Wang (2018)
Graphene-coated iron oxide nanoparticles	Adsorption	25–175	74	–	–	Khare et al. (2018)

fungal species in Cr (VI) reduction exerts different results such as *Saccharomyces cerevisiae* from culture collection bank reduced 200 mg/L of Cr (VI) in 24 h with 85% efficiency (Mahmoud and Mohamed 2017), *A. niger* was capable of reducing 18.125 mg/L having efficiency 96.3 and operating duration was seven days (Sivakumar 2016), *Paecilomyces lilacinus* isolated from tannery effluent reduced 200 mg/L Cr in 120 h with 100% removal (Sharma and Adholeya 2011).

4.3.2.2 Bioremediation by Bacteria

Cr (VI) remediation using bacteria proved to be a very efficient, cheaper, no chemical input, less energy requiring method that converts it in less toxic Cr (III) form. Both gram positive and gram negative bacteria, living and dead cells are efficient in remediation approaches. A work reported ability of chromium biosorption in *B. circulans* (34.5 mg Cr g^{-1} of dry weight), *B. megaterium* (32.0 mg Cr g^{-1} of dry weight) and *B. coagulans* (39.9 mg Cr g^{-1} of dry weight) and it was found out that the biosorption ability of living and dead cells of *B. coagulans* and *B. megaterium* were compared and dead cells were found to be more effective for chromium biosorption. Some of the bacterial species applied for the treatment of hexavalent chromium reduction are provided in Table 4.2.

4.3.2.3 Bioremediation Using Algae

Biosorption by algae is another remediation method for Cr (VI) which involves adsorption of metal on the algal cell surface, and may further follows accumulation inside the cell. Specific molecules like phytochelatins, metallothioneins, guluronic acid, alginates, sulfated polysaccharides with hydroxyl, amino, carboxyl, and sulfate as functional groups trigger Cr (VI) remediation. Variety of algal species has been used in Cr (VI) removal like, *Euglena*, *Scenedesmus*, *Cladophora* sp. *Selenastrum*, *Ceramium virgatum*, *Spirulina* sp. *Nostoc linckia* and *Chlorella vulgaris*. It was studied by (Pradhan et al. 2017) using *Chlorella vulgaris* for 3.22 mg/L of hexavalent chromium. At 28 °C, complete reduction was observed within 12 days. Furthermore, organelles (Chloroplasts) were extracted from *Chlorella vulgaris* for reduction and the results stated that it adsorbed total chromium (21%) and reduced 70% of Cr (VI). An algal species, *Sargassum cymosum*, has been used in Cr (VI) reduction as an electron donor and the reduction was due to acidic carboxylic group associates with the surface of the biomass which mediates sequestration of trivalent chromium. During the reduction process, the oxidation of biomass forms the binding sites on the surface.

Table 4.2 Different bacterial species in Cr (VI) reduction

Species	Cr (VI) concentration (mg/L)	Duration of reaction (h)	% efficiency	Growth condition	References
Cellulosimicrobium sp.	50, 100, 200, and 300	24 and 96	99.33 and 96.8	–	Bharagava and Mishra (2018)
Bacillus circulans BWL1061	50	–	100	–	Liu et al. (2017)
Serratia sp.	4, 8, 12, 16, 20	36 and 48	100	Aerobic	Upadhyay et al. (2018)
Bacillus sp. (CSB-4)	10–500	144	90	–	Dhal et al. (2010)
Ochrobactrum sp.	300	–	96.5	–	Chen et al. (2016)
Acinetobacter baumannii L2	1000	24	99.58	–	Sathishkumar et al. (2016)

4.4 Mechanism of Cr Reduction by Microbes

Microbial remediation is the process of quickly degrading the lethal pollutants to naturally safer limit in water, sludge, soil, residues, and subsurface materials. (Asha Latha and Sandeep Reddy 2013). The different remediation mechanisms followed by microbes are biosorption, bioaccumulation, and biotransformation. Biosorption is a reversible, passive, and rapid process that involves a biosorbent and a sorbate. (Ahluwalia and Goyal 2007). Enormous variety of microorganisms have been applied for biosorption activity such as cyanobacteria, algae, microalgae (Khoubestani et al. 2015; Kwak et al. 2015; Nemr et al. 2015), yeast (Fernandez et al. 2013; Farina 2012; Khani et al. 2012) fungi (Huang et al. 2016), and bacteria (Wu et al. 2015; Bahafid et al. 2013). Structural integrity and many functional groups like hydroxyl, amino, carboxylate, and phosphate are provided by microbial cell wall that helps in binding of heavy metal ions. The sorption of metal ions requires energy consumption which is provided by citoplasmatic metal binding proteins. A study by (Thatoi et al. 2014) found out that hexavalent chromium removal involves adsorption on functional groups like polysaccharides, amide I, amide II, amide III, carboxyl, and sulfonate and which further accumulates within the cell and thus biotransforming hexavalent chromium to its trivalent form. Biotransformation of Cr (VI) to Cr (III) is mediated by soluble cytosolic proteins or insoluble cell membrane enzymes (Viti et al. 2014; Kadlec and Wallace 2009). Biotransformation in plants is mediated by chemical or enzymatic process. The reduction of Cr (VI) by chemically induced mechanism is mediated by cysteine, sulfite, thiosulfates, and glutathione that are present in the plant cell. The enzymatic method of reduction is carried out by diverse group of bacteria such as *Bacillus* sp., *Pseudomonas* sp., *Staphylococuusarlettae* sp. etc. The presence of soluble and membrane-bound reductases such as flavin reductase, cytochromes, and hydrogenases is used by the bacteria that can use chromate as the terminal electron acceptor in electron transport system. Also, presence of different chromate reductase such as YieF, LpDH ChrR, and NemA, and that are present in section of cytoplasm else are membrane bounded helps in transforming activity. The mechanism of chromium reduction varies with different microorganisms. In yeast, the detoxification occurs indirectly by riboflavin and sulfate and is released to the extracellular medium by the yeast cells. (Fedorovych et al. 2009). A pictorial representation is depicting the reduction of Cr (VI) by microorganism and their effects associated with the process in Fig. 4.1. A flowchart showing different scale-up approach for Cr (VI) reduction is depicted in Fig. 4.2.

4.5 Cr Removal by Constructed Wetlands

Constructed wetlands (CW) play an important role in chromium removal process involving a combination of biological and physico-chemical processes which includes sedimentation, attachment to porous media, plant uptake, and precipitation as insoluble forms (mainly sulfides and (oxy-) (hydroxides) (Maine et al. 2009). Rhizosphere is the most efficient reaction zone where both biological and physico-chemical processes and interaction of microorganisms, plants, and pollutants takes place. CW vegetation in Cr removal follows release of root exudates which impacts metal toxicity and their mobility and provides surface area for microbial growth to occur, and the tissues accumulates Cr in themselves. Root zone accumulates metals and inhibits metal mobility from roots to shoots in vascular

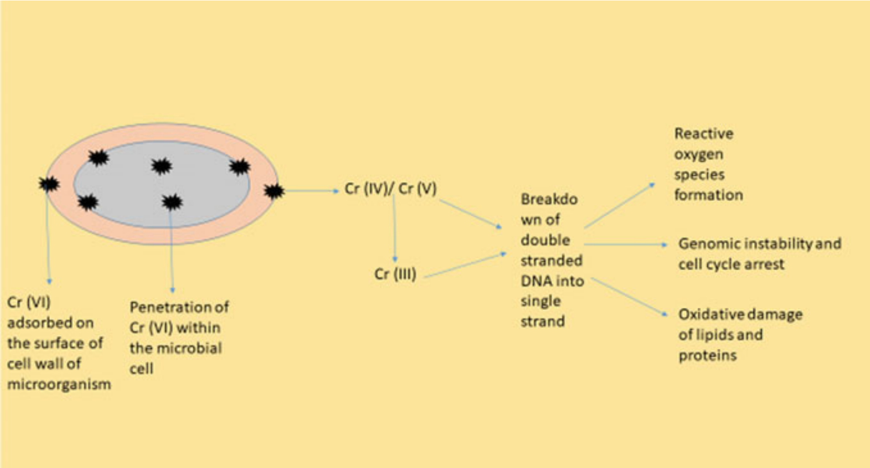
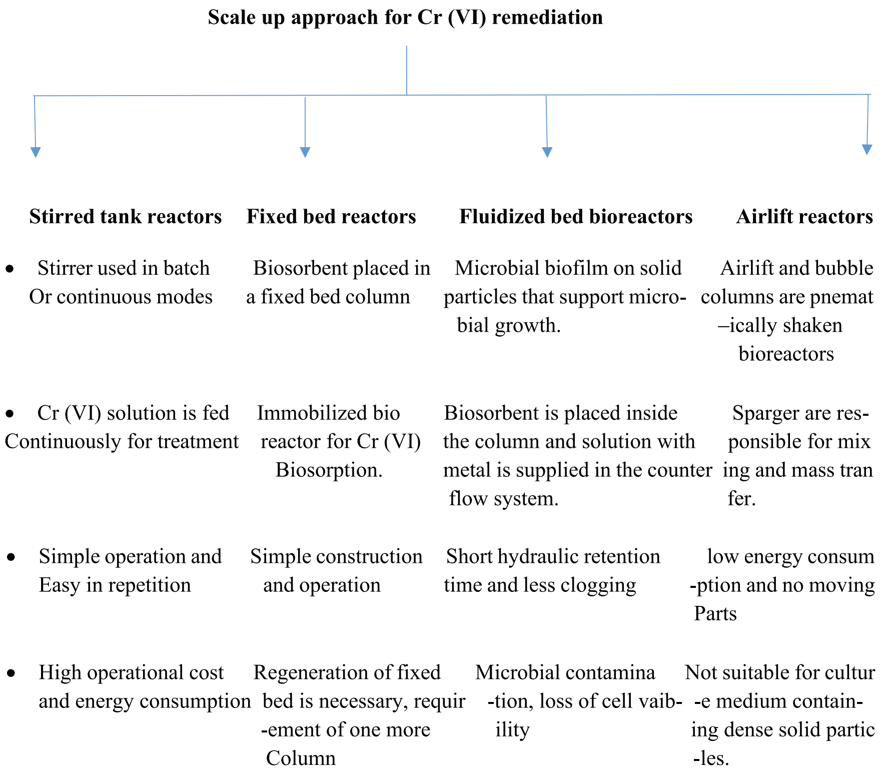


Fig. 4.1 Chromium reduction by microbes and the possible effects associated with cell



Scale up approach for Cr (VI) remediation

Stirred tank reactors	**Fixed bed reactors**	**Fluidized bed bioreactors**	**Airlift reactors**
• Stirrer used in batch Or continuous modes	Biosorbent placed in a fixed bed column	Microbial biofilm on solid particles that support microbial growth.	Airlift and bubble columns are pnematically shaken bioreactors
• Cr (VI) solution is fed Continuously for treatment	Immobilized bio reactor for Cr (VI) Biosorption.	Biosorbent is placed inside the column and solution with metal is supplied in the counter flow system.	Sparger are responsible for mixing and mass transfer.
• Simple operation and Easy in repetition	Simple construction and operation	Short hydraulic retention time and less clogging	low energy consumption and no moving Parts
• High operational cost and energy consumption	Regeneration of fixed bed is necessary, requirement of one more Column	Microbial contamination, loss of cell vaibility	Not suitable for culture medium containing dense solid particles.

Fig. 4.2 Flowchart showing different scale-up approach for Cr (VI) reduction

plants, and also the complex compounds formed with carboxyl group prohibits movement of metals to the shoots. It has been stated by many researchers that Cr ions itself have the binding capability with cell walls of plant tissues which inhibit their translocation. Plants take up metals in their ionic forms by metal ion carriers or channels. Cr ions form chelating compounds with chelators like glutathione, metallothionein protein, organic acids, and phytochelatin within the cells to reduce metal toxicity. Upon entering into the roots, they are either accumulated in the roots or translocated into the shoots through xylem tissues. Afterward, the movement of these ions from shoot xylem to leaf tissue takes place. Absorption of metal ions by root cells takes place via plasmalemma and via passive diffusion by cell walls in the roots of aquatic plants. In the root cells, both Cr (VI) and Cr (III) enter via symplast method where reduction of Cr (VI) to Cr (III) form takes place and get stored in the root zone. The movement of Cr ions is limited in aerial parts and mainly dependent on chemical structure inside the tissue. But uptake of Cr (VI) can damage root membranes due to its high oxidation power and it also restricts uptake of some essential elements like K, Fe, Mn, P, Mg, and Ca due to similarity in their ionic forms.

Microorganisms too have vital role in CW function as they involve metal reduction mainly by an energy-dependent active process called as bioaccumulation and another one is nonenergy-dependent passive process known as biosorption. In CW, microorganisms influence metals by biosorption, metal speciation, methylation of heavy metals and precipitation by sulfate reduction. Metal sorption by some bacteria occurs by formation of amorphous mineral inclusions. Mycorrhizae forms a symbiotic connection between roots and soil and provides adsorptive surface area for metals present in toxic form in the soil (Table 4.3).

4.6 Biostimulation

Biostimulation is the modification of the process to enhance the growth of existing bacteria during course of bioremediation. Various nutrients and electron accepters or donors like lactate, molasses, or acetate are required in the modification process. Based on the physico-chemical properties and indigenous microbial communities, the efficiency of each electron donors in this process depends. It helps in heavy metal reduction and microbial growth kinetics in a specified environmental condition. A study conducted by (Brodie et al. 2011) stated that in presence of acetate as an electron donor, 16 mM Cr (VI) was reduced to zero within 25 days. Some more experiments were conducted by (Varadharajan et al. 2015) using variety of electron donors for chromium reduction based on lactate polymerization. The experiments involved treatment of Cr (VI) contaminated groundwater using different electron donors such as polylactate cysteine, primer hydrogen release compound (HRC), and extended HRC. Both the electron donors proved to be effective in overall reduction process with enhanced biomass and their activity.

4.7 Pilot-Scale Studies

Generally, the findings obtained from laboratory experimental setup do not essentially equate to the results from large scale on-site operating conditions. A very restricted number of pilot-scale experiments have been implemented for Cr (VI) remediation (Table 4.4).

4.8 Future Perspectives in Chromium Removal

The development and certain modification in the reduction processes offer great opportunities for the ongoing heavy metal pollution problem. Fungi and bacteria have been used recently in the proteomic or transcriptomic studies on their response to hexavalent chromium. Certain modifications such as use of immobilized

Table 4.3 Different types of constructed wetlands operational for Cr (VI) reduction

Types of constructed wetlands (CW)	Cr concentration (mg/L)	Porous media used in CW	Time (days)	zTypes of plants used	Removal efficiency (%)	Effect on plants	References
Free water surface CW	0.018	Sediment	7–12	*T. domingensis* *E. crassipes* *E. crassipes* + *T. domingensis*	88 7 30		Hadad et al. (2010)
	0.033	Muddy sediment	7–12	*Typha domingensis*	85	Biomass and plant height was higher than natural wetlands	Di Luca et al. (2011)
	0.4	Sediment	7–12	*Typha domingensis*	90		Fibbi et al. (2012)
Horizontal surface flow CW	0.0008–0.0158	Gravel	2.1	*Phragmites australis*	72		Dotro et al. (2012)
	1.1, 0.08–5.9	Granitic rock	5.2.4	*Typha latifolia*	50–95		Kelvin and Tole (2011)
	0.5	Gravel	11	Macro-hydroplants	60		Yadav et al. (2010)
Vertical flow CW	10, 15, 20	Gravel	6–48 h	*C. indica* L.	98.3	Continuous plant growth and production of new biomass	Mant et al. (2006)
	10–20	Gravel	6 h	*Penisetum purpureum* *Brachiaria decumbens* *Phragmites australis*	78.1 68.5 56.7		Kongroy et al. (2012)
Hybrid CW systems	0.016	Gravel and soil	–	*Cyperus alternifolius*, SSF—*Phragmites australis*, *Vetiveria zizanioides*, *Typha orientalis*, FWS-*P. australis*, *T. orientalis*, *Eleocharis dulcis*,	44		Lara et al. (2017)

Table 4.4 Pilot-scale studies for Cr (VI) reduction

Type of reactor used	Method of reduction	Cr (VI) concentration	Operating time (days)	Efficiency (%)	References
Arthrobacter viscosus biofilm supported on granular activated carbon	Biosorption	10 and 100 mg/L	30	99.9 and 72, respectively	Quintelas et al. (2009)
Biobarrier	–	50 mg/L	180	–	Jeyasingh et al. (2011)
Acinetobacter haemolyticus in ChromeBac™ system	–	17–81 mg/L	60	100	Ahmad et al. (2010)
Aerobic packed-bed mixed cultures	–	5.5	3 h	100	Tziotzios et al. (2008)
Aerobic trickling filter mixed cultures	–	5–100	0.3–6 h	100	Dermou and Vayenas (2007)
Desulfomicrobium norvegicum in fixed bed column	–	15 mg/L	18	100	Battaglia-Brunet et al. (2006)

microbial cells and enzymes in combination with nanotechnology like infusion of carbon nanotubes into calcium alginate beads have better efficiency in Cr (VI) reduction. Application of nanomaterials with metal reducing bacteria can be efficient as they act as an electron donor, thus accelerating Cr (VI) reduction into Cr (III) (Gutierrez-Corona et al. 2016; Seo and Roh 2015). Genetically, engineered bacteria have the great adaptability and treatment efficiency for the removal of chromium compounds. Development of technologies like combining electrochemical and biological processes together may prove to be helpful in treatment of chromium released from tannery effluent in future. Bioaugmented microorganisms have diverse metabolic pathways and robustness which is a must requirement for high-scale application (He et al. 2014).

4.9 Conclusion

Diversity in anthropogenic activities and industrialization has increased the risk of life due to heavy metal pollution. Among the heavy metal, Cr (VI) possesses a great threat to environment as well as life of living beings due to its mutagenic, carcinogenic, and teratogenic behavior. Different Cr (VI) remediation techniques like biosorption and biotransformation involving variety of microorganisms have been implemented and proven to be cost-effective, eco-friendly and efficient. Presence of functional groups like polysaccharides, amide I, amide II, amide III, carboxyl, and sulfonate mediates the Cr (VI) accumulation inside the cell, thereby transforming Cr (VI) into Cr (III) form. Use of different types of constructed wetlands has been also proven to be effective in treatment process. Despite of all these above-explained treatment technology, there is a gap between laboratory outcomes and pilot-scale studies of Cr contaminated sites. A suitable operational strategy may fulfill the gap and can be applied to Cr contaminated sites.

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