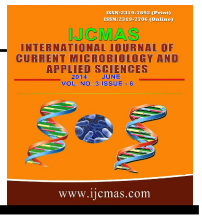
Int.J.Curr.Microbiol.App.Sci (2014) 3(6) 383-398

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 **Volume 3 Number 6 (2014) pp. 383-398**
http://www.ijcmas.com



Review Article

Microbial removal of hexavalent chromium and scale up potential

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A B S T R A C T

With increasing industrialization and technology developments, hexavalent chromium is continuously released into the environment and poses a serious threat to society because of their toxicity, accumulates in the food chain and persists in nature. Chromium removal by biosorption process offers an alternative bioremediation of industrial effluents as well as recovery of metal ions from aqueous solution. Models developed were presented to determine the number of adsorption sites required to bind each chromium ions. In the present manuscript, based on the literatures and our research findings for removal of Cr(VI) from aqueous solution by living and non living microbial biomass was reviewed. Microbial biomass generated as a by-product of fermentative processes offers great potential for adopting an economical chromium recovery system. In addition modeling and mechanism of chromium interaction, different types of biosorbent for chromium removal, pilot scale studies and their potential in future were predicted.

K e y w o r d s

Bioremediation, Biosorption, Hexavalent chromium, chrome effluent, waste biomass

Introduction

Presence of heavy metal ions in natural river water bodies is a severe socio-environmental problem caused by the discharge of industrial wastewater. Heavy metal ions are widespread pollutants of great environmental concern as they are non-degradable and thus persistent in nature that accumulates in the food chain, which with time reach detrimental levels in living systems, resulting in serious health hazards such as irritation in lungs and stomach, cancer in digestive tract, low growth rates in plants and death of animals (Acevedo-Aguilar et al., 2006; Cheung and Gu, 2007; Orozco et al., 2008).

Chromium is a geochemical component of anthropogenic origin and is widely distributed in rocks, minerals soils, and fresh water. The two typical oxidative states of chromium in the environment are hexavalent, Cr(VI), and trivalent, Cr(III) that have widely contrasting toxicity and transport characteristics: hexavalent chromium is more toxic with high water solubility and mobility,

while trivalent chromium is less soluble in water, less mobile and harmful (Chojnacka, 2010). Nutritionally, Cr(III) is an essential component of a balanced human and animal diet for preventing adverse effects in the metabolism of glucose and lipids. Although Cr(III) in small amount is an important nutrient needed by the body, swallowing large amounts of Cr(III) may also cause health problems e.g. lung cancer (Costa, 2003) birth defects and the decrease of reproductive health (Marsh and Mclnerney, 2001). This metal may cause death in animals and humans, if ingested in high doses. Hexavalent chromium is a potent, extremely toxic and is associated with abnormal enzyme activities altered blood chemistry, lowered resistance to pathogenic organism, behavioral modifications, osmo-regulatory upset, alternations in populations structure and species diversity indices and inhibition of photosynthesis (Cheung and Gu, 2007; Kumar et al., 2008; Sethuraman and Balasubramanian, 2010). Routes of human exposure to chromium compounds include ingestion of food and water, inhalation of airborne particulates and contact with numerous manufactured items containing chromium compounds. Generally, when administered orally to animals in food or water.

Chromium is one of the major available environmental pollutant in nature and is frequently present in wastewater from various industrial units such as electroplating, leather tanning, metal finishing, cement, mining, dyeing, fertilizer, photography, printed circuit board and chromate manufacturing industries that causes severe environmental and public health problems (Demirbas et al., 2004; Quintelas et al., 2009). Its concentrations in industrial wastewater ranges from 0.5 to 270 mg/L; the tolerance limit of Cr(VI) for discharge into inland surface water is 0.1 mg/L and in potable water is 0.05 mg/L. Keeping in mind, the toxic effects of chromium and International Standard for disposal of waste, the concerned industries must minimize the total chromium level in wastewater. It may also be possible to minimize the toxic Cr(VI) level by transferring it to its trivalent form, which is almost non-toxic and even an essential trace element for growth. Therefore, the removal of Cr(VI) from wastewater prior to its discharge into natural water systems, adjoining land masses and sewer systems, requires serious and immediate attention. An additional problem is constituted by growing costs of their storage, dump preservation and transport of waste.

Conventional physic-chemical methods for removal of hexavalent chromium from wastewater, including ion exchange resins, reverse osmosis, reduction, coagulation and precipitation are highly expensive and also ineffective at lower metal concentration in large volume of wastewater. In addition, these processes require huge quantities of chemicals that generate enormous quantity of toxic chemical sludge; disposal of resultant creates secondary pollution.

Environmental friendly processes need to be developed to clean up the environment without generating harmful waste by-products (Vieira and Volesky, 2000; Wang and Chen, 2009; Ahmad et al., 2010). Bioremediation processes are very attractive in comparison to physic-chemical methods for Cr(VI) removal because they are less expensive and highly efficient even at low heavy metal concentrations (Gravrilescu, 2004; Cheung and Gu, 2007; Chojnacka, 2010;

Ahluwalia, 2012). Biological treatment stimulates great interest because of their lower impact on the environment as opposed to chemical treatment. Recent studies had shown that certain species of bacteria are capable of transforming hexavalent chromium form into trivalent chromium form that is much less toxic, less mobile and is available for biological uptake. Microbes may protect themselves from toxic substances in the environment by transforming toxic compounds through oxidation, reduction or methylation into more volatile, less toxic or readily precipitating forms (Gadd, 1990; Volesky and Schiewer, 2000; Quintelas et al., 2009; Ahmad et al., 2010). The aim of this paper is to present the state of the art of chromium biosorption investigation and to compare the results found in the literature. Chromium biosorption, modeling and mechanism of chromium interaction, different types of biosorbent for chromium removal, pilot scale studies and their potential in future were predicted.

Models have an important role in technology transfer from a laboratory to industrial scale. The biosorption process is very quick and the equilibrium is reached within few minutes. Biosorption isotherms are important for the description of how biosorbate interacts with a biosorbent and are critical in optimizing the use of biosorbent. Adsorption isotherm represents the equilibrium distribution of chromium ions between the aqueous and solid phases, when the concentration increases. Isotherm studies provide information on the capacity of biosorbent, which is the most important parameter for a sorption system. Sorption isotherms are characterized by certain constants and describe the mathematical relationship between the quantity of adsorbate and concentration of adsorbate remaining in the solution at equilibrium (Gravrilescu, 2004; Chojnacka, 2010). In biosorption, the chromium ions adsorbed at the surface of microbial cell wall and could be well represented by conventional isotherms. An attempt was made to test for Langmuir and Freundlich isotherms models on the experimental data (Ahluwalia and Goyal, 2010). The understanding of the mechanism by which microbes accumulate Cr(VI) is crucial to the development of microbial processes for concentration, removal and recovery from aqueous solution. Metabolism-independent metal binding to the cell walls and external surfaces is the only mechanism present in the case of non living biomass.

Metabolism-independent uptake essentially involves adsorption process such as physical, chemical and ionic adsorption. A variety of ligands located on the fungal cell walls are known to be involved in metal chelation. These include carboxyl, amine, hydroxyl, phosphate and sulfahydryl groups. Metal ions can be adsorbed by complexing with negatively charged reaction sites on the cell surface (Gupta et al., 2000; Ahluwalia and Goyal, 2007). Chromium biosorption by microbial biomass mainly depend on the components on the cell, especially through cell surface and the spatial structure of the cell wall. Various polysaccharides, including cellulose, chitin, alginate and glycan etc. existed in fungi and/ or algal cell walls, have been proved to play a very important role in chromium binding. Some functional groups have been found to bind metal ions, especially carboxyl group. There are some evidence to confirm that the O-, N-, S-, or P-containing groups participate directly in binding a certain metals (Ahluwalia and Goyal, 2007; 2010). Earlier findings [Volesky and Schiewer, 2000; Gupta et al., 2000;

Cheung and Gu, 2007; Park et al., 2008; Wang and Chen, 2009] revealed that some functional groups have been found on the surface of biomass, involved in sorption and chelation of a number of bivalent metal cations are polar or anionic in nature such as carboxylate, amine, phosphate and hydroxyl groups of polysaccharide materials of the cell wall. In most of the fungi, carboxyl and phosphate groups are involved in chromium binding in addition to amine, amide and alkane groups (Ahluwalia and Goyal, 2010). Similarly, *Rhizopus arrhizus* also contain chitin and chitosan in their cell wall, which were also involved in chromium adsorption [Bai and Abraham, 1998; Ismael et al., 2004).

Effect of the contact time on adsorption of chromium by free and immobilized biomass of *R. arrhizus* was co-related with both physical and chemical sorption mechanisms and the first phase of chromium biosorption was attributed to surface adsorption due to the ion exchange between the carboxyl groups of uronic acid present in the cell structure, which are known as metal sequestering sites. Further instrumental techniques such as X-ray absorption fine structure and Fourier transform infrared analyses investigated the involvement of carboxyl and amide functional groups whereas scanning electron microscopy and atomic force microscopy examined accumulation of Cr(III) precipitates on bacterial surfaces. Through quantitative analysis of chromium distribution, the binding ratio of Cr(III) in supernatant, cell debris and cytoplasm as 22%, 54% and 24%, respectively (Chen et al., 2012). Hence, knowledge of the chemical or physiological reactions during the Cr(VI) uptake might enable specification and control of process parameters to increase the rate, quantity and specificity of chromium accumulation [Cheung and Gu, 2007; Volesky and Schiewer, 2000; Ahluwalia and Goyal, 2010].

Removal of hexavalent chromium with microbial biomass

Bioremediation of hexavalent chromium by microorganisms are gaining much attention since these have proven to be useful in biotechnological practice. Metal uptake by microorganisms is an environment-friendly alternative of heavy metal remediation. Microbial reduction of toxic hexavalent chromium has practical importance, because biological strategies provide green technology that is cost-effective. Both living and non-living microbial biomass are capable of taking up metal ions from aqueous solution. Microorganisms take up metal ions either actively (bioaccumulation) and/or passively (biosorption).

Removal of Cr(VI) by living biomass

Many microbes by cellular activities and their products significantly contribute in the biogeochemical cycles. The physiological states of the organism, age of the cells, availability of micronutrients during their growth and environmental conditions during the biosorption process such as pH, temperature, biomass concentration, and other electron acceptors as well as presence of certain co-ions, are important parameters that affect the performance of a living biosorbent. With the addition of biological inhibitors such as penicillin, cycloserine, or chloramphenicol, the loss of Cr(VI) reduction activity in microbial cells under reducing conditions clearly indicates that Cr(VI) reduction is an enzymatically catalyzed reactions. The efficiency of metal concentration on the biosorbent is

also influenced by metal solution chemical features (Asatiani et al., 2004; Bajgai et al., 2012) Das and Guha, 2009). Further, microorganisms have excellent nucleation sites for grained mineral formation, due to their high surface area and volume ratio and the presence of electronegative charges on the cell wall (Bai and Abraham, 2005) that gives microorganism the ability to bind metal cations. Various microbial species have been shown to be relatively efficient in the bioaccumulation of uranium, copper, lead, other metal ions from polluted effluents, both as immobilized cells and in the mobilized state. Many indigenous organisms isolated from sites contaminated with heavy metals toxicity and these microbial activities have always been the natural starting point for all biotechnological applications. It is therefore, necessary to isolate bacterial strains with novel metabolic capabilities and to establish degradation pathways both biochemically and enzymatically.

Living mycelium of white-rot fungus *Phanerochaete chrysosporium* exhibited the highest copper and chromium adsorption capacity of 90.6 and 48.6mg/g. The biosorption capacity was found to increase with increase of solute concentration. Further, the cellular biomass of the *Cladosporium neoformans* (98%) and *Helmintosporium* sp. (63%) showed the highest adsorption at pH 2.0 and 4.0 respectively, at 28°C after 24 hrs of incubation, with 0.2 mg/L of biomass (Ismael et al., 2004). The Cr(III) sorption experiments onto *Kappaphycus alvarezii* (Kang et al., 2011) waste biomass were conducted at different pH values (2–6) under the conditions of initial metal concentration of 10–50mg/L and the chemical compositions of Cr-Cu and Cr-Cd. Mycelial growth of *Trichoderma harzianum* (Sarkar et al., 2010) showed inhibition up to 94% at 40 mg Cr(VI)/L concentration followed by 30mg/L (91%). Moreover, the removal of Cr(VI) (92.7%) with cell-free extracts of Bacillus cereus was attained at a temperature 37°C, pH 7.0-9.0, and biomass of 20g/L, which was close to that of the whole cells (96.85%), indicating that the Cr(VI) reductase generated by *B. cereus* is primarily intracellular (Zhao et al., 2012; Chen et al., 2012). *Brevibacterium casei* (Das and Misra, 2010) can effectively reduce the Cr(VI) up to 99% in 12 hrs at neutral pH and temperature of 30°C. Similarly, Enterobacter cloacae showed 85% removal of Cr(VI) from aqueous solution at pH 2.0, initial concentration 25mg/L and at temperature 35°C (Sethuraman and Balasubramanian, 2010). Similarly, Streptomyces sp. MC1 was able to accumulate up to 3.54mg of Cr(III) per gram of wet biomass, reducing the 98% of Cr(VI) and removing 13.9% of chromium from the culture medium supernatants (Polti et al., 2011) under different culture conditions. Amoroso et al., (2001) determined Cr(VI) bioaccumulation by two *Streptomyces* strains that able to accumulate Cr(VI) 5-10mg/g of cell in minimal medium. Cr(VI) bioaccumulation by *Streptomyces griseus* in complex medium was up to 3mg/g cell (Laxman and More, 2002).

Aspergillus niger and *Aspergillus parasiticus* exhibited the Cr(VI) removal of 96.3% and 91.6% within 96hrs of incubation at initial concentration of 20mg/L and had residual Cr(VI) concentrations of only 0.74±0.55 and 1.69±0.29mg/L respectively. Moreover, the active mycelia of both fungi showed significantly ($P<0.001$) higher Cr(VI) removal than inactivated mycelia after incubation at 30°C for 72 hrs. Incubation of cell–free extracts of both fungi with

NADH at 30°C for 2 hrs showed Cr(VI) reduction of 68.0% and 55.5% for *A. niger* and *A. parasiticus*, respectively. These findings suggest that uptake and metabolic reduction processes in fungi are able to tolerate the toxic effects of hexavalent chromium (Shugaba et al., 2012). It was investigated that chromium biotransformation from hexavalent to trivalent form was slightly higher in nutrient/biological synthetic media than that of Industrial effluent as there might be some constituents in effluent hampering transformation process or necessary enzyme production. Removals of heavy metals using different biosorbents have been found to be highly selective depending on the typical binding profile of the biosorbents.

Successful application of bioaccumulation process depends on the parameter like initial metal concentration and contact time. However, major limitation of using growing systems for removal of metals is that cell growth is inhibited when the metal concentration is high, resulting in poor metal removal (Donmez and Aksu, 1999). This problem could be overcome by the use of metal tolerant organism. This tolerance and removal capacities were found to be the essential characteristics of growing biomass used in a metal ion removal process.

Removal of Cr(VI) by non living biomass

Biosorption is a property of certain types of inactive, non living microbial biomass to bind and concentrate heavy metals from even very dilute aqueous solution. Biomass exhibits this property, acting just as chemical substance and as an ion exchange of biological origin. It is particularly the cell wall structure of certain algae, fungi and bacteria, which was found responsible for this phenomenon (Vieira and Volesky, 2000). The removal of hexavalent chromium from aqueous solution by using non living biomass is an innovative and alternative technology. Bioremediation has emerged as one of the most desirable approaches for cleaning up many environmental pollutants that uses biological systems to catalyze the biodegradation and/or biotransformation of various toxic chemicals to less harmful forms (Ahluwalia and Goyal, 2007, 2013; Park et al., 2008). Moreover, considerable potential exists for these naturally existing, abundant and cheap sources of biomass, for use as adsorbents. Their efficiency depends on the capacity, affinity and specificity including physic-chemical nature.

Different researchers (Gavrilescu, 2004; Cheung and Gu, 2007; Wang and Chen, 2009; Chojnacka, 2010) summarized the results achieved with bacteria, fungi, algae, and other plant derived biomass for the uptake of heavy metals for the aqueous solution. Tables 1 summarizes the different types of biosorbent of non-living biomass of fungi, bacteria, algae and other biosorbents used for the removal of Cr(VI) from aqueous solution and wastewater. Adsorption intensity of non living *Rhizopus arrhizus* biomass for chromium(VI) from aqueous solution has been investigated. Influence of pH, contact time, absorbent to liquid ratio was studied. Maximum adsorption was noticed at pH 2 with 8hr contact time. 98% adsorption of chromium was observed with chromium solution (100mg/L) when contacted with 1% biomass (Sheno Merrin et al., 1994). The Cr(VI) removal potential of waste mycelium from the industrial xylanase-producing strain *Aspergillus awamori*

(Gochev et al., 2010) exhibited pH 1.5, temperature 30°C, initial concentration of 50mg/L having biomass concentration 0.5 to 2g/100mL. Non living biomass of *Aspergillus terreus* by product of fermentation industry, showed the 100% removal efficiency of Cr(VI) from chrome effluent at the initial concentration of 95mg/L up to 15 days in continuous column sorption system that showed an overall chromium biosorption capacity of 12.6mg Cr(VI)/g (dry biosorbent), including the insignificant amount absorbed through dynamic sorption by the biomass packed in the column (Ahluwalia and Goyal, 2013). Reduction of hexavalent chromium was studied in three bench-scale continuous stirred tank reactors. *Pseudomonas* sp., were investigated to giving 83 to 87% chromate reduction in 72hr batch assays with 60mg Cr(VI)/L in synthetic medium, whereas chromate reduction efficiency in three different continuous stirred tank reactors was 81% to 91% and 100% for influent Cr(VI) concentrations of 15 to 124 and 5mg/L, respectively, fed different levels of chromate (5 to 124 mg/L) at 28 to 30°C and pH 6.8. The feed rate was varied over the range 0.5 to 1.0L/d to obtain hydraulic retention time of 36 to 72hr (Gopalan and Veermani, 1994).

Pilot Scale Studies

Most of the studies on the bioremediation of hexavalent chromium have been performed using synthetic solutions of chromium(VI) prepared in the laboratory. Efforts were carried out globally by the researchers for removal and/or reduction of hexavalent chromium from the real wastewater at scale up level. The increase in usage of chromium in industry leads to discharge of enormous quantity of hexavalent chromium into the environment. Pilot scale studies are essential for the execution of a biosorption system at industrial level and helped researchers to realize the limitations associated with using biosorption with inactive microbial biomass in an industrial application, mainly due to the cost of formulating the biomass into an appropriate biosorbent material. The biofilm of *Arthrobacter viscosus* supported on GAC was tested for the initial Cr(VI) concentrations of 10–100mg/L. The chromium uptake 11.35mg/g and 14.55mg/g, respectively were obtained at pilot-scale bioreactor, for the initial chromium concentrations of 10 and 100mg/L (Quintelas et al., 2009).

The assay for the initial concentration of 10mg/L and 100mg/L was followed during 226 days and 104 days respectively. The volume of chromium solution treated was of 8140 liter for the assay with the initial concentration of 10mg/L and 3732 liter for the more concentrated solution. Similarly, Battaglia-Brunet et al., (2006) showed a removal percentage of Cr(VI) of 100% during the first 18 days of experimental assay. These studies were developed in a pilot bioreactor, inoculated with a bacterial population containing the sulfate reducing organism *Desulfomicrobium norvegicum*, for the treatment of Cr(VI) solution with an initial concentration of 15mg/L. Further, Barros et al. (2007) observed the average removal percentage of chromium from the reactor inoculated with wastewater sludge 90.4% (initial concentration of 10mg/L) varying from 96.1 to 60.8% up to 30 days in lab scale whereas an average removal percentage of 99.9% was obtained, varying from 100% to 99.3% in the pilot scale bioreactor during the first 30 days, for the initial concentration of 10mg/L. Quintelas et al., (2009) obtained 11.35mg/g and 14.55mg/g

chromium removal from the initial chromium concentrations of 10 and 100mg/L. Rehman et al. (2009) reported the removal of chromium through biological mechanisms in dual stage process. The first stage was of attached growth using plastic media for biofilm formation and second one suspended growth process, operated under aerobic conditions.

The inlet concentration Cr(VI) examined were about 10-50µg/L, with removal efficiency 20-82% respectively. The reduction rates were significantly affected by the change in inlet Cr(VI) concentration. Contaminant loading varied from 137.93 to 689.66µg/m^2/d based on biofilm area. The enzymatic reduction of Cr(VI) to Cr(III) by chromium resistant bacteria, *Acinetobacter haemolyticus*, immobilized onto carrier material inside a 0.2m3 bioreactor constitutes the ChromeBac™ system. The complete reduction from Cr(VI) to Cr(III) was obtained immediately after the start of bioreactor operation, when neutralized electroplating wastewater with Cr(VI) concentration of 17–81mg/L was fed into the bioreactor (0.11–0.33m^3/h). Performance of the bioreactor was not affected by fluctuations in pH (6.2–8.4), Cr(VI) conc. (17–81mg/L), nutrient (liquid pineapple waste, 1–20% v/v) and temperature (30–38°C), up to 10 days without loss in activity (Ahmad et al., 2010).

The other microbial biosorbents reported are *Streptomyces rimosus* (Addour et al., 1999), xylanase-producing strain of Aspergillus awamori (Cheung and Gu, 2007), *Aspergillus niger* from fermentative industry (Natarajan et al., 1999), *B. lentus*, *A. oryzae or Saccharomyces cerevisiae* (Vianna et al., 2000), and cells of *Saccharomyces cerevisiae* from brewery (Wang and Chen, 2009) with varying degree of ease and efficiency. In our previous studies, non living biomass of *Aspergillus terreus*, waste from fermentation industry showed the 100% removal efficiency with chrome effluent (pH 2.0; initial concentration 60-127mg/L chromium(VI); flow rate 5-6 liter/h for 8 h/d) up to six weeks in 20 liter up-flow sorption column. The loading capacity of microbial waste biomass with chrome from the effluent was found to be 12.6mg/g dry biomass (Ahluwalia and Goyal, 2013).

No doubt, bioremediation technology is a cleaner and useful technology to remove Cr(VI) from the industrial wastewater. Interdisciplinary efforts having different kinds of scientific backgrounds apart from engineering such as biochemistry, microbiology, ecology and geology could make a significant contribution in elucidating the bioremediation of chromium. Scientists worldwide are attempting to select out suitable biosorbents with a better detoxification ability of hexavalent chromium from wastewater.

As the biosorption process of hexavalent chromium involves mainly cell surface sequestration, cell wall modification can greatly alter the binding of metal ions. A number of methods had been employed for cell wall modification of microbial and plant derived biomass in order to enhance the chromium binding capacity of biomass and to elucidate the mechanism of biosorption. As a result, scientists are studying new and alternative technologies to remove trace metals from polluted water and industrial effluent.

Table 1:Chromium adsorption capacity by different microbial and other biosorbent

Microorganisms	Adsorption capacity (mg/g)	Reference
FUNGI		
Arthrobacter viscous	12.6	Silva et al., 2009
Aspergillus awamori	-	Gochev et al., 2010
Aspergillus foetidus		Prasanjit and Sumathi, 2005
Aspergillus niger	-	Goyal et al., 2003; Ahluwalia and Goyal, 2010
Aspergillus niger	117.33	Khambhaty et al., 2009
Aspergillus parasiticus	0.587	Shugaba et al., 2012
Aspergillus sydowi	1.76	Kumar et al. 2008
Aspergillus terreus	96.5	Dias et al., 2002
Candida lipolyica	10	Ye et al., 2010
Candida utilis	-	Muter et al., 2002
Cladosporium resinae	10.69	Ahluwalia and Goyal, 2010
Cyberlindnera fabianii		Bahafid et al., 2013
Fusarium solani	60	Sen and Dastidar, 2011
Mucor hiemalis	30.5	Polti et al., 2011
Mucor meihi	-	Tobin and Roux, 1998
Paecilomyces sp.	38	Cárdenas-González and Acosta-Rodríguez, 2010
Paecilomyces variotii	10.35	Ahluwalia and Goyal, 2010
Penicillium chrysogenum	-	Park et al., 2005
Penicillium purpurogenum	36.5	Say et al., 2004
Phanerochaete chrysosporium	11.2	Ahluwalia and Goyal, 2010
Phanerochaete chrysosporium	48.6	Amoroso et al., 2001
Rhizopus arrhizus	8.40	Nourbakhsh et al., 1994
Rhizopus arrhizus	11	Bai and Abraham, 1998
Rhizopus arrhizus	78	Aksu and Balibek, 2007
Rhizopus nigricans	47	Bai and Abraham, 2001
Rhizopus nigricans	12.7	Bai and Abhram, 2003
Rhizopus oligosporus	126	Ariff et al., 1999
Saccharomyces cerevisiae	-	Nourbakhsh et al., 1994
Termitomyces clypeatus	11.1	Das and Guha, 2009
Trametes versicolor	-	Bayramoglu et al., 2003
Trichoderma harzianum	-	Sarkar et al., 2012
Trichoderma viride	-	Holda and Kisielowska, 2013
Cyberlindnera fabianii	-	Bahafid et al., 2013
BACTERIA		
Aeromonas caviae	284.4	Loukidou et al., 2004
Bacillus amyloliquefaciens	-	Das et al., 2014

Bacillus megaterium	30.7	Srinath et al., 2002
Bacillus coagulans	39.9	Srinath et al., 2002
Bacillus licheniformis	69.4	Zhou et al., 2007
Bacillus sphaericus	-	Velásquez and Dussan, 2009
Lentinus edodes	21.5	Chen et al., 2006
Manganese oxidising bacteria	50	Stutz et al., 1993
Ochrobactrum anthropi	-	Ozdemir et al., 2003
Ocimum basilicium	-	Melo and D'Souza, 2004
Pseudomonas sp.	95	Ziagova et al., 2007
Staphylococcus xylosus	143	Ziagova et al., 2007
Streptomyces noursei	1.2	Mattuschka and Straube, 1993
Thiobacillus ferrooxidans	-	Celaya et al., 2000
Trichoderma gamsii	44.8	Kavita and Keharia, 2012
Trichosporon cutaneum	-	Bajgai et al., 2012
Zooglea romigera	2	Nourbakhsh et al., 1994
Enterococcus casseliformis	512	Saranraj et al., 2010
ALGAE		
Chlorella vulgaris	3.5	Nourbakhsh et al., 1994
Cladophora crispate	3	Nourbakhsh et al., 1994
Dunaliella sp.	58	Donmez and Aksu, 2002
Kappaphycus alvarezii	0.86	Kang et al., 2011
Neurospora crassa	15.85	Tunali et al., 2005
Pachymeniopis sp.	225	Lee et al., 2000
Padina boergesenii	49	Dulymamode et al., 2001
Scenedesmus obliquus	-	Donmez and Aksu, 1999
Spirogyra sp.	-	Gupta et al., 2001
Spirulina platensis	-	Babu et al., 2013
Ulothrix zonata	-	Malkoc and Nuhoglu, 2003
Spirulina sp.	90.91	Rezaei H, 2013
OTHERS		
Activated baggase carbon	-	Mor et al., 2002
Almond Green Hull	2.04	Sahrananvard et al., 2011
Banana Skin	249	Park et al., 2008
Cupressus Female Cone	119	Murugan and Subramanian, 2003
Ecklonia	233	Park et al., 2004
Eucalyptus bark	-	Sarin and Pant, 2006
Litchi chinensis Sonn Peel	-	Acosta-Rodriguez et al., 2012
Pine leaves	0.27	M orshedzadeh et al., 2007
Raw rice bran	0.07	Oliveira et al., 2005
Sunflower head waste	7.85	Jain et al., 2013
Wheat bran	0.94	Nameni et al., 2008
Palm tree Branches	-	Shouman et al., 2013
Calotropis procera	32.26	Overah, 2011

Recent studies have suggested that it may be possible to increase the uptake and the specificity of biosorbents using the tools of molecular biology by targeting engineered metal binding proteins to the cell surface. Increased understanding of metabolic pathways in the microorganism responsible for metal solubilization, and improving their survival rates and stability opens the door to the manipulation of parameters such as kinetics and metal selectivity, with the aim of enhancing the removal and/or recovery of chromium.

Ultimately, there is a requirement to develop and propose to the market, a reliable, robust, simple and effective process designs in order to arrive at a success in commercialization of the chromium biosorption process. This lies in the hybrid technology, combing the new biosorption process with the well-proved treatment process or reactor configuration. From an overview of microbial sorbents and microbial waste biomass as sorbent candidate, it could be concluded that laboratory/pilot scale trials do show their potential for commercialization since they possess good chromium-binding capacity.

Moreover, to promote the application of biosorption process at commercial level, the biosorption process applications has to be done in conjunction with industrial users/ clients. Since industries are required to diminish the contents of chromium(VI) in their effluents to acceptable levels. However, there is a need to have more knowledge of the basic mechanisms involved in order to develop better and effective biosorbents. The judicious choice of biosorbent can also compete out the commercial ion exchange resins, which have conventionally been used in the removal of chromium. These finding are potentially useful because microbial and plant derived sorbent could be harnessed to the detoxification of chromate contaminated industrial and mining waste. This needs further research as the potential of these sorbent indicate the possibility of their exploitation in chromium(VI) and other heavy metal bioremediation in the future.

Acknowledgement

The author is thankful to the head of the institute for the support extended and colleagues for the review of the manuscript.

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