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Journal of Hazardous Materials B121 (2005) 109–117

Journal of Hazardous Materials

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Bioremediation of Cr(VI) in contaminated soils

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Received 19 June 2004; received in revised form 26 January 2005; accepted 30 January 2005
Available online 26 February 2005

Abstract

Ex situ treatment of hexavalent chromium (Cr(VI)) contaminated soil using a bioreactor–biosorption system was evaluated as a novel remediation alternative. Leaching of Cr(VI) from the contaminated soil using various eluents showed that desorption was strongly affected by the solution pH. The leaching process was accelerated at alkaline conditions (pH 9). Though, desorption potential of ethylene diamine tetra acetic acid (EDTA) was the maximum among various eluents tried, molasses (5 g/L) could also elute 72% of Cr(VI). Cr(VI) reduction studies were carried out under aerobic and facultative anaerobic conditions using the bacterial isolates from contaminated soil. Cr(VI) reduction was moderately higher in aerobic conditions than in facultative anaerobic conditions. The effect of various electron donors on Cr(VI) reduction was also investigated. Among five electron donors screened, peptone (10 g/L) showed maximum Cr(VI) reduction followed by molasses (10 g/L). The time required for complete Cr(VI) reduction was increased with increase in the initial Cr(VI) concentration. However, specific Cr(VI) reduction was increased with increase in initial Cr(VI) concentration. Sulfates and nitrates did not compete with Cr(VI) for accepting the electrons. A bioreactor was developed for the detoxification of Cr(VI). Above 80% of Cr(VI) reduction was achieved in the bioreactor with an initial Cr(VI) concentration of 50 mg/L at an HRT of 8 h. An adsorption column was developed using *Ganoderm lucidum* (a wood rooting fungus) as the adsorbent for the removal of trivalent chromium (Cr(III)) and excess electron donor from the effluent of the bioreactor. The specific Cr(III) adsorption capacity of *G. lucidum* in the column was 576 mg/g. The new biosystem seems to be a promising alternative for the ex situ bioremediation of Cr(VI) contaminated soils.

Keywords: Biotransformation; Biosorption; Contaminated soil; Hexavalent chromium; *Ganoderma lucidum*

1. Introduction

Chromium is widespread in the environment and is derived from both natural and anthropogenic sources. Chromium is released into the environment by a large number of industrial operations such as electro plating, chromate manufacturing, leather tanning and wood preservation [1]. Though chromium exists in nine valence states ranging from −2 to +6, Cr(III) and Cr(VI) are of major environmental significance because of their stability in the natural environment [2]. Cr(VI) is toxic, carcinogenic, and mutogenic to animals as well as humans and is associated with decreased plant growth and changes in plant morphology [3] In contrast, trivalent chromium [Cr(III)] is relatively less toxic and less mobile.

The conventional treatment methodology for soils and groundwater systems contaminated with hexavalent chromium is excavation (or) pumping of the contaminated material, addition of chemical reductant, precipitation followed by sedimentation, or ion exchange and/or adsorption. These are practiced both in situ and ex situ systems [4]. These physico-chemical methods suffer from high costs associated with energy and chemical consumption. The search for new and innovative technology for the remediation of Cr(VI) pollution has attracted the attention on the biotransformation potential of certain microorganisms. Microbial reduction of toxic hexavalent chromium to less soluble trivalent form as a normal function of their metabolism seems to be a potential method for the remediation of Cr(VI) contamination.

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doi:10.1016/j.jhazmat.2005.01.018

Many microbes have been reported to reduce Cr(VI) under either aerobic or anaerobic conditions [5–14]. In addition some species are capable of reducing Cr(VI) both aerobically and anaerobically depending on the oxidation reduction potential (ORP) of the environment [15,16]. The physiological mechanisms responsible for Cr(VI) reduction appear to vary significantly among various organisms. In some cases intracellular enzymes were responsible for Cr(VI) biotransformation, where as in other cases Cr(VI) reduction took place extra cellularly [17,18]. The carbon source/electron donor preferences also varied considerably depending on the microbial consortia employed [12,14].

Bioaccumulation of metals by various micro- and macroorganisms is reported under various conditions [19–22] The metal uptake can be either a passive process or metabolism dependent active process. When it is a passive process, dead microorganisms are preferred over living cells as it is easy to maintain the reactor system. In such cases, macroorganisms are having an edge over microorganisms due to the elimination of energy intensive solid liquid separation process [20] *Ganoderma lucidum*, a wood rotting fungus is reported to have very high heavy metal uptake capacity. Researchers have reported that the specific metal uptake capacity of this mushroom is higher than powdered activated carbon (PAC), the most commonly used adsorbent [23]

Though many studies were carried out for the treatment of Cr(VI) contaminated water/wastewater, not much research has been carried out on the remediation of Cr(VI) contaminated soils either using in situ or ex situ bioremediation techniques. Turick et al. [24] demonstrated the Cr(VI) reduction in a contaminated soil by indigenous microbial consortium under anaerobic condition. Organic amended soils reduced Cr(VI) in ground water from 1 mg/L to less than 50 μg/L [25] Under anaerobic conditions, indigenous microbes reduced 65% of Cr(VI) from contaminated soil with the addition of glucose. Tseng and Benefieldt [26] studied the in situ bioremediation of Cr(VI) contaminated soil by supplying various carbon sources.

Information available on the ex situ treatment of Cr(VI) contaminated soil is scarce. For small volumes of highly contaminated soil, ex situ remediation is still a promising alternative. For ex situ treatment, basically three steps have to be optimized, leaching of Cr(III) and Cr(VI), transformation of Cr(VI) to Cr(III) and subsequent removal of Cr(III) from the system.

In the present study, development of a biological system for the treatment of Cr(VI) contaminated soils is described. The treatment system consists of a leaching column followed by an immobilized bioreactor for the biotransformation of Cr(VI) to Cr(III) and a biosorption column as a polishing unit. The optimum conditions for leaching and biotransformation were evaluated using batch experiments.

2. Materials and methods

2.1. Soil samples

Soil samples were collected from chromium contaminated site located at Ranipet, Vellore district of Tamilnadu, India. The concentration of Cr(VI) in the contaminated soil was in the order of 5.1 mg/g. The soil contained 10.2 mg/g of total chromium out of which 5.1 mg/g was Cr(VI). The pH of the soil was 5.96 with an organic content of 6.9%.

2.2. Nutrient media

The general growth medium (M1) for bacteria consisted of peptone (10 g), beef extract (2 g), yeast extract (1 g), sodium chloride (5 g/L) in 1 L of distilled water. The media (M2) for Cr(VI) reduction experiments consisted of K_2HPO_4 (1.06 g/L), $+KH_2PO_4$ (0.2 g/L), $MgSO_4{\cdot}7H_2O$ (0.5 g/L), $CaCl_2$ (0.0 5g/L), KNO_3 (2 g/L), NaCl (1 g/L), carbon source (10 g/L) and 1 mL of trace element solution [31]. All media were autoclaved at 120 °C and 15 psi for 15 min and stored at room temperature until use. A total of five carbon sources namely, peptone, dextrose, citrate, molasses and sewage were employed in various studies. Agar slants for storing the microbial consortia was prepared by adding 15 g/L of agar and 50 mg/L of Cr(VI) to general growth media (M1).

2.3. Cr(VI) desorption studies

The various eluents employed in the study were tap water, distilled water, citrate (1 M), EDTA (0.2 M), and molasses (5 g/L). Tap water with varying pH (2–9) was also used for the study. Schematic of the experimental set up is shown in Fig. 1. The experimental columns were made of glass with an internal diameter of 1 cm and a height of 50 cm. A constant flow rate of 5 $m^3/m^2/h$ in downward direction was maintained all throughout the study. Soil samples collected from the contaminated site was autoclaved, dried, crushed, sieved and homogenized. The autoclaving was done to remove the microbes, which may affect the leaching process, by their action. A 10 g of the soil was filled in the column for leachability study using each eluent. The effluents were collected at frequent intervals and analyzed for Cr(VI) concentration. The operation was continued until the concentration of Cr(VI) in the effluent reached non-detectable limits (0.1 ppm).

2.4. Enrichment and cultivation of Cr(VI) reducing bacterial strains

The Cr(VI) reducing bacterial consortia were enriched from the soil samples collected from chromium contaminated site located in Ranipet, Tamilnadu, India. The soil was contaminated with the chromium sludge discharged from chromate manufacturing industry. Five grams of soil sample was added to 100 mL of sterile growth media M1 with 10 mg/L of Cr(VI) and incubated in a shaking incubator for 24 h at 35 °C.

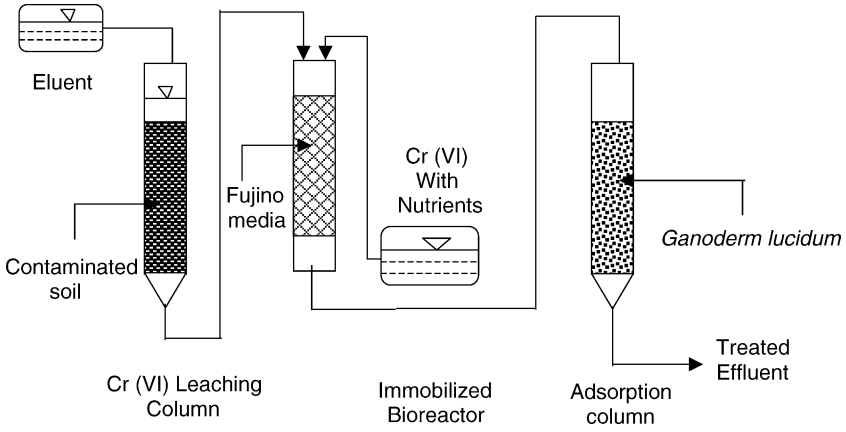

Fig. 1. Schematics of the experimental setup for bioremediation of Cr(VI) contaminated soils.

After 1 day, when significant growth was observed, 1 mL of the supernatant of the slurry was transferred to 100 mL of fresh nutrient media (M1) and incubated at 35 °C. The consortia used for the Cr(VI) reduction was developed by a series of transfers at every 24 h by gradually increasing the Cr(VI) concentration. Once the enriched consortium was ready, bacterial isolates were prepared by repeated serial dilutions and streaking on agar plates. Identical colonies were separated based on their morphology and was streaked on agar slants using an inoculating needle, and incubated at 35 °C for 24 h and stored at 4 °C until needed for further experimentation.

2.5. Screening of enriched cultures and electron donors

The enriched cultures were screened for the chromium(VI) reduction based on their specific chromium reduction capacity under aerobic and facultative anaerobic conditions with initial Cr(VI) concentrations of 50 ppm and 100 ppm. To maintain aerobic condition shake flasks with cotton plug was used. For conducting experiments under facultative anaerobic conditions, the reaction mixture was flushed with nitrogen gas for 2 min and immediately closed the bottles with airtight silicon caps. Peptone was used as an electron donor for this study. For screening of electron donors, the most promising microorganism (the one which gave max specific Cr(VI) reduction during screening test) from the enriched cultures was employed. The studies were carried out in aerobic conditions. Five carbon sources namely, peptone, acetate, dextrose, molasses and sewage were employed as electron donors for Cr(VI) reduction. Overnight cultures were harvested by centrifuging at $5000 \times g$ for 10 min and then transferred to 100 mL of previously sterilized nutrient broth (M2) in 250 mL flasks. Cr(VI) was then added from a sterilized stock $K_2Cr_2O_7$ solution so that final Cr(VI) concentration was 50 mg/L. The microbial concentration in the mixture was 670 mg/L in all the five flasks, which was maintained by measuring the optical density. Appropriate controls containing the nutrients along with Cr(VI) but without cells were always included to monitor the abiotic Cr(VI) reduction. All batch experiments were conducted thrice and the average value is reported.

2.6. Bioreactor for Cr(VI) reduction

The bioreactor (Fig. 1) was made out of perplex tubes (i.d. = 5 cm). The total length of the reactor was 60 cm and the bed height was 50 cm. Corrugated PVC materials (fugino material) with an approximate diameter of 1 cm and a length of 1.5 cm was used as the packing media. The leachate (using 5 g/L molasses as eluent) from the soil column along with mineral medium (M2) was sprinkled over the packed bed from the top of the reactor at a rate of 95 mL/h corresponding to an HRT (hydraulic retention time) of 8 h. The system was operated in facultative anaerobic conditions without any aeration. Enriched microorganisms were used as the seed for the reactor. Effluent samples were collected centrifuged and analyzed for Cr(VI), Cr(III) and total chromium, sulfates and DO daily whereas nitrates and COD concentrations were monitored once in 5 days. DO concentration was monitored at two places, i.e. 5 cm from the top of the reactor and at the bottom of the reactor.

2.7. Polishing treatment unit

An adsorption column (Fig. 1) using *G. lucidum*, a wood rotting fungus, as adsorbent was employed as the polishing unit. *G. lucidum* was collected from tropical forest of Kerala, India, dried in an oven at 80 °C for 24 h, and cooled to room temperature, grounded to a grain size of 1–2 mm using a grinder (Sumeet, India) and appropriate sieves. These grains were soaked in 1N NaOH for 24 h and then washed with distilled wateruntilthe pH reached 6.8–7.2. The adsorption column was made of glass (i.d. 1 cm) with a height of 50 cm. The bed depth was 20 cm. The effluent from the bioreactor was collected and passed through the adsorption column in down flow mode with a flow rate of 1.527 $m^3/m^2/h$. The effluent was collected and analyzed for Cr(VI), total chromium

and COD regularly. The adsorbent was regenerated using 1N HCl whenever required.

2.8. Analytical procedures

The samples were collected at pre-fixed intervals and centrifuged at $4500 \times g$ for 15 min. Hexavalent chromium was determined colorimetrically at 540 nm using diphenyl carbazide reagent in acidic solution. The samples for total chromium analysis were first digested with a mixture of sulphuric–nitric acids and oxidized with potassium permanganate before reacting with diphenyl carbazide and determined colorimetrically (APHA, AWWA, 1995). Cr(III) concentration was determined by taking the difference between total chromium concentration and Cr(VI) concentration. The analysis was counter checked randomly by atomic absorption spectrophotometer. The chromium content of soil was determined after digesting the sample as per standard methods [27]. Cell density was determined by measuring the absorbance using a 1 cm cuvette at 440 nm. Cell dry weight was determined as total suspended solids according to the procedure of APHA [27]. Organic matter concentration was analyzed as chemical oxygen demand (COD) by employing closed reflux method [27]. Digestion of the samples was carried out in a HACH COD digester (Hach, USA).

Sulfates and nitrates were analyzed as per standard methods for the analysis of water and wastewater [27]. Dissolved oxygen (DO) was measured using a DO meter (Orion, USA).

3. Results and discussion

3.1. Cr(VI) desorption studies

Present study employed ex situ bioremediation technique for the treatment of Cr(VI) contaminated soil. The optimum desorption conditions for Cr(VI) from the contaminated soil was evaluated. To achieve this, desorption studies were carried out using, distilled water, EDTA, citrate, molasses and tap water. To study the effect of pH on Cr(VI) desorption from the contaminated soil, tap water with varying pH were employed. The results are given in Fig. 2. Cr(VI) desorption affected significantly by the pH. The percentage Cr(VI) desorption increased with increase in pH. Desorption was maximum at high pH and reduced gradually as the pH value decreased. Cr(VI) concentration in the leachate was in the order of 100 mg/L in the beginning, but gradually reduced to non-detectable range (<0.1 ppm) within a few hours. The study was continued until the Cr(VI) concentration in the leachate was in the non-detectable levels.

The surface of most of the natural soils is negatively charged, which favour the adsorption of cations or less negatively charged anions. Cr(VI) in the contaminated soil usually exists in the form of $HCrO_4^-$ and CrO_4^{2-} depending on the surrounding aqueous environment pH. At a pH above 7, most of the Cr(VI) exists in the form of CrO_4^{2-} whereas at lower

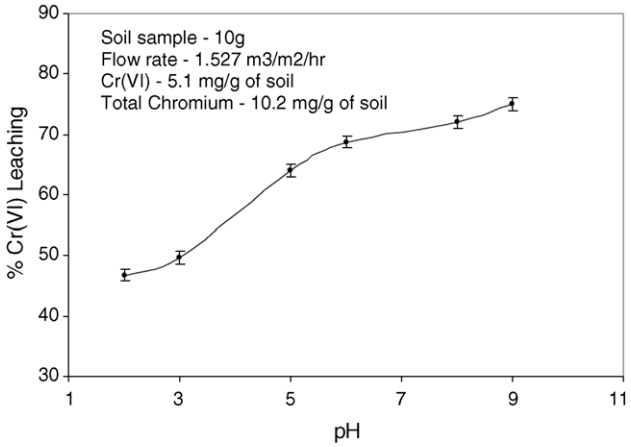

Fig. 2. Effect of pH on Cr(VI) leaching.

pH, Cr(VI) tends to be in the form of $HCrO_4^-$ [28] CrO_4^{2-} is weakly adsorbed to the soil compared to $HCrO_4^-$. Zachara et al. [29] suggested that CrO_4^{2-} adsorbs onto soil colloids as a weak outer-sphere complex. Thus, the CrO_4^{2-} ion is not held strongly onto soil particles. Intuitively, CrO_4^{2-} can be readily leached from the soil surface. This may be the reason for the higher leaching of Cr(VI) at an elevated pH.

The leachability study was also performed using other eluents like distilled water, citrate (IM), EDTA (0.2 M), and molasses (5 g/L). Results are shown in Fig. 3. As expected, EDTA affected maximum Cr(VI) desorption among the eluents tried. EDTA is a known strong complexing agent with the metals. But molasses also desorbed around 71% of total Cr(VI), which was almost same as the amount leached out by tap water at a pH 9.0. The desorption potential of citrate, which is a strong organic complexing agent was almost same as that of molasses. Organic compounds are able to form complexes with metals though it may not be as strong as EDTA or cyanide. Distilled water could affect only the metal ions, which are attached to the matrix due to the weak van der Waals force. As molasses is available as a waste material

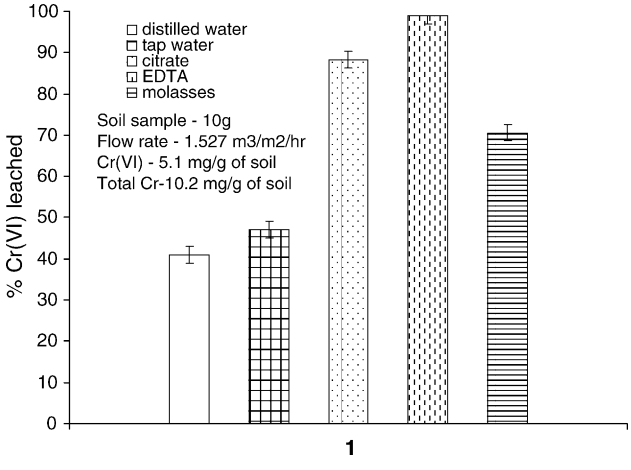

Fig. 3. Cr(VI) desorption potential of various eluents.

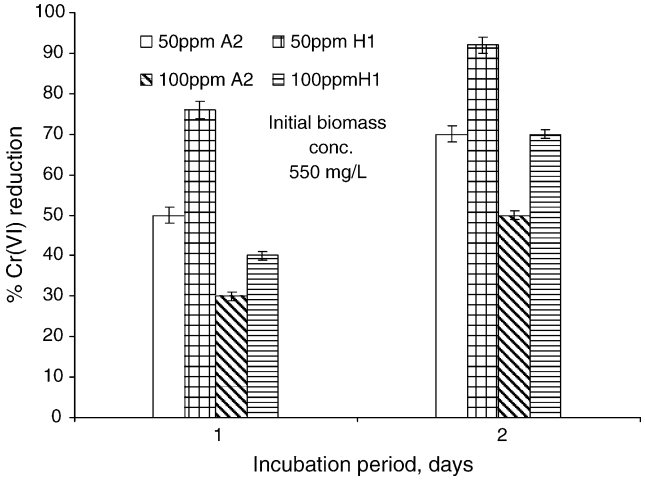

Fig. 4. Cr(VI) Reduction under Aerobic Conditions by H1 and A2 Bacterial Isolates.

from distillery industry, it was selected as the carbon source as well as the eluent for the present study. It could desorb the same amount of Cr(VI) under the worst conditions that can exist in the field. Dry autoclaved soil was used for leachability study. Hence, the chance of biotransformation of Cr(VI) in presence of organic matter is ruled out.

3.2. Evaluation of optimum conditions for Cr(VI) reduction

3.2.1. Screening of the enriched microbial cultures

Bacterial isolates collected and enriched from the chromium-contaminated soils were screened for their Cr(VI) reduction potential under aerobic and facultative anaerobic conditions. The bacterial culture H1 isolated from a well in the contaminated site showed high reduction potential compared to A2 which was isolated from a marshy place in the vicinity both in aerobic and facultative anaerobic conditions (Figs. 4 and 5). The Cr(VI) concentration in the surrounding was much higher in case of H1 (above 500 ppm) compared

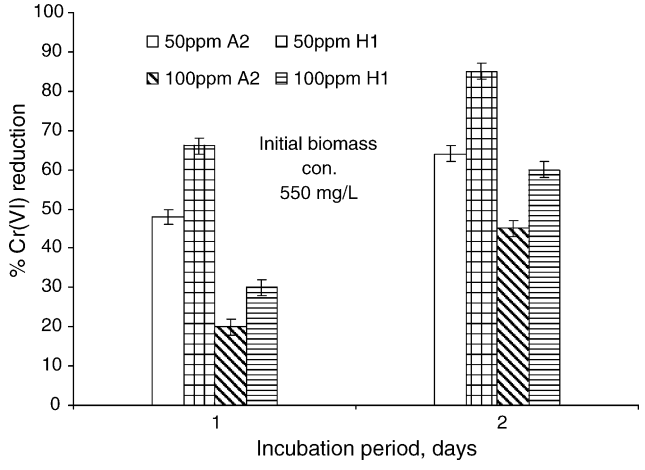

Fig. 5. Cr(VI) reduction under anaerobic conditions by H1 and A2 bacteria.

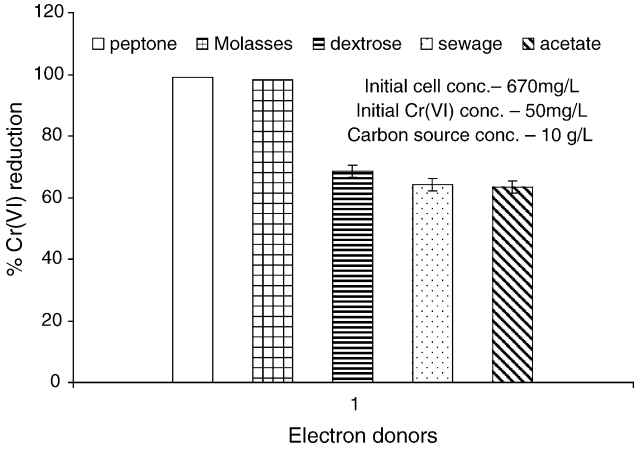

Fig. 6. Effect of electron donors on Cr(VI) reduction.

to A2 (50 ppm). This may be the reason for the better performance of bacterial isolate H1. Cr(VI) reduction was slightly higher in aerobic condition compared to facultative anaerobic conditions. Tseng and Benefieldt [26] also reported a higher Cr(VI) reduction by indigenous microbes under aerobic condition especially when the initial Cr(VI) concentration was higher. Anaerobic microbes are usually more sensitive to toxic compounds like heavy metals [30] There was no Cr(VI) reduction in the control reactor with out any microorganisms, which demonstrates the role of microorganism in the reduction of Cr(VI). As aerobic systems require more energy for aeration compared to facultative anaerobic systems, it was decided to develop a reactor working on facultative anaerobic conditions.

3.2.2. Screening of electron donors

The Cr(VI) reduction studies were carried out using various electron donors such as peptone, molasses, dextrose, sewage, and acetate to find out the most effective and economical one. Among the electron donors screened, peptone and molasses showed almost same Cr(VI) reduction as shown in Fig. 6. Molasses was selected as electron donor for further studies, as it was available plenty as a waste material in the vicinity. Moreover, by employing molasses, the treatment cost can be considerably reduced which is an added advantage especially for developing countries.

3.2.3. Effect of initial Cr(VI) concentration

The initial Cr(VI) concentration affected the Cr(VI) reduction. The time required for the Cr(VI) reduction was increased with increase in initial Cr(VI) concentration (Fig. 7). But the rate of Cr(VI) reduction was the same for various concentration ranges tried. The isolated bacteria were able to reduce even 400 mg/L of Cr(VI). But above 200 mg/L the complete Cr(VI) reduction was not observed even after 4 days. The specific Cr(VI) reduction was increased with an increase in the initial Cr(VI) concentration may be due to the inhibition effect of Cr(VI) at high concentration which might have reduced the biomass production. Since the specific Cr(VI)

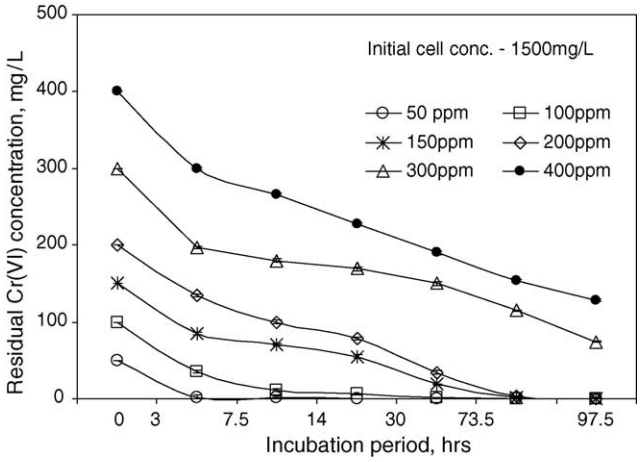

Fig. 7. Effect of Initial Cr(VI) concentration on biotransformation of Cr(VI).

concentration was calculated per unit biomass, the decrease in biomass concentration increase the value. No significant Cr(VI) reduction in the control (<2%, data not shown) indicates that the abiotic Cr(VI) reduction is negligible in the system.

3.2.4. Effect of electron donor concentration on Cr(VI) reduction

As the concentration of electron donor increased, the effective Cr(VI) reduction was also increased to a certain extent afterwards it remained as a constant (Fig. 8). There was no substrate inhibition observed. Initially the system followed a first-order kinetics with respect to substrate concentration gradually it turned to zero order as the concentration of molasses increased. Cr(VI) reduction in the presence of other oxi-anions like sulfate and nitrate were evaluated. Sulfate or nitrate ions up to a concentration range of 400 mg/L (Table 1) could not affect the Cr(VI) reduction. Cell free controls were

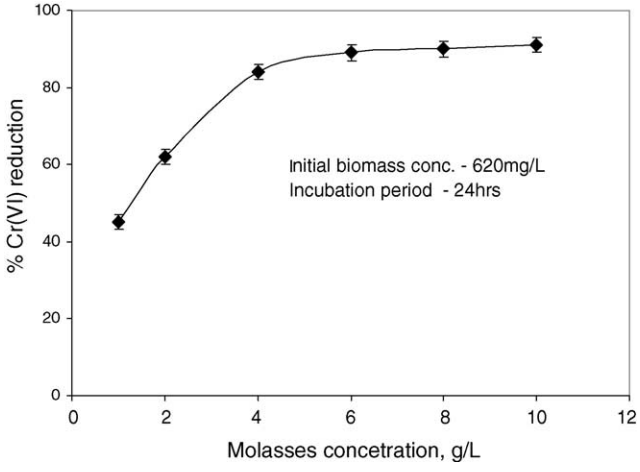

Fig. 8. Effect of carbon source concentration on Cr(VI) reduction, (a) Cr(VI) concentration in influent and effluent; (b) COD—influent and effluent; (c) Cr(III)—influent and effluent; (d) DO—influent and effluent; (e) Sulfate—influent and effluent; (f) Nitrate—influent and effluent.

Table 1
Effect of sulfate and Nitrate on Cr(VI) reduction

Molasses concentration (g/L)	Electron acceptors	Concentration of electron acceptor (mg/L)	Cr(VI) reduction (%)
10	SO_4^{2-}	0	71.06
		50	72.72
		100	72.08
		200	74.24
		300	73.88
		400	73.28
10	NO_3^-	0	70.68
		50	71.52
		100	71.28
		200	72.08
		300	71.7
		400	71.28

Initial Cr(VI) concentration – 50 mg/L, initial biomass concentration – 330 mg/L.

employed in all the cases (results not shown). Cr(VI) reduction was very insignificant in the controls.

3.3. Immobilized reactor for Cr(VI) reduction

Once the optimum condition for Cr(VI) reduction was established, an immobilized bioreactor was designed and operated to evaluate the performance of the system. The results are presented in Fig. 9. Initially the bioreactor was fed with 10 mg/L of Cr(VI) along with nutrients (M2) with 5 mg/L of molasses. The bioreactor could achieve 90% of Cr(VI) reduction within seven days of operation. The influent Cr(VI) concentration was increased to 20 mg/L on the 8th day of operation. Once the reactor could affect more than 80% of Cr(VI) reduction, the influent Cr(VI) concentration was increased. Even at an initial concentration of 50 mg/L, the reactor could achieve more than 80% efficiency in terms of Cr(VI) reduction. Though the biomass concentration in the reactor was increased continuously, there was no clogging or extra pressure drop in the system. The system was operated in facultative anaerobic conditions without any external air supply. The Dissolved oxygen was completely consumed by the facultative microorganisms within 5 cm length of the reactor. There was no significant change in sulfate and nitrate concentrations in the influent and effluent of the bioreactor shows that SO_4^{2-} and NO_3^- were not reducing in the system.

The total chromium concentration in the influent and effluent remained almost same. This shows that there was no accumulation of Cr(III) or Cr(VI) in microbial cells. Entire Cr(VI) transformed remained in the solution. From this, one may conclude that some extra cellular enzymes mediate the Cr(VI) reduction. Cr(III) usually react with water to form $Cr(OH)_3$ in natural environment and get precipitated. As discussed earlier, Cr(III) forms complexes with organic matter which in turn increase the solubility of the particular species. As the ligand (organic matter) was abundantly available, which prevented the precipitation of Cr(III) as $Cr(OH)_3$ and kept entire metal in solution. The dissolved oxygen of

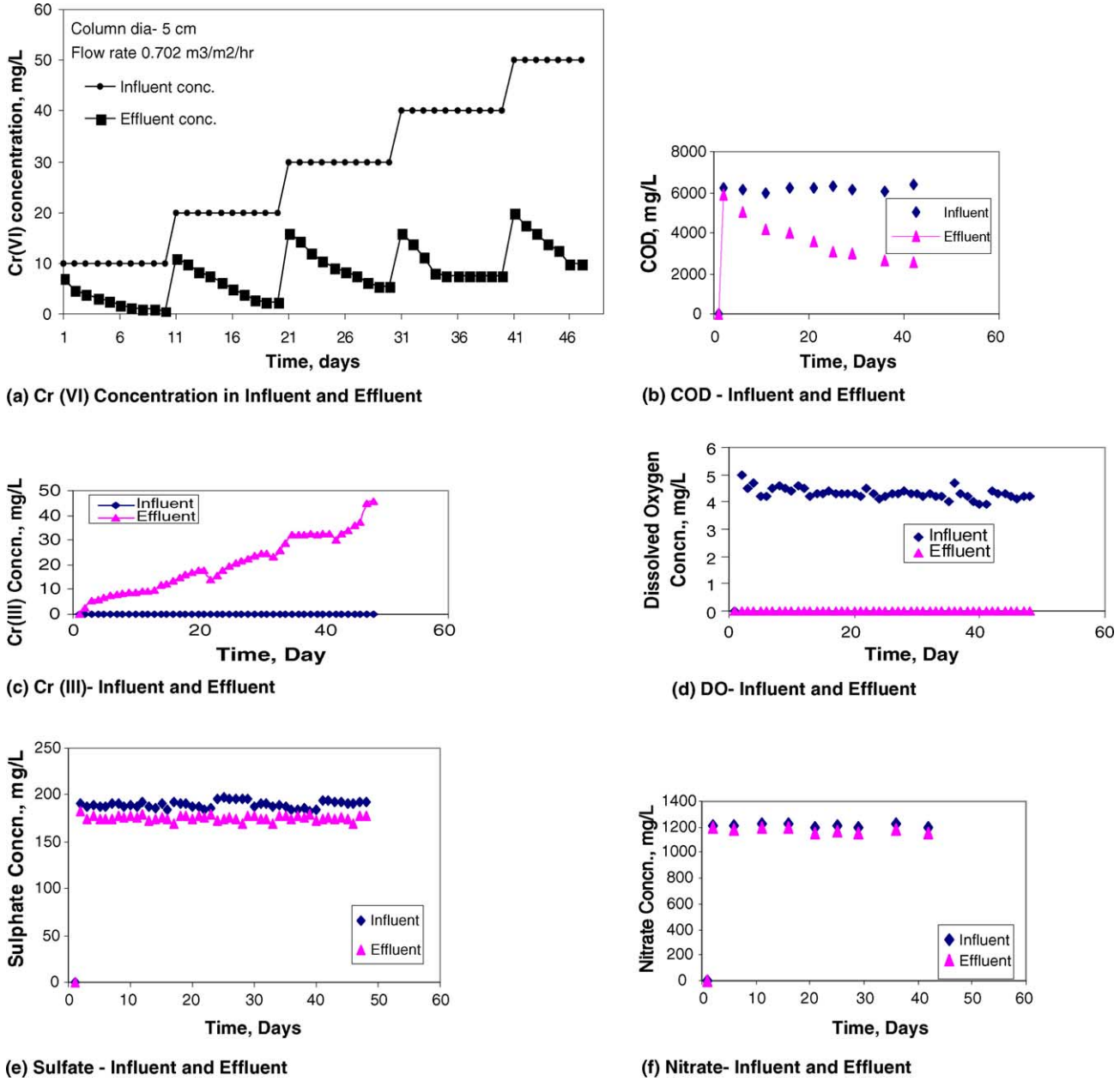

Fig. 9. Performance of immobilized bioreactor.

the effluent was in the range of 0–0.3 mg/L. From this it is clear that the system was working under facultative anaerobic conditions.

To see the effect of HRT on Cr(VI) reduction, the HRT of the system was reduced from 8 to 4 h and Cr(VI) concentration was monitored in the effluent. With the influent Cr(VI) concentration of 50 mg/L the reactor could affect more than 60% Cr(VI) reduction at an HRT of 4 h.

3.4. Performance of the polishing treatment unit

The effluent from the Cr(VI) reducing bioreactor was having a high concentration of Cr(III), organic matter and some un-transformed Cr(VI). It is not advisable to discharge this effluent to inland or surface water. To treat this effluent, a polishing treatment system was designed and its performance was evaluated. An adsorption column using *G. lucidum*, a wood rooting fungi, as adsorbent was used as the post-treatment unit. The column was filled with the adsorbent. The effluent from bioreactor on 47th day was collected and passed through the adsorption column. The effluent Cr(III) and COD concentrations were monitored at regular intervals. The performance of the post-treatment unit is given in Fig. 10.

The adsorption column was able to remove more than 95% of Cr(III) in the initial 3 h. There after Cr(III) sorption was gradually decreased, as the adsorption capacity of the adsorbent depleted. The study was continued until the adsorption column was exhausted. The column was completely

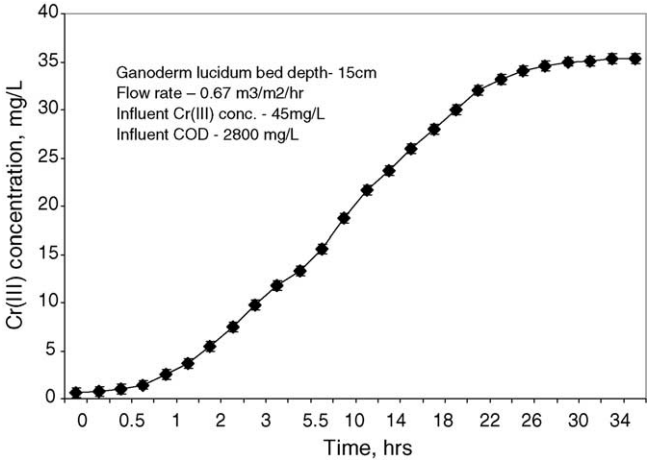

Fig. 10. Breakthrough curve for Cr(III).

exhausted after 36 h and during this period less than 5% of Cr(III) adsorption was observed. The maximum adsorption capacity of *G. lucidum* was calculated based on the break through curve and was found to be 576 mg/g. Removal of carbonaceous material by the adsorption column was also monitored. The presence of organic matter significantly affected the Cr(III) adsorption. The organic matter present in the influent might have competed with Cr(III) for adsorption sites. This may be the reason for reduction in Cr(III) adsorption capacity within a short time.

The adsorption of organic matter was less compared to that of Cr(III) by the adsorption column (Fig. 11). Though the column was not able to remove organic matter completely it was effective in the removal of Cr(III). The complete organic matter removal can be achieved by other relatively simple biological means if necessary. Supplying less quantity of molasses to the biosystem can reduce the COD of the effluent. To optimize this process further studies are required. In short, the Biosystem for Cr(VI) biotransformation followed by the polishing unit seems to be effective for the treatment of Cr(VI) bearing waste. Moreover, the system is economical and environmental friendly as it is utilizing only naturally available waste materials.

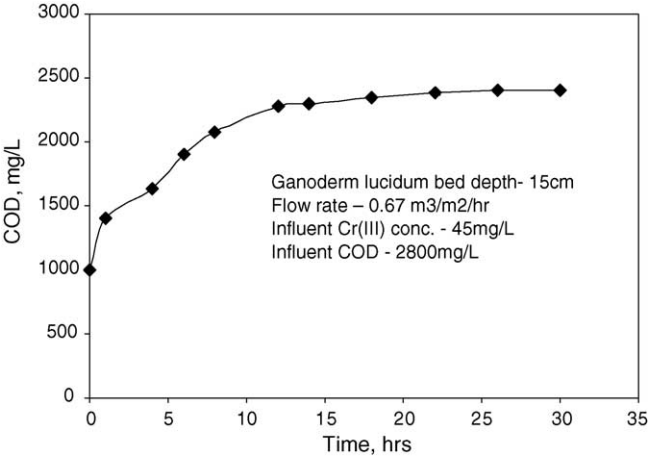

Fig. 11. Breakthrough curve for COD.

4. Conclusions

The isolated microbial consortium from contaminated soil showed good Cr(VI) reduction capacity. The microbes were able to sustain a high Cr(VI) concentration in the order of 400 mg/L. The influence of pH was significant in Cr(VI) desorption. The Cr(VI) desorption was enhanced at alkaline conditions (pH 9). Among the five eluents employed, EDTA (0.1 M) had the maximum desorption capacity. However, molasses also showed significant amount of Cr(VI) desorption capacity. The initial Cr(VI) concentration and carbon source employed affect the Cr(VI) reduction capacity. Molasses showed high feasibility as an electron donor. Presence of sulfates and nitrates did not inhibit the Cr(VI) reduction in the system. The time required for Cr(VI) reduction was increased with the increase in initial Cr(VI) concentration. However, the specific Cr(VI) reduction also increased with the increase in the initial C(VI) concentration though the reduction rate was almost same. The Cr(VI) reduced effectively in immobilized bioreactor. More than 80% Cr(VI) reduction was observed for 50 mg/L of Cr(VI) concentration within 8 h. Adsorption column of powdered *G. lucidum*, showed promising Cr(III) removal capacity. Moreover, the system also removed the unspent organic matter. The biosystem developed in the present investigation is a viable treatment option for chromium-contaminated soils. The system is environmental friendly, as it is utilizing only naturally available waste materials.

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