

Full Length Research Paper

Microbial conversion of Cr (VI) in to Cr (III) in industrial effluent

Muhammad Faisal and Shahida Hasnain*

Department of Botany, University of The Punjab, Quaid-e-Azam Campus, Lahore-54590, Pakistan.

Accepted 26 April, 2000

Bacterial strains (CrT-11, CrT-12, *Bravibacterium* sp. CrT-13, CrT-14) were isolated from the effluents of tanneries. All strains could resist very high concentration of K_2CrO_4 that is up to 40 mg ml^{-1} on nutrient agar and 25 mg ml^{-1} in nutrient broth. They have wide pH (5 to 9) and temperature (24 to 42°C) growth range. They exhibited multiple metals (Ni, Zn, Mn, Cu, Co, Pb) and antibiotics (streptomycin, ampicillin, tetracycline, kanamycin, chloramphenicol) resistances. All the strains were able to reduce Cr (VI) in to Cr (III) aerobically. *Bravibacterium* sp. CrT-13 accumulates and reduce more Cr (VI) at all the concentrations applied in comparison to the other strains. These bacterial strains also take up and reduce Cr (VI) present in industrial effluents, and their reduction potential was not significantly affected in the presence of different metallic salts.

Key words: Cr (VI) reduction, bacteria, industrial effluent, heavy metals.

INTRODUCTION

The current pattern of industrial activity alters the natural flow of materials and introduces novel chemicals into the environment. In areas polluted as a result of industrial activity, concentrations of toxic substances often exceed the levels normally found in soil, waterways, and sediment. When toxic substances accumulate in the environment and in food chains, they can profoundly disrupt biological processes.

Hexavalent chromium, Cr (VI), is the toxic form of chromium released during many industrial processes including electroplating, leather tanning, and pigment manufacture. Chromium is an essential element required for normal carbohydrate and lipid metabolism (Anderson, 1998). Its deficiency leads to increase in risk factors associated with diabetes and cardiovascular diseases

including elevated circulating insulin, glucose, triglycerides, total cholesterol and impaired immune function. Contrary to deficiency symptoms, several factors make chromate contamination as a matter of intense concern, particularly its toxic, mutagenic (Cheng and Dixon, 1998), carcinogenic (Shumilla et al., 1999) and teratogenic (Asmatullah et al., 1998) effects. Removal of this toxic form of chromium by its reduction to the much less harmful and physically immobile state Cr (III) is now our concern.

Bioremediation of soluble hexavalent chromium can be obtained by utilizing microbes in wastewaters. Several bacterial strains (*Pseudomonas ambigua*, *Desulfovibrio vulgaris*, *Enterobacter cloacae* HO-1, *Alcaligenes eutrophus*, *Dinococcus radiodurans* R1) has been described for their ability to reduce hexavalent chromium into insoluble low valence form Cr (III) both aerobically and aerobically (DeLeo and Ehrlich, 1994; Fredrickson et al., 2000; McLean and Beveridge, 2001). Hence the

*Corresponding author. E-mail: mohdfaysal@yahoo.com.

chromate reducing bacteria are most crucial for the immobility of soluble hexavalent chromium in the environment. The goal of this study was to develop a system to describe chromate reduction alone and in the presence of other toxic contaminants.

MATERIALS AND METHODS

Microorganisms Characterization

Selected strains were characterized morphologically, biochemically, and physiologically following Gerhardt et al. (1994). The impact of potassium chromate, pH and temperature on the growth of these strains was observed in nutrient broth. Fresh inoculum from overnight cultures adjusted to 10^8 cells ml^{-1} was added to nutrient broth containing different concentrations of potassium chromate. Cultures were grown at 37 °C for 24 h and growth was monitored at 600 nm. Different heavy metals (NiSO_4 , 500 $\mu\text{g ml}^{-1}$; ZnSO_4 , 700 $\mu\text{g ml}^{-1}$; MnSO_4 , 1500 $\mu\text{g ml}^{-1}$; CuSO_4 , 1000 $\mu\text{g ml}^{-1}$; CoCl_2 , 500 $\mu\text{g ml}^{-1}$; HgCl_2 , 50 $\mu\text{g ml}^{-1}$ and $\text{Pb}(\text{NO}_3)_2$, 1000 $\mu\text{g ml}^{-1}$), and antibiotics (streptomycin, 500 $\mu\text{g ml}^{-1}$; ampicillin, 300 $\mu\text{g ml}^{-1}$; tetracycline, 30 $\mu\text{g ml}^{-1}$; kanamycin, 40 $\mu\text{g ml}^{-1}$; chloramphenicol, 5 $\mu\text{g ml}^{-1}$) were used to check the multiple metals and antibiotics resistance profile of these strains.

16S rRNA gene sequencing

To confirm taxonomic identity, one strain (CrT-13) was selected for 16S rRNA gene sequencing. DNA was extracted and a part (500 bp) of the 16S rRNA gene was amplified, and sequenced using fluorescent di-deoxy terminator cycle sequencing chemistry in an ABI PRISM® (automated DNA sequencer). The data was compared to the MicroSeq® databases (ACCUGENIX™ Newark DE 19702).

Cr (VI) uptake

For uptake experiment three initial K_2CrO_4 concentrations, 100, 500, and 1000 $\mu\text{g ml}^{-1}$, were used. The inoculum was prepared as follow. i) One gram of fresh cell pellet was dried at 60°C for 48 h (dried cells). ii) Same amount of pellet was heat-killed at 121°C for 20 min (Heat killed). iii) Same amount was used untreated (live cell mass).

All experiments were conducted in 250 ml conical flasks containing 100 ml of chromium solution. Before mixing the bacterial strains, the pH of the chromium solution was adjusted to the required value with 0.01N NaOH. Bacterial cell suspension was added to metal solution and was placed in an incubating shaker at 150 rpm. At regular time intervals, samples were taken aseptically and were centrifuged at 10,000 rpm for 10 min at 4°C. Pellet obtained were digested and the amount of chromium accumulated was determined spectrophotometrically at 540 nm in a spectrophotometer using diphenylcarbazide as the complexing agent (APHA, 1990).

Cr (VI) reduction

To check the chromate reduction potential of these isolates, Deleo and Ehrlich (1994) medium (Grams per liter: Tryptone 10, Yeast extract 5, NaCl 5, Citric acid 1, NaH_2PO_4 6.9) was used. Three initial chromate concentrations, 100, 500, and 1000 $\mu\text{g ml}^{-1}$ and two cells concentrations, 2.4×10^7 and 9.6×10^7 cells ml^{-1} were used. Cultures were inoculated from cell growing in log phase. Reduction

experiments were conducted in 250 ml conical flasks containing 100 ml of medium. Cultures were placed in an incubating shaker at desired temperature. The initial pH of these experiments was 7. At selected points, samples were withdrawn aseptically and were processed to check the amount of hexavalent chromium reduced. Reduction of chromate was measured by colorimetric method following DeLeo and Ehrlich (1994) using spectrophotometer (Model S-300 DL, R & M marketing, England) at 540 nm. Each treatment was conducted in triplicate.

Effect of Heavy Metals on Cr (VI) Reduction

The isolates were also assessed for their ability to reduce Cr (VI) in the presence of different heavy metals (Zn, 200 $\mu\text{g ml}^{-1}$; Ni, 200 $\mu\text{g ml}^{-1}$; Mn, 200 $\mu\text{g ml}^{-1}$; Cu, 200 $\mu\text{g ml}^{-1}$; Co, 50 $\mu\text{g ml}^{-1}$ and Ag, 50 $\mu\text{g ml}^{-1}$). The amount of Cr (VI) reduced was measured as described above. Each treatment was conducted in triplicate.

Cr (VI) Reduction in industrial effluent

In order to check the hexavalent chromium reduction efficiency of these strains in industrial effluents, samples were collected in sterilized bottles. The physico-chemical parameters of the effluent sample was as follow: pH 5-6, temperature 27-29°C, Cr (VI) 300 $\mu\text{g ml}^{-1}$; Fe 21 $\mu\text{g ml}^{-1}$; Cu 10 $\mu\text{g ml}^{-1}$; Zn 4 $\mu\text{g ml}^{-1}$; Ni 11 $\mu\text{g ml}^{-1}$; Co 2 $\mu\text{g ml}^{-1}$; Pb 1 $\mu\text{g ml}^{-1}$; Mn 1 $\mu\text{g ml}^{-1}$. In this effluent sample some nutritional requirements for bacterial growth were also added. Two different dilution of effluent sample were used; sample I and sample II containing 150 and 300 $\mu\text{g ml}^{-1}$ of Cr (VI), respectively. After inoculation these samples were incubated for 40 h at 37°C. Cr (VI) reduced was measured as describe above.

RESULTS

Strains isolation and characterization

The current study deals with four bacterial strains (CrT-11, CrT-12, *Bravibacterium* sp. CrT-13 and CrT-14). All were isolated from the effluents of tanneries. Strains CrT-11, CrT-12 and CrT-14 were gram-negative motile rods while strain *Bravibacterium* sp. CrT-13 was gram positive. All were aerobic in nature. They were unable to hydrolyse starch and arginine. Except strain *Bravibacterium* sp. CrT-13, all were able to reduce nitrate into nitrite. None of them could denitrify (Table 1).

Nevertheless, the growth of all the strains decreased with increasing concentration of chromate salt, but all of them could grow in the presence of 25 mg ml^{-1} of K_2CrO_4 . *Bravibacterium* sp. CrT-13 exhibited relatively poor growth at all the concentrations. In the presence of chromate (1 mg ml^{-1}) the lag phase in the strains CrT-11, CrT-12 and *Bravibacterium* sp. CrT-13 prolonged (Figure 1b). The temperature preference remains the same (37°C), both in the presence and absence of chromate salt. Growth of the strains was much reduced at low temperature (24°C; Figure 2a). These strains preferred pH 7 both in simple nutrient broth and in chromate supplemented media. In the presence of chromate, the growth was very poor at pH 5 as compared to chromate

Table 1. Morphological and biochemical characteristics of bacterial isolates.

Characteristics	Strains				Characteristics	Strains			
	CrT-11	CrT-12	CrT-13	CrT-14		CrT-11	CrT-12	CrT-13	CrT-14
Colony shape	Circular	Circular	Circular	Circular	Voges Proskauer	-	-	-	-
Colony elevation	Convex	Convex	Convex	Convex	Nitrate reduction	+	+	-	+
Colony size (mm)	2.4	1.9	1.3	1.4	Denitrification	-	-	-	-
Colony margin	Entire	Rods	Rods	Rods	H ₂ S production	-	-	-	-
Cell shape	Rods	L.Yell	Yellow	L.Yell	OF	Aerobic	Aerobic	Aerobic	Aerobic
Cell size	1.0-0.4	1.2-0.5	1.2-0.6	2.0-0.4	Acid from sucrose	-	-	-	-
Gram staining	-ve	-ve	+ve	-ve	Acid from maltose	-	-	-	-
Capsules staining	-	-	-	-	Acid from mannitol	-	-	-	-
Spore staining	-	-	-	-	Acid from lactose	-	-	-	-
Urease test	-	-	-	-	Growth on malonate	-	-	-	-
Motility	+	+	+	+	Growth on EMB	+	+	-	+
Catalase	+	+	+	+	MacConkey agar	+	+	+	+
Cytochrome	+	+	-	+	Brilliant green bile	-	-	-	-
Arginine hydrolysis	-	-	-	-	King'A	-	-	-	-
Starch hydrolysis	-	-	-	-	King'B	-	-	-	-
Methyl red	-	-	-	-	Plasmid	+	+	+	+

Table 2. Heavy metals resistance profile of chromium resistant bacterial isolates.

Strains	Heavy metals ($\mu\text{g ml}^{-1}$)					
	NiSO ₄	ZnSO ₄	Pb (NO ₃) ₂	CuSO ₄	CoCl ₂	MnSO ₄
CrT-11	500	500	1000	1000	300	1500
CrT-12	700	700	1000	1000	300	1500
CrT-13	400	500	1000	1000	200	1500
CrT-14	400	400	1000	1000	300	1500

Table 3. A. Effects of different heavy metals on the reduction potential of the strains. **B.** Chromate reduction in industrial effluents. a*. Initial chromate concentration 150 $\mu\text{g ml}^{-1}$. b**. Initial chromate concentration 300 $\mu\text{g ml}^{-1}$.

Source	Strains			
	CrT-11	CrT-12	CrT-13	CrT-14
A. Metals ($\mu\text{g ml}^{-1}$) % Cr (VI) Reduced				
Control	28.24%	36.20%	24.50%	27.20%
Ni (200)	28.00%	38.60%	24.60%	28.50%
Mn (200)	30.20%	34.20%	25.60%	29.40%
Zn (200)	31.40%	37.00%	27.50%	31.40%
Cu (200)	28.21%	36.50%	25.10%	23.41%
Co (50)	26.20%	34.12%	24.20%	24.96%
B. Industrial effluents				
a*	71.10%	93.12%	68.20%	79.00%
b**	56.03%	72.12%	47.22%	58.66%

free nutrient broth (Figure 2b). Besides chromate, they also showed multiple metals and antibiotics resistance (Table 3). Nevertheless tolerance profile of different strains was different. All bacterial strains were sensitive to HgCl₂ at 50 $\mu\text{g ml}^{-1}$ but their tolerance towards others

metals was very high (Table 2). These strains show sensitivity to 500 $\mu\text{g ml}^{-1}$ of streptomycin and 40 $\mu\text{g ml}^{-1}$ of kanamycin. All the strains are resistant to 25 $\mu\text{g ml}^{-1}$ of tetracycline. Excluding *Bravibacterium* sp. CrT-13, these strains are also resistant to 300 $\mu\text{g ml}^{-1}$ of ampicillin.

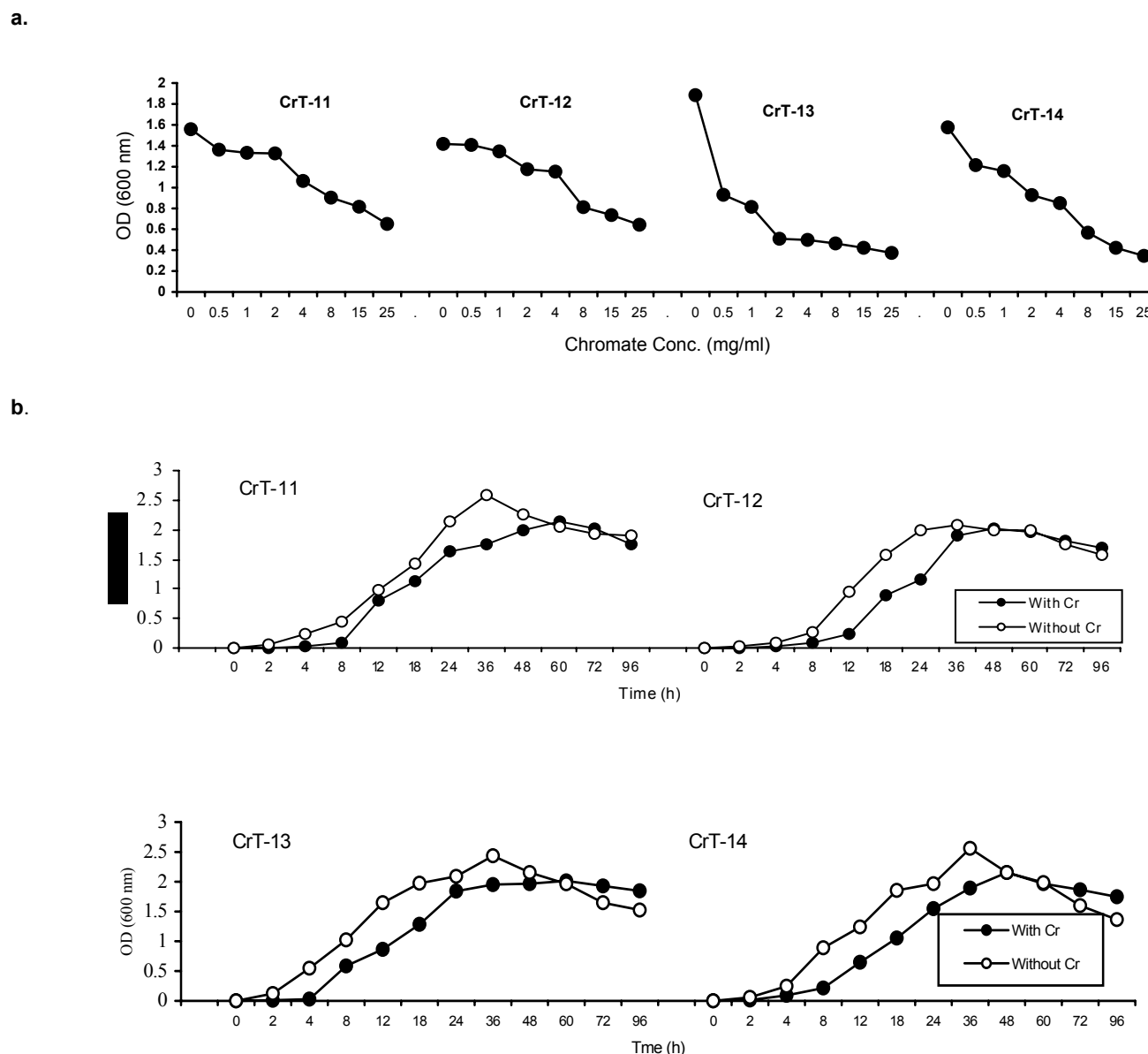


Figure 1. Growth responses of bacterial strains a) at different concentration of potassium chromate, b) after different time of incubation in the presence and absence of chromate (1 mg ml^{-1}).

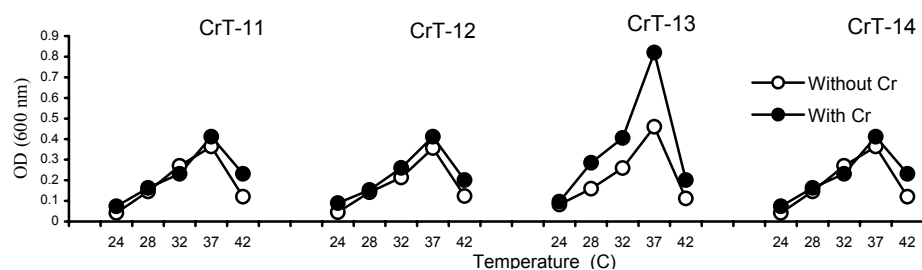
Strain identification through 16S rRNA gene sequencing

The 16S rRNA gene is the most widely accepted gene used for bacterial classification and identification. Signature nucleotides of 16S rRNA genes allow classification even if a particular sequence has no match in the database, since otherwise unrecognizable isolates can be assigned to phylogenetic branches at the class, family, genus, or subgenus levels. The results of 16S rRNA gene sequencing are presented in the Figure 5. Identification of the isolate based on its partial (500 bp) 16S rRNA gene sequences assigned it to the gram-positive, *Bravibacterium* sp. CrT-13.

Chromium uptake

The ability of cells to accumulate toxic hexavalent chromium from solution was determined at different (100 , 500 and $1000 \text{ } \mu\text{g ml}^{-1}$) chromate concentrations. Living cells showed higher chromate uptake than heat killed and dried cell mass. In the first fifteen minutes of contact time, the amount of chromium accumulated by the living cells of strain CrT-11 was 2.8 , 3.7 and 13.9 mg g^{-1} dry weights at an initial chromate concentration of 100 , 500 and $1000 \text{ } \mu\text{g ml}^{-1}$, respectively. In heat-killed cells, the accumulations were 3.3 , 3.6 and 12.6 mg g^{-1} dry weights. The amount of chromium accumulated by the dried cell mass is 2.2 , 3.1 and 8.3 mg g^{-1} dry weight. It was

a.



b.

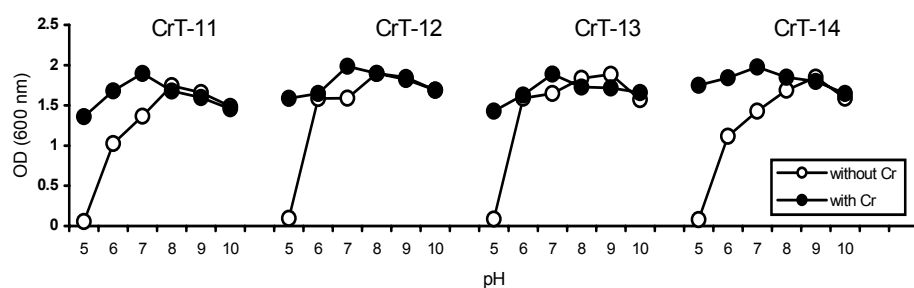


Figure 2. Growth responses of bacterial strains in chromate supplemented (1 mg ml⁻¹) and chromate free nutrient broth at different (a) temperatures (24-42°C) and (b) growth pHs (5-9).

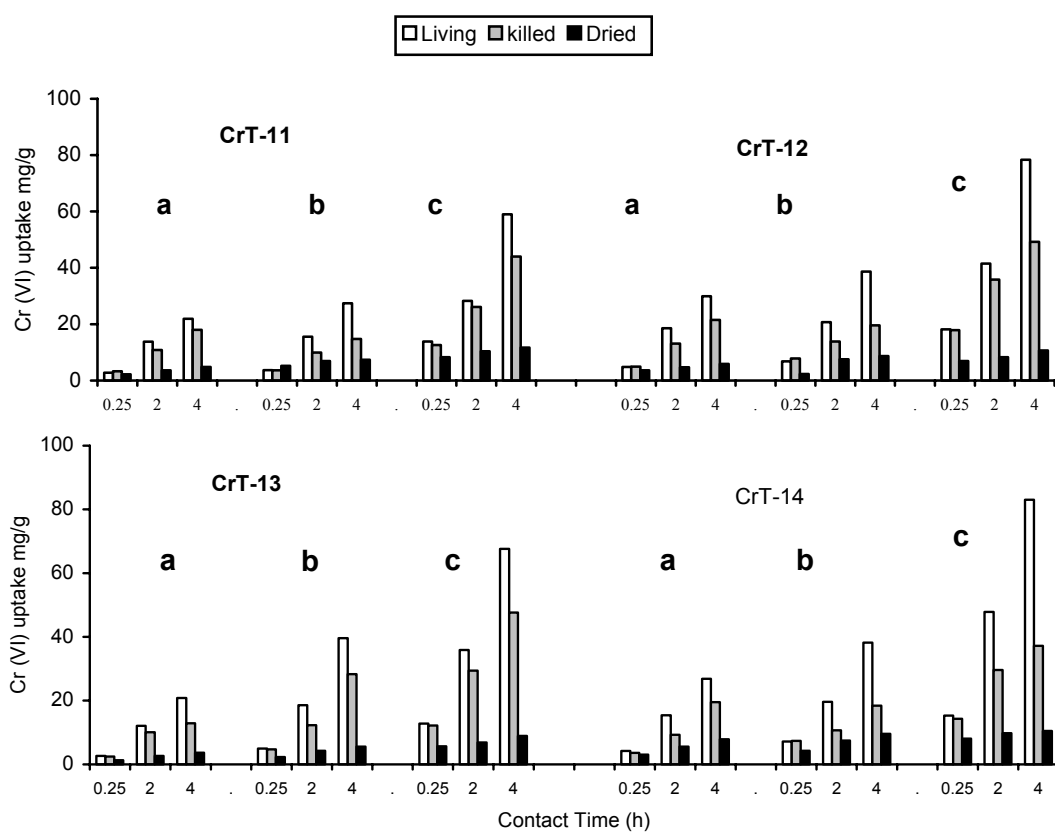


Figure 3. Uptake of potassium chromate at three initial K₂CrO₄ concentrations (a) 100, (b) 500 and (c) 1000 µg ml⁻¹. Cells were used as dried, heat killed and as live.

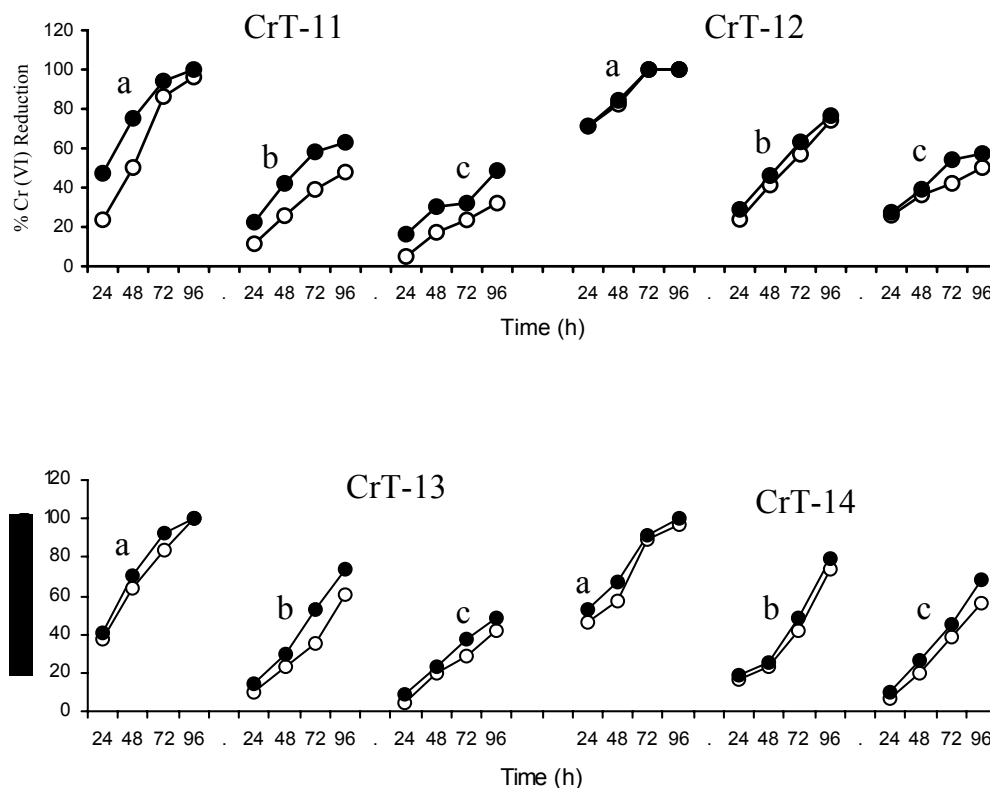


Figure 4. Reduction of K_2CrO_4 by Bacterial strains at three level of chromate. Reduction was monitor after 24, 48, 72 and 96 h of growth incubation. Open circle (o) represent 2.4×10^7 cells ml^{-1} and solid circle (●) represent 9.6×10^7 cells ml^{-1} used for initial inoculation. (a) Cr (VI) $100 \mu g ml^{-1}$; (b) Cr (VI) $500 \mu g ml^{-1}$; (c) Cr (VI) $1000 \mu g ml^{-1}$.

observed that after 2 and 4 h, chromium accumulated by the living cells was much more higher, specially at higher concentration relative to the other two categories i.e., heat-killed and dried cells. In this strain (CrT-11), after 4 h contact time the uptake values of 21.9, 27.4 and 59.0 $mg g^{-1}$ dry weight were observed in the living cells when initial metal solution was 100, 500 and 1000 $\mu g ml^{-1}$, respectively, but in case of dried cell mass the values were 4.8, 7.4 and 11.7 $mg g^{-1}$ dry weight which are much less compared with living cell mass. Almost same trend was observed in others three strains in this respect. In all cell types, the amount of chromium accumulation increased as contact time of cells with metal solution increased.

Cr (VI) reduction

Medium containing three levels of initial K_2CrO_4 concentrations, 100, 500 and 1000 $\mu g ml^{-1}$ was inoculated with two different inoculum size, 2.4×10^7 and 9.6×10^7 cells ml^{-1} . The reduction of hexavalent chromium by these bacterial strains in the medium resulted in the production of offwhite residues that was the sign of chromate reduction. After 72 h samples containing initial Cr (VI) concentration of 100 $\mu g ml^{-1}$ with

inoculum of 2.4×10^7 and 9.6×10^7 cells ml^{-1} , CrT-11 reduces almost 74.12 and 86.25% of Cr (VI), respectively, while strain CrT-12 completely reduce all the chromate at the same contact time. The reduction pattern of all the strains are depicted in Figure 4.

Cr (VI) reduction in industrial effluent

Cr (VI) reduction potential of these strains was also checked directly in the industrial effluent sample collected from a highly polluted metal finishing setup. In a sample that contains an initial chromate concentration of 150 $\mu g ml^{-1}$ along with other pollutants, CrT-11, CrT-12, *Bravibacterium* sp. CrT-13 and CrT-14 reduces approximately 71.10, 93.12, 68.20 and 79.0% of Cr (VI), respectively, within 40 h incubation period (Table 3).

Effect of Heavy Metals on Cr (VI) Reduction

Addition of different heavy metals at low concentration in the reduction medium did not affect significantly on the reduction potential of these strains. In all strains, 50 $\mu g ml^{-1}$ of $CoCl_2$ inhibited the Cr (VI) reduction proficiency of the strains to some extent while 200 $\mu g ml^{-1}$ $ZnSO_4$

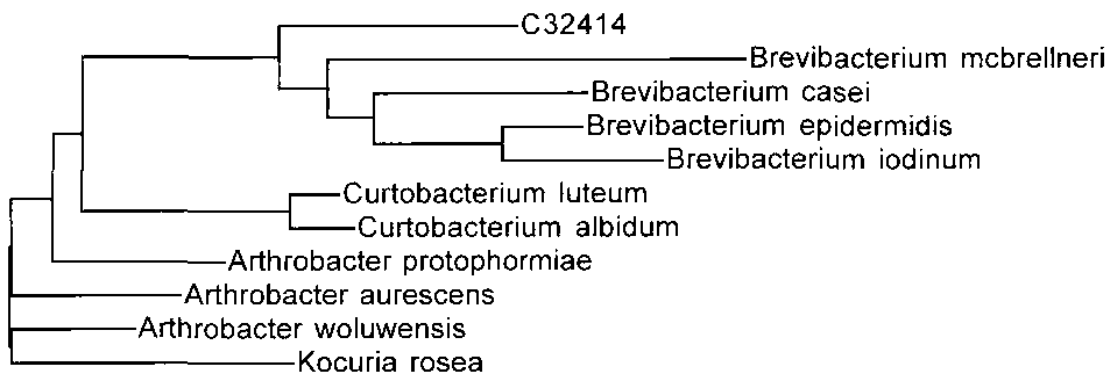


Figure 5. Phylogenetic relationship of *Bravibacterium* sp. CrT-13 (C32414) to other bacteria.

partially promoted the reduction of Cr (VI) in to Cr (III) by all strains. 200 $\mu\text{g ml}^{-1}$ MnSO_4 make some enhancement in the reduction ability of the strains (Table 3).

DISCUSSION

All strains used in this study showed very high-level resistance against potassium chromate both in nutrient broth (up to 25 mg ml^{-1}) and on nutrient agar (40 mg ml^{-1}). Such a high level resistance has not been previously reported. Chromium resistant bacteria isolated from effluent of tanneries could resist up to 250 $\mu\text{g ml}^{-1}$ of Cr (VI) in the medium (Basu et al., 1997). Megharaj et al. (2003) also reported strains, which were isolated from polluted soil, could resist up to 100 $\mu\text{g ml}^{-1}$ of Cr (VI). Besides, chromium strains have a broad range of heavy metals (Mn, Ni, Zn, Pb, Cu and Co) and antibiotics (streptomycin, ampicillin, tetracycline, kanamycin, Chloramphenicol) resistances, which shows a positive sign for the application of these strains in the treatment of industrial effluents. Strains reported by Filali et al., (2000) also exhibited different heavy metals and antibiotics resistances.

It was found that the amount of chromium accumulated by the cells increased with increase in concentration of chromium from 100 to 1000 $\mu\text{g ml}^{-1}$ K_2CrO_4 . Actually our strains shows very high level resistance to chromate and majority of them could resist up to 40 mg ml^{-1} of K_2CrO_4 on the nutrients agar plates. When we increase the initial chromate concentration from 100 to 500 $\mu\text{g ml}^{-1}$ the chromate content in the cell become almost doubled and same situation was observed by increasing the initial chromate concentration from 500 to 1000 $\mu\text{g ml}^{-1}$. The rate of chromate accumulation was initially rapid but maximum quantity of chromate was achieved after 4 hours incubation period. Overall results show that the living cells exhibited better chromate uptake compared to heat killed and dried cells.

All strains were able to reduce Cr (VI) after different incubation periods. The reduction of Cr (VI) has also recently been reported by others investigators. Bacterial

strains such as *Desulfomicrobium norvegicum* (Michel et al., 2003), *Bacillus* (Camargo et al., 2003), *Shewanella* (Guha et al., 2001; Viamajala et al., 2003; Middleton et al., 2003) *Desulfovibrio* (Chardin et al., 2002), *Escherichia coli* (Puzon et al., 2002), *Pseudomonas* (McLean and Beveridge, 2001), and *Alcaligenes* (Peitzsch et al., 1998) have been reported to successfully reduce Cr (VI) into Cr (III). Our results revealed that different heavy metals at low concentration did not significantly affect the reduction potential of these strains but they might be problematic at higher concentrations. McLean and Beveridge (2001) also observed that at low concentrations copper (40 mg L^{-1}) and arsenic (20 mg L^{-1}) had no significant effects on the reduction potential of *Pseudomonads* (CRB5), but at high concentration (120 mg L^{-1}) arsenic strongly inhibit the Cr (VI) reduction. Hg and Ag have proven to be strong inhibitors in chromate reduction by *Pseudomonas putida* (Ishibashi et al., 1990). The hexavalent chromium reduction studies described by these investigators, however, were performed under different conditions but at a low level concentration, whereas the present work was performed at high concentrations (200 $\mu\text{g ml}^{-1}$) of different heavy metals.

Hexavalent chromium reduction potential of strain *Bravibacterium* sp. CrT-13 was almost better in both effluent sample I and II as compared to others strains. This strain reduces almost 72.12% and 93.12% of Cr (VI) in sample I and II, respectively after 40 h incubation period. Hardoyo and Ohtake (1991) have also observed Cr (VI) reduction in industrial effluent collected from metal finishing plant. They found that in *Enterobacter cloaca* HO1, significant inhibition in Cr (VI) reduction was observed when the effluent contain 220 $\mu\text{g ml}^{-1}$ of Cr (VI), 25 $\mu\text{g ml}^{-1}$ of Cu, 26 $\mu\text{g ml}^{-1}$ of Mn and 0.02 $\mu\text{g ml}^{-1}$ of Zn. In another study Ganguli and Tripathi, 2002, also observed the reduction of Cr (VI) present in electroplating effluent with the help of *Pseudomonas aeruginosa* A2Chr in two-bioreactor system. All strains but especially *Bravibacterium* sp. CrT-13 showed amazing performance in this respect, which suggests that a hexavalent chromium reduction system of this nature can be economical to run.

ACKNOWLEDGEMENTS

Research grant received from Ministry of Science and Technology under the Biotechnology Research project is highly acknowledged.

REFERENCES

- Anderson RA (1998). Effects of chromium on body composition and weight loss. *Nutr. Rev.* 56(9): 266-270.
- APHA (1976). Standard methods for the examination of water and wastewater. 16th eds. American Public Health Association. Washington, D. C.
- Asmatulla, Qureshi SN, Shakoori AR (1998). Hexavalent chromium induced congenital abnormalities in chick embryos. *J. Appl. Toxicol.* 18(3): 167-171.
- Basu M, Bhattacharya S, Paul AK (1997). Isolation and characterization of chromium resistant bacteria from tannery effluent. *Bull. Environ. Contam. Toxicol.* 58: 535-542.
- Camargo FA, Okeke BC, Bento FM, Frankenberger WT (2003). In vitro Reduction of hexavalent chromium by a cell free extract of *Bacillus* sp. ES 29 stimulated by Cu (2+). *Appl. Microbiol. Biotechnol.* 62: 569-573.
- Chardin B, Gallice P, Sari JC, Bruschi M (2002). Thermodynamics of cleaning-up of waste waters polluted by chromium. *J. Therm. Anal. Calorimet.* 70: 475-482.
- Cheng L, Dixon K (1998). Analysis of repair and mutagenesis of chromium induced DNA damage in yeast mammalian cells and transgenic mice. *Environ. Health Perspect.* 106: 1027-1032.
- DeLeo PC, Ehrlich HL (1994). Reduction of hexavalent chromium by *Pseudomonas fluorescens* LB 300 in batch and continuous cultures. *Appl. Microbiol. Biotechnol.* 40: 756-759.
- Filali-Meknassi Y, Tyagi RD, Narasiah KS (2000). Simultaneous sewage sludgedigestion and metal leaching: effect of aeration. *Process Biochem.* 36: 263-273.
- Fredrickson JK, Kostandarithes HM, Li S W, Plymale AE, Daly MJ (2000). Reduction of Fe (III), Cr (VI), U(VI), and Tc(VII) by *Deinococcus radiodurans* R1. *Appl. Environ. Microbiol.* 66 (5): 2006-2011.
- Ganguli A, Tripathi AK (2002). Bioremediation of toxic chromium from electroplating, effluents by chromate-reducing *Pseudomonas aeruginosa* A2Chr in two bioreactors. *Appl. Microbiol. Biotechnol.* 58 : 416-420.
- Gerhardt P, Murry RGE, Wood WA, Kreig NR (1994). *Methods for General and molecular Bacteriology*. American Society for Microbiology, Washington, D.C.
- Guha H, Jayachandran K, Maurrasse F (2001). Kinetics of chromium (VI) reduction by a type strain *Shewanella alga* under different growth conditions. *Environ. Pollut.* 115 (2): 209-218.
- Hardoyo KJ, Ohtake H (1991). Effects of heavy metal cations on chromate reduction by *Enterobacter cloacae* strain HO1. *J. Gen. Appl. Microbiol.* 37: 519.
- Ishibashi Y, Cervantes C, Silver S (1990). Chromium reduction in *Pseudomonas putida*. *Appl. Environ. Microbiol.* 56: 2268-2270.
- McLean J, Beveridge TJ (2001). Chromate reduction by a *Pseudomonas* isolated from a site contaminated with chromated copper arsenate. *Appl. Environ. Microbiol.* 67: 1076-1084.
- Megharaj M, Avudainayagam S, Neidu R (2003). Toxicity of hexavalent chromium and its reduction by bacteria isolated from soil contaminated with tannery waste. *Curr. Microbiol.* 47: 51-54.
- Michel C, Giudici-Ortoni MT, Baymann F, Bruschi M (2003). Bioremediation of Chromate by Sulfate-Reducing Bacteria, Cytochromes C₃ and hydrogenases. *Water Air Soil Pollut.* 3: 161-169.
- Middleton SS, Latmani RB, Mackey MR, Ellisman MH, Tebo BM, Criddle CS (2003). Cometabolism of Cr (VI) by *Shewanella oneidensis* MR-1 produces cell-associated reduced chromium and inhibits growth. *Biotechnol. Bioeng.* 83: 627-637.
- Peitzsch N, Eberz G, Nies DH (1998). *Alcaligenes eutrophus* as a bacterial chromate sensor. *Appl. Environ. Microbiol.* 64(2): 453-458.
- Puzon GJ, Petersen JN, Roberts AG, Kramer DM, Xun LA (2002). Bacterial flavin reductase system reduces chromate to a soluble chromium (III)-N₄/I₄ complex. *Biochem. Biophys. Res.* 294 (1): 76-81.
- Shumilla AJ, Broderick JR, Wang Y, Barchowsky A (1999). Chromium Cr (VI) inhibits the transcriptional activity of nuclear factor- B by decreasing the interaction of p65 with cAMP-responsive element-binding protein. *J. Biol. Chem.* 274 (51): 36207-36212.
- Viamajala S, Peyton BM, Petersen JN (2003). Modeling chromate reduction in *Shewanella oneidensis* MR-1: Development of a novel dual enzyme kinetic model. *Biotechnol. Bioeng.* 83: 790-797.