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Bio-concentration of chromium—an *in situ* phytoremediation study at South Kaliapani chromite mining area of Orissa, India

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Abstract Mine waste water at South Kaliapani usually contains toxic levels of hexavalent Cr(VI). The present *in situ* study was conducted at South Kaliapani chromite mine area in Orissa state, India, to assess the phytoremediation ability of three plants, namely, rice (*Oryza sativa* L.), paragrass (*Brachiaria mutica*), and an aquatic weed (*Eichhornia crassipes*), in attenuating Cr(VI) from mine waste water and to correlate the bio-concentration factors (BCF) of Cr. Water hyacinth (*E. crassipes*) showed 24% to 54% reduction whereas paragrass (*B. mutica*) was able to reduce 18% to 33% of Cr(VI) from mine water. This reduction was studied over a period of 100 days of plant growth. The reduction was observed through a passage of a sum total of 2,000 sq. ft. cultivated plots and ponds separately. Reduction in Cr(VI) content in mine water varies with plant age as well as with the distance of passage. Cr accumulation and BCF values increased with high soil Cr levels as well as the age of plants. High BCF and transportation index (Ti) values, i.e., 10,924 and 32.09, respectively, were noted for water hyacinth. The Ti values indicated that the root-to-shoot translocation of Cr was very high after 100 days of growth. The total accumulation rate was maximum (8.29 mg Cr kg dry biomass^{-1} day $^{-1}$) in paragrass. The BCF values for roots were noted to be higher than those of leaves, stems, and grains of the 125-day-old plants. Hence, paragrass and water hyacinth may be used as tools of phytoremediation to combat the problem of *in situ* Cr contamination.

Keywords Hexavalent chromium · Phytoaccumulation · Bio-concentration factor · Total accumulation rate · Transportation index

Introduction

India is the second largest producer of chromites in the world. Open cast chromite mining activity leads to various environmental problems due to the released hexavalent chromium (VI). Contamination of soil and water in chromite mining areas is a widespread and serious problem. Orissa state accounts for 98% of the total chromite reserve of the country and the South Kaliapani chromite mine area of Orissa contributes about 97% of the total chromite reserve of the state (IBM 2004). As a result of growing open cast mining activities in the area, the environment is under threat. The element chromium exists in two stable states,

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i.e., hexavalent chromium (Cr-VI) and trivalent chromium (Cr-III). Cr(VI) is the most toxic form of chromium (WHO 1997) and is largely produced from anthropogenic sources, mining, and various industrial activities. Chromium toxicity results in the inhibition of plant growth and metabolism, which includes stunted growth, chlorosis, reduced crop yield, delayed germination, senescence, premature leaf fall, biochemical lesions, loss of enzyme activities, and reduced biosynthesis (Panda and Patra 1997a, b, 1998, 2000; Srivastava et al. 1999; Zayed et al. 1998; Zayed and Terry 2003; Mohanty et al. 2005a, 2009).

The objectives of this study were mainly to investigate the extent of chromium contamination by mine waste water and mine soil in the study area. The study encompasses the phytoaccumulation ability of the plants with reference to the bio-concentration factor (BCF), total accumulation rate (TAR), and transportation index (Ti) while the attenuation of Cr^{+6} from mine waste water using green plants like rice (*Oryza sativa* L. var. Khandagiri), paragrass (*Brachiaria mutica* (Forssk) Stapf), and water hyacinth (*Eichhornia crassipes* (Mart.) Solms-Laub) is being studied. The *in situ* phytoremediation program emphasizes

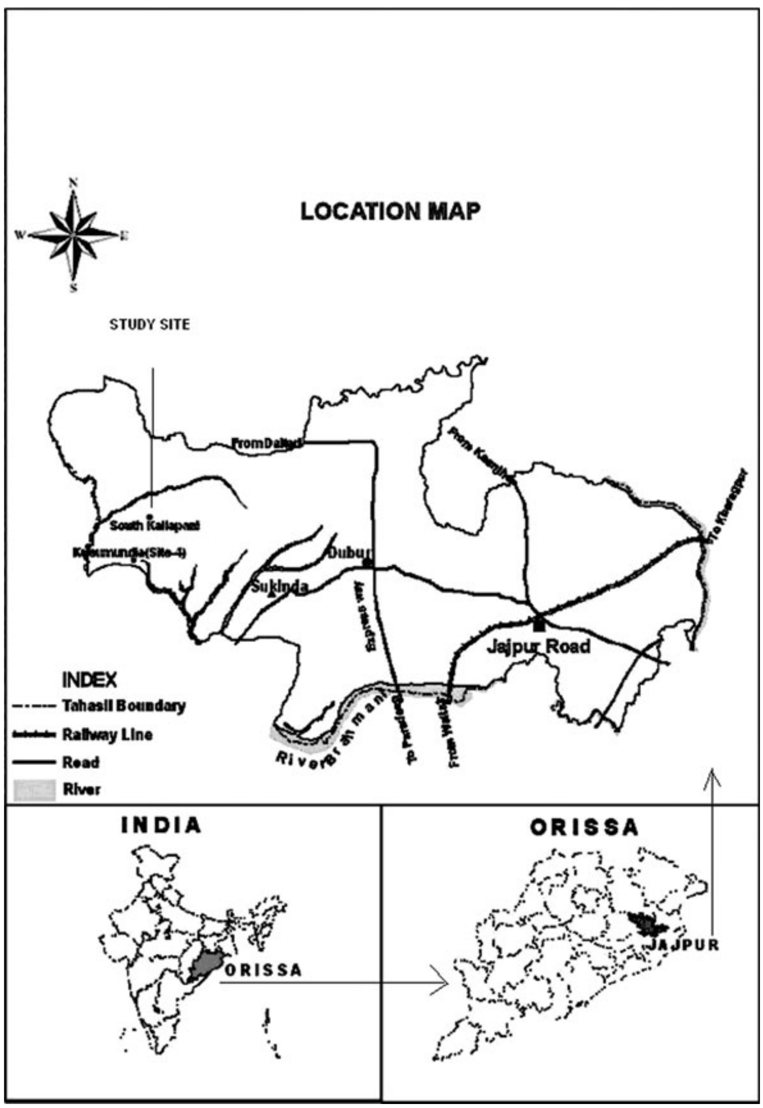

Fig. 1 Map showing the location of the study site (South Kaliapani)

the rhizofiltration and phytoextraction ability of the test plants and attenuating the toxicity load of Cr(VI) from irrigated mine waste water. This paper presents an overview of the existing sources of chromium in the study sites and its bioaccumulation in test plants. This study was an effort to know the severity of chromium pollution in the environment and its accumulation in plants through a designed *in situ* phytoremediation program.

Materials and methods

Study site

The study was undertaken at South Kaliapani chromite mine area of Sukinda valley of Orissa, India. It is located within latitudes 20°53′ and 21°05′ and longitudes 85°40′ and 85°53′ (Fig. 1). The experimental land of 10,000 sq ft. was selected for the cultivation of test plants near the mining site of Orissa Mining Corporation. The plot design was made showing the passage of irrigated untreated mine waste water through successive experimental plots of rice, paragrass, and ponds of water hyacinth (Table 1). Experimental plots of 20 × 25-ft size were arranged in a completely randomized design with four replicates. Cr(VI)-contaminated mine waste water (untreated) was passed through each experimental plot and pond (size, 25 × 20 × 2 ft) in a zigzag pathway with an area coverage of 500 sq. ft. passage route to 2,000 sq. ft. (for four consecutive plots/ponds).

Plant materials

The study was conducted by using rice (*O. sativa* L. var. Khandagiri), paragrass (*B. mutica* (Forssk.) Stapf), and water hyacinth (*E. crassipes* (Mart.) Solms-Laub) to serve as a tool of phytoremediation for attenuating Cr(VI) from contaminated untreated mine waste water. Four-week-old paragrass saplings were taken from Fodder Research Institute, Cuttack, Orissa. The water hyacinth weeds of same plant age were collected from the roadside ponds of Phulnakhra. The abovementioned plants were transplanted at the study site. The 21-day-old rice seedlings were transplanted in the experimental plots.

Cultivation and fertilizer treatment

The cultivation practice and the method of fertilizer treatment in the cultivated plots of rice were made as per the Kharif Manual (2006). The rice seedlings were raised at the experimental site. Three-week-old rice seedlings were transplanted with 10-in. spacing. Four rice seedlings were transplanted in a bunch. The N/P/K combination was applied in the experimental plots in the ratio of 40:20:20. The commercial fertilizers used in the field are urea, gromer, and DAP. Before the fertilizer treatment, the experimental field soil (sandy loam) was amended with green manure at the rate of 12.5 tonnes per hectare. The rooted paragrass plantlets in a bunch of two were transplanted with 1-in. spacing and N (234 kg ha^{-1}), P_2O_5 (51 kg ha^{-1}), and K_2O (81 kg ha^{-1}) were applied in the plots of paragrass after transplantation.

Table 1 Design of experimental plots at Sukinda South Kaliapni chromite mine area, Orissa, India

Treatments	Plot number	Area of passage (sq. ft)
Mine waste water	–	0
R-F	1	500
	2	1,000
	3	1,500
	4	2,000
R+F	5	2,500
R+F	6	500
	7	1,000
	8	1,500
	9	2,000
	10	2,500
PG+F	11	500
	12	1,000
	13	1,500
	14	2,000
R+F	15	2,500
WH	16	500
	17	1,000
	18	1,500
	19	2,000
R+F	20	2,500

R − F rice without fertilizer treatment, *R + F* rice with fertilizer treatment, *PG+F* paragrass with fertilizer treatment, *WH* water hyacinth ponds

Sampling and analysis

Soil, water, and plant sampling were carried out as follows. Soils were randomly sampled from the experimental sites chosen for the cultivation of rice and paragrass. The soil was air-dried for 5 days and ground to the desired soil size (<2 mm). The sieved soils were analyzed for physico-chemical parameters. The sampling of mine waste water was conducted before and after its passage through different experimental cultivated plots of rice during the different periods of plant growth. Water analysis was carried out for estimation the of physico-chemical parameters before and after its passage through different cultivated plots/ponds. The mine waste water samples were used for irrigation of cultivated plots and filling the water hyacinth ponds. Plants growing in different experimental plots were sampled on 75, 100 and 125 days after transplantation. Seedlings before transplantation and after 75 and 100 days of growth were collected from different experimental plots and analyzed for total Cr content in the root, stem, leaves, and grains (Bonet et al. 1991). Before the analysis of total Cr and total Fe content, the roots of all test plants were rinsed with 0.01 N HCl followed by washing with distilled water to remove mixed Fe and Cr hydrous oxides, which may have precipitated on the root surfaces.

Analysis of physico-chemical parameters

The untreated mine waste water used for irrigation in the experimental plots and ponds was analyzed for pH, electrical conductivity (E.C.), total dissolved solids (TDS), PO_4^{-2} , P, NO_3–N, NO_3^-, Ca, Mg, Na, and Cr^{+6} (APHA 1995). Soil analyses were conducted for pH, E.C., and other chemical parameters, i.e., TDS, PO_4^{-2}, P, NO_3–N, NO_3^-, Cr, Ca, and Mg (APHA 1995). The above analyses were made as per the Soil and Irrigation Water Analysis Manual (HACH 1992).

Untreated mine waste water, after its passage through different cultivated plots of paragrass and ponds of water hyacinth, was analyzed for its Cr(VI) content using HACH-DR-890 colorimeter (APHA 1995). The analyses were performed for waste water collected at different passage distances, i.e., 500, 1,000, 1,500, and 2,000 sq. ft., and also at different ages of the plants, i.e., 75 and 100 days after transplantation (DAT). The observations for Cr(VI) level in supplied mine waste water of experimental plots were taken after 75 and 100 days of transplantation of paragrass saplings. Although the flow of water to cultivated fields of rice and paragrass was slow and continuous (900 ml min^{-1}), the amount of Cr(VI) in irrigated mine waste water was reduced significantly, which is positively correlated with the biomass of the growing plants. The harvested plants were separated into shoot and root parts, oven-dried at 70°C for 72 h, ground, and digested using a solution of $HNO_3/HClO_4$ (10:1 v/v) for Cr analysis in an inductive plasma atomic emission spectrometry. Soil samples were collected at the harvesting stage (125 days after transplantation) for the analysis of total Cr and other chemical properties.

Plant masses were analyzed for BCF, TAR, and Ti as per the following method (Zurayk et al. 2002; Ghosh and Singh 2005b).

$$\mathrm{BCF} = \frac{\text{Cr concentration plant tissue(mg/kg)}}{\text{initial concentration of chromium in the external nutrients}}$$

$$\mathrm{TAR} = \frac{(\text{shoot concentration} \times \text{shoot biomass} + \text{root concetration} \times \text{root biomass})}{[(\text{shoot biomass} + \text{root biomass}) \times \text{days of growth}]}$$

N.B.: TAR (mg/kg/day), biomass (gm dry wt.) and concentration (mg/kg dry matter)

$$\mathrm{Ti} = \frac{\text{Cr concentration of leaves(mg/kg)}}{\text{Cr concentration of root (mg/kg)}} \times 100$$

Table 2 Physico-chemical parameters of the experimental field soil

Physicochemical properties	Before Ploughing	After Ploughing
PH	7.2	6.7
E.C. (mS cm^{-1})	0.05	0.08
W.H.C (%)	36.32	49.89
PO_4^{-2}–P (kg/ha)	24.25	24.49
NO_3–N (kg/ha)	20.75	28.21
Organic C (mg/kg)	31.5	59
Exchangeable K (kg/ha)	194	194
Total Cr (mg/kg dry soil)	11,170	11,170
Total Fe (mg/kg dry soil)	223,415	223,415

Statistical analysis and presentation of data

Soil, water, and plants were each sampled in triplicate and the data presented in the figures and tables are AM ± SEM.

Results and discussion

Soils of the experimental site at South Kaliapani mines were slightly alkaline and contained very low concentrations of N, P, and K (Table 2). The soil samples showed high values of chromium (1,1170 mg/kg^{-1} dry soil) which exceeds the recommended guideline (natural soil, 30–300 mg kg^{-1} as described by Katz and Salem (1994)). The Cr(VI) level in mine waste water was noted as 0.65 mg l^{-1} . This value was higher than the permissible limit as recorded for fresh water life, 0.001 mg l^{-1}; irrigation water, 0.008 mg l^{-1}; and drinking water, 0.01 mg l^{-1} (Krishnamurthy and Wilkens 1994; Pawlisz 1997).

High alkaline pH value (8.4) and Cr(VI) content of mine waste water are presented in Table 3. Phosphorus (P) and NO_3–N level were much less and noted to be 0.37 mg l^{-1} and 2.96 mg l^{-1}, respectively, as compared to normal irrigation water (Table 3). The Cr(VI) in the irrigated waste water was 0.65 mg l^{-1}, which crosses the toxic limit, i.e., > 0.008 mg l^{-1}. The level of Cr(VI) in irrigated water reflects the value of available chromium in growing plant parts and such data are presented in Table 4 (Rice) and Figs. 4 (Paragrass) and 5 (Water hyacinth). Na content (7.78 mg l^{-1}) was also found to be high in mine waste water whereas a very low amount of Ca–Mg (2.2 mg l^{-1}) was noted. Irrigated mine water from different experimental plots/ponds were sampled and analyzed for Cr(VI) content. The Cr(VI) level was found to decrease with an increase in water passage area of flowing mine waste water (Fig. 2a, b). The reduction in Cr(VI) level in irrigated mine waste water was calculated in terms of percent of decrease in Cr(VI) level in the experimental plots and ponds (Fig. 2a, b). After 100 days of transplantation, the percentage reduction of Cr(VI) level in running irrigated mine water through successive plots and ponds of 2,000-sq. ft. passage distance was in the following order for the different test plants:

$$\text{Paragrass } (19-33\%) < \text{water hyacinth } (21-54\%) < \text{rice } (22-72\%)$$

The percent reduction of Cr(VI) was less for the plants grown for 75 days, which may be attributed to low biomass content as compared to plants grown for 100 days (Mohanty et al. 2005b). It was also observed that the plot-wise sequential reduction of the Cr(VI) level of irrigated mine waste water was significant (Fig. 2a, b). Cr(VI) in running water changed from a toxic (0.65 mg l^{-1}) to non-toxic (0.07 mg l^{-1}) condition after passing through 2,500 sq. ft. of successive cultivated plots of 100-days-old grown rice during the flowering stage.

Table 3 Physico-chemical properties of Cr^{+6}-contaminated mine waste water irrigated in experimental plots of rice

pH	E.C. (mS)	TDS (mS cm^{-1})	PO_4^{-2} (mg l^{-1})	P (mg l^{-1})	NO_3–N (mg l^{-1})	NO_3^- (mg l^{-1})	Ca and Mg (mg l^{-1})	Na (meq l^{-1})	Cr^{+6} (mg l^{-1})
8.4	0.5	0.125	0.81	0.37	2.96	13.03	2.2	7.78	0.66

Chromium contamination in soil

The physico-chemical parameters of the soils of the experimental field were presented in Table 2. The comparative soil quality study showed that the pH was ideal for crop production. The pH value of soil after plowing and compost amendment was 6.7, which is optimum for most of the crops (HACH 1992). The change in pH from 7.2 to 6.7 may be attributed to the addition of compost and enhanced microbial activity. The E.C., NO_3–N, and organic carbon content significantly increased after plowing and green manure amendment. The NO_3–N content of the experimental field soil was less under high soil Cr content, which may be due to the negative correlation of N mineralization with contamination level (Bath 1989). Total Cr (11,170 mg kg^{-1} dry soil) and Fe content (2, 23, and 415 mg kg^{-1} dry soil) of soils in experimental plots were very high in comparison with normal soil (Krishnamurthy and Wilkens 1994; Pawlisz 1997). In the present context, the soil Cr concentration was relatively high because the Cr concentration of natural soil ranges from 5–3,000 mg kg^{-1} dry soil (Zayed and Terry 2003). The experimental field soil can be categorized as serpentine as the range of Cr concentration is from 634–125,000 mg kg^{-1} (Adriano 1986). Total chromium content of the field soil (on dry weight basis) falls from 11,170 mg kg^{-1} to a minimum of 5,150 mg kg^{-1} and maximum of 8,030 mg kg^{-1} after 125 days of crop growth. After 75 days of crop growth, the soil chromium content was within the range from 3,100 to 9,400 mg kg^{-1} dry soil. After 100 days of crop growth during the flowering stage, the soil chromium content ranges from 5,350 to 8,200 mg kg^{-1} dry soil (Fig. 3). The decrease in Cr content of soils may be attributed to the ability and rate of accumulation of Cr in response to the age of plant growth.

The total chromium content of different plant parts showed a high degree of variation (Table 4; Figs. 4 and 5). Cr accumulation was more in roots than in stems and leaves during all stages of plant growth. The maximum accumulation of total Cr was observed in the roots of plants on 100 DAT in comparison to 75 and 125 days after transplantation. The total Cr accumulation in grains was extremely low (5–23 mg kg^{-1}) as

Table 4 Total Cr content Rice of plant samples collected from different experimental plots during pre-flowering (75 DAT), flowering (100 DAT), and harvesting (125 DAT) stages of rice growth (values are arithmetic mean ± standard error of mean)

Plant sample	Plot no.	Total Cr content (mg /kg dry mass)									
		Root			Stem			Leaves			Grain
		Days after transplantation			Days after transplantation			Days after transplantation			
		75	100	125	75	100	125	75	100	125	125
R−F	1	2815 ± 12.1	3076 ± 12.3	2404.5 ± 13.7	65.5 ± 1.2	27.5 ± 1.5	400 ± 3.6	56.5 ± 2.3	408.5 ± 1.5	498.5 ± 5.2	23.5 ± 5.4
	4	2940 ± 11.5	3370 ± 11.8	2800 ± 11.8	242.5 ± 3.8	126.5 ± 2.1	22.5 ± 1.1	107 ± 2.5	69.5 ± 2.1	169.5 ± 3.2	19 ± 5.6
R+F	5	4578 ± 11.8	1729 ± 7.3	3650 ± 12.6	124.5 ± 1.1	28.5 ± 2.6	25 ± 2.1	162 ± 1.9	55.5 ± 2.2	155.5 ± 2.6	10.5 ± 3.5
R+F	6	1389.5 ± 11.9	409.5 ± 2.5	3064 ± 15.4	238 ± 2.3	164.5 ± 1.7	170 ± 5.8	26 ± 1.8	70.5 ± 2.3	170.5 ± 2.1	5 ± 0.21
	9	4643.5 ± 11.5	1684 ± 15.2	3212.5 ± 15.6	116.5 ± 1.1	42.5 ± 2.1	56.5 ± 2.6	9 ± 0.5	25 ± 2.5	125 ± 2.4	5 ± 0.11
	10	2936 ± 12.1	1399.5 ± 11.3	3170 ± 15.8	152 ± 1.5	86.5 ± 1.8	37.5 ± 3.1	45 ± 1.2	63.5 ± 2.6	163.5 ± 2.3	21.5 ± 1.7

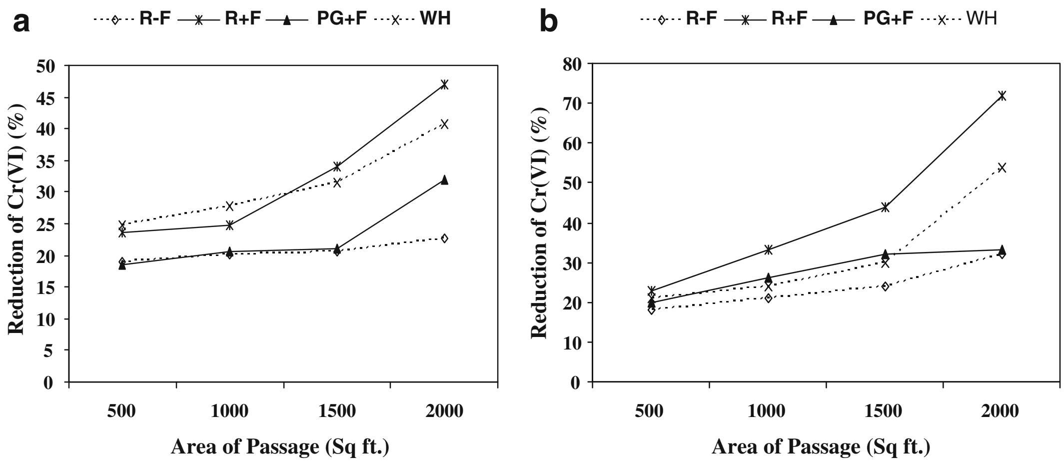

Fig. 2 **a**, **b** Reduction percent of Cr(VI) content from irrigated mine waste water after its passage through cultivated plots of paragrass and ponds of water hyacinth (**a**, 75 DAT; **b**, 100 DAT)

compared to that in roots, stems, and leaves of rice. On the other hand, the edible parts of the plants grown in uncontaminated soils have been shown to accumulate Cr in the range from 0.05 to 10 mg kg^{-1} (Katz and Salem 1994). The aerial parts of the plants showed ten to 100-fold less Cr

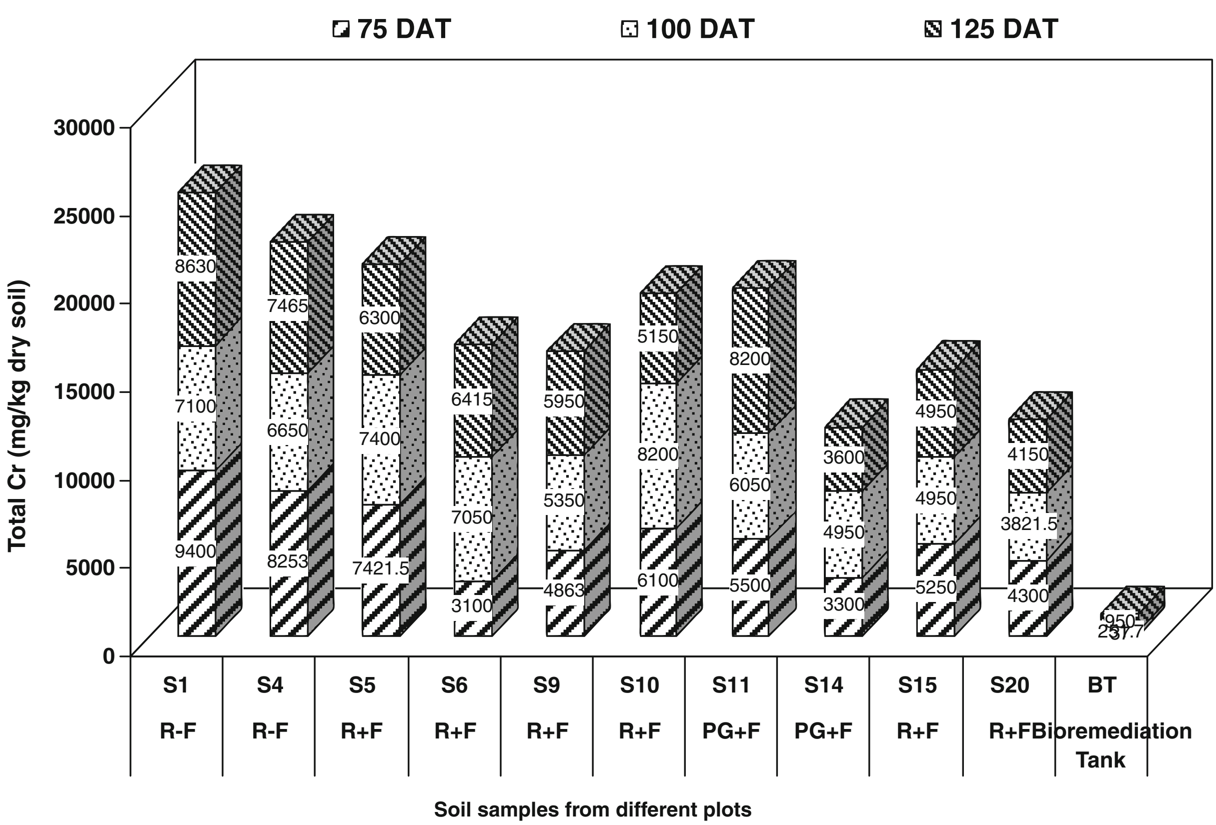

Fig. 3 Total Cr content of soil samples from different experimental plots on 75, 100 and 125 DAT

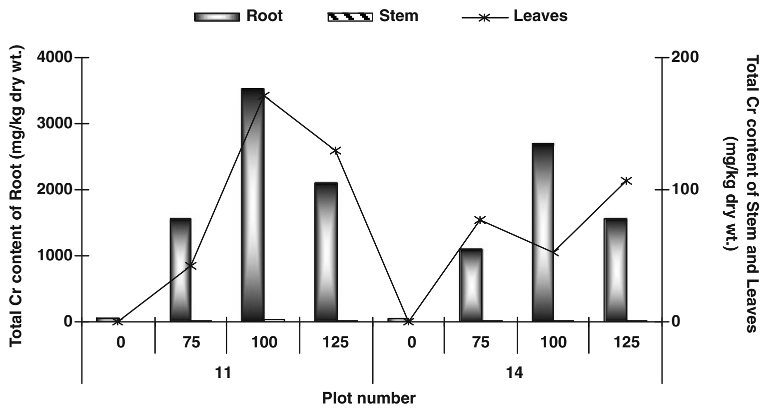

Fig. 4 Total Cr content of paragrass grown in different experimental plots for 75, 100, and 125 DAT

as compared to roots. Similar types of result were also reported earlier by several workers (Zayed and Terry 2003; Pulford and Watson 2003; Ghosh and Singh 2005a; Dong et al. 2007; Zhang et al. 2007; Erenoglu et al. 2007). High bioavailability of metals in roots and low translocation to shoots is the most common resistance trait (Zayed and Terry 2003; Dickinson and Lepp 1997). Chromium concentration in plants growing in "normal" soil is usually less than 1 mg kg^{-1}, rarely exceeds 5 mg kg^{-1}, and is typically in the order of 0.02–0.2 mg Cr kg^{-1} dry weight (Zayed and Terry 2003). The high Cr accumulation in root cells was supported by Shanker et al. (2004) who suggested the immobilization of chromium from the vacuoles.

Cr accumulation and BCF generally increased with increasing external Cr levels (soil Cr concentration 11,170 mg kg^{-1} dry soil) as well as the age of plants. BCF (10,924) and Ti values (32.09) were highest for water hyacinth. The Ti values of different plants indicated that the root-to-shoot translocation of Cr was very high after 100 days of growth period, which indicates their ability to translocate Cr from the root to the shoot, or to compartmentalize it, in order to continue the absorption of Cr from the substrate. A better translocation is advantageous to phytoextraction as it can reduce Cr concentration and thus reduce the toxicity potential to the root, and translocation to the shoot is one of the mechanisms of resistance to high Cr concentration (Ghosh and Singh 2005a). Ti was highest in water hyacinth plants. All of the plants showed a general trend of fall in Ti with an increase in chromium concen-

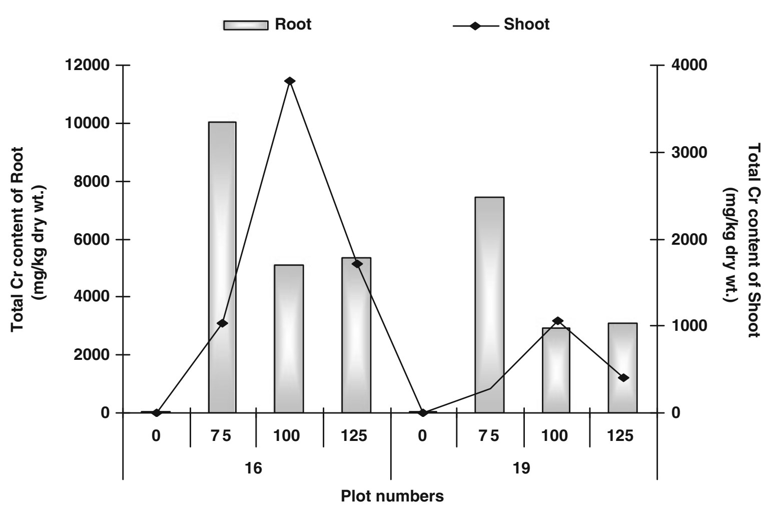

Fig. 5 Total Cr content of water hyacinth collected from different experimental plots on 0, 75, 100, and 125 DAT.

Table 5 Bio-concentration factor, transportation index, and total accumulation rate of plants from different experimental plots

Treatment plots	Plant	Ti			Bio-concentration factor of total plant			TAR ($mg\ kg^{-1}\ day^{-1}$)
		75 DAT	100 DAT	125 DAT	75 DAT	100 DAT	125 DAT	
1	R-F	2.01	3.10	16.99	0.263	0.286	0.290	0.26
4	R-F	3.64	3.12	2.48	0.294	0.322	0.261	0.91
5	R+F	3.55	9.46	1.52	0.435	0.172	0.335	1.32
6	R+F	1.87	44.44	2.30	0.148	0.068	0.296	1.19
9	R+F	0.19	4.99	0.78	0.427	0.162	0.295	2.84
10	R+F	1.53	6.75	2.00	0.280	0.141	0.293	2.55
11	PG+F	2.68	4.85	6.16	0.145	0.334	0.201	8.23
14	PG+F	6.94	1.95	6.84	0.108	0.247	0.150	8.29
15	R+F	2.49	5.15	1.27	0.315	0.219	0.169	1.09
16	WH	10.25	74.66	32.09	17,127.71	13,804.18	10,924.15	0.43
19	WH	3.76	36.48	12.84	11,944.27	6,162.54	5,422.60	1.17
20	R+F	1.47	1.40	1.58	0.474	0.248	0.263	1.41

tration and days of exposure to Cr. The BCF of Cr increased with an increase in time, this means that Cr accumulated up to maturity as shown in Table 5. The amount of chromium decreased with an increase in time, which depicts that the accumulation of chromium was non-linear and showed a negative correlation. The BCF values for roots were generally maximum than the leaves, stems, and grains of the plants during 125 days of growth. TAR, Ti, and BCF values were found to be high for rice plants treated with chemical fertilizers. The recovery of Cr can be interpreted from the values of TAR, which was maximum (8.29 mg kg^{-1} dry biomass per day) in paragrass (Table 5). Thus, paragrass and water hyacinth can be used as tools of rhizofiltration and phytoextraction to combat the problem of *in situ* Cr contamination. The study provides the idea of biomass-based phytoextraction using high-biomass-producing paragrass species growing luxuriantly under field conditions with high root accumulation capacity. The results indicate that the plant species differ significantly in Cr uptake capacity. The Cr accumulation in different test plants also differ as verified from their respective BCF, TAR, and Ti values. The extensive and massive fibrous root system of water hyacinth could be a helpful means for filtering out the pollutants at the mining sites for the mine waste water to be used for irrigation purposes. A future study will be undertaken to establish the dose-dependent stress impact of Cr application on growth and metabolism in rice. Further phytoremediation strategies will be carried out to reduce chromium bioavailability in plants. The study will give a suggestive measure for the farmers who grow crops at the chromium-contaminated sites.

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References

Adriano, D. C. (1986). *Trace elements in the environment. Chapter 5: Chromium* (p. 533). New York: Springer.

APHA (American Public Health Association) (1995). *Standard methods for the examination of water and waste water*, 19th edn. Washington, DC: American Public Health Association, 20005.

Bath, E. (1989). Effects of heavy metals in soil on microbial processes and populations (a review). *Water, Air and Soil Pollution, 47*, 335–379.

Bonet, A., Poschenrieder, C. H., & Barcelo, J. (1991). Chromium-III iron interaction in Fe deficient and Fe sufficient bean plants. I. Growth and nutrient content. *Journal of Plant Nutrition, 14*(4), 403–414.

Erenoglu, B. E., Patra, H. K., Khodr, H., Römheld, V., & Wirén, N. V. (2007). Uptake and apoplasmic retention of EDTA and phytosiderophore-chelated chromium (III) in maize. *Journal of Plant Nutrition and Soil Science, 170*(6), 788–795.

Dickinson, N. M., & Lepp, N. W. (1997). Metals and trees: Impacts, responses to exposure and exploitation of resistance traits. In R. Prost (Ed.), *Contaminated soils,* *the 3rd International conference on the biogeochemistry of trace elements* (pp. 247–254). Paris: INRA.

Dong, J., Wu, F., Huang, R., & Zang, G. (2007). A chromium tolerant plant growing in Cr-contaminated land. *International Journal of Phytoremediation, 9*, 167–179.

Ghosh, M., & Singh, S. P. (2005a). A review on phytoremediation of heavy metals and utilization of its by-products. *Applied Ecology and Environmental Research, 3*(1), 1–18.

Ghosh, M., & Singh, S. P. (2005b). Comparative uptake and phytoextraction study of soil induced chromium by accumulator and high biomass weed species. *Applied Ecology and Environmental Research, 3*(2), 67–79.

HACH (1992). Soil and irrigation water manual, SIW kit. 24960-88. USA.

IBM (Indian Bureau of Mines) (2004). Annual report of IBM. Govt. of India.

Katz, S. A., & Salem, H. (1994). *The biological and environmental chemistry of chromium*. New York: VCH.

Kharif Manual (2006). Agriculture Department, Orissa University of Agricultural Technology, Government of Orissa, India

Krishnamurthy, S., & Wilkens, M. M. (1994). Environmental chemistry of Cr. *Northeastern Geology, 16*(1), 14–17.

Mohanty, M., Jena, A. K., & Patra, H. K. (2005a). Effect of chelated chromium compounds on chlorophyll content and activities of catalase and peroxidase in wheat seedlings. *Indian Journal of Agricultural Biochemistry, 8*(1), 25–29.

Mohanty, M., Pattnaik, M. M., Mishra, A. K., & Patra, H. K. (2005b). Assessment of soil and water quality of chromite mine area of South Kaliapani (Sukinda, Orissa). *Bulletin of Environmental Science, 23*(2), 109–113.

Mohanty, M., Pattanaik, M. M., Misra, A. K., & Patra, H. K. (2009). Chromium detoxification from mine waste water by rice—a case study at South Kaliapani chromite mine area, Sukinda, Orissa. *e-Planet, 7*(1), 26–31, ISSN: 0974-4398/2008.

Panda, S. K., & Patra, H. K. (1997a). Physiology of chromium toxicity in plants—a review. *Plant Physiology and Biochemistry, 24*(1), 10–17.

Panda, S. K., & Patra, H. K. (1997b). Some of the toxicity lesions produced by chromium (VI) during the early phase of seed germination in wheat. *Journal of Indian Botanical Society, 76*, 303–304.

Panda, S. K., & Patra, H. K. (1998). Attenuation of nitrate reductase activity by chromium ions in excised wheat leaves. *Indian Journal of Agricultural Biochemistry, 2*(2), 56–57.

Panda, S. K., & Patra, H. K. (2000) Does chromium (III) produce oxidative damage in excised wheat leaves? *Journal of Plant Biology, 27*(2), 105–110.

Pawlisz, A. V. (1997). Canadian water quality guidelines for Cr. *Environmental Toxicology and Water Quality, 12*(2), 123–161.

Pulford, I. D., & Watson, C. (2003). Phytoremediation of heavy metal contaminated land by trees—a review. *Environment International, 29*, 529–540.

Shanker, A. K., Djanaguiraman, M., Sudhagar, R., Chandrashekar, C. N., & Pathmanabhan, G. (2004). Differential antioxidative response of ascorbate glutathione pathway enzymes and metabolites to chromium speciation stress in green gram (*Vigna radiata* (L.) R.Wilczek) roots. *Plant Science, 166*, 1035–1043.

Srivastava, S., Prakash, S., & Srivastava, M. M. (1999). Chromium mobilization and plant availability—the impact of organic complexing ligands. *Plant Soil, 212*, 203–208.

WHO (World Health Organisation) (1997). *Health and environment in sustainable development*. Geneva

Zayed, A. M., & Terry, N. (2003). Chromium in the environment: factor affecting biological remediation. *Plant Soil, 249*, 139–156.

Zayed, A., Lytle, C. M., Qian, J. H., & Terry, N. (1998). Chromium accumulation, translocation and chemical speciation in vegetable crops. *Planta, 206*, 293–299.

Zhang, X. H., Liu, J., Huang, H. T., Chen, J., Zhu, Y. N., & Wang, D. Q. (2007). Chromium accumulation by the hyperaccumulator plant *Leersia hexandra* Swartz. *Chemosphere, 67*, 1138–1143.

Zurayk, R., Sukkariyah, B., Baalbaki, R., & Ghanem, D. A. (2002). Ni phytoaccumulation in *Mentha aquatica* L. and *Mentha sylvestris* L. *Water Air and Soil Pollution, 139*, 355–364.