

Chenopodium: a prospective plant for phytoextraction

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Abstract Leaf samples were collected from 40 accessions of *Chenopodium* spp. and assessed for six heavy metals (Fe, Zn, Cu, Ni, Cr and Cd) accumulation to explore the use of *Chenopodium* for phytoextraction of heavy metals. The results suggest that *Chenopodium* spp. have the ability to accumulate large quantities of heavy metals in the leaf tissues even when they are present in low concentrations in the soil. *C. quinoa* is a better accumulator of Ni, Cr and Cd than the rest of the species, while *C. album* accessions are good copper accumulators. Bioconcentration factor for chromium ranged from 0.36 (*C. album* “Chandanbathua”) to 6.57 (*C. quinoa* Ames 13719) with 13 accessions of *C. quinoa* scoring above the mean value. High heritability coupled with high genetic advance was recorded for Ni, Cr and Cd, which indicated a major role of additive gene action in the inheritance of these characters. Zinc showed significant positive association with iron (0.351**), nickel (0.659**), chromium (0.743**) and cadmium (0.288**). Nickel was significantly and negatively associated with

copper (−0.663**), while it was positively and significantly correlated with chromium (0.682**) and cadmium (0.461**). Considering the accumulation efficiency of *Chenopodium* spp. with respect to heavy metals, this genus should be further explored for decontamination of metal polluted soils, with plant breeding playing an important role in evolving new plant types with higher capacity of heavy metal accumulation.

Keywords *Chenopodium* · Foliage · Heavy metals · Bioconcentration · Phytoextraction

Introduction

Pollution of agricultural soil by heavy metals has imposed a long-term risk on environmental sustainability and human health. This is of immense importance to the developing and underdeveloped countries where problem of soil contamination has reached alarming levels due to population explosion, rapid industrial development and paucity of funds for pollution control and restoration of the environment. Various anthropogenic activities such as mining, smelting, use of internal combustible engines, chemical fertilizers and pesticides, energy production processes and municipal wastes contribute to heavy metal contamination of the biosphere. The major heavy metal contaminants are cadmium, mercury, copper, zinc, chromium and nickel, which are found in water and soil in dissolved state. These heavy metals are absorbed through the root systems and induce deleterious effects like leaf chlorosis, inhibition of root growth and deficiency of essential elements in most of the plants (Kim et al. 2003). However, some plants accumulate heavy metals by binding to cystine rich proteins or peptides with little adverse effects (Kim et al. 2003). These

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metals are also associated with human health hazards ranging from dermatitis to cancer (Chaney 1980; Paustenbach et al. 1992; McLaughlin et al. 1999).

These heavy metals need to be removed from the soil for agro-ecological sustainability and human benefit. Various efficient soil clean up techniques are available (Mulligan et al. 2001) but most of them are costly, labour intensive and cause soil disturbances due to which they have found limited acceptability among the communities. Recently there has been growing interest in the use of plants for remediation of heavy metal contaminated soil and water. This technology termed as phytoextraction, requires translocation of heavy metals from the contaminated surface to easily harvestable parts (Kumar et al. 1995; Salt et al. 1995; Reeves and Baker 2000). The advantages of using metal accumulating plants for the removal of metals from contaminated soils include lower costs, generation of recyclable metal rich plant residue, and applicability to a range of toxic metals, minimal environmental disturbance and public acceptance (Kumar et al. 1995).

Researchers all over the world are searching new plant species for phytoextraction and bioremediation purposes. The present study is the first report on heavy metal accumulation capacity of *Chenopodium* spp. and the potential of selected accessions for use in phytoextraction. The present study was basically conducted for ascertaining the nutritional and non-nutritional composition of the leaves of *Chenopodium* spp. However, the results obtained were interesting and so we decided to extend our work to bring out some new information regarding the concentration of heavy metals in the genus and its prospective use for phytoextraction of heavy metals. Numerous reports are available which have suggested manipulation of germplasm and use of selection strategies to reduce heavy metal concentration in different plant species (Li et al. 1997; Liu et al. 2005). However, very little has been said about decontamination of metal polluted soil by integrating environmental science with plant breeding. The present investigation, perhaps for the first time, combines both the disciplines and suggests the utilization of plant breeding for environmental restoration. A suitable breeding plan for use in phytoextraction of different heavy metals has been formulated and discussed.

Materials and methods

Experimental site and materials

The experiment was conducted at the experimental field of National Botanical Research Institute, Lucknow. The experimental site is situated at an altitude of 120 m above sea level at 26.5°N latitude and 80.5°E longitude. The experimental material comprised 40 accessions of

Chenopodium spp. including 18 accessions of *C. quinoa*, 13 of *C. album*, 4 of *C. giganteum*, 2 of *C. berlandieri* spp. *nuttalliae* and 1 accession of *C. bushianum*, *C. murale* and *C. ugandae* (Table 1).

Experimental set up

The material was sown as a winter crop in mid November 2003 in a randomized block design with three replications. The plot size for each accession was 4 m², with row-to-row and plant-to-plant distance of 25 and 15 cm, respectively. 20 tons/ha of compost was added in the field prior to sowing to enhance the productivity and water holding capacity of the soil. Each accession was sown in a separate plot and thinning was done to maintain plant density within rows. Normal cultural practices were followed during the experiment. Irrigation was provided as and when needed. No chemical fertilizer was applied either before or during the experiment. No fungicide or insecticide was used during the experiment. The leaves were collected 30 days after germination when the plants had attained an above-ground height of 20 cm and were ready for edible use.

The soil of the experimental site was sandy loam with a pH of 6.8 ± 0.04 , electrical conductivity of $479 \pm 1.26 \mu\text{S cm}^{-1}$ and organic matter content of 1.06%. The mineral content in the soil was as follows: Fe = 27.80 mg kg⁻¹ DW, Zn = 64 mg kg⁻¹ DW, Cu = 6.3 mg kg⁻¹ DW, Ni = 21.8 mg kg⁻¹ DW, Cr = 28.6 mg kg⁻¹ DW and Cd = 1.2 mg kg⁻¹ DW.

Parameters estimated

For determination of mineral composition, leaves of each accession from each replication were collected from lower, middle and upper regions of the plant, bulked together and transported to the laboratory. All the samples were analyzed in triplicate. The leaves were first oven dried and then digested in 1:4 mixture of HClO₃ and HNO₃ (v/v). A total of six heavy metals were analyzed in triplicate. Iron (Fe), zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr) and cadmium (Cd) were determined using atomic absorption spectrophotometer (Perkin Elmer 5100).

Statistical analysis

The raw data was compiled by taking the means of all the plants taken for each treatment and replication for different traits. The mean values were subjected to further statistical and biometrical analysis. The phenotypic (PCV) and genotypic coefficient of variation (GCV), heritability in

Table 1 Accessions of *Chenopodium* used in the present study

S. no.	Accessions	Source	2n
1	<i>C. quinoa</i> Willd. CHEN 33/84	IPK Gatersleben, Germany	36
2	<i>C. quinoa</i> Willd. CHEN 92/91	IPK Gatersleben, Germany	36
3	<i>C. quinoa</i> Willd. CHEN 67/78	IPK Gatersleben, Germany	36
4	<i>C. quinoa</i> Willd. CHEN 84/79	IPK Gatersleben, Germany	36
5	<i>C. quinoa</i> Willd. PI 510532	USDA	36
6	<i>C. quinoa</i> Willd. PI 510536	USDA	36
7	<i>C. quinoa</i> Willd. PI 510537	USDA	36
8	<i>C. quinoa</i> Willd. PI 510547	USDA	36
9	<i>C. quinoa</i> Willd. PI 587173	USDA	36
10	<i>C. quinoa</i> Willd. PI 614881	USDA	36
11	<i>C. quinoa</i> Willd. PI 614883	USDA	36
12	<i>C. quinoa</i> Willd. Ames 13719	USDA	36
13	<i>C. quinoa</i> Willd. Ames 13762	USDA	36
14	<i>C. quinoa</i> Willd. Ames 22156	USDA	36
15	<i>C. quinoa</i> Willd. Ames 22158	USDA	36
16	<i>C. quinoa</i> Willd. PI 584524	USDA	36
17	<i>C. quinoa</i> Willd. PI 433232	USDA	36
18	<i>C. quinoa</i> Willd. PI 478410	USDA	36
19	<i>C. berlandieri</i> spp. <i>nuttalliae</i> PI 568155	USDA	36
20	<i>C. berlandieri</i> spp. <i>nuttalliae</i> PI 568156	USDA	36
21	<i>C. bushianum</i> Ames 22376	USDA	54
22	<i>C. giganteum</i> CHEN 86/85	IPK Gatersleben, Germany	54
23	<i>C. giganteum</i> Ames 86650	USDA	54
24	<i>C. giganteum</i> PI 596372	USDA	54
25	<i>C. giganteum</i> “local”	India	54
26	<i>C. murale</i> “local”	India	18
27	<i>C. album</i> “local red”	India	18
28	<i>C. album</i> “chandanbathua”	India	18
29	<i>C. album</i> “Chandigarh”	India	36
30	<i>C. album</i> “Mexico”	Mexico	36
31	<i>C. album</i> PRC 9801	India	54
32	<i>C. album</i> PRC 9802	India	54
33	<i>C. album</i> PRC 9803	India	54
34	<i>C. album</i> PRC 9804	India	54
35	<i>C. album</i> IC 107296	India	54
36	<i>C. album</i> IC 107297	India	54
37	<i>C. album</i> PI 605700	USDA	54
38	<i>C. album</i> “local 6x”	India	54
39	<i>C. album</i> “Iowa”	USDA	54
40	<i>C. ugandae</i> CHEN 77/78	Gatersleben, Germany	36

broad sense (h^2) and expected genetic advance (GA%) were estimated according to Singh and Chaudhary (1985) as given below:

Genotypic and phenotypic correlation coefficients were calculated using the formula proposed by Johnson et al. (1955).

$$GCV = \frac{\sqrt{\sigma^2 g}}{\bar{x}} \times 100$$

$$PCV = \frac{\sqrt{\sigma^2 p}}{\bar{x}} \times 100$$

$$\text{Heritability} = \frac{\sigma^2_g}{\sigma^2_p}$$

$$\text{Genetic advance (GA)} = i\sigma_p h^2$$

where,

σ^2_g = genotypic variance, σ^2_p = phenotypic variance, $\bar{x}$ = general mean of character, i = standardized selection differential, a constant (2.06), σ_p = phenotypic standard deviation ($\sqrt{\sigma^2_p}$).

The significance of phenotypic correlation coefficient was tested against “ r ” values for “ r ” table of Fisher and Yates (1938) for $(v - 2)$ degree of freedom and $P = 0.05$ and $P = 0.01$, where “ v ” is the number of treatments.

The significance of genotypic correlation coefficients was tested by transforming r to quantify Z as in the formula given below (Srivastava et al. 1972):

$$Z = \frac{1}{2} \log e(1 - r) - \log e(1 - r) \\ = \frac{(\frac{1}{2} \log e(1 - r))}{(1 - r)}$$

“ Z ” is distributed almost normally independent of sample size, hence “ r ” 0.01 = $\sqrt{1/(n - 3)}$ corresponding total $df = L$ and r is an appropriate value of genotypic correlation.

Results

The analysis of variance revealed significant genetic differences in amount of accumulated metals among the strains for all the six metals, which validated further statistical analysis (data not shown). The mineral content in the leaves of 40 accessions of *Chenopodium* spp. is presented in Table 2.

Mineral composition

Iron

Of the 40 accessions analyzed, iron content ranged from 756.00 to 923.30 mg kg⁻¹ dry weight (DW), with an overall mean of 839.16 ± 5.27 . The two accessions of *C. berlandieri* spp. *nuttalliae* contained high amounts of iron, while all the accessions of *C. giganteum* had iron content below average (820.70, 802.30, 814.00 and 810.00 mg kg⁻¹ DW).

Zinc

Only 14 accessions showed higher zinc content than the overall mean (148.81 ± 12.37 mg kg⁻¹ DW), which comprised 10 accessions of *C. quinoa*, 2 of *C. berlandieri*

spp. *nuttalliae* and 1 *C. giganteum* and *C. album* each. *C. quinoa* Ames 13719 recorded the highest zinc content (361.70 mg kg⁻¹ DW), that was more than ten times higher than the lowest value viz. *C. album* PRC 9801 (31.50 mg kg⁻¹ DW).

Copper

Copper content among the accessions ranged from 103.90 (*C. quinoa* Ames 13719) to 146.60 (*C. giganteum* PI 596372), with an average of 132.14 ± 1.93 mg kg⁻¹ DW. Twenty-five accessions showed above average value for this mineral, which consisted of one accession of *C. murale* and *C. ugandae* each, all accessions of *C. album*, *C. giganteum*, *C. berlandieri* spp. *nuttalliae* and four accessions of *C. quinoa*.

Nickel

C. quinoa Ames 22156 contained the highest amount of nickel (221.90 mg kg⁻¹ DW), followed by *C. quinoa* Ames 13719 (184.10 mg kg⁻¹ DW) and *C. quinoa* PI 614881 (183.80 mg kg⁻¹ DW). No trace of the mineral was found in 13 accessions comprising 2 accessions of *C. berlandieri* spp. *nuttalliae*, 1 of *C. murale* and 10 of *C. album*. The mean nickel content among the 40 accessions was 66.14 ± 10.74 mg kg⁻¹ DW.

Chromium

Three accessions of *C. quinoa* viz. Ames 13719, PI 510536 and Ames 22156 contained the largest amounts of chromium that exceeded 100 mg kg⁻¹ DW (188.00, 135.20 and 133.40 mg kg⁻¹ DW, respectively). The chromium levels in the rest of the accessions ranged from 10.30 for *C. album* “local red” to 85.90 mg kg⁻¹ DW for *C. quinoa* PI 510547. Twenty-nine accessions contained less than 50 mg chromium per kg of dry weight of leaf tissue.

Cadmium

The amount of cadmium in the experimental material ranged from 4.80 to 134.20 mg kg⁻¹ DW, with an overall mean of 23.99 ± 3.78 mg kg⁻¹ DW. Eleven accessions recorded above the mean values, while eleven others had cadmium contents of less than 10 mg kg⁻¹ DW dry weight. All accessions of *C. album*, *C. giganteum* and *C. berlandieri* spp. *nuttalliae* except *C. giganteum* CHEN 86/85 showed low cadmium concentrations.

Table 2 Mean values $\pm$ SE (mg kg⁻¹ DW) over three replications for various heavy metals in different accessions of *Chenopodium*

Accessions	Fe	Zn	Cu	Ni	Cr	Cd
<i>C. quinoa</i> Willd. CHEN 33/84	845.67 $\pm$ 36.41	164.60 $\pm$ 5.10	125.10 $\pm$ 2.17	92.33 $\pm$ 2.10	39.40 $\pm$ 1.82	31.23 $\pm$ 1.92
<i>C. quinoa</i> Willd. CHEN 92/91	826.33 $\pm$ 23.55	306.67 $\pm$ 8.68	111.57 $\pm$ 1.93	142.77 $\pm$ 3.45	39.37 $\pm$ 1.06	13.63 $\pm$ 0.76
<i>C. quinoa</i> Willd. CHEN 67/78	875.00 $\pm$ 19.67	114.47 $\pm$ 5.94	124.47 $\pm$ 2.15	154.77 $\pm$ 2.96	74.27 $\pm$ 2.11	17.57 $\pm$ 0.46
<i>C. quinoa</i> Willd. CHEN 84/79	815.67 $\pm$ 30.20	227.20 $\pm$ 10.22	116.10 $\pm$ 2.08	87.50 $\pm$ 1.55	46.23 $\pm$ 1.84	27.80 $\pm$ 1.93
<i>C. quinoa</i> Willd. PI 510532	851.33 $\pm$ 24.29	143.50 $\pm$ 4.36	114.53 $\pm$ 3.17	106.10 $\pm$ 1.06	55.70 $\pm$ 1.93	134.17 $\pm$ 2.02
<i>C. quinoa</i> Willd. PI 510536	865.00 $\pm$ 31.05	318.23 $\pm$ 11.97	123.23 $\pm$ 2.82	132.63 $\pm$ 0.98	135.20 $\pm$ 3.56	34.43 $\pm$ 1.62
<i>C. quinoa</i> Willd. PI 510537	837.33 $\pm$ 19.10	122.17 $\pm$ 4.69	117.10 $\pm$ 3.59	106.77 $\pm$ 1.12	59.23 $\pm$ 2.00	23.53 $\pm$ 0.54
<i>C. quinoa</i> Willd. PI 510547	792.00 $\pm$ 14.65	117.73 $\pm$ 4.44	118.57 $\pm$ 1.69	116.83 $\pm$ 2.19	85.93 $\pm$ 2.93	33.57 $\pm$ 1.08
<i>C. quinoa</i> Willd. PI 587173	830.67 $\pm$ 13.33	185.80 $\pm$ 7.10	122.13 $\pm$ 2.88	141.03 $\pm$ 3.00	37.90 $\pm$ 1.68	69.20 $\pm$ 0.89
<i>C. quinoa</i> Willd. PI 614881	894.00 $\pm$ 17.15	352.40 $\pm$ 13.08	134.30 $\pm$ 2.01	183.80 $\pm$ 4.24	56.07 $\pm$ 2.08	19.03 $\pm$ 0.19
<i>C. quinoa</i> Willd. PI 614883	872.00 $\pm$ 34.68	211.47 $\pm$ 9.15	118.57 $\pm$ 1.73	78.43 $\pm$ 0.64	82.13 $\pm$ 3.11	40.43 $\pm$ 0.74
<i>C. quinoa</i> Willd. Ames 13719	852.00 $\pm$ 14.84	361.67 $\pm$ 12.67	103.87 $\pm$ 1.62	184.13 $\pm$ 2.49	187.97 $\pm$ 4.69	64.17 $\pm$ 0.55
<i>C. quinoa</i> Willd. Ames 13762	838.00 $\pm$ 16.99	57.97 $\pm$ 1.56	118.77 $\pm$ 1.99	96.27 $\pm$ 1.77	43.53 $\pm$ 1.05	5.73 $\pm$ 0.09
<i>C. quinoa</i> Willd. Ames 22156	853.00 $\pm$ 2.09	249.50 $\pm$ 4.11	137.50 $\pm$ 2.88	221.90 $\pm$ 2.54	133.37 $\pm$ 2.12	17.07 $\pm$ 0.45
<i>C. quinoa</i> Willd. Ames 22158	863.33 $\pm$ 8.17	138.20 $\pm$ 2.63	125.20 $\pm$ 3.94	62.33 $\pm$ 0.91	13.77 $\pm$ 1.09	44.13 $\pm$ 1.99
<i>C. quinoa</i> Willd. PI 584524	846.33 $\pm$ 32.00	109.00 $\pm$ 3.25	135.57 $\pm$ 3.75	159.97 $\pm$ 2.99	32.60 $\pm$ 1.65	36.10 $\pm$ 1.06
<i>C. quinoa</i> Willd. PI 433232	841.67 $\pm$ 30.85	216.90 $\pm$ 6.54	105.30 $\pm$ 1.08	85.57 $\pm$ 1.66	84.37 $\pm$ 2.84	23.53 $\pm$ 1.14
<i>C. quinoa</i> Willd. PI 478410	836.33 $\pm$ 18.57	108.43 $\pm$ 2.81	133.70 $\pm$ 2.22	69.93 $\pm$ 1.50	58.53 $\pm$ 1.56	46.90 $\pm$ 1.66
<i>C. berlandieri</i> spp. <i>nuttalliae</i> PI 568155	923.33 $\pm$ 35.26	149.10 $\pm$ 4.59	140.67 $\pm$ 2.64	0.00 $\pm$ 0.00	26.43 $\pm$ 1.00	9.47 $\pm$ 0.50
<i>C. berlandieri</i> spp. <i>nuttalliae</i> PI 568156	913.33 $\pm$ 37.82	155.17 $\pm$ 6.12	141.27 $\pm$ 3.83	0.00 $\pm$ 0.00	17.23 $\pm$ 1.11	10.27 $\pm$ 0.41
<i>C. bushianum</i> Ames 22376	840.33 $\pm$ 13.94	97.23 $\pm$ 2.11	124.60 $\pm$ 2.18	127.17 $\pm$ 2.96	18.80 $\pm$ 0.94	19.00 $\pm$ 0.22
<i>C. giganteum</i> CHEN 86/85	820.67 $\pm$ 7.69	154.87 $\pm$ 4.98	138.57 $\pm$ 2.01	163.80 $\pm$ 3.85	33.53 $\pm$ 1.57	44.77 $\pm$ 1.98
<i>C. giganteum</i> Ames 86650	802.33 $\pm$ 27.59	53.03 $\pm$ 0.99	140.33 $\pm$ 4.59	2.03 $\pm$ 0.16	29.30 $\pm$ 1.16	6.73 $\pm$ 0.40
<i>C. giganteum</i> PI 596372	814.00 $\pm$ 16.44	119.57 $\pm$ 2.05	146.60 $\pm$ 3.55	27.13 $\pm$ 1.69	18.67 $\pm$ 0.99	8.13 $\pm$ 0.31
<i>C. giganteum</i> “local”	810.00 $\pm$ 26.29	105.60 $\pm$ 1.57	139.17 $\pm$ 3.08	22.77 $\pm$ 1.17	18.03 $\pm$ 1.23	13.43 $\pm$ 0.68
<i>C. murale</i> “local”	756.00 $\pm$ 7.51	128.43 $\pm$ 3.64	141.70 $\pm$ 4.65	0.00 $\pm$ 0.00	21.67 $\pm$ 1.77	9.80 $\pm$ 0.70
<i>C. album</i> “local red”	800.33 $\pm$ 14.22	33.93 $\pm$ 0.51	146.27 $\pm$ 4.04	0.00 $\pm$ 0.00	10.27 $\pm$ 0.56	14.73 $\pm$ 0.49
<i>C. album</i> “Chandanbathua”	855.00 $\pm$ 25.58	117.67 $\pm$ 4.30	142.47 $\pm$ 6.23	17.00 $\pm$ 0.78	16.20 $\pm$ 1.49	12.23 $\pm$ 0.81
<i>C. album</i> “Chandigarh”	833.00 $\pm$ 20.07	123.47 $\pm$ 5.11	144.80 $\pm$ 4.80	0.00 $\pm$ 0.00	17.03 $\pm$ 1.04	17.23 $\pm$ 0.97
<i>C. album</i> “Mexico”	781.67 $\pm$ 21.36	121.57 $\pm$ 1.95	138.47 $\pm$ 2.12	12.03 $\pm$ 0.55	21.73 $\pm$ 1.16	9.37 $\pm$ 0.55
<i>C. album</i> PRC 9801	821.33 $\pm$ 19.14	31.53 $\pm$ 0.59	137.33 $\pm$ 5.07	0.00 $\pm$ 0.00	14.43 $\pm$ 0.68	12.73 $\pm$ 0.82
<i>C. album</i> PRC 9802	837.33 $\pm$ 15.65	100.33 $\pm$ 2.57	143.37 $\pm$ 5.11	0.00 $\pm$ 0.00	17.60 $\pm$ 1.08	9.60 $\pm$ 0.29
<i>C. album</i> PRC 9803	828.67 $\pm$ 12.28	114.53 $\pm$ 5.02	141.63 $\pm$ 6.00	0.00 $\pm$ 0.00	20.80 $\pm$ 0.27	14.77 $\pm$ 0.17
<i>C. album</i> PRC 9804	819.33 $\pm$ 17.77	123.30 $\pm$ 4.30	135.53 $\pm$ 3.17	0.00 $\pm$ 0.00	27.33 $\pm$ 0.99	6.73 $\pm$ 0.09
<i>C. album</i> IC 107296	878.00 $\pm$ 10.69	99.77 $\pm$ 1.16	144.27 $\pm$ 4.14	0.00 $\pm$ 0.00	22.93 $\pm$ 1.14	18.97 $\pm$ 0.46
<i>C. album</i> IC 107297	858.33 $\pm$ 9.16	124.10 $\pm$ 2.07	140.50 $\pm$ 4.22	0.00 $\pm$ 0.00	21.23 $\pm$ 1.09	8.70 $\pm$ 0.19
<i>C. album</i> PI 605700	845.33 $\pm$ 26.18	120.20 $\pm$ 3.00	145.63 $\pm$ 4.13	0.00 $\pm$ 0.00	24.83 $\pm$ 0.85	9.77 $\pm$ 0.44
<i>C. album</i> “local 6x”	869.33 $\pm$ 21.96	104.53 $\pm$ 1.69	145.10 $\pm$ 6.90	11.20 $\pm$ 1.02	23.07 $\pm$ 0.67	10.33 $\pm$ 0.36
<i>C. album</i> “Iowa”	808.00 $\pm$ 13.64	167.17 $\pm$ 2.11	138.30 $\pm$ 2.10	0.00 $\pm$ 0.00	24.73 $\pm$ 1.07	4.80 $\pm$ 0.40
<i>C. ugandae</i> CHEN 77/78	815.33 $\pm$ 12.55	101.30 $\pm$ 3.09	143.07 $\pm$ 1.65	39.43 $\pm$ 1.66	15.87 $\pm$ 0.69	5.93 $\pm$ 0.35
Mean	839.16	148.81	132.13	66.14	43.18	23.99
SE	5.27	12.37	1.93	10.74	6.04	3.78

Bioconcentration factor

The bioconcentration factor (BCF) is the ratio of heavy metal content in a plant part to the soil level of heavy metal. The bioconcentration factors of the different

accessions for six heavy metals are provided in Table 3. BCF for iron and copper ranged from 27.19 to 33.21 and from 16.49 to 23.27, respectively. All the accessions of *C. album* showed higher BCF values for copper than the mean value (20.97 $\pm$ 0.31). On the contrary, zero value of

Table 3 Bioconcentration factors for different heavy metals in 40 accessions of *Chenopodium* spp.

Accessions	Fe	Zn	Cu	Ni	Cr	Cd
<i>C. quinoa</i> Willd. CHEN 33/84	30.42	2.57	19.86	4.23	1.38	26.00
<i>C. quinoa</i> Willd. CHEN 92/91	29.72	4.79	17.71	6.55	1.38	11.33
<i>C. quinoa</i> Willd. CHEN 67/78	31.47	1.79	19.76	7.10	2.60	14.67
<i>C. quinoa</i> Willd. CHEN 84/79	29.34	3.55	18.43	4.01	1.62	23.17
<i>C. quinoa</i> Willd. PI 510532	30.62	2.24	18.17	4.87	1.95	111.83
<i>C. quinoa</i> Willd. PI 510536	31.12	4.97	19.56	6.08	4.73	28.67
<i>C. quinoa</i> Willd. PI 510537	30.12	1.91	18.59	4.90	2.07	19.58
<i>C. quinoa</i> Willd. PI 510547	28.49	1.84	18.83	5.36	3.00	28.00
<i>C. quinoa</i> Willd. PI 587173	29.88	2.9	19.38	6.47	1.33	57.67
<i>C. quinoa</i> Willd. PI 614881	32.16	5.51	21.32	8.43	1.96	15.83
<i>C. quinoa</i> Willd. PI 614883	31.37	3.3	18.83	3.60	2.87	33.67
<i>C. quinoa</i> Willd. Ames 13719	30.65	5.65	16.49	8.44	6.57	53.50
<i>C. quinoa</i> Willd. Ames 13762	30.14	0.91	18.86	4.42	1.52	4.75
<i>C. quinoa</i> Willd. Ames 22156	30.68	3.9	21.83	10.18	4.66	14.25
<i>C. quinoa</i> Willd. Ames 22158	31.05	2.16	19.87	2.86	0.48	36.75
<i>C. quinoa</i> Willd. PI 584524	30.44	1.7	21.52	7.34	1.14	30.08
<i>C. quinoa</i> Willd. PI 433232	30.28	3.39	16.71	3.93	2.95	19.58
<i>C. quinoa</i> Willd. PI 478410	30.08	1.69	21.22	3.21	2.05	39.08
<i>C. berlandieri</i> spp. <i>nuttalliae</i> PI 568155	33.21	2.33	22.33	0.00	0.92	7.92
<i>C. berlandieri</i> spp. <i>nuttalliae</i> PI 568156	32.85	2.42	22.43	0.00	0.60	8.58
<i>C. bushianum</i> Ames 22376	30.23	1.52	19.78	5.83	0.66	15.83
<i>C. giganteum</i> CHEN 86/85	29.52	2.42	22.00	7.51	1.17	37.33
<i>C. giganteum</i> Ames 86650	28.86	0.83	22.27	0.09	1.02	5.58
<i>C. giganteum</i> PI 596372	29.28	1.87	23.27	1.24	0.65	6.75
<i>C. giganteum</i> “local”	29.14	1.65	22.10	1.05	0.63	11.17
<i>C. murale</i> “local”	27.19	2.01	22.49	0.00	0.76	8.17
<i>C. album</i> “local red”	29.33	1.58	22.71	0.00	0.56	4.92
<i>C. album</i> “Chandanbathua”	28.79	0.53	23.22	0.78	0.36	12.25
<i>C. album</i> “Chandigarh”	30.76	1.84	22.62	0.00	0.57	10.17
<i>C. album</i> “Mexico”	29.96	1.93	22.98	0.55	0.59	14.33
<i>C. album</i> PRC 9801	28.12	1.90	21.98	0.00	0.76	7.83
<i>C. album</i> PRC 9802	29.54	0.49	21.79	0.00	0.50	10.58
<i>C. album</i> PRC 9803	30.12	1.57	22.76	0.00	0.62	8.00
<i>C. album</i> PRC 9804	29.81	1.79	22.48	0.00	0.73	12.33
<i>C. album</i> IC 107296	29.47	1.93	21.51	0.00	0.95	5.58
<i>C. album</i> IC 107297	31.58	1.56	22.90	0.00	0.80	15.83
<i>C. album</i> PI 605700	30.87	1.94	22.30	0.00	0.74	7.25
<i>C. album</i> “local 6x”	30.41	1.88	23.11	0.51	0.87	8.17
<i>C. album</i> “Iowa”	31.27	1.63	23.03	0.00	0.81	8.58
<i>C. ugandae</i> CHEN 77/78	29.06	2.61	21.95	1.81	0.86	4.00
Mean	30.19	2.32	20.97	3.03	1.51	19.99
SE	0.19	0.19	0.31	0.49	0.21	3.15

BCF was estimated in 10 accessions of *C. album*, 2 of *C. berlandieri* and 1 entry of *C. murale* for nickel. BCF for chromium ranged from 0.36 (*C. album* “Chandanbathua”) to 6.57 (*C. quinoa* Ames 13719) with 13 accessions of

C. quinoa scoring above average values. *C. quinoa* PI 510532 showed the highest BCF value for cadmium (111.83), followed by *C. quinoa* PI 587173 (57.67) and *C. quinoa* Ames 13719 (53.50), the mean being 19.99.

Selection parameters

The values of genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability and genetic advance are presented in Table 4. Nickel, cadmium and chromium showed high coefficient of variation values, while iron and copper had low estimates for these metals. Moderate to high heritability was observed for all the metals, which ranged from 66.86% for iron to 99.16% for nickel. The expected genetic advance varied from 6.19 to 210.23. Maximum genetic advance was found for nickel (210.23), followed by cadmium (202.57) and chromium (180.80).

Correlation studies

The phenotypic and genotypic correlations among various characters are presented in Table 5. The genotypic correlation coefficients were generally higher than the corresponding phenotypic values for most of the metals. Throughout the remainder of this section, reference will be made only to genotypic correlations. Zinc showed significant positive association with iron (0.351**), nickel (0.659**), chromium (0.743**) and cadmium (0.288**), and negative correlation with copper (−0.589**). Nickel was significantly and negatively associated with copper (−0.663**), while it was positively and significantly correlated with chromium (0.682**) and cadmium (0.461**). Chromium and cadmium showed average positive correlation between each other (0.382**).

Discussion

Mean levels of heavy metals in the foliage of *Chenopodium* spp. grown in non-contaminated area used as control in the study increased in the order of Cd (24.00 mg kg^{−1} DW) < Cr (43.20 mg kg^{−1} DW) < Ni (66.10 mg kg^{−1} DW) < Cu (132.10 mg kg^{−1} DW) < Zn (148.80 mg kg^{−1} DW) < Fe (83.92 mg kg^{−1} DW). These results are similar to the bioaccumulation patterns of heavy metals in different plant parts of algae (Harding and Whitton 1981), mosses

(Kelly et al. 1987), and higher plants like *Agrostis* (Hogan and Rauser 1981), *Phaseolus* (Hardiman et al. 1984) and *Triticum* (Nan et al. 1999). The concentration of Cu and Cd in *Chenopodium* spp. is greater than that reported for flax, cotton and hemp; the crops considered suitable for cultivation on metal polluted soils (Schneider et al. 1996; Yanchev et al. 2000; Angelova et al. 2004). Cu and Cd concentrations in *Chenopodium* also compares favourably to *Prosopis juliflora*, a bushy tree recommended for decontamination of heavy metal polluted soils (Senthilkumar et al. 2005). However, the bioaccumulation coefficients increased in the order of Cr (1.51) < Zn (2.32) < Ni (3.03) < Cd (19.99) < Cu (20.97) < Fe (30.19). Our results are similar to those obtained in crops like *Brassica*, where the bioaccumulation coefficient increased in the order of Zn < Cd < Cu (Dushenkov et al. 1995). Kim et al. (2003) also obtained greatest bioaccumulation coefficient for copper while working on *Polygonum thunbergii*.

Plant genotype is considered as the most important factor affecting the heavy metal uptake by plants. The uptake and accumulation of heavy metals varies greatly with plant species and within cultivars within a species (Li et al. 1995; Gaudchau and Schneider 1996; Li et al. 1997; Hocking and McLaughlin 2000; Liu et al. 2005). The present study showed that heavy metal concentration in *Chenopodium* varied greatly among different accessions and species, suggesting that the genus has a large genetic variability in its ability to accumulate heavy metals. Several species like *C. album*, *C. berlandieri* spp. *nuttalliae*, *C. giganteum* and *C. murale* are used as leafy vegetable and foliage crop in many parts of the world (Risi and Galwey 1989; Partap et al. 1998; Bhargava et al. 2005; Bhargava et al. 2006). Our results support the consumption preferences for these species by the natives since these species have a lesser tendency to accumulate toxic metals like Ni, Cd and Cr in the leaf tissues, thus justifying the use of their foliage for edible purposes. On the other hand, the ability of *C. quinoa* (which is not used as foliage/vegetable) to concentrate heavy metal in the leaves is remarkable. The accumulation of Zn, Ni, Cr and Cd was higher in the leaves of *C. quinoa* as compared to other species. Several accessions of *C. quinoa* accumulate more Cu and Zn than

Table 4 Selection parameters for different heavy metals in *Chenopodium* spp.

Selection parameters/metals	GCV	PCV	Heritability (%)	Genetic advance
Fe	3.67	4.49	66.86	6.19
Zn	48.92	59.05	68.65	83.51
Cu	8.78	10.10	75.57	15.73
Ni	102.49	102.92	99.16	210.23
Cr	88.26	88.76	98.88	180.80
Cd	99.20	100.08	98.25	202.57

GCV genotypic coefficient of variation, PCV phenotypic coefficient of variation

Table 5 Genotypic (G) and phenotypic (P) correlation coefficients between various heavy metals in *Chenopodium* spp.

Traits		Zn	Cu	Ni	Cr	Cd
Fe	G	0.351**	−0.065	0.187	0.198	0.117
	P	0.234**	−0.065	0.155	0.161	0.107
Zn	G		−0.589**	0.659**	0.743**	0.288**
	P		−0.418**	0.538**	0.604**	0.237**
Cu	G			−0.663**	−0.657*	−0.562**
	P			−0.573**	−0.575**	−0.469**
Ni	G				0.682**	0.461**
	P				0.680**	0.458**
Cr	G					0.382**
	P					0.376**

*, ** Significance at 5 and 1%, respectively

Polygonum thunbergii, an aquatic plant that grows vigorously in industrially polluted regions (Kim et al. 2003). Within *C. quinoa*, there was more than threefold difference for Ni (62.30–221.90 mg kg^{−1} DW), sixfold difference for Zn (58.00–361.70 mg kg^{−1} DW) and more than 13-fold difference for Cr (13.80–188.00 mg kg^{−1} DW) concentrations. A very wide variation in Cd concentrations has been found among the 18 accessions of *C. quinoa* ranging from 5.70 to 134.20, which points towards the presence of significant differences within the species with regard to heavy metal accumulation. The 4 accessions of *C. giganteum* also showed a large amount of variation in Zn, Ni and Cd concentration in their leaves. *C. quinoa* Ames 13719 showed relatively high amounts of all the heavy metals except copper, and had high BCF values for these metals, therefore suggesting greater prospects of this accession for decontaminating heavy metal polluted soils. *C. quinoa* PI 510532 is a hyperaccumulator of cadmium since the level of cadmium in the accession exceeds the limit prescribed for a hyperaccumulator (Reeves and Baker 2000). Other accessions, which can be categorized as potent accumulators of Cd are *C. quinoa* PI 587173, *C. quinoa* PI 478410, *C. quinoa* Ames 22158 and *C. giganteum* CHEN 86/85. Apart from this, other accumulators of heavy metals include *C. quinoa* CHEN 92/91 and *C. quinoa* PI 614881 for Zn and Ni, *C. quinoa* PI 584524, *C. quinoa* PI 587173 and *C. giganteum* CHEN 86/85 for Ni and Cd, *C. quinoa* PI 510536 and *C. quinoa* Ames 22156 for Ni, Cr and Zn. It would be interesting to observe the responses of these accessions to increased soil concentration of heavy metals and this would really bring out the actual potential of this crop for phytoextraction and bioremediation purposes.

From the viewpoint of a breeder, the presence of sufficient genetic variability in the base population is a prerequisite for any crop-breeding programme. The characters of economic importance are generally quantitative in nature and exhibit a considerable degree of interaction with environment. Thus, it becomes necessary to compute

variability present in the breeding material and its partitioning into genotypic, phenotypic and environmental ones. In the present investigation, adequate variability was observed in all the metals under study. The values of PCV were generally higher than the corresponding GCV values for all the metals, though the differences were small, which suggests that the variability was primarily due to genotypic differences.

In the strict sense, the question of whether a character is hereditary or environmental has no meaning. The genes cannot cause a character to develop unless they have proper environment, and conversely no amount of manipulation of the environment will cause a character to develop unless necessary genes are present. Nevertheless, it must be recognized that the variability observed in some characters was caused primarily by differences in the genes carried by different individuals and that the variability in other characters is due to differences in the environment to which individuals have been exposed.

Heritability is a measure of the genetic relationship between parent and progeny and has been widely used to assess the degree to which a character may be transmitted from parent to offspring. Knowledge of heritability of a character is important as it indicates the possibility and extent to which improvement is possible through selection (Robinson et al. 1949). It also indicates the relative importance of heredity and environment in the expression of these characters. The heritability estimates were moderate to high for all the heavy metals, which indicates that all the traits are under genotypic control. However, it will be pertinent to admit here that the total genotypic variance is made up of additive genetic variance and non-additive or unfixable variance. In the present investigation, it was not possible to partition the total genetic variance in these two sub groups and, therefore, the estimates of variability may be slightly higher.

High heritability alone does not guarantee large gain from selection unless sufficient genetic gain attributable to additive gene action is present. Genetic advance in a

trait is a product of heritability and selection differential expressed in unit of standard deviation and has an added advantage over heritability as a guiding factor in selection programme, where characters to be improved are desired. In the present study, high heritability coupled with high genetic advance was recorded for Ni, Cr and Cd, which indicated a major role of additive gene action in the inheritance of these characters. Fe and Cu showed moderate heritability along with low genetic advance, which revealed the major role of non-additive gene action in the transmission of these characters from parents to offspring. Thus, chances of improvement in these traits seem difficult.

The correlation studies also presented some interesting results. Cu was negatively correlated with all the heavy metals, which suggests that selection for improved copper content is not possible without adversely affecting the concentration of other heavy metals. Zn, Ni, Cr and Cd shared significant positive association among each other. Earlier, Herawati et al. (2000) have also reported significant positive correlation between Cd and Zn concentrations in rice. Our findings could have positive implications with regard to the use of *Chenopodium* for bioremediation purposes. The accumulation of three major soil contaminants viz. Ni, Cr and Cd in plants has high heritability, genetic advance and positive correlation amongst each other. This implies that for breeding advanced lines/ideal plant type with greater capacity of heavy metal accumulation, indirect selection could prove to be effective.

Conclusions

The results of the present investigation suggest that *Chenopodium* spp. have the ability to accumulate large quantities of heavy metals in the leaf tissue even when they are present in low concentrations in the soil. *C. quinoa* is a better accumulator of Ni, Cr and Cd than the rest of the species. Thus, the species provides scope for decontamination of heavy metal polluted soils in view of its ability to accumulate heavy metals, especially Cu and Cd, several folds higher than their available levels in the soil. Considering the accumulation efficiency of *Chenopodium* spp. to heavy metals, this genus could be further explored for decontamination of metal polluted soils. Efficient utilization of breeding techniques could prove extremely beneficial for developing novel plant types that could be used for phytoextraction and bioremediation purposes.

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