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**REGULAR ARTICLE**

# Genotype x environment interaction studies in *Chenopodium album* L.: an underutilized crop with promising potential

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**ABSTRACT**

This study was carried out to evaluate the performance of different germplasm lines of *Chenopodium album* L. in successive foliage cuttings, as well as to study the magnitude and pattern of genotype × environment interaction for different morphological and quality traits. Thirteen germplasm lines of *C. album* were evaluated for three consecutive years at Lucknow, India. Data recorded was foliage yield and values for five morphological and three quality traits. Leaf protein among the lines ranged from 3.63-4.51 g $100g^{-1}$ with a mean of 4.06 g $100g^{-1}$, leaf carotenoids ranged from 0.98-1.40 mg $g^{-1}$. Two diploid and four hexaploid lines had a high stability for foliage yield. Two germplasm lines of *C. album* CA-VI and CA-XI were the only lines, which showed stability for all quality traits. Lines CA-I, CA-VI and CA-XIII showed stability for foliage yield and were high yielding. This indicates the possibility of simultaneous selection for high yield and broad adaptation.

**Key Words**: *Chenopodium album; genotype × environment interaction; stability; foliage yield; protein; carotenoids; ascorbic acid*.

## INTRODUCTION

A tremendous increase in world population has resulted in intensive agriculture in many parts of the world, which requires farm mechanization, and increased inputs of labor, high yielding varieties, chemical fertilizers, and pesticides. These higher inputs have created high pressure on fragile agro-ecosystems. Modern agriculture has increased homogeneity and mono-cropping. This has resulted in a loss of agro-biodiversity and frequent crop losses due to pathogen infestations. There is a need for a gradual shift from input-intensive to

environmentally-sound sustainable agriculture. The modeling of traditional farming systems to modern needs, with increased organic linkages might be a good option for sustainability of agricultural production and the maintenance of agro-ecological stability. This would also require a shift in focus towards increasing production by the utilization of agriculturally marginal lands (Partap et al., 1998). Members of the genus *Chenopodium* (Chenopodiaceae) are promising in this regard as they can thrive and flourish under stress (Bhargava et al., 2003, 2006a; Jacobsen et al., 2003) and on soils with minimum cultural inputs.

*Chenopodium* spp. have been cultivated for centuries as leafy vegetables and as a subsidiary grain crop in different parts of the world (Risi and Galwey, 1984). Ancient Indian texts describe numerous medicinal properties of the genus (Kirtikar and Basu, 2001). Ethnic communities in the region have used chenopod leaves for urinary troubles (Bakshi et al., 1999) and to remove intestinal worms (Singh et al., 2003). At present chenopods are being cultivated in the watersheds of several rivers of the western Himalayas, hilly areas of North Bengal, the watershed of the Teesta River and in several states of north-eastern India (Joshi, 1991; Partap et al., 1998). Although only 3 species viz. *C. quinoa*, *C. pallidicaule* and *C. berlandieri* subsp. *nuttalliae* are reported to be cultivated (Bhargava et al., 2006b), the leaves and tender stems of numerous other chenopod species are consumed as food and fodder (Kunkel, 1984; Partap, 1990; Moerman, 1998; Partap et al., 1998). *Chenopodium* foliage is an inexpensive and rich source of protein, carotenoids and vitamin C (Koziol, 1992; Prakash et al., 1993; Bhargava et al., 2006c). Although *C. album* is ranked among top 10 weeds of the world (Holm et al., 1977), it is grown in the north-western Himalayan region as a subsidiary food crop in mixed farming systems, particularly multiple cropping systems (Partap and Kapoor, 1985, 1987). It is cultivated in this region for its nutritionally rich grain as well as a fodder crop and a pot-herb (Partap, 1990). Over 90% of families in the region cultivate *Chenopodium* and utilize almost every plant part for various purposes. Apart from edible purposes, it is also used as a fuel and in the preparation of alcoholic drinks (Partap et al., 1998). However, on the Indo-Gangetic Plains, *C. album* is not cultivated but is weeded out from other crops and sold in local markets for consumption as a pot-herb.

Seeing the potential of chenopods as a cheap source of protein and other nutrients, there is a need for their genetic improvement through breeding. The identification of high yielding, stable germplasm with good quality is a major objective in any crop-breeding program. Plant material when planted in different environments exhibits different genotypic responses due to environmental variation. Consistent performance across different sites and/or years is referred to as stability. The partitioning of the genotype × environment interaction (GEI) into stability statistics assignable to each genotype evaluated across a range of environments is useful in selecting stable genotypes in any crop breeding program. Plants showing a high genotype × environment interaction (GEI) effect are not suited to diverse environments (Thillainathan and Fernandez, 2002) and this severely limits the selection of superior genotypes. Plant breeders continuously strive to broaden the genetic base of a crop to prevent vulnerability to changing environments. A study of GEIs gives information on the suitability of genotypes over wide range of agro-climatic conditions. A number of statistical models are available to evaluate yield stability of a genotype in yield trials (Eberhart and Russel, 1966; Tai, 1971; Shukla, 1972; Yan and Kang, 2003). Although stability estimates for grain yield in chenopods are available (Risi and Galwey, 1991; Bertero et al., 2004; Bhargava et al., 2005), studies on the foliage yield of vegetable chenopods are rare (Bhargava et al., 2007). The aim of this study was to ascertain the performance of different germplasm lines of *C. album* in response to successive foliage cuts and to study the magnitude and pattern of GEIs for different morphological and quality traits. The study also explores the prospects of *C. album* for agro-ecological sustainability and agricultural diversification with reference to its suitability for cultivation on the Indo-Gangetic Plains.

## MATERIALS AND METHODS

### EXPERIMENTAL SITE AND GERMPLASM

The investigation was conducted at National Botanical Research Institute (N.B.R.I.), Lucknow experiment field, at 26.5°N 80.5°E and 120 m above sea level. This subtropical region is at the core of the Indo-Gangetic Plains and has marked differences in summer and winter temperatures. It supports two types of crop system:

(i) Summer, 20 to 40°C.

(ii) Winter, 2.5 to 19°C.

*Chenopodium album* is grown as a winter crop and appears as a weed on the Indo-Gangetic Plains, at the start of winter. However, at harvest the maximum temperature may reach 30°C.

A large collection of *Chenopodium* spp. is maintained at the N.B.R.I., Lucknow. It includes local and introduced germplasm lines of *C. album*. We evaluated three diploid, one tetraploid and nine hexaploid *C. album* accessions (Table 1).

Table 1. Germplasm lines, their ploidy level, chromosome number and origin

| S. No. | *C. album* germplasm line | 2n | Origin | Source |
|---|---|---|---|---|
| CA-I | PRC 9802 | 54 | Himachal Pradesh, India | N.B.R.I. |
| CA-II | IC 107297 | 54 | Himachal Pradesh, India | N.B.R.I. |
| CA-III | 'Mexico' | 36 | Mexico | Mexico |
| CA-IV | 'local red' | 18 | Lucknow, India | N.B.R.I. |
| CA-V | 'Siliguri' | 18 | Siliguri, India | N.B.R.I. |
| CA-VI | 'amaranticolor' | 54 | Himachal Pradesh, India | N.B.R.I. |
| CA-VII | 'H.P.' | 54 | Himachal Pradesh, India | N.B.R.I. |
| CA-VIII | PI 605700 | 54 | Michigan, USA | USDA |
| CA-IX | CHEN 60/76 | 54 | Belgium | IPK Gatersleben, Germany |
| CA-X | CHEN 95/97 | 54 | Unknown | IPK Gatersleben, Germany |
| CA-XI | 'Czech' | 54 | Czech Republic | Czech Republic |
| CA-XII | 'Iowa' | 54 | Iowa, USA | USA |
| CA-XIII | 'Chandanbathua' | 18 | India | N.B.R.I. |

### EXPERIMENTAL SET UP AND CULTURAL PRACTICES

The material was evaluated over three consecutive years (2002-2003, 2003-2004 and 2004-2005) in a randomized block design with 3 replicates sown in the experimental field of the N.B.R.I. Maximum and minimum temperatures for each crop year are given in Table 2. Rainfall is not reported because the experiments were irrigated. The field was disc ploughed, harrowed and raked to obtain a good seed bed before sowing. The experimental site soil was a sandy loam with a pH of 6.8 ± 0.04, an electrical conductivity of 479 ± 1.26 μs $cm^{-1}$ and an organic matter content of 1.06 %. Prior to sowing 20 t $ha^{-1}$ of compost was added to the experimental field to enhance soil water holding capacity. Plot size in all years was 4 $m^2$ with 6 rows $plot^{-1}$, spaced at 30 cm apart. Normal cultural practices were followed during crop growth. Irrigation was provided as and when needed, which was determined by ascertaining the soil moisture level. No chemical fertilizer was applied. This was primarily to ascertain the potential of the crop for subsistence agriculture since most farmers in the region are poor and seek low input crops. Each germplasm line was sown in a separate plot which was hand thinned to maintain within row plant density. No fungicides or insecticides were applied. Plots were hand weeded every 20 d.

The first foliage cut was taken 3-wk after sowing. Subsequent cuts were at 15 d intervals. There was a total of three cuts $year^{-1}$. Data was recorded from five randomly selected plants

from each plot at each harvest for five morphological traits: plant height (cm), branches plant$^{-1}$, leaves plant$^{-1}$, leaf size (cm$^2$), and stem diameter (cm). Foliage yield was recorded on a plot basis for each cutting and pooled for total foliage yield. Besides this, three leaf quality traits carotenoid content (mg g$^{-1}$), fiber (%) and protein (g 100g$^{-1}$) levels were estimated at each cutting from the plant samples. Fiber content was estimated using dried leaves while carotenoid and protein content were estimated on a fresh leaf basis. The extraction and estimation of carotenoids was according to Jensen (1978). Fiber content was estimated using the method of Watson (1994) while protein content was estimated following the Lowry et al. (1951) method.

Table 2. Weather parameters for the 3 consecutive years of the trial.

| Year | 2002-03 | 2003-04 | 2004-05 |
|---|---|---|---|
| Temperature (°C) | | | |
| Minimum | 9.67 | 10.33 | 11.00 |
| Maximum | 19.00 | 18.67 | 22.60 |
| Dew Point (°C) | 10.00 | 9.67 | 11.34 |
| Wind velocity (km hr$^{-1}$) | 4.33 | 3.67 | 6.34 |

*STATISTICAL ANALYSIS*

The raw data was compiled by taking the means of all plants taken for each treatment and replication for the different traits over the 3 experimental years. Joint regression analysis was performed (Eberhart and Russel, 1966) and the regression coefficient (βi) and deviation from the regression ($\delta_i^2$) were calculated for each line (Eberhart and Russel, 1966). Three other stability parameters Hanson's $D_i$ (1970), Tai's $\lambda_i$ (1971) and Shukla's $s_i^2$ (1972), were also used to measure stability. A germplasm line was regarded as stable if its contribution to the G × E interaction was less than average for more than 3 stability parameters. The average was defined as the mean of the respective stability parameter.

## RESULTS

The analysis of variance for the 6 morphological and 3 quality traits is given in Table 3. The nine traits showed highly significant values for the MSS due to genotype. The MSS due to environments was highly significant for leaf carotenoid content and all morphological traits except plant height. The GEI MSS were significant for leaves plant$^{-1}$, leaf size, stem diameter and foliage yield.

The performance of the different germplasm lines over the three years (environments) for morphological traits is given in Tables 4 and 5, and for qualitative traits in Table 6. Although the mean of the 13 lines was highest for plant height, leaves plant$^{-1}$ and leaf size in the second year, the highest foliage yield was recorded in year 1 (5.72 ± 0.64 kg plot$^{-1}$). Only one of the three diploid lines, CA-XIII gave a high foliage yield (5.70 kg plot$^{-1}$). The sole tetraploid line, CA-III, gave a marginally higher yield than the mean (Table 5). However, the bulk of the experimental material was hexaploid comprising 5 exotic and 4 indigenous lines. All the indigenous hexaploid lines performed well and gave high yields in all three years on an overall mean basis. Line CA-II gave the highest foliage yield in years 1, 2 and 3 at 9.41, 9.11 and 6.60 kg plot$^{-1}$ respectively, (mean 8.37 kg plot$^{-1}$). This was almost 60% greater than the mean of the 13 lines. The high yielding lines CA-I, CA-II, CA-VI and CA-VII generally had thick stems and large leaves in all three years. Among the other lines, CA-III had high values for all morphological traits except leaf size.

Table 3. Mean sum of squares (MSS) from joint regression analysis of 13 lines of *C. album* over 3 years (Env.)

| Source of variation | df | Plant height (cm) | Branches plant$^{-1}$ | Leaves plant$^{-1}$ | Leaf size (cm$^2$) | Stem diameter (cm) | Foliage yield (kg plot$^{-1}$) | Carotenoid (mg g$^{-1}$) | Protein (g 100g$^{-1}$) | Fiber (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Replicates within Env. | 6 | 0.739 | 0.184 | 0.208 | 0.315 | 0.000 | 0.114 | 0.003 | 0.008 | 0.288 |
| Genotype | 12 | 16.612*** | 5.590*** | 48.362*** | 196.562*** | 0.013*** | 13.03*** | 0.081*** | 0.223*** | 1.854*** |
| Env. + (Gen. × Env.) | 26 | 2.897 | 0.946 | 7.964*** | 7.704*** | 0.013*** | 0.865*** | 0.000 | 0.006 | 0.054 |
| Environment | 2 | 4.445 | 3.130* | 64.496*** | 55.592*** | 0.149*** | 7.593*** | 0.004** | 0.016 | 0.096 |
| Gen. × Env. | 24 | 2.768 | 0.763 | 3.253*** | 3.713*** | 0.002*** | 0.304* | 0.000 | 0.005 | 0.050 |
| Environment (Linear) | 1 | 8.890* | 6.260** | 128.990*** | 111.190*** | 0.299*** | 15.190*** | 0.008** | 0.032* | 0.193 |
| Gen. × Env. (Linear) | 12 | 3.690 | 1.072 | 6.237*** | 7.206*** | 0.004*** | 0.505** | 0.000 | 0.004 | 0.046 |
| Pooled deviation | 13 | 1.704*** | 0.420* | 0.249 | 0.204 | 0.000 | 0.096* | 0.000 | 0.005 | 0.050 |
| Pooled Error | 72 | 0.257 | 0.182 | 0.566 | 0.347 | 0.000 | 0.046 | 0.004 | 0.006 | 0.161 |
| Total | 38 | 7.228 | 2.412 | 20.721 | 67.343 | 0.013 | 4.708 | 0.026 | 0.074 | 0.622 |

*, ** and *** significant at 0.05, 0.01 and 0.001 probability level respectively

The protein content among lines ranged from 3.63 to 4.51 g 100g$^{-1}$ with an average of 4.06 g 100g$^{-1}$ (Table 6). Line CA-III had the highest protein content in all years and overall. Seven lines out yielded their arithmetic means for protein content. Mean carotenoid content ranged from 0.98 mg g$^{-1}$ in CA-XII to 1.40 mg g$^{-1}$ in lines CA-VI, CA-II, and CA-VII. Line CA-XI had a high protein and carotenoid in all years, but was low in fiber. Fiber was >10 % in all 13 lines and ranged from 10.06 % (CA-IX) to 12.62 % (CA-XII), with a mean of 11.24 %. Only four lines CA-VIII, CA-X, CA-XII and CA-XIII had above average fiber content.

The values of the five stability parameters for morphological traits are shown in Tables 4 and 5, and the qualitative traits in Table 6. The $\delta^2di$ values were zero for stem diameter and carotenoid content in all 13 lines. Low $\delta^2di$ values of 0.01-0.30 were obtained for foliage yield and from 0 to 0.023 for protein content. Out of the 13 lines, six had high stability for foliage yield, of these two lines were diploid and four were hexaploid. Line CA-XI also had high stability for the other morphological traits while line CA-XIII was stable for four morphological traits. Lines CA-VI and CA-XI were the only lines that showed stability for all quality traits (Table 6). All the indigenous lines except CA-XIII were stable for protein content. Eight lines had high stability for leaf protein content. The majority of the lines exhibited differential stability with regard to the quality traits. Lines CA-XII and CA-XIII were only stable for fiber, line CA-I for protein and line CA-III for carotenoid content. Line CA-VIII did not show stability for any of the three quality components.

An overview of morphological and quality traits according to ploidy level is shown in Table 7. The diploid lines had the lowest values for leaf size, stem diameter and foliage yield, while the hexaploid lines had lowest values for plant height, branches plant$^{-1}$ and leaves plant$^{-1}$. The hexaploid lines had the largest leaves, thickest stem and the highest yield. For quality traits, the diploid, tetraploid and hexaploid lines had the highest fiber, protein and carotenoid content, respectively (Table 7).

Table 4. Mean values and stability parameters for morphological traits plant height, branches/plant and leaves/plant over 3 years (Env.) in *C. album*.

| | Env. 1 | Env. 2 | Env. 3 | Mean ± SE | $\beta_i$ | $\delta_2 di$ | $s^2$ | $\lambda_i$ | $D_i$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Plant height (cm) | | | | | |
| CA-I | 15.47 | 16.13 | 14.54 | 15.38±0.46 | 0.97 | 0.34 | 0.22 | 1.19 | 2.87 |
| CA-II | 16.44 | 20.82 | 13.56 | 16.94±2.11 | 5.26 | 7.50 | 11.79 | 12.58 | 6.90 |
| CA-III | 16.30 | 21.23 | 15.96 | 17.83±1.70 | 4.92 | 0.55 | 6.56 | 1.14 | 6.10 |
| CA-IV | 12.40 | 10.34 | 13.44 | 12.06±0.91 | 2.37 | 0.86 | 5.11 | 5.26 | 1.07 |
| CA-V | 15.17 | 17.87 | 13.20 | 15.41±1.35 | 3.32 | 3.20 | 4.07 | 0.13 | 5.06 |
| CA-VI | 13.47 | 14.55 | 12.53 | 13.52±0.58 | 1.38 | 0.45 | 0.34 | 1.41 | 3.22 |
| CA-VII | 14.47 | 13.18 | 15.28 | 14.31±0.61 | 1.54 | 0.34 | 2.83 | 2.47 | 1.05 |
| CA-VIII | 14.03 | 13.95 | 16.10 | 14.69±0.70 | 0.80 | 2.23 | 2.65 | 8.32 | 2.05 |
| CA-IX | 11.00 | 13.05 | 13.30 | 12.45±0.73 | 1.20 | 1.91 | 1.62 | 3.69 | 3.30 |
| CA-X | 13.20 | 12.67 | 14.05 | 13.31±0.40 | 0.81 | 0.23 | 1.48 | 1.72 | 1.47 |
| CA-XI | 7.80 | 8.28 | 9.51 | 8.53±0.51 | 0.13 | 1.24 | 1.27 | 4.23 | 2.23 |
| CA-XII | 14.47 | 15.42 | 14.77 | 14.89±0.28 | 0.82 | 0.28 | 0.13 | 0.02 | 2.64 |
| CA-XIII | 14.77 | 15.74 | 15.24 | 15.25±0.28 | 0.79 | 0.24 | 0.10 | 0.11 | 2.62 |
| Mean ±SE | 13.77 ±0.65 | 14.87 ±1.02 | 13.96 ±0.48 | 14.20±0.65 | 1.87 | 1.49 | 2.94 | 3.25 | 3.12 |
| | | | | Branches plant$^{-1}$ | | | | | |
| CA-I | 8.91 | 8.69 | 9.55 | 9.05±0.26 | 0.90 | 0.17 | 0.03 | 0.03 | 1.54 |
| CA-II | 9.61 | 10.91 | 9.88 | 10.13±0.40 | 0.58 | 0.59 | 1.13 | 2.87 | 1.02 |
| CA-III | 11.37 | 12.13 | 10.70 | 11.40±0.41 | 1.31 | 0.01 | 1.60 | 0.80 | 0.44 |
| CA-IV | 11.22 | 9.82 | 12.42 | 11.15±0.75 | 2.36 | 0.50 | 0.90 | 1.60 | 2.68 |
| CA-V | 9.82 | 9.71 | 10.44 | 9.99±0.23 | 0.08 | 0.18 | 0.03 | 0.01 | 1.47 |
| CA-VI | 9.83 | 10.06 | 9.89 | 9.93±0.07 | 0.09 | 0.16 | 0.32 | 0.08 | 0.86 |
| CA-VII | 9.30 | 9.29 | 9.82 | 9.47±0.17 | 0.62 | 0.18 | 0.01 | 0.01 | 1.34 |
| CA-VIII | 11.60 | 10.11 | 13.23 | 11.64±0.90 | 2.93 | 0.54 | 1.45 | 1.51 | 3.07 |
| CA-IX | 10.90 | 9.84 | 11.06 | 10.60±0.38 | 0.92 | 0.29 | 0.24 | 1.41 | 1.69 |
| CA-X | 9.30 | 10.80 | 13.66 | 11.25±1.28 | 4.07 | 1.66 | 3.74 | 2.86 | 3.98 |
| CA-XI | 6.40 | 6.82 | 6.27 | 6.50±0.16 | 0.45 | 0.11 | 0.60 | 0.26 | 0.66 |
| CA-XII | 10.33 | 9.06 | 10.80 | 10.06±0.52 | 1.42 | 0.46 | 0.39 | 1.78 | 2.06 |
| CA-XIII | 10.73 | 10.80 | 11.97 | 11.17±0.40 | 1.41 | 0.16 | 0.02 | 0.60 | 1.89 |
| Mean ±SE | 9.95 ±0.38 | 9.85 ±0.36 | 10.74 ±0.52 | 10.18±0.38 | 1.32 | 0.38 | 0.80 | 1.06 | 1.75 |
| | | | | Leaves plant$^{-1}$ | | | | | |
| CA-I | 13.73 | 15.11 | 10.45 | 13.10±1.38 | 1.06 | 0.35 | 0.11 | 0.18 | 3.85 |
| CA-II | 13.63 | 13.98 | 10.95 | 12.85±0.96 | 0.71 | 0.01 | 0.79 | 0.54 | 2.79 |
| CA-III | 22.27 | 27.15 | 14.81 | 21.41±3.59 | 2.79 | 0.52 | 18.8 | 0.01 | 9.26 |
| CA-IV | 20.13 | 24.93 | 15.70 | 20.25±2.66 | 2.06 | 0.15 | 6.93 | 0.65 | 7.00 |
| CA-V | 16.67 | 17.80 | 12.12 | 15.53±1.73 | 1.31 | 0.40 | 1.11 | 0.92 | 4.71 |
| CA-VI | 13.88 | 15.97 | 10.67 | 13.51±1.54 | 1.20 | 0.54 | 0.21 | 0.01 | 4.25 |
| CA-VII | 10.80 | 11.40 | 11.26 | 11.15±0.18 | 0.02 | 0.34 | 5.77 | 0.21 | 0.68 |
| CA-VIII | 16.87 | 18.13 | 14.70 | 16.57±1.00 | 0.78 | 0.53 | 0.28 | 0.01 | 2.92 |
| CA-IX | 25.50 | 28.53 | 22.65 | 25.56±1.70 | 1.31 | 0.28 | 0.70 | 0.26 | 4.63 |
| CA-X | 16.13 | 18.02 | 14.44 | 16.20±1.03 | 0.80 | 0.42 | 0.29 | 0.12 | 3.00 |
| CA-XI | 15.92 | 16.26 | 16.85 | 16.34±0.27 | 0.15 | 0.31 | 7.85 | 0.24 | 0.48 |
| CA-XII | 13.70 | 13.91 | 12.58 | 13.40±0.41 | 0.31 | 0.46 | 2.82 | 0.08 | 1.47 |
| CA-XIII | 15.80 | 17.37 | 13.79 | 15.65±1.04 | 0.81 | 0.53 | 0.20 | 0.01 | 3.01 |
| Mean ±SE | 16.54 ±1.11 | 18.35 ±1.46 | 13.92 ±0.92 | 16.27±1.11 | 1.02 | 0.37 | 3.53 | 0.25 | 3.70 |

Table 5. Mean values and stability parameters for leaf size, stem diameter and foliage yield over 3 years (Env.) in *C. album*.

| | Env. 1 | Env. 2 | Env. 3 | Mean±SE | $\beta_i$ | $\delta_2 di$ | $s^2$ | $\lambda_i$ | $D_i$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Leaf size (cm²) | | | | | |
| CA-I | 26.93 | 32.63 | 20.05 | 26.54±3.64 | 3.04 | 0.34 | 21.11 | 0 | 9.71 |
| CA-II | 27.00 | 29.50 | 23.39 | 26.63±1.77 | 1.49 | 0.30 | 1.21 | 0.06 | 5.16 |
| CA-III | 12.27 | 14.54 | 8.40 | 11.74±1.79 | 1.49 | 0.18 | 1.31 | 0.24 | 5.18 |
| CA-IV | 3.73 | 3.87 | 3.35 | 3.65±0.15 | 0.13 | 0.34 | 3.85 | 0.01 | 1.17 |
| CA-V | 13.13 | 14.64 | 11.46 | 13.08±0.92 | 0.77 | 0.34 | 0.25 | 0.01 | 3.05 |
| CA-VI | 22.80 | 26.83 | 20.88 | 23.50±1.75 | 1.42 | 0.85 | 1.58 | 1.77 | 5.07 |
| CA-VII | 22.77 | 22.73 | 23.84 | 23.11±0.36 | 0.27 | 0.20 | 8.27 | 0.26 | 0.38 |
| CA-VIII | 12.97 | 14.39 | 10.98 | 12.78±0.99 | 0.83 | 0.34 | 0.14 | 0.01 | 3.23 |
| CA-IX | 5.10 | 6.95 | 2.74 | 4.93±1.22 | 1.02 | 0.34 | 0.02 | 0.10 | 3.78 |
| CA-X | 11.10 | 12.30 | 10.45 | 11.28±0.54 | 0.44 | 0.26 | 1.60 | 0.15 | 2.12 |
| CA-XI | 4.67 | 4.84 | 5.25 | 4.92±0.17 | 0.10 | 0.26 | 6.20 | 0.15 | 0.58 |
| CA-XII | 19.00 | 21.82 | 13.31 | 18.04±2.50 | 2.08 | 0.35 | 6.27 | 0.93 | 6.93 |
| CA-XIII | 13.07 | 13.74 | 11.00 | 12.60±0.82 | 0.67 | 0.13 | 0.65 | 0.35 | 2.80 |
| Mean ±SE | 14.96 ±2.25 | 16.83 ±2.57 | 12.70 ±2.02 | 14.83±2.25 | 1.06 | 0.32 | 4.03 | 0.31 | 3.78 |
| | | | | Stem diameter (cm) | | | | | |
| CA-I | 0.55 | 0.72 | 0.38 | 0.55±0.10 | 1.60 | 0 | 0.005 | 0 | 0.21 |
| CA-II | 0.59 | 0.75 | 0.40 | 0.58±0.10 | 1.63 | 0 | 0.005 | 0.03 | 0.21 |
| CA-III | 0.52 | 0.65 | 0.34 | 0.50±0.09 | 1.45 | 0 | 0.003 | 0.23 | 0.19 |
| CA-IV | 0.38 | 0.48 | 0.25 | 0.37±0.07 | 1.07 | 0 | 0 | 0.13 | 0.13 |
| CA-V | 0.45 | 0.53 | 0.35 | 0.44±0.05 | 0.87 | 0 | 0 | 0.03 | 0.10 |
| CA-VI | 0.61 | 0.68 | 0.49 | 0.59±0.05 | 0.89 | 0 | 0 | 0.37 | 0.10 |
| CA-VII | 0.59 | 0.62 | 0.55 | 0.59±0.02 | 0.33 | 0 | 0.006 | 0.01 | 0.01 |
| CA-VIII | 0.50 | 0.58 | 0.40 | 0.49±0.05 | 0.84 | 0 | 0 | 0.01 | 0.09 |
| CA-IX | 0.45 | 0.57 | 0.29 | 0.44±0.08 | 1.27 | 0 | 0.001 | 0.15 | 0.16 |
| CA-X | 0.43 | 0.61 | 0.35 | 0.46±0.07 | 1.21 | 0 | 0.002 | 1.50 | 0.16 |
| CA-XI | 0.51 | 0.55 | 0.50 | 0.52±0.01 | 0.22 | 0 | 0.009 | 0.25 | 0.02 |
| CA-XII | 0.47 | 0.59 | 0.41 | 0.49±0.05 | 0.82 | 0 | 0.001 | 0.77 | 0.10 |
| CA-XIII | 0.46 | 0.53 | 0.35 | 0.45±0.05 | 0.81 | 0 | 0.001 | 0.12 | 0.09 |
| Mean ±SE | 0.50 ±0.01 | 0.60 ±0.02 | 0.39 ±0.02 | 0.50±0.01 | 1.00 | 0 | 0.002 | 0.28 | 0.12 |
| | | | | Foliage yield (kg plot$^{-1}$) | | | | | |
| CA-I | 6.55 | 6.52 | 5.45 | 6.17±0.36 | 0.81 | 0.03 | 0.03 | 0.23 | 0.57 |
| CA-II | 9.41 | 9.11 | 6.60 | 8.37±0.89 | 2.01 | 0.01 | 0.72 | 0.26 | 1.86 |
| CA-III | 5.34 | 5.89 | 4.23 | 5.15±0.49 | 0.96 | 0.30 | 0.20 | 3.74 | 0.92 |
| CA-IV | 3.82 | 3.13 | 2.94 | 3.30±0.27 | 0.48 | 0.11 | 0.27 | 1.97 | 0.44 |
| CA-V | 5.21 | 4.62 | 3.84 | 4.56±0.40 | 0.87 | 0.01 | 0.04 | 0.68 | 0.66 |
| CA-VI | 7.70 | 7.26 | 6.12 | 7.03±0.47 | 1.06 | 0.04 | 0 | 0.10 | 0.83 |
| CA-VII | 9.14 | 8.73 | 5.42 | 7.76±1.18 | 2.66 | 0.01 | 1.93 | 0.25 | 2.56 |
| CA-VIII | 4.56 | 4.94 | 4.28 | 4.59±0.19 | 0.30 | 0.06 | 0.40 | 1.51 | 0.34 |
| CA-IX | 3.59 | 3.07 | 1.92 | 2.86±0.49 | 1.11 | 0.03 | 0.01 | 0.22 | 0.88 |
| CA-X | 3.54 | 3.51 | 2.84 | 3.30±0.23 | 0.51 | 0.04 | 0.16 | 0.09 | 0.24 |
| CA-XI | 1.81 | 1.23 | 0.92 | 1.32±0.26 | 0.52 | 0.04 | 0.21 | 1.16 | 0.39 |
| CA-XII | 7.48 | 6.54 | 6.27 | 6.76±0.37 | 0.66 | 0.24 | 0.24 | 3.45 | 0.67 |
| CA-XIII | 6.23 | 6.10 | 4.76 | 5.70±0.47 | 1.06 | 0.04 | 0 | 0.16 | 0.83 |
| Mean ±SE | 5.72 ±0.64 | 5.43 ±0.64 | 4.28 ±0.48 | 5.14±0.58 | 1.00 | 0.07 | 0.32 | 1.06 | 0.86 |

Table 6. Mean values and stability parameters for carotenoids, leaf protein and fiber over 3 years (Env.) in *C. album*.

| | Env. 1 | Env. 2 | Env. 3 | Mean | $\beta_i$ | $\delta_2 di$ | $s^2$ | $\lambda$i | $D_i$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Carotenoids (mg g$^{-1}$) | | | | | |
| CA-I | 1.04 | 1.00 | 1.12 | 1.05 ± 0.03 | 1.61 | 0 | 0 | 0.040 | 0.07 |
| CA-II | 1.38 | 1.44 | 1.23 | 1.35 ± 0.06 | 0.95 | 0 | 0.003 | 0.340 | 0.05 |
| CA-III | 1.00 | 0.99 | 1.02 | 1.00 ± 0.01 | 0.85 | 0 | 0 | 0.030 | 0.05 |
| CA-IV | 1.00 | 1.03 | 1.10 | 1.04 ± 0.03 | 0.90 | 0 | 0.001 | 0.010 | 0.01 |
| CA-V | 1.22 | 1.21 | 1.13 | 1.18 ± 0.02 | 0.55 | 0 | 0 | 0.002 | 0.04 |
| CA-VI | 1.42 | 1.37 | 1.42 | 1.40 ± 0.01 | 1.44 | 0 | 0 | 0.003 | 0.06 |
| CA-VII | 1.38 | 1.33 | 1.33 | 1.34 ± 0.02 | 0.77 | 0 | 0.001 | 0.140 | 0.06 |
| CA-VIII | 1.28 | 1.24 | 1.21 | 1.24 ± 0.02 | 1.64 | 0 | 0 | 0.005 | 0.07 |
| CA-IX | 1.23 | 1.19 | 1.24 | 1.22 ± 0.01 | 1.42 | 0 | 0 | 0.006 | 0.06 |
| CA-X | 1.45 | 1.41 | 1.29 | 1.38 ± 0.05 | 1.35 | 0 | 0 | 0 | 0.06 |
| CA-XI | 1.25 | 1.23 | 1.29 | 1.26 ± 0.02 | 0.45 | 0 | 0 | 0.02 | 0.04 |
| CA-XII | 1.01 | 0.91 | 1.01 | 0.98 ± 0.03 | 3.12 | 0 | 0.002 | 0.002 | 0.10 |
| CA-XIII | 1.22 | 1.13 | 1.15 | 1.17 ± 0.03 | 1.65 | 0 | 0.002 | 0.3 | 0.08 |
| Mean ±SE | 1.22 ±0.04 | 1.19 ±0.05 | 1.19 ±0.04 | 1.20 ± 0.04 | 1.28 | 0 | 0.0006 | 0.069 | 0.06 |
| | | | | Protein (g 100g$^{-1}$) | | | | | |
| CA-I | 3.67 | 3.69 | 3.73 | 3.70 ± 0.02 | 0.63 | 0.010 | 0 | 0.010 | 0.07 |
| CA-II | 4.40 | 4.40 | 4.49 | 4.43 ± 0.03 | 0.86 | 0 | 0.002 | 0.360 | 0.11 |
| CA-III | 4.45 | 4.51 | 4.57 | 4.51 ± 0.02 | 1.23 | 0.010 | 0 | 0.006 | 0.10 |
| CA-IV | 4.19 | 4.16 | 4.23 | 4.19 ± 0.02 | 0.28 | 0 | 0.002 | 0.229 | 0.07 |
| CA-V | 4.14 | 4.10 | 4.02 | 4.09 ± 0.03 | 0.32 | 0 | 0.003 | 0.438 | 0.09 |
| CA-VI | 4.00 | 4.05 | 4.12 | 4.06 ± 0.03 | 0.41 | 0.010 | 0.001 | 0.101 | 0.07 |
| CA-VII | 4.07 | 4.14 | 4.10 | 4.10 ± 0.02 | 0.72 | 0.010 | 0 | 0.065 | 0.08 |
| CA-VIII | 3.47 | 3.80 | 3.63 | 3.63 ± 0.10 | 3.78 | 0.010 | 0.023 | 0.711 | 0.27 |
| CA-IX | 3.88 | 3.96 | 3.79 | 3.87 ± 0.05 | 0.25 | 0.010 | 0.01 | 1.532 | 0.12 |
| CA-X | 3.77 | 3.72 | 3.90 | 3.80 ± 0.05 | 0.85 | 0.010 | 0.005 | 0.001 | 0 |
| CA-XI | 4.13 | 4.19 | 4.24 | 4.19 ± 0.03 | 0.30 | 0 | 0.001 | 0.188 | 0.07 |
| CA-XII | 3.76 | 3.88 | 4.09 | 3.91 ± 0.10 | 3.95 | 0.010 | 0.022 | 0.547 | 0.27 |
| CA-XIII | 4.22 | 4.29 | 4.35 | 4.29 ± 0.03 | 1.63 | 0.010 | 0.001 | 0.079 | 0.13 |
| Mean ±SE | 4.01 ±0.08 | 4.07 ±0.07 | 4.10 ±0.08 | 4.06 ± 0.07 | 1.17 | 0.007 | 0.005 | 0.328 | 0.11 |
| | | | | Fiber (%) | | | | | |
| CA-I | 10.50 | 11.48 | 11.27 | 11.08 ± 0.30 | 5.74 | 0.13 | 0.216 | 0.037 | 0.85 |
| CA-II | 10.68 | 10.51 | 11.73 | 10.97 ± 0.38 | 0.31 | 0.15 | 0.025 | 0.109 | 0.18 |
| CA-III | 10.71 | 10.48 | 11.09 | 10.76 ± 0.18 | 0.73 | 0.01 | 0.106 | 0.633 | 0.48 |
| CA-IV | 11.25 | 10.93 | 11.21 | 11.13 ± 0.10 | 1.08 | 0.13 | 0.059 | 0.220 | 0.21 |
| CA-V | 10.78 | 11.13 | 10.94 | 10.95 ± 0.10 | 1.59 | 0.15 | 0.011 | 0.057 | 0.36 |
| CA-VI | 10.55 | 10.79 | 10.56 | 10.63 ± 0.08 | 0.77 | 0.14 | 0.012 | 0.094 | 0.28 |
| CA-VII | 10.65 | 10.48 | 10.71 | 10.61 ± 0.07 | 0.25 | 0.14 | 0.026 | 0.123 | 0.20 |
| CA-VIII | 12.22 | 12.46 | 12.05 | 12.24 ± 0.12 | 0.05 | 0.09 | 0.052 | 0.328 | 0.32 |
| CA-IX | 10.20 | 10.04 | 10.14 | 10.07 ± 0.04 | 0.50 | 0.17 | 0 | 0.014 | 0.20 |
| CA-X | 11.90 | 12.60 | 12.22 | 12.24 ± 0.20 | 3.23 | 0.09 | 0.09 | 0.105 | 0.60 |
| CA-XI | 11.01 | 10.99 | 11.28 | 11.09 ± 0.09 | 0.94 | 0.13 | 0.019 | 0.129 | 0.32 |
| CA-XII | 12.53 | 12.59 | 12.75 | 12.62 ± 0.06 | 1.03 | 0.16 | 0.002 | 0.033 | 0.28 |
| CA-XIII | 12.01 | 12.21 | 11.86 | 12.03 ± 0.10 | 0.04 | 0.11 | 0.039 | 0.243 | 0.28 |
| Mean ±SE | 11.14 ±0.21 | 11.28 ±0.25 | 11.37 ±0.20 | 11.26 ± 0.21 | 1.25 | 0.12 | 0.050 | 0.163 | 0.35 |

Table 7. Mean values over 3 years for 6 morphological and 3 quality traits in *C. album* lines based on ploidy level.

| Trait/Ploidy level | Diploid lines | Tetraploid lines | Hexaploid lines |
|---|---|---|---|
| Plant height (cm) | 14.24 | 17.83 | 13.78 |
| Branches plant$^{-1}$ | 10.77 | 11.40 | 9.85 |
| Leaves plant$^{-1}$ | 17.14 | 21.41 | 15.41 |
| Leaf size (cm$^2$) | 9.78 | 11.74 | 16.86 |
| Stem diameter (cm) | 0.42 | 0.50 | 0.52 |
| Foliage yield (kg plot$^{-1}$) | 4.52 | 5.15 | 5.35 |
| Carotenoid (mg g$^{-1}$) | 1.13 | 1.00 | 1.25 |
| Protein (g 100g$^{-1}$) | 4.19 | 4.51 | 3.97 |
| Fiber (%) | 11.37 | 10.76 | 11.28 |

## DISCUSSION

This study showed the existence of wide phenotypic variability for foliage yield and its quality components in *C. album* suggesting the potential for selecting the best accessions in terms of their adaptation and foliage quality. Stem diameter was the only morphological trait that was more strongly influenced by environment than by genotype. The G × E component of variation for other morphological traits was significant but negligible compared with the genotypic component. The magnitude of the main effect MS suggests that foliage yield was more strongly influenced by genotype than by year This is supported by the different performance of the lines which produced from 1.32 kg plot$^{-1}$ in CA-XI to 8.37 kg plot$^{-1}$ in CA-II. Earlier, Bhargava et al. (2006c) reported a negative impact of high temperature on foliage yield of *C. album* probably due to destruction of chlorophyll since the temperature gradually increased as the season progressed. This negative impact of high temperature on foliage yield was also observed in this study. Foliage yield was lowest in year 3 (mean 4.28 kg plot$^{-1}$). This year had the highest minimum and maximum temperatures over the three years. Exotic lines fared badly compared to indigenous lines. This may be because outside the Indian sub-continent, *C. album* is rarely used as a vegetable and is regarded as a major weed (Holm et al., 1977). Thus, the exotic lines are probably uncultivated wild types. In India, *C. album* is a weed in both the Himalayan and the North Indian Plains. Locals consume tender leaves and stem, but selection, proper cultivation or plant improvement are not practiced on the Plains. However, in the western Himalayan region, *C. album* is cultivated as a grain and vegetable crop (Partap and Kapoor, 1985; Partap et al., 1998). It is therefore possible that the hill growers have practiced selection for *C. album* improvement in vegetable types. Our results support this as four lines collected from the western-Himalayan region CA-I, CA-II, CA-VI and CA-VII gave high foliage yields in all years. The exotic and indigenous undomesticated lines gave lower yields.

The GEI effects for quality traits were low and smaller than the genetic component. Such low G × E effects for qualitative traits that were less than genotypic and location effects were reported by Lukow and McVetty (1991) and Peterson et al. (1992). In this work quality traits appear to be more strongly influenced by genotype than by environment or by G × E effects. A similar dominant influence of the genotypic component was reported for groat lipid content in oat grain (Doehlert et al., 2001). Our results differ from those of Rharrabti et al. (2003) who reported high environmental influence on the majority of quality parameters in durum wheat. This may be because they conducted multilocational trials under both rain fed and irrigated conditions. This led to a greater environmental effect. In our experiment plants were harvested over a short duration and plants did not reach maturity so no seed was

produced, as a result the influence of the environment may have been reduced. Nevertheless, further work is needs to ascertain the real cause of these low environmental and GEI effects in *C. album*, especially as GEI reports for this species are rare.

Green vegetables have long been recognized as an abundant and cheap source of protein, vitamins and minerals (Aletor et al., 2002; Shukla et al., 2006a). Carotenoids are important, as they are vitamin A precursors and have been shown to function as antioxidants (de Pee and West, 1996; Rock, 1997; Pavia and Russel, 1999). Similarly ascorbic acid is an antioxidant and anticancer agent (Shibata et al., 1992). Our study indicates that *C. album* foliage is high in protein as reported by Prakash et al., (1993) and Bhargava et al. (2006c). The protein content of *C. album* is considerably higher than that reported in foliage of other crops like *Lactuca sativa* (0.7-1.1%) (Watson, 1971) and vegetable amaranth (2.51%) (Shukla et al., 2004, 2006b), but it is lower than in cassava (7.1-8.2%) (Watson, 1971). The carotenoid content of fresh leaves is comparable to other species of *Chenopodium* (Prakash et al. 1993; Bhargava et al. 2007), but is lower than in *Amaranthus* (Shukla et al., 2006b). The quality components are present at each time of cutting making it an important edible crop. Thus, the accessions could be as cheap source of carotenoids and protein.

It has been reported that grain protein content is increased under high temperature and drought conditions probably due to degradation of leaf pigments and the enzyme RuBisCo (Wrigley et al., 1994; Garcia del Moral et al., 1995; Fernandez-Figares et al., 2000). However, an increase in leaf protein content has rarely been reported in vegetable chenopods. In our study, the crop months of year three were warmer than the other two years. It is possible that the high temperatures in 2004-05 led to greater degradation of pigments and RuBisCo, which gave a higher leaf protein content in 2004-05. Degradation of leaf pigments in *C. album*, as temperature increased was reported in Bhargava et al. (2006c).

Leafy vegetables generally have low nutrient concentrations as a result they have to be consumed in large amounts. However, they also tend to have a high fiber content which makes them unsuitable for consumption in large quantities as it lowers digestibility, causes intestinal irritation and decreases nutrient utilization (Johns, 1987). Chenopod leaves contain high quantities of crude fiber at about 3.5%, which is higher than in vegetable amaranth (Shukla et al., 2006b). This could be a reason for the low utilization of chenopods as a vegetable compared to other foliage crops like *Amaranthus*, cassava and lettuce. To popularize chenopods as a vegetable there is a need to select lines with low to medium fiber and high protein content. In this study, all cultivated lines except CA-I were high in protein and carotenoid, and low in fiber. The results show the selection efficiency of the hill farmers of India, as the cultivated lines were high yield for most of the traits. These lines have been selected for use in a breeding program to produce novel plants with high yield and quality.

Lines CA-I, CA-VI and CA-XIII showed stability for foliage yield and were high yielding. This indicates the possibility of simultaneous selection for both high yield and broad adaptation, features considered desirable for conserving germplasm (Kang, 1998). Lines CA-IV, CA-V, CA-VI, CA-X and CA-XI were stable for leaf carotenoids and protein. Thus these lines may be useful in developing nutritionally superior varieties. The high yielding line, CA-XIII, was less stable for quality traits and thus may vary when grown in different environments. However, this qualitatively unstable line may be recommended for specific regions where it can attain high quality trait performance. Some lines were stable for one trait and unstable for another, suggesting that the genetic factors involved in genotype × environment effects differed among traits (Grausgruber et al., 2000; Rharrabti et al., 2003). Most of the qualitatively stable lines had high values for leaf protein and carotenoids suggesting stability is not negatively influenced by high performance, as reported for winter wheat quality (Grausgruber et al., 2000). Although line CA-XI had a high protein and carotenoid content and a low fiber content, that would suit consumer preferences its low foliage yield renders it unsuitable for use as a vegetable on the Indo-Gangetic Plains and other regions with similar agro-climatic conditions. However, this line could be used as a

donor parent for introgression of desirable quality traits into high yielding but qualitatively deficient lines.

Improvement of vegetable chenopods requires an integrated selection program to maximize foliage yield and quality along with trait stability. The absence of commercial varieties of this crop makes further research important to popularize its cultivation and use. . A large proportion of the population in the developing world, especially in poor communities, face protein and vitamin deficiencies due to the high cost of a nutritionally rich diet. Utilization of this crop would assist in mitigating protein and vitamin A deficiency in these people. This study confirms the potential of this crop for sustainable agriculture as no chemical fertilizers, pesticides or fungicides were used to grow the crop. Thus, the crop offers good prospects for diversification of agricultural systems in the Indo-Gangetic Plains and regions with similar agro-climatic conditions and would help combat protein and vitamin A deficiency among poor communities of the region.

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