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Combining ability and heterosis for concentration of mineral elements and protein in common bean (*Phaseolus vulgaris* L.)

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Abstract: Bean is one of the most consumed pulse crops in the world. Hence, the quality of the protein and mineral content is important for producers and consumers. Line × tester methods were used to determine the combining ability and heterosis of protein content and mineral accumulation in common beans that were crosses of PV1, PV2, PV3, PV4, PV5, PV6, Sehirali 90, Akman 98, and Yunus 90. Mean squares of line × tester interactions were significant for all of the investigated traits and indicated the prevalence of nonadditive variance; moreover, the value of the s^2_{gca}/s^2_{sca} ratio for all characters was less than 1 and indicated predominance of nonadditive gene effects. Line × tester analysis revealed significant general combining ability and specific combining ability (SCA) effects for all the traits. Among the parents, PV2 and Yunus 90 were found to have high general combining abilities for protein and minerals. The most promising specific combiners for protein and minerals were from crosses PV1 × Akman 98, PV2 × Akman 98, and PV5 × Yunus 90. The average heterosis for protein was –0.70% in the F_1 generation. The crosses PV1 × Akman 98, PV2 × Akman 98, and PV5 × Yunus 90 for protein content had significant estimates of both SCA effects and heterosis, suggesting the predominance of nonadditive gene action for the trait in these crosses. Additionally, only potassium content showed significant differences among the bean lines, while the testers exhibited nonsignificant differences for all of the investigated features. Analysis of the data indicated that the selection of parents should be based on per-seed content, as well as combining ability and heterosis, in order to improve protein and mineral contents in the common bean.

Key words: Combining ability, common bean (*Phaseolus vulgaris* L.), heterosis, minerals, protein

1. Introduction

Pulses are a valuable source of protein, calcium (Ca), iron (Fe), thiamine, and riboflavin in poorer areas of the world (Norton et al., 1985). For that reason, in many parts of the world and especially in the tropics, consumption of pulses is associated with poverty. In India, however, it is accepted where religion or local customs prevent consumption of meat or dairy products. Pulses, including beans, are important sources of protein in many regions of the world (Ceyhan, 2006). Pulses are also an excellent source of dietary fiber, vitamins, photochemicals (phenolic acid, anthocyanins), and minerals (Akçin, 1988).

The common bean (*Phaseolus vulgaris* L.) constitutes an important part of human nutrition in the world. In recent years, consumption of legumes, and especially dry beans, has increased in the United States and some West European countries. This is due to an increased consciousness of consumers about the nutritional characteristics in foods (Peksen and Artik, 2005).

Common bean is known as a "super food" due to its protein, dietary fiber, and mineral content, and due to it being a daily food for more than 300 million people all over the world (Saleh et al., 2012). Common bean genotypes have a wide range of mineral content, which causes differences in quality. In a previous study that was also conducted in Konya, mineral content in the common bean were determined as 1873.88–2248.34 mg/100 g for potassium (K), 94.60–213.32 mg/100 g for Ca, 663.66–770.50 mg/100 g for phosphorus (P), 172.75–195.42 mg/100 g for magnesium (Mg), 43.15–54.65 mg/100 g for sodium (Na), 6.70–8.85 mg/100 g for Fe, and 1.85–2.25 mg/100 g for zinc (Zn) in dry bean seeds (Ceyhan, 2006). The nutritional value of common bean is highly regarded in vegetarian diets, due to high content of protein, minerals, and vitamins. Furthermore, in developing countries, the common bean is used as a meat substitute for protein. The seeds of the common bean contain high amounts of phaseolin, cholestrine, lecithin, phasine, and dextrin. In

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addition, including dry bean in the human diet increases K, P, Ca, Mg, boron (B), sulfur (S), and Fe (Akçin, 1988).

Former studies showed the following results for mineral contents: 81.71–136.83 ppm for Fe, 0.69–1.26 mg/g for Ca, 2.65–5.77 mg/g for K, 0.43–0.61 mg/g for Mg, and 0.2–0.5 mg/g for P in *Eruca sativa* L. and *Diplotaxis tenuifolia* L. accessions (Bozokalfa et al., 2009); 17–62 ppm for Fe, 12–18 ppm for Zn, 266–944 ppm for Ca, and 787–1.089 ppm for Mg in potato (Brown et al., 2012); 41.5–53.0 ppm for Fe and 7.8–12.9 ppm for manganese (Mn) in potato (Haynes et al., 2012); and 200.0–426.1 mg/100 g and 93.3–315.6 mg/100 g for Mn, 19.3–68.5 mg/100 g and 18.8–56.2 mg/100 g for Ca, and 195.0–323.3 mg/100 g and 181.6–296.1 mg/100 g for K in cabbage parents and hybrids, respectively (Singh et al., 2009). A previous study reported that amounts of K, Mn, and Zn might be increased by selecting convenient genotypes of the *Eruca sativa* L. and *Diplotaxis tenuifolia* L. plants (Bozokalfa et al., 2009). Brown et al. (2012) investigated genetic variation among advanced potato breeding clones for tuber Ca and Mg amounts and the extent of genotype × environment interactions on these characteristics. They planted the potato genotypes in 3 distinct trials at different locations. Results of the study revealed that the genotype × environment interactions were significant in all trials. In a previous report, it was estimated that genetic variation for Cu content was moderately high (Haynes et al., 2012). For plant breeding programs, different genotypes should be used in the trials to investigate specific adaptation abilities (Ceyhan et al., 2012).

The present study is a breeding work to increase the content of protein and minerals in genotypes of the common bean. Recent studies have usually focused on the seed yield, but food quality is an important factor for human health, as well. Therefore, promising genotypes and crosses were evaluated on the basis of general combining ability (GCA) and specific combining ability (SCA) performance and some suggestions were given for better breeding approaches that focus on increasing the concentrations of minerals and protein in dry bean.

2. Materials and methods

2.1. Plant materials

The 6 genotypes (PV1, PV2, PV3, PV4, PV5, and PV6) used as lines (females) were the advanced generations of true breeding lines having high protein and mineral contents reported by Ceyhan et al. (2008b), Ülker and Ceyhan (2008), Harmankaya et al. (2009), and Varankaya and Ceyhan (2012). The 3 testers (males), Sehirali 90, Akman 98, and Yunus 90, are registered by the Agricultural Research Institute of Transition Zone, Turkey. These varieties are produced commercially in many parts of Turkey (Ceyhan, 2004).

2.2. Site and soil

Konya is located at 32°31′N, 37°52′E at an altitude of 1020 m above mean sea level. According to the meteorological data of 2009, the average daytime temperature was 20.9 °C for the 5-month period that coincides with the common bean's growing season. The total precipitation and relative humidity were 77.0 mm and 43.5%, respectively, which were less than the 27-year average (83.8 mm and 46.7%). The soil in this region is mostly clay-loam, with an average level of organic matter of 2.25% at a depth of 0–30 cm and lower percentages at 30–60 cm depth. The available P content ranged from 13.4 kg ha^{-1} to 17.9 kg ha^{-1} and Zn varied from 0.32 ppm to 0.34 ppm, which is considerably low for common bean cultivation. Low presence of these elements in the soil was largely due to the high rate of lime, which was 34.4%–37.6%, with pH 8.00–8.05. According to the soil analysis, the levels of Fe (8.74–14.74 ppm), Cu (1.70–1.74 ppm), and Mn (7.50–5.76 ppm) were sufficient.

2.3. Field experiment

The trial was conducted in the year 2008 with the first sowing on 20 April. Sowing was continued every other 10 days for 4 different sowing dates. Staggered planting was done to facilitate hybridization program. The sowings were made with rows of 2 m in length, 1 m of interrow distance, and 20 cm of distance above rows for easier hybridization (Ceyhan and Kahraman, 2013). The hybridization process was performed according to Eser (1974), Ceyhan (2003), and Ceyhan and Kahraman (2013), as explained below. The 9 genotypes were subjected to hybridization in 2008 with line × tester methods (Singh and Chaudhary, 1979; Ceyhan, 2003; Ceyhan et al., 2008b).

The experiment was set up according to the randomized complete block design with 3 replications at the trial site of Selçuk University, Konya, Turkey. The parents and crosses were sown on 15 May 2009 in a single row that was 2 m long by 50 cm wide, with 20 cm between plots. Ten seeds per plot were sown at a depth of 5 cm. Diammonium phosphate (18N-46P) fertilizer was applied at a rate of 150 kg ha^{-1} during sowing. Sprinkler irrigation was provided to the plots for germination and stem elongation. Later, drip irrigation was provided up to 5 times, depending on soil moisture level. Hand weeding was done to keep the experimental field weed-free. Plots were harvested manually, from 28 August to 8 September 2009, depending on the maturity of the genotypes.

2.4. Protein content

After the harvest, samples of parents and F_1 hybrids were prepared separately from each plot. The seeds were thrashed manually to remove all useless matter such as dust and stones. A total of 30 g of sample was taken from each plot. The samples were ground and dried at 50 °C for 48 h. N content in the ground samples was determined by using a Kjeldahl device (AACC, 1990). The nitrogen values were multiplied by using 6.25 coefficients to calculate crude protein ratio.

2.5. Mineral analysis

The samples were dried in a drying cabin at 65 °C until dry weight was achieved. A total of 0.3 g was weighed from the samples and added to 5 mL of concentrated HNO_3 and 2 mL of H_2O_2 (30% w/v). This solution was dissolved in a microwave (Cem-MARSx press) under high temperature (210 °C) and pressure (200 psi). The dissolved samples were added to deionized water to reach a final volume of 20 mL. Concentration of the minerals in the samples were determined by ICP-AES (Varian Vista). Each step of the procedure was strictly followed to standard reference (Burt, 2004) materials of US National Institute of Standards and Technology.

2.6. Statistical analysis

F_1 breeding values of the plant material were calculated and evaluated by analyzing the data on heterosis and combining ability for protein and mineral contents. Variance analysis was done by using the means of investigated quality traits. The line × tester method (Kempthorne, 1957; Singh and Chaudhary, 1979) was followed to analyze genetic components of each characteristic. Midparent heterosis (MPH) was calculated by using the formula of Sarawat et al. (1994):

MPH = [(value of F_1 – mean of parents) × 100] / mean of parents.

3. Results

Line × tester analysis was applied to all measured protein and mineral contents of the genotypes, which showed significant differences in terms of statistical analysis (Table 1). Variance components of the minerals (Table 1) showed higher s^2_{sca} values than s^2_{gca} values for all of the features. Nine parents (6 lines and 3 testers), along with 18 F_1 hybrids, showed a wide range of variability for protein and mineral content (Table 2). In general, hybrid protein content was the same as in the parental lines except for PV2, Akman 98, and Yunus 90. Most of the F_1 hybrids were also rich in Fe, Zn, Mg, and S content compared to parents. Protein, B, Mn, and Ca contents were estimated to be lower in F_1 hybrids than in high parents (Table 2). GCA estimates of the 9 genotypes for 10 characters showed that PV2, PV4, PV5, Sehirali 90, and Yunus 90 were the best combiners for protein content (Table 3). The PV3 line was a poor general combiner when mineral content was considered, except for Zn, Ca, and P, while line PV4 was a poor general combiner for many of the analyzed minerals, except B, Zn, and K, in addition to having low protein content. Tester Akman 98 was a poor general combiner for all minerals studied. Yunus 90 only showed poor general combining for K. PV1, PV6, and Yunus 90 was a good general combiner for B; PV1, PV2, PV5, and Yunus 90 for Fe and Mn; PV1, PV3, PV4, PV5, and Sehirali 90 for Zn; PV3, PV6, and Yunus 90 for Ca; PV1 and PV4 for K; PV5 and PV6 for Mg; PV2 and PV6 for P; PV1, PV2, and Yunus 90 for S content (Table 3).

The estimates of SCA for the 10 characters in 18 crosses resulted in 6 crosses. PV1 × Akman 98, PV2 × Akman 98, PV3 × Sehirali 90, PV4 × Yunus 90, PV5 × Yunus 90, and PV6 × Sehirali 90 demonstrated highly significant SCA effects for protein content (Table 4). Good specific combiners for B were PV1 × Sehirali, 90 PV2 × Akman 98, PV4 × Sehirali 90, PV5 × Yunus 90, and PV6 × Yunus 90. Crosses PV1 × Akman 98, PV2 × Yunus 90, PV3 × Sehirali 90, PV4 × Sehirali 90, and PV6 × Akman 98 were good combiners for Fe content. The best specific combiners for Mn were PV1 × Yunus 90, PV3 × Sehirali 90, PV5 × Akman 98, and PV6 × Sehirali 90. The crosses PV1 × Akman 98, PV2 × Akman 98, PV3 × Yunus 90, PV4 × Yunus 90, PV5 × Yunus 90, and PV6 × Sehirali 90 showed highly significant positive SCA effects for Zn content. The crosses PV1 × Akman 98, PV2 × Sehirali 90, PV3 × Akman 98, PV3 × Yunus 90, PV4 × Yunus 90, PV6 × Sehirali 90, and PV6 × Yunus 90 produced highly significant positive SCA effects for Mg content. For Ca, highly significant positive SCA effects were exhibited by crosses PV1 × Akman 98, PV1 × Yunus 90, PV2 × Sehirali 90, PV3 × Akman 98, PV3 × Yunus 90, PV4 × Yunus 90, PV5 × Sehirali 90, PV5 × Akman 98, and PV6 × Yunus 90. Significant positive SCA effects for K and P content were observed in 2 cross combinations: PV4 × Sehirali 90 and PV6 × Yunus 90. For S content, high positive SCA effects were displayed by crosses PV1 × Akman 98, PV2 × Yunus 90, PV3 × Sehirali 90, PV4 × Akman 98, PV5 × Yunus 90, and PV6 × Yunus 90 (Table 4).

Genotypic effects in the investigated traits and heterosis were observed in F_1, particularly for protein and certain mineral content (Table 5). Heterosis values for Zn and Mg content were significantly positive in all of the F_1 hybrids except for PV3 × Sehirali 90, implying the presence of additive gene action involving the traits (Ceyhan and Avci, 2005; Avci and Ceyhan, 2006). Heterosis values for protein content ranged from –18.18% (PV3 × Akman 98) to 27.17% (PV5 × Yunus 90) in the F_1 generation. The range for heterosis of mineral content was –21.38% (PV3 × Akman 98) to 21.32% (PV6 × Yunus 90) for B, –23.15% (PV6 × Sehirali 90) to 39.89% (PV5 × Yunus 90) for Fe, –53.87% (PV6 × Akman 98) to 31.58% (PV1 × Yunus 90) for Mn, 4.99% (PV6 × Yunus 90) to 58.56% (PV5 × Yunus 90) for Zn, –55.34% (PV1 × Sehirali 90) to 49.78% (PV6 × Yunus 90) for Ca, –6.33% (PV3 × Yunus 90) to 8.60% (PV4 × Sehirali 90) for K, –2.97% (PV3 × Sehirali 90) to 20.33% (PV5 × Yunus 90) for Mg, –13.87% (PV3 × Yunus 90) to 20.24% (PV6 × Yunus 90) for P, and –4.03% (PV3 × Sehirali 90) to 37.83% (PV2 × Yunus 90) for S (Table

Table 1. Analysis of variance (ANOVA) for protein content and various mineral elements in beans.

Source of variation	df	Protein	B	Fe	Mn	Zn
Replication	2	0.326	0.241	0.676	2.168	0.023
Treatments	26	18.263**	7.799**	149.895**	103.384**	183.786**
Parents	8	33.670**	6.159**	65.951**	47.233**	61.837**
Par vs. hyb	1	11.690**	8.819**	182.970**	56.666**	100.782**
Hybrids	17	6.763**	3.585**	259.161**	1346.805**	2570.445**
Line	5	15.388	14.294	255.126	65.109	155.786
Tester	2	10.016	8.912	54.307	81.792	88.522
Line vs. tester	10	10.176**	6.062**	172.625**	47.419**	75.732**
Error	52	0.093	0.145	7.301	2.425	2.224
s^2_{gca}		0.045	0.001	0.003	0.003	0.008
s^2_{sca}		3.877	0.031	0.508	0.205	0.342
s^2_{gca}/s^2_{sca}		0.012	0.026	0.006	0.014	0.022
s^2_D		0.091	0.002	0.006	0.006	0.015
s^2_H		3.361	0.020	0.551	0.250	0.245
Source of variation	df	Ca	K	Mg	P	S
Replication	2	3553.839	32,335.675	431.849	92,240.074	11,023.294
Treatments	26	1,928,311.073**	767,581.455**	53,729.765**	419,072.012**	98,161.379**
Parents	8	585,985.611**	1,407,505.506**	21,498.603**	447,893.803**	61,692.433**
Par vs. hyb	1	2,628,667.409**	509,390.185**	30,926.654**	415,794.976**	68,876.063**
Hybrids	17	760,857.067**	37,440.641	699,231.961**	244,207.309	887,763.320**
Line	5	2,991,195.618	1,383,122.951**	43,715.986	700,920.139	67,697.047
Tester	2	2,800,204.869	90,539.548	1360.019	21,849.430	112,696.229
Line vs. tester	10	2,413,095.812**	156,293.929**	30,445.314**	352,021.503**	60,701.538**
Error	52	8450.083	39,366.770	885.511	66,490.052	3635.197
s^2_{gca}		64.633	105.867	0.144	19.121	2.451
s^2_{sca}		9023.31	1573.974	80.817	953.458	253.315
s^2_{gca}/s^2_{sca}		0.007	0.067	0.002	0.020	0.010
s^2_D		129.267	211.733	0.289	38.242	4.902
s^2_H		8015.486	389.757	98.533	951.772	190.221

*: P < 0.05; **: P < 0.01.

Table 2. Means of the investigated characteristics in the parent and F_1 hybrids of beans.

Genotypes / F1 hybrids	Protein (%)	B (mg/100 g)	Fe (mg/100 g)	Mn (mg/100 g)	Zn (mg/100 g)
PV1	21.63 hi	16.80 cd	48.60 h–k	24.57 de	34.67 lm
PV2	18.83 mno	15.57 ef	45.93 jkl	28.77 bc	30.93 no
PV3	26.57 b	18.67 b	60.60 cd	26.67 cd	42.63 hi
PV4	22.83 ef	14.70 g–j	54.00 e–i	25.77 cd	36.03 klm
PV5	21.87 gh	14.50 ijk	46.03 jkl	32.67 a	29.40 o
PV6	19.10 mno	16.57 cd	50.23 g–k	34.87 a	30.47 no
Sehirali 90	27.33 a	15.50 efg	54.90 d–g	23.73 def	39.40 ij
Akman 98	18.90 mno	18.13 b	51.33 f–j	26.70 cd	31.17 no
Yunus 90	18.50 o	16.73 cd	53.67 e–i	23.47 def	37.03 jkl
PV1 × Sehirali 90	20.50 j	17.13 c	53.40 e–i	14.47 kl	47.80 d–g
PV1 × Akman 98	21.03 ij	15.50 efg	66.63 ab	16.60 jkl	49.63 b–e
PV1 × Yunus 90	18.93 mno	17.20 c	60.40 cd	31.60 ab	47.60 d–g
PV2 × Sehirali 90	20.40 jk	14.33 jk	56.33 def	18.03 g–j	45.37 gh
PV2 × Akman 98	22.40 fg	18.40 b	54.87 d–g	21.10 fgh	45.87 fgh
PV2 × Yunus 90	21.77 gh	14.60 h–k	67.93 ab	20.37 f–i	38.33 jk
PV3 × Sehirali 90	22.77 ef	14.73 g–j	62.67 bc	16.10 jkl	49.67 b–e
PV3 × Akman 98	18.60 no	14.47 ijk	51.40 f–j	15.77 jkl	45.03 gh
PV3 × Yunus 90	18.47 o	16.20 de	45.23 kl	17.70 ijk	51.30 bc
PV4 × Sehirali 90	22.33 fg	16.00 def	58.20 cde	15.37 jkl	48.77 c–f
PV4 × Akman 98	19.77 kl	15.40 e–h	54.43 e–h	17.73 h–k	44.87 gh
PV4 × Yunus 90	23.80 d	16.80 cd	51.40 f–j	17.47 i–l	55.33 a
PV5 × Sehirali 90	23.20 de	13.80 kl	51.07 f–k	20.37 f–i	49.97 b–e
PV5 × Akman 98	20.53 j	13.17 l	56.17 def	26.33 cd	47.13 efg
PV5 × Yunus 90	25.67 c	15.27 f–i	69.73 a	21.23 efg	52.70 ab
PV6 × Sehirali 90	21.30 hi	16.47 cd	40.40 l	16.40 jkl	50.63 bcd
PV6 × Akman 98	19.43 lm	16.63 cd	50.50 f–k	14.20 l	33.13 mn
PV6 × Yunus 90	19.20 lmn	20.20 a	48.13 ijk	17.87 g–j	35.43 klm
Genotypes / F1 hybrids	Ca (mg/100 g)	K (mg/100 g)	Mg (mg/100 g)	P (mg/100 g)	S (mg/100 g)
PV1	2773.70 k	14,437.43 il	1549.13 ij	4472.50 di	1611.30 h–k
PV2	3303.33 ef	14,809.17 di	1559.30 ij	4370.47 ei	1565.47 ijk
PV3	3147.60 fgh	16,358.00 a	1751.00 ef	5405.70 a	1901.93 b
PV4	2904.00 ijk	14,250.73 kl	1614.07 hi	4479.07 di	1711.07 fgh
PV5	3066.03 gj	15,534.37 b	1543.33 j	4158.97 hi	1578.03 ijk
PV6	3959.23 c	14,530.73 gk	1630.73 gh	4141.80 i	1549.70 jk
Sehirali 90	3089.63 ghi	14,354.17 jkl	1740.87 ef	4297.07 ghi	1850.77 b–e
Akman 98	3567.37 d	14,558.40 gk	1637.53 gh	4714.20 ch	1505.53 k
Yunus 90	2444.13 l	14,623.57 fk	1739.80 ef	4671.47 ci	1538.60 k
PV1 × Sehirali 90	1309.30 p	15,240.17 bcd	1736.60 ef	4581.43 ci	1926.27 b
PV1 × Akman 98	2063.27 no	15,384.70 bc	1882.10 c	4529.93 di	2126.47 a
PV1 × Yunus 90	2773.20 k	15,148.70 be	1733.17 ef	4757.30 bg	1874.53 bc
PV2 × Sehirali 90	4492.33 b	14,732.33 ej	1981.30 a	4868.80 af	1851.03 be
PV2 × Akman 98	1891.47 o	14,824.77 di	1846.90 cd	5004.17 ad	1870.37 bcd
PV2 × Yunus 90	2203.57 mn	14,963.40 cg	1730.90 ef	5282.53 ab	2139.20 a
PV3 × Sehirali 90	1984.20 o	15,106.03 be	1694.13 fg	4499.20 di	1800.73 bg
PV3 × Akman 98	3555.13 d	15,067.63 cde	1881.47 c	4608.03 ci	1684.93 ghi
PV3 × Yunus 90	4121.20 c	14,509.57 hk	1870.87 c	4339.93 fi	1723.10 eh
PV4 × Sehirali 90	2284.23 lm	15,531.77 b	1747.63 ef	5123.13 abc	1802.37 bg
PV4 × Akman 98	2459.87 l	15,176.80 bcd	1714.03 f	4465.37 di	1906.20 b
PV4 × Yunus 90	3478.20 de	14,903.03 dh	1794.13 de	4220.20 ghi	1840.37 bf
PV5 × Sehirali 90	2946.03 ijk	14,996.37 cf	1956.43 ab	4478.97 di	1744.50 cg
PV5 × Akman 98	2877.87 jk	14,724.53 ej	1908.77 bc	4109.40 i	1740.93 dh
PV5 × Yunus 90	2963.43 hk	14,945.67 dg	1975.30 a	4148.27 i	2064.73 a
PV6 × Sehirali 90	3167.57 fg	14,076.17 l	1908.03 bc	4291.97 ghi	1743.97 cg
PV6 × Akman 98	3443.03 de	14,039.80 l	1742.17 ef	4911.87 ae	1674.40 gj
PV6 × Yunus 90	4795.43 a	14,362.63 jkl	1975.30 a	5298.57 ab	2108.17 a

Values in the same column with the same letter are not significantly different.

Table 3. Estimates of general combining ability (GCA) effects on protein content and various mineral elements in beans.

Genotypes	Protein	B	Fe	Mn	Zn
PV1	–0.961**	0.071**	0.465**	0.207**	0.176**
PV2	0.406**	–0.013	0.422**	0.102**	–0.340**
PV3	–1.172**	–0.077**	–0.239**	–0.229**	0.208**
PV4	0.850**	0.016	–0.082	–0.196**	0.307**
PV5	2.017**	–0.183**	0.349**	0.383**	0.335**
PV6	–1.139**	0.186**	–0.915**	–0.266**	–0.685**
SE	0.101	0.013	0.090	0.052	0.050
Sehirali 90	0.633**	–0.049**	–0.182**	–0.203**	0.211**
Akman 98	–0.822**	–0.031**	0.017	–0.019	–0.231**
Yunus 90	0.189**	0.081**	0.164**	0.222**	0.020
SE	0.072	0.009	0.064	0.037	0.035
Genotypes	Ca	K	Mg	P	S
PV1	–88.526**	38.374**	–5.378**	–1.706	10.785**
PV2	–7.140**	–3.395	1.530	41.189**	8.563**
PV3	28.633**	2.030	–2.225**	–15.756**	–13.165**
PV4	–19.309**	32.975**	–8.580**	–3.705	–1.826
PV5	–0.474	1.474	10.910**	–39.440**	–1.785
PV6	86.816**	–71.458**	3.743**	19.419**	–2.573
SE	3.064	6.614	0.992	8.595	2.010
Sehirali 90	–23.657**	7.302	–0.038	0.064	–5.643**
Akman 98	–21.875**	–0.441	–0.850	–3.515	–3.402**
Yunus 90	45.532**	–6.862	0.888	3.452	9.045**
SE	2.167	4.677	0.701	6.078	1.421

*: $P < 0.05$; ** : $P < 0.01$.

5). Means of heterosis in F_1 hybrids were positive for Zn (32.02%), Mg (10.69%), Fe (6.84%), S (13.74%), P (2.42%), and K (0.59%), while they were negative for protein (–0.70%), B (–3.52%), Mn (–27.04%), and Ca (–2.00%) in the dry bean genotypes (Table 5).

4. Discussion

Only K content demonstrated significant differences among the bean lines. Testers exhibited nonsignificant differences for all traits investigated. However, the interaction of line × tester showed significant differences for all traits. That may be due to nonadditive effects, such as supplemental epistasis effects in the bean. A similar study on the ridge gourd (*Luffa acutangula* Roxb.) showed that the content of P, K, Ca, S, Fe, Zn, and Mn exhibited higher values of dominance variance than additive genetic variance, greater-than-unity values of average degrees of dominance, and low narrow-sense heritability (less than 50%). Mineral content of the fresh fruits were predominantly ascribed to the nonadditive genetic component.

The value of the s^2_{gca}/s^2_{sca} ratio was less than 1 for the accumulation of mineral elements, indicating that nonadditive gene effects such as dominance and epistasis were both or individually involved in expression of the traits. Content of mineral elements in the bean showed lower s^2_D than s^2_H, indicating significant nonadditive gene action for the trait. Hence, these economic traits are under the control of nonadditive gene effects, and one can utilize direct selection to develop bean varieties with improved mineral and protein content (Ceyhan et al., 2008a; Singh et al., 2012). In addition, the identification of parents by their high mean and positively significant GCA effects for these traits is important for improvement of the cultivated genotypes. A previous study reported the importance of additive gene effects over nonadditive gene effects for Fe and Zn in the common bean (Guzman-Maldonado et al., 2003; Singh et al., 2012). Similarly, Blair et al. (2009) revealed that, in the common bean, the inheritance of accumulation of both Fe and Zn was predominantly quantitative in a recombinant inbred line population

Table 4. Estimates of special combining ability (SCA) effects on protein content and various mineral elements in beans.

F_1 hybrids	Protein	B	Fe	Mn	Zn
PV1 × Sehirali 90	−0.289	0.102**	−0.493**	−0.439**	−0.266**
PV1 × Akman 98	1.700**	−0.080**	0.632**	−0.409**	0.360**
PV1 × Yunus 90	−1.411**	−0.022	−0.139	0.849**	−0.094
PV2 × Sehirali 90	−1.756**	−0.095**	−0.156	0.023	0.006
PV2 × Akman 98	1.700**	0.293**	−0.502**	0.146	0.499**
PV2 × Yunus 90	0.056	−0.198**	0.658**	−0.169**	−0.505**
PV3 × Sehirali 90	2.189**	0.009	1.138**	0.161**	−0.111
PV3 × Akman 98	−0.522**	−0.036	−0.187	−0.056	−0.132
PV3× Yunus 90	−1.667**	0.026	−0.951**	−0.104	0.244**
PV4 × Sehirali 90	−0.267	0.043**	0.534**	0.054	−0.300**
PV4 × Akman 98	−1.378**	−0.036	−0.042	0.107	−0.248**
PV4 × Yunus 90	1.644**	−0.007	−0.492**	−0.161**	0.548**
PV5 × Sehirali 90	−0.567**	0.022	−0.611**	−0.025	−0.208**
PV5 × Akman 98	−1.778**	−0.060**	−0.299**	0.388**	−0.049
PV5 × Yunus 90	2.344**	0.038**	0.910**	−0.363**	0.257**
PV6 × Sehirali 90	0.689**	−0.081**	−0.413**	0.227**	0.879**
PV6 × Akman 98	0.278	−0.082**	0.398**	−0.176**	−0.429**
PV6 × Yunus 90	−0.967**	0.163**	0.014	−0.051	−0.450**
SE	0.176	0.022	0.156	0.090	0.086
F_1 hybrids	Ca	K	Mg	P	S
PV1 × Sehirali 90	−50.272**	−9.071	−4.698**	−4.209	0.694
PV1 × Akman 98	23.342**	13.125	10.664**	−5.780	18.473**
PV1 × Yunus 90	26.929**	−4.054	−5.966**	9.989	−19.167**
PV2 × Sehirali 90	186.645**	−18.086	12.865**	−18.367	−4.607
PV2 × Akman 98	−75.224**	−1.099	0.236	−1.251	−4.915
PV2 × Yunus 90	−111.421**	19.185	−13.101**	19.618	9.522**
PV3 × Sehirali 90	−99.940**	13.860	−12.098**	1.618	12.090**
PV3 × Akman 98	55.370**	17.763	7.447**	16.080	−1.730
PV3 × Yunus 90	44.570**	−31.623**	4.650**	−17.697	−10.360**
PV4 × Sehirali 90	−21.996**	25.488**	−0.392	51.960**	0.915
PV4 × Akman 98	−6.215	−2.266	−2.940**	−10.238	9.058**
PV4 × Yunus 90	28.211**	−23.222**	3.332**	−41.722**	−9.972**
PV5 × Sehirali 90	25.350**	3.449	0.998	23.279	−4.913
PV5 × Akman 98	16.750**	−15.991	−2.957**	−10.099	−7.510**
PV5 × Yunus 90	−42.100**	12.543	1.959	−13.180	12.423**
PV6 × Sehirali 90	−39.787**	−15.639	3.325**	−54.280**	−4.179
PV6 × Akman 98	−14.023**	−11.532	−12.450**	11.289	−13.376**
PV6 × Yunus 90	53.810**	27.172**	9.126**	42.992**	17.554**
SE	5.307	11.455	1.718	14.887	3.481

* : P < 0.05; ** : P < 0.01.

Table 5. Estimates of heterosis for protein content and various mineral elements in beans.

F_1 hybrids	Protein	B	Fe	Mn	Zn
PV1 × Sehirali 90	−16.27**	6.09**	3.19**	−40.10**	29.07**
PV1 × Akman 98	3.78**	−11.26**	33.36**	−35.24**	50.78**
PV1 × Yunus 90	−5.65**	2.58**	18.12**	31.58**	32.78**
PV2 × Sehirali 90	−11.62**	−7.73**	11.74**	−31.30**	29.00**
PV2 × Akman 98	18.73**	9.20**	12.82**	−23.92**	47.72**
PV2 × Yunus 90	16.61**	−9.60**	36.41**	−22.02**	12.80**
PV3 × Sehirali 90	−15.52**	−13.76**	8.51**	−36.11**	21.09**
PV3 × Akman 98	−18.18**	−21.38**	−8.16**	−40.91**	22.04**
PV3 × Yunus 90	−18.05**	−8.47**	−20.83**	−29.39**	28.79**
PV4 × Sehirali 90	−10.96**	5.96**	6.89**	−37.91**	29.30**
PV4 × Akman 98	−5.27**	−6.19**	3.35**	−32.40**	33.53**
PV4 × Yunus 90	15.16**	6.89**	−4.52**	−29.05**	51.46**
PV5 × Sehirali 90	−5.69**	−8.00**	1.19**	−27.78**	45.25**
PV5 × Akman 98	0.74**	−19.31**	15.37**	−11.29**	55.64**
PV5 × Yunus 90	27.17**	−2.24**	39.89**	−24.35**	58.66**
PV6 × Sehirali 90	−8.26**	2.70**	−23.15**	−44.03**	44.94**
PV6 × Akman 98	2.28**	−4.13**	−0.56	−53.87**	7.52**
PV6 × Yunus 90	2.13**	21.32**	−7.35**	−38.74**	4.99*
Mean	−0.70	−3.52	6.84	−27.04	32.02
$LSD_{5\%}$	0.597	0.075	0.530	0.306	0.293
$LSD_{1\%}$	0.416	0.052	0.370	0.213	0.204
F_1 hybrids	Ca	K	Mg	P	S
PV1 × Sehirali 90	−55.34**	5.87	5.57**	4.48	11.28
PV1 × Akman 98	−34.92**	6.12	18.12**	−1.38	36.45
PV1 × Yunus 90	6.30	4.25	5.39**	4.05	19.02
PV2 × Sehirali 90	40.54**	1.03	20.07**	12.35	8.37
PV2 × Akman 98	−44.94**	0.96	15.55**	10.17	21.81
PV2 × Yunus 90	−23.32**	1.68	4.93**	16.85	37.83
PV3 × Sehirali 90	−36.38**	−1.63	−2.97**	−7.26	−4.03
PV3 × Akman 98	5.89	−2.53	11.05**	−8.93	−1.10
PV3 × Yunus 90	47.40**	−6.33	7.19**	−13.87	0.16
PV4 × Sehirali 90	−23.78**	8.60	4.18**	16.75	1.20
PV4 × Akman 98	−23.98**	5.36	5.43**	−2.86	18.52
PV4 × Yunus 90	30.07**	3.23	6.99**	−7.76	13.26
PV5 × Sehirali 90	−4.28	0.35	19.14**	5.94	1.76
PV5 × Akman 98	−13.23**	−2.14	20.02**	−7.37	12.92
PV5 × Yunus 90	7.56	−0.88	20.33**	−6.05	32.50
PV6 × Sehirali 90	−10.13	−2.54	13.18**	1.72	2.57
PV6 × Akman 98	−8.51	−3.47	6.61**	10.93	9.61
PV6 × Yunus 90	49.78**	−1.47	17.21**	20.24	36.53
Mean	−2.00	0.59	10.69	2.42	13.74
$LSD_{5\%}$	18.036		5.839		
$LSD_{1\%}$	12.579		4.072		

derived from a cross of low × high mineral genotypes. In other studies, however, monogenic inheritance for seed Zn accumulation was reported (Forster et al., 2002; Cichy et al., 2005). Another study investigated inheritance and correlation for mineral concentrations such as Fe, Zn, Cu, Mn, K, and Ca in cabbage (*Brassica oleracea* var. *capitata* L.). For the field trials, a total of 71 cabbage genotypes were used as material, which included cultivars, germplasms, and F_1 hybrids. The investigated minerals differed very significantly and suggested the presence of an adequate value of variability. A high rate for heritability (more than 80%) in high genetic advances and the rate (more than 40%) of uptake and accumulation of Fe, Zn, Cu, Mn, and Ca indicated the predominance of additive genes that could be improved by hybridization according to the selection breeding method. As a result, it was revealed that the inheritance and correlation for mineral concentrations would be useful for developing mineral-rich and productive genotypes (Singh et al., 2013).

In this study, only PV3 was found to be a good general combiner for protein and minerals. The effect of GCA was high, owing to the effects of additive and additive × additive genes (Guzman-Maldonado et al., 2003; Ceyhan and Avci, 2005; Avci and Ceyhan, 2006; Ceyhan et al., 2008a; Blair et al., 2009; Singh et al., 2012; Ceyhan and Kahraman, 2013). These genes are favorable to breeding works. The GCA value of the used genotypes showed that none of the parents were remarkable in a positive direction when considering the investigated mineral contents. This situation could be explained by the amount of and demand for multiple crossings between optimum couples to develop mineral-enriched genotypes (Singh et al., 2012).

The most promising specific combiners for protein and minerals were PV1 × Yunus 90 and PV6 × Sehirali 90. That could be due to the presence of high magnitudes of nonadditive complementary epistatic effects (Guzman-Maldonado et al., 2003; Ceyhan et al., 2008a; Blair et al., 2009; Singh et al., 2012). This finding is in line with the results of Ceyhan (2003) for protein content in pea.

The crosses PV1 × Akman 98, PV2 × Akman 98, and PV5 × Yunus 90 for protein; PV4 × Sehirali 90 and PV6 × Yunus 90 for B; PV1 × Akman 98, PV2 × Yunus 90, PV4 × Sehirali 90, and PV6 × Akman 98 for Fe; PV1 × Yunus 90 for Mn; PV1 × Akman 98, PV2 × Akman 98, PV3 × Yunus 90, PV5 × Yunus 90, and PV6 × Sehirali 90 for Zn; PV2 × Sehirali 90, PV3 × Yunus 90, PV4 × Yunus 90, and PV6 × Yunus 90 for Ca; and PV1 × Akman 98, PV2 × Sehirali 90, PV3 × Yunus 90, PV4 × Yunus 90, PV6 × Sehirali 90, and PV6 × Yunus 90 for Mg had significant estimates of both SCA effects and heterosis, suggesting the prevalence of nonadditive gene action for these traits in the crosses (Guzman-Maldonado et al., 2003; Ceyhan and Avci, 2005; Avci and Ceyhan, 2006; Ceyhan et al., 2008a; Blair et al., 2009; Singh et al., 2012). Therefore, selection of these traits in conventional breeding methods would not be effective in such crosses (Ceyhan and Avci, 2005; Ceyhan et al., 2008a; Singh et al., 2012). A similar result was also reported by Ceyhan (2003) for protein content in pea.

This study revealed the importance of nonadditive gene effects in protein and minerals in bean. Among the parental lines, PV2 and Yunus 90 were the best general combiners for protein content, along with other traits, and thus could be used in bean improvement programs. The most promising specific combiners for protein content and other traits were PV1 × Akman 98, PV2 × Akman 98, and PV5 × Yunus 90, which could be utilized in hybrid bean development. Mineral content was identified as the best selection criterion in bean breeding.

Singh et al. (2009) studied cabbage (*Brassica oleracea* var. *capitata* L.) to determine the heterosis for mineral elements (Fe, Zn, Cu, Mn, K, and Ca). They found significant mean squares in parents and hybrids for all minerals, which indicated the prevalence of sufficient variation. Results of that study showed that none of the hybrids had potential for all the minerals, suggesting the need for multiple-crossing breeding works such as 3-way cross-hybrid, double cross-hybrid, population improvement, synthetics, or composites to increase the mineral content in cabbage head without decreasing its vigor advantage for yield and other economic characteristics. Mineral composition is an important characteristic for the human diet, besides being an important factor for harvesting, processing, transportation, classifying, packaging, and other features (Akçin, 1988).

Consequently, the results of the present study revealed that, for the purpose of increasing protein and mineral content in the common bean, selection of parents should be based on per-seed content in addition to combining ability and heterosis.

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