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Combining ability analysis for grain yield and its contributing traits in Chickpea (*Cicer arietinum* L.) under variable environmental conditions

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ABSTRACT

Combining ability of eight chickpea genotypes (GNG-1958, GNG-1581, CSG-8962, KWR-108, GNG-1488, H-82-2, Pant G-186 and DCP-92-3) was assessed in an 8×8 half diallel without reciprocals. The 36 genotypes (8 parents and 28 F₁ crosses) were grown in a Randomized Block Design with three replications in three environments during rabi 2025–26: timely sown irrigated (E₁, 1 November), late sown irrigated (E₂, 25 November) and timely sown under conserved moisture (E₃, 1 November). Eleven traits were analysed following Griffing's Model I, Method 2. GCA and SCA effects were significant for nearly all traits, indicating both additive and non-additive gene action, with their relative importance varying among traits and environments. GCA $\times$ environment and SCA $\times$ environment interactions were significant for selected traits. GNG-1958 was the best general combiner for grain yield per plant, pods per plant, secondary branches, 100-seed weight and harvest index, while KWR-108 was best for earliness, short stature and protein content. GNG-1958 $\times$ GNG-1581 and Pant G-186 $\times$ GNG-1488 showed significant positive SCA effects for grain yield per plant in all three environments. These parents and crosses can be used to develop high-yielding, early-maturing and well-adapted chickpea genotypes.

Keywords: Chickpea, Combining ability, General combining ability, Specific combining ability, Gene action

Introduction

Chickpea (*Cicer arietinum* L.) is one of the oldest domesticated pulse crops, an annual diploid legume ($2n = 2x = 16$) of the family Fabaceae that originated in the Fertile Crescent of the Near East (Gowda *et al.*, 2015) [1]. It has two major groups: desi (*Microsperma*) with small, angular, dark seeds and pigmented plants, and kabuli (*Macrosperma*) with large, cream-coloured seeds and unpigmented plants (Admas *et al.*, 2021) [2]. Chickpea contains about 22% protein along with minerals, vitamins and dietary fibre, and its regular consumption is associated with benefits against cardiovascular diseases, gastrointestinal disorders, type 2 diabetes and certain cancers (Zhang *et al.*, 2024) [3]. Chickpea contributes about 50% of India's total pulse production. The leading producing states are Maharashtra (25.97%), Rajasthan (20.65%), Madhya Pradesh (18.59%) and Gujarat (10.10%) (Praween *et al.*, 2024) [4]. Combining ability analysis helps identify promising parents and desirable cross combinations for developing improved varieties (Sindhu *et al.*, 2000; Patil *et al.*, 2004) [6, 5], and also reveals the nature of gene action. The present study was therefore undertaken to identify superior parents and cross combinations and to understand the gene action governing grain yield and its contributing traits under different environments.

Materials and methods

The experiment was conducted at the Agricultural Research Station, Sriganganagar, Rajasthan. Eight chickpea genotypes (GNG-1958, GNG-1581, CSG-8962, KWR-108, GNG-1488, H-82-2, Pant G-186 and DCP-92-3) were crossed in an 8×8 half diallel without reciprocals. The 36 genotypes (8 parents and 28 F₁ crosses) were evaluated in a randomized block design with three replications during rabi 2025–26 in three environments: timely sown irrigated (E₁, 1 November), late sown irrigated (E₂, 25 November) and timely sown under conserved moisture (E₃, 1 November). Each plot was a single row of 2 m length with 30 cm $\times$ 10 cm spacing, and all recommended agronomic practices were followed. Observations were recorded on five randomly selected competitive plants for days to 50% flowering, days to maturity, plant height (cm), primary and secondary branches per plant, pods per plant, seeds per pod, 100-seed weight (g), grain yield per plant (g), harvest index (%) and protein content (%). Combining ability analysis followed Griffing (1956a) [7], Model I, Method 2.

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Results and discussion

Analysis of variance for combining ability (Table 1) showed that GCA and SCA variances were highly significant for all characters in all three environments, except SCA for pods per plant in E₁ and harvest index in E₃. This indicated the importance of both additive and non-additive gene action in the inheritance of these characters. Environmental effects were significant for all characters. GCA × environment interaction was significant for days to maturity, primary branches per plant, seeds per pod and protein content, and SCA × environment interaction for primary branches per plant. Similar involvement of additive and non-additive gene effects in chickpea was reported by Lakhote *et al.* (2020) [8], Malge *et al.* (2021) [9], Choudhary *et al.* (2023a, b) and Quatadath *et al.* (2024) [10].

The ratio $\sigma^2_{gca}/\sigma^2_{sca}$ was less than unity for days to 50% flowering (0.27–0.39), days to maturity (0.06–0.29), plant height (0.24–0.68), primary branches per plant (0.07–0.14), grain yield per plant (0.56–0.66) and protein content (0.13–0.51), indicating predominance of non-additive gene action. It exceeded unity for secondary branches per plant (1.35–2.36), pods per plant (1.46–2.52) and 100-seed weight (2.57–2.87), indicating predominance of additive gene action. For seeds per pod (1.27, 0.37 and 0.66) and harvest index (0.37, 0.63 and 1.55), the relative importance of additive and non-additive effects changed from one environment to another. Similar trait-wise differences were reported by Bhardwaj *et al.* (2009) [11], Jha *et al.* (2019) [12] and Saba *et al.* (2020) [13].

Estimates of GCA effects (Tables 2 and 3) showed that no parent was a good general combiner for all the characters studied. GNG-1958 was the most promising general combiner for grain yield per plant (0.74, 0.80 and 0.70 in E₁, E₂ and E₃, respectively) and showed significant desirable GCA effects in all environments for days to 50% flowering, secondary branches per plant, pods per plant (3.52, 4.61 and 3.89), 100-seed weight (6.12, 5.86 and 5.74) and harvest index (1.02, 1.01 and 1.13), but it had poor GCA for seeds per pod and protein content. GNG-1488 was a good general combiner for days to maturity, plant height (shorter), primary and secondary branches, pods per plant, seeds per pod, grain yield per plant (0.38, 0.39 and 0.39) and harvest index. Pant G-186 showed desirable GCA for pods per plant, 100-seed weight, grain yield per plant (0.55, 0.43 and 0.47) and harvest index; CSG-8962 for secondary branches and grain yield per plant; and GNG-1581 for primary and secondary branches, pods per plant and seeds per pod, although it was poor for 100-seed weight and protein content. KWR-108 had significant negative GCA effects for days to 50% flowering (–1.82, –1.48 and –2.23), days to maturity and

plant height (–6.77, –4.79 and –4.46) and significant positive effects for protein content (0.47, 0.49 and 0.33) in all environments. It can therefore serve as a source of earliness, reduced plant height and protein content, although it was a poor combiner for grain yield and most yield components. DCP-92-3 was a good combiner for early flowering, seeds per pod and protein content, whereas H-82-2 showed no desirable GCA for any character and had significantly negative GCA for grain yield per plant, pods per plant and harvest index.

The three best crosses for each character on the basis of SCA effects are given in Table 4, along with the GCA status of their parents; none of the crosses ranked high for all characters. For grain yield per plant, Pant G-186 × GNG-1488 (1.76, 1.83 and 1.83; good × good) and GNG-1958 × GNG-1581 (1.34, 1.76 and 1.18, good × average) recorded positive and significant SCA effects in all three environments. These two crosses were also among the best for pods per plant, secondary branches per plant and harvest index. Pant G-186 × GNG-1488 (5.89, 6.33 and 6.76) and CSG-8962 × Pant G-186 (4.89, 4.51 and 4.44) were significant for pods per plant in all environments, while GNG-1958 × Pant G-186 (3.83, 3.66 and 2.26) and GNG-1958 × GNG-1581 (3.32, 2.53 and 2.68) were the best for harvest index. For 100-seed weight, GNG-1958 × GNG-1581 (2.12, 2.47 and 1.95) and GNG-1958 × H-82-2 (2.53, 1.93 and 1.61) were significant in all environments, and all three best crosses involved the good combiner GNG-1958 with a poor combiner. For earliness, Pant G-186 × H-82-2 had significant negative SCA effects for days to 50% flowering in all environments (–6.24, –3.98 and –4.89), while GNG-1958 × GNG-1581 and GNG-1581 × DCP-92-3 were best for days to maturity. GNG-1958 × KWR-108 and CSG-8962 × DCP-92-3 showed significant negative SCA effects for plant height; GNG-1581 × KWR-108 was the only cross with significant positive SCA for primary branches per plant in all environments (0.56, 0.44 and 0.50); KWR-108 × Pant G-186 was best for protein content (0.85, 0.78 and 0.61); and GNG-1581 × Pant G-186 for seeds per pod (significant in E₂ and E₃).

Most of the top SCA crosses for grain yield per plant, pods per plant, secondary branches per plant, 100-seed weight and harvest index had at least one good general combiner as a parent (Table 4), indicating the role of additive × additive or additive × dominance interaction in their high SCA effects. In contrast, the best crosses for earliness and plant height mostly involved average × average or poor combiners, pointing to dominance and epistatic (non-additive) effects. The best cross combinations for yield and its components can thus be obtained by crossing at least one parent with good GCA (Lakhote *et al.*, 2020) [8].

Table 1. Analysis of variance (mean squares) for general (GCA) and specific (SCA) combining ability and the ratio $\sigma^2_{gca}/\sigma^2_{sca}$ in three environments for yield and its contributing traits.

Character	GCA (df = 7)			SCA (df = 28)			Error (df = 70)			$\sigma^2_{gca} / \sigma^2_{sca}$		
	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃
Days to 50% flowering	32.14**	21.45**	27.54**	15.07**	7.99**	9.82**	5.03	2.86	3.77	0.27	0.36	0.39
Days to maturity	28.56**	78.83**	13.04**	29.18**	32.14**	18.66**	8.61	8.13	3.33	0.10	0.29	0.06
Plant height (cm)	83.09**	72.48**	68.60**	17.40**	32.32**	35.30**	6.11	10.78	10.75	0.68	0.29	0.24
Primary branches per plant	0.45**	0.19**	0.21**	0.35**	0.19**	0.27**	0.06	0.04	0.04	0.14	0.10	0.07
Secondary branches per plant	7.95**	5.38**	3.20**	0.62**	0.63**	0.42**	0.29	0.25	0.20	2.36	1.37	1.35
Pods per plant	88.91**	122.45**	97.10**	9.69	11.51*	11.88**	6.42	5.96	5.60	2.52	2.10	1.46
Seeds per pod	0.07**	0.04**	0.03**	0.01*	0.01**	0.01**	0.01	0.00	0.00	1.27	0.37	0.66
100-seed weight (g)	65.34**	59.65**	58.09**	2.84**	2.74**	2.30**	0.53	0.44	0.29	2.81	2.57	2.87
Grain yield per plant (g)	4.42**	4.24**	3.54**	1.01**	0.94**	0.72**	0.40	0.21	0.14	0.66	0.56	0.58
Harvest index (%)	8.27**	10.02**	9.57**	3.16**	2.75*	1.80	1.28	1.38	1.27	0.37	0.63	1.55
Protein content (%)	0.85**	1.25**	0.37**	0.50**	0.35**	0.30**	0.15	0.13	0.08	0.20	0.51	0.13

* ** significant at 5% and 1% levels, respectively. E₁ = timely sown irrigated, E₂ = late sown irrigated, E₃ = timely sown under conserved moisture. σ^2_{gca} and σ^2_{sca} are the general and specific combining ability variance components.

Table 2. Estimates of general combining ability (GCA) effects of parents for days to 50% flowering, days to maturity, plant height, primary branches per plant, secondary branches per plant and pods per plant in three environments.

Parent	Days to 50% flowering			Days to maturity			Plant height (cm)			Primary branches per plant			Secondary branches per plant			Pods per plant		
	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃
GNG-1958	-2.62**	-1.88**	-1.86**	-0.56	0.68	0.73	1.63*	2.83**	0.75	0.09	0.06	0.12*	0.67**	0.53**	0.57**	3.52**	4.61**	3.89**
GNG-1581	0.68	0.69	0.94	1.51	-4.72**	-0.07	0.34	-0.19	0.46	0.33**	-0.05	0.17**	0.93**	0.81**	0.51**	2.07**	2.52**	1.82*
CSG-8962	2.52**	1.59**	1.14	1.77*	2.98**	1.40*	1.68*	1.37	-0.10	0.08	0.18**	-0.19**	0.44**	0.20*	0.32*	0.90	0.53	0.98
KWR-108	-1.82**	-1.48**	-2.23**	-2.09*	-2.12*	-1.73**	-6.77**	-4.79**	-4.46**	-0.13	-0.11	-0.09	-1.08**	-0.87**	-0.62**	-3.55**	-4.00**	-3.56**
Pant G-186	1.32	0.46	0.47	1.14	1.74*	1.50**	1.36	2.76**	3.34**	-0.07	-0.04	-0.02	0.27	0.30*	0.14	2.19**	2.36**	2.42**
H-82-2	0.65	0.96	1.31*	0.88	2.34**	-0.23	1.69*	1.69	3.14**	-0.25**	0.03	-0.08	-1.63**	-1.32**	-1.07**	-4.68**	-5.50**	-4.69**
GNG-1488	0.88	1.42**	1.94**	-2.79**	-2.69**	-0.93	-0.98*	-2.42*	-2.41*	0.20**	0.16**	0.20**	0.40*	0.44**	0.12	1.43	1.45*	1.53*
DCP-92-3	-1.62*	-1.77**	-1.73**	0.14	1.81*	-0.67	1.07	-1.25	-0.73	-0.25**	-0.23**	-0.12	0.01	-0.09	0.04	-1.87*	-1.96**	-2.39**
SE (gi) ±	0.66	0.50	0.57	0.87	0.84	0.54	0.73	0.97	0.97	0.08	0.06	0.06	0.16	0.15	0.13	0.75	0.72	0.70
SE (gi - gj) ±	1.00	0.76	0.87	1.31	1.28	0.82	1.11	1.47	1.47	0.11	0.09	0.09	0.24	0.23	0.20	1.13	1.09	1.06

*, ** significant at 5% and 1% levels, respectively. E₁ = timely sown irrigated, E₂ = late sown irrigated, E₃ = timely sown under conserved moisture. SE (g_i) = standard error of a GCA effect; SE (g_i - g_j) = standard error of the difference between two GCA effects.

Table 3. Estimates of general combining ability (GCA) effects of parents for seeds per pod, 100-seed weight, grain yield per plant, harvest index and protein content in three environments.

Parent	Seeds per pod			100-seed weight (g)			Grain yield per plant (g)			Harvest index (%)			Protein content (%)		
	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃	E ₁	E ₂	E ₃
GNG-1958	-0.14**	-0.10**	-0.05**	6.12**	5.86**	5.74**	0.74**	0.80**	0.70**	1.02**	1.01**	1.13**	-0.27*	-0.33**	-0.02
GNG-1581	0.06*	0.10**	0.10**	-1.51**	-1.39**	-1.62**	0.21	0.23	0.05	0.02	0.09	0.35	-0.33**	-0.41**	-0.23**
CSG-8962	-0.06*	-0.05**	-0.03	-0.92**	-1.00**	-0.81**	0.40*	0.31*	0.33**	-0.31	-0.08	0.10	-0.05	0.36**	0.00
KWR-108	-0.07**	-0.05**	-0.06**	-0.36	-0.49*	-0.38*	-0.44*	-0.28*	-0.28*	0.18	-0.40	-0.42	0.47**	0.49**	0.33**
Pant G-186	0.03	-0.00	-0.03	0.44*	0.45*	0.52**	0.55**	0.43**	0.47**	0.73*	1.13**	0.78*	0.02	-0.06	0.23**
H-82-2	-0.00	0.03	0.03	-1.46**	-1.39**	-1.31**	-0.90**	-0.94**	-0.99**	-0.65	-1.24**	-1.30**	-0.09	-0.21	-0.01
GNG-1488	0.12**	0.04**	0.06**	-0.99**	-1.08**	-1.03**	0.38*	0.39**	0.39**	0.77*	0.95**	0.83*	-0.16	-0.21	-0.13
DCP-92-3	0.06**	0.04*	-0.02	-1.33**	-0.96**	-1.12**	-0.94**	-0.94**	-0.66**	-1.75**	-1.46**	-1.46**	0.40**	0.37**	-0.17*
SE (gi) ±	0.02	0.02	0.02	0.22	0.20	0.16	0.19	0.14	0.11	0.34	0.35	0.33	0.12	0.11	0.08
SE (gi - gj) ±	0.03	0.02	0.03	0.33	0.30	0.24	0.28	0.21	0.17	0.51	0.52	0.50	0.17	0.16	0.12

*, ** significant at 5% and 1% levels, respectively. E₁ = timely sown irrigated, E₂ = late sown irrigated, E₃ = timely sown under conserved moisture. SE (g_i) = standard error of a GCA effect; SE (g_i - g_j) = standard error of the difference between two GCA effects.

Table 4. Top three crosses for each character on the basis of SCA effects, along with the GCA status of their parents, in three environments.

Character	Cross	SCA effects			GCA of parents
		E ₁	E ₂	E ₃	
Days to 50% flowering	Pant G-186 × H-82-2	-6.24**	-3.98*	-4.89**	A × A
	GNG-1581 × CSG-8962	-2.14	-5.51**	-5.52**	A × P
	GNG-1958 × GNG-1488	-6.88**	-3.11*	-2.52	G × P
Days to maturity	GNG-1581 × DCP-92-3	-9.75**	-9.37**	-6.12**	A × A
	GNG-1958 × GNG-1581	-9.39**	-8.24**	-5.85**	A × A
	Pant G-186 × GNG-1488	-11.45**	-7.00**	-2.09	P × G
Plant height (cm)	CSG-8962 × DCP-92-3	-6.03**	-12.54**	-13.03**	A × A
	GNG-1958 × KWR-108	-10.27**	-9.37**	-11.49**	P × G
	H-82-2 × GNG-1488	-8.35**	-8.69**	-5.66	P × G
Primary branches per plant	GNG-1958 × GNG-1488	1.18**	0.48**	0.26	A × G
	CSG-8962 × DCP-92-3	0.48*	0.32	0.89**	A × P
	CSG-8962 × Pant G-186	0.73**	0.27	0.62**	A × A
Secondary branches per plant	Pant G-186 × GNG-1488	1.42**	1.73**	0.95*	A × G
	CSG-8962 × Pant G-186	1.52**	0.97*	0.92*	G × A
	GNG-1958 × GNG-1581	0.46*	1.17*	1.00*	G × G
Pods per plant	Pant G-186 × GNG-1488	5.89*	6.33**	6.76**	G × G
	GNG-1958 × GNG-1581	4.29	5.08*	5.94**	G × G
	CSG-8962 × Pant G-186	4.89*	4.51*	4.44*	A × G
Seeds per pod	GNG-1581 × Pant G-186	0.11	0.21**	0.20**	G × A
	GNG-1581 × CSG-8962	0.14*	0.17**	0.08	G × P
	GNG-1581 × DCP-92-3	0.12	0.15**	0.07	G × G
100-seed weight (g)	GNG-1958 × GNG-1581	2.12**	2.47**	1.95**	G × P
	GNG-1958 × H-82-2	2.53**	1.93**	1.61**	G × P
	GNG-1958 × GNG-1488	1.30	1.76**	2.23**	G × P
Grain yield per plant (g)	Pant G-186 × GNG-1488	1.76**	1.83**	1.83**	G × G
	GNG-1958 × GNG-1581	1.34*	1.76**	1.18**	G × A
	CSG-8962 × KWR-108	0.70	1.63**	0.47	G × P
Harvest index (%)	GNG-1958 × Pant G-186	3.83**	3.66**	2.26*	G × G
	GNG-1958 × GNG-1581	3.32**	2.53*	2.68*	G × A
	Pant G-186 × GNG-1488	1.87	2.68*	1.69	G × G
Protein content (%)	GNG-1581 × H-82-2	0.51	0.94**	0.97**	P × A
	KWR-108 × Pant G-186	0.85*	0.78*	0.61*	G × A
	KWR-108 × GNG-1488	0.36	0.67*	1.06**	G × A

G = good, A = average, P = poor. A parent is good or poor when its GCA effect is significant in the desirable or undesirable direction in at least two environments, and average otherwise. *, ** significant at 5% and 1% levels, respectively. E₁ = timely sown irrigated, E₂ = late sown irrigated, E₃ = timely sown under conserved moisture. Crosses are ranked on the mean SCA effect in the desirable direction.

GCA is attributed to additive gene action and additive × additive interaction, which are fixable, whereas SCA is attributed to non-additive, non-fixable gene action. The predominance of SCA for days to 50% flowering, days to maturity, plant height, primary branches per plant, grain yield per plant and protein content suggests that selection in early segregating generations may be less effective for these characters, whereas the higher GCA variance for secondary branches per plant, pods per plant and 100-seed weight offers greater scope for selection and fixation of desirable alleles. As chickpea is self-pollinated,

Conclusion

Significant GCA and SCA effects for all traits showed that both additive and non-additive gene action govern grain yield and its contributing traits in chickpea, and their magnitude varied across environments. GNG-1958 was the most promising general combiner for grain yield per plant, pods per plant, secondary branches per plant, 100-seed weight and harvest index, and KWR-108 for early flowering, early maturity, shorter plant height and protein content. Pant G-186,

exploitation of heterosis is not feasible; however, crosses with high SCA involving at least one good general combiner, such as Pant G-186 × GNG-1488 and GNG-1958 × GNG-1581, could produce transgressive segregants in advanced generations if the additive effects of the good combiner and complementary epistatic effects act in the same direction. The significant GCA × environment and SCA × environment interactions further emphasise the need to evaluate promising parents and crosses across environments to identify stable combinations.

CSG-8962 and GNG-1488 also showed desirable GCA for several yield-related characters.

GNG-1958 × GNG-1581 and Pant G-186 × GNG-1488 had consistently positive and significant SCA effects for grain yield per plant in all three environments. Pant G-186 × H-82-2 (early flowering), GNG-1958 × GNG-1581 and GNG-1581 × DCP-92-3 (early maturity) and KWR-108 × Pant G-186 (protein content) also performed consistently. Non-additive effects predominated for several traits, making

early-generation selection less effective for them, whereas additive effects predominated for secondary branches per plant, pods per plant and 100-seed weight. These parents and crosses, evaluated across environments, can be exploited to develop stable, high-yielding and well-adapted chickpea genotypes.

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