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Combining ability and gene action and heritability studies in Chilli (*Capsicum Annuum* L.)

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Abstract
A field experiment was conducted to key genetic parameters such as combining ability, the nature of gene action and heritability of important yield and yield contributing traits in chilli. To achieve this, a half diallel mating design was employed using eight genetically diverse parental lines. This design resulted in the development of 28 F_1 hybrids, which were subsequently evaluated during the summer season of 2023. The estimates of general combining ability (GCA) effects revealed that the parental lines Sel.10-2, Sel.59-2-2, Sel.64-1, and Sel.14-6-2 were identified as good general combiners, as they exhibited significant GCA effects in the desirable direction for several key traits, particularly those related to earliness and yield contributing characters. Estimates of specific combining ability (SCA) effects indicated that the cross combinations P_2 X P_3, P_3 X P_5, P_3 X P_8, P_6 X P_7, P_6 X P_8 and P_7 X P_8 exhibited significant and positive SCA effects for the majority of yield and yield related traits. The magnitude of σ^2GCA/σ^2SCA was found to be less than 1 indicating the predominance of non-additive gene action for all the growth and yield characters except for average weight of fruit which showed additive gene action. The narrow sense heritability for all yield and yield contributing characters ranged between 2.10% to 55.40%.

Keywords: Chilli (*Capsicum annuum* L.), combining ability, general combining ability (GCA), specific combining ability (SCA), gene action, heritability, half diallel mating design

Introduction

Chilli commonly called hot pepper belongs to the nightshade family (Solanaceae) and the genus Capsicum. This genus includes a broad array of pepper species, ranging from mild to extremely hot. Among these, there are five main domesticated species: Capsicum annuum, *Capsicum frutescens*, *Capsicum chinense*, *Capsicum baccatum* and *Capsicum pubescens* among these, C. annuum first domesticated in Mexico is the most globally important, encompassing virtually all commercially grown chili and sweet pepper varieties. (Thamburaj and Singh, 2019) [14]. Chili peppers are believed to have originated in Central or South America; however, for *C. annuum* in particular, Mexico is regarded as the center of its morphological diversity.

Globally, India ranks among the top producers, consumers, and exporters of chilli.

Chilli is grown on a large scale across many Indian states with Andhra Pradesh, Telangana, Karnataka, Madhya Pradesh, Maharashtra and West Bengal among the major chilli-producing regions. India's chillies are exported mainly to various Asian countries, such as China, Sri Lanka, Malaysia, Bangladesh, Singapore, Thailand and the United Arab Emirates (UAE), among others. Indian chillies enjoy a strong global reputation, especially because of two commercially important qualities: their bright red colour and their characteristic pungency levels.

Chillies are primarily used as food adjuncts which impart flavour, colour and pungency in foods and are indispensable in Indian cuisine. Beyond their culinary appeal, chilli peppers are packed with impressive health promoting properties. They are rich in vitamins, particularly in vitamin C and contain capsaicin, a compound associated with various health advantages. Capsaicin mainly known for its antioxidant and anti-inflammatory effects, contributing to improved metabolism, cardiovascular health and pain relief. The septa and placenta tissues contain the pungent principal capsaicin (Deshpande and Anand, 1998) [4].

In India, the total area under chilli cultivation changes from year to year, and the country produces a very large quantity of chilli annually. The yield (productivity) of chilli differs widely among various states and regions. On average, depending on environmental conditions, pest outbreaks, market demand, cultivation methods and use of modern farming techniques, chilli yields may vary substantially.

Materials and Methods

In the present investigation eight genetically diverse parental lines of chilli were used as the experimental material *viz*., (P1) Sel.1-1, (P2) Sel.8-2, (P3) Sel.10-2, (P4) Sel.27-1, (P5) Sel.30-3, (P6) Sel. 59-2-2, (P7) Sel.64-1, (P8) Sel.14-6-2 were crossed in all the possible combinations to get 28 F1 hybrids in diallel mating system without reciprocal.

All the eight parents and 28 F1s were transplanted for evaluation for combining ability, gene action and heritability studies during summer 2023 in randomized block design with three replications at AICRP on Vegetable Crops, Department of Horticulture, MPKV Rahuri. All standard cultivation practices were implemented to ensure the healthy growth of the crop for evaluation. The data were analysed for sixteen quantitative characters. Data were collected on various parameters, including plant height, number of primary branches per plant, plant spread (S-N), plant spread (E-W), days to flower initiation, days to 50% flowering, days to fruit set, length of fruit, diameter of fruit, fruit pedicel length, number of seeds per fruit, average weight of fruit, number of fruits per plant, fruit yield per plant, fruit yield per plot and fruit yield per hectare.

Combining ability

Analysis of variance for combining ability

The analysis was done according to procedure detailed by Griffings (1956) [6] Model I (fixed effect model) and Method II (parents and one set of F_1's excluding reciprocals). The mathematical model for combining ability analysis is assumed to be

$$X_{ij} = \mu + g_i + g_j + \frac{1}{bc} + \sum k \sum I\, e_{ijkl}$$

ij = l, ……………, p (Parents)
k = l, ……………, b (replications)
l = l, ……………, c

Where,
μ = Population mean
g_i = gca effect of i^{th} parent
g_j = gca effect of j^{th} parent
S_{ij} = sca effect of the cross between i^{th} parent and j^{th} parent such that $S_{ij} = S_{ji}$
e_{ijkl} = The environmental effect related to $ijkl^{th}$ observations on ij^{th} individual in k^{th} block as female parent and j^{th} as male parent

Table a: ANOVA for combining ability

Sources	D. F.	S.S.	M.S.S.	E.M.S.
GCA	P-1	S_g	M_g	$\sigma^2_e + (P + 2)\ 1/(P-1)\ \Sigma\ g_i^2$
SCA	P(P-1)/2	S_s	M_s	$\sigma^2_e + 2/P(p-1)\ \Sigma_i\ \Sigma_j\ S_{ij}$
Error	(r-1) (t-1)	S_e	M_e	σ^2_e

Where,
r = Number of replications
t = Number of treatments
M_g = M.S.S. GCA
M_s = M.S.S. SCA
M_e = E.M.S.S.

b. Estimation of sum of squares

The sum of squares was estimated as follows

S_g = 1/P + 2 {i ($X_i + I_n$) 2 - 4/P X2}

S_s = X_{ij}2 = 1/(P + 2) i ($X_i + X_{ii}$) 2 + 2/(P + 1) (P + 2) X2.... i sj

Where,
S_g = Sum of squares due to gca
S_s = Sum of squares due to sca
P = Number of parents
M = Degree of freedom for error mean square (r-1) (t-1)
X_i = Row total of the array involving i^{th} parent ΣX_{ij}
X. = Grand total of ½ P (P-1) progenies $\Sigma\Sigma X_{ij}$
X_{ii} = Mean value of i^{th} parent
X_{ij} = the mean value of ij^{th} cross

c. Estimation of various effects

gca and sca effects were estimated as follows

μ = 2/P (P + 1) X…

g_i = 1/(P + 2) ($X_i + X_{ij}$ - 2/P X..)

S_{ij} = X_{ij} - 1/(P + 2_ {Xi + X_{ii} + X_j + X_{jj}} + 2/(P + 1) (P + 2) X...

d. Significance of combining ability

Significance of combining ability was tested as below.

1. $\mathrm{Var}\,(g_i) = \frac{P-1}{P(P+1)}\,\sigma_e^2$
2. $\mathrm{Var}\,(S_{ij}) = \frac{P(P-1)}{P(P+1)(P+2)}\,\sigma_e^2$
3. $\mathrm{Var}\,(S_{ij}) = \frac{P^2+P+2}{(P+1)(P+2)}\,\sigma_e^2\ (i \neq j)$
4. $\mathrm{Var}\,(g_i - g_j) = \frac{2}{(P+2)}\,\sigma_e^2\ (i \neq j)$
5. $\mathrm{Var}\,(S_{ii} - S_{jj)}) = \frac{2(P-2)}{(P+2)}\,\sigma_e^2\ (i \neq j)$
6. $\mathrm{Var}(S_{ij} - S_{jk}) = \frac{2(P+1)}{(P+2)}\,\sigma_e^2\ (i \neq j\ \neq k)$
7. $\mathrm{Var}\,(S_{ij} - S_{lj}) = \frac{2(P+1)}{P+2}\,\sigma_e^2\ (i \neq j, k, l; k, k \neq l)$

For testing significance of combining ability effects or difference between effects critical difference was worked out as.

C.D. = S.E. x t x 2

Where,
S.E. = Variance
t = table't' value at error d. f. at 5% and 1% level of Significance

Gene action
Under certain assumptions Griffing (1956) [6] has demonstrated that

$2\ \sigma^2 gca = \sigma^2 A + ½ + \sigma^2 A A$………

$\sigma^2 sca = \sigma^2 A + ½ + \sigma^2 A A + ½ + \sigma^2 A D + ½ + \sigma^2 DD$……..

Therefore,
- Additive genetic variance ($\sigma^2 A = 2\ \sigma^2$ gca)
- Non additive genetic variance ($\sigma^2 D = \sigma^2$ sca)

Estimation of Heritability
Heritability is defined as the ratio of genotypic to phenotypic variance. The percentage of heritability in a narrow sense was calculated for a variety of characters, as shown below (Falconer, 1981) [5].

$$h^2_{(ns)} = \frac{\sigma^2_A}{\sigma^2_A + \sigma^2_D + \sigma^2_e} \times 100$$

Where,
$\sigma^2 A$ = Additive genetic variance
$\sigma^2 D$ = Dominance variance
σ^2_e = Environmental variance

Further, heritability was calculated and classified as high (above 30%), moderate (10-30%) and low (5-10%) following Robinson (1966) [12] method of heritability classification.

Results and Discussion
Combining Ability
Analysis of variance for combining ability in 8 x 8 half diallel of chilli
The data presented in Table 1 regarding analysis of variance (ANOVA) was conducted to examine differences among replications, genotypes and other sources of variation for each character studied. The results showed that all characters exhibited statistically significant differences among the genotypes except number of primary branches per plant and diameter of fruit at both the 5 and 1 percent significance levels.

General Combining Ability
Data presented in Table 2 with respect to the general combining ability in chilli for all the characters.

Plant Height (cm)
Among the eight parents, P_6 (5.30), P_8 (6.43), showed significantly positive GCA effect for plant height and were found the good combiner for this trait.

Number of Primary Branches per Plant
Out of eight parents, P_7 (0.23) showed significantly positive GCA effect for the number of primary branches per plant and only single parent found good combiner for this trait.

Plant Spread (cm) (S-N)
Among the eight parents, P_4 (1.21), P_5 (1.66) and P_8 (3.66), showed significantly positive GCA effect for plant spread in S-N direction and were registered the good combiner for this character.

Plant Spread (cm) (E-W)
Out of eight parents, P_3 (3.01) and P_8 (1.90) showed significantly positive GCA effect for the plant spread in E-W direction and were recorded good combiner for this trait.

Days to Flower Initiation
Out of eight parents, P_2 (-0.60), P_3 (-0.33) and P_4 (-0.96) showed significantly negative GCA effect for days to flower initiation and were registered the good combiner for this trait. The general combining ability for the initiation of flowering is affected by multiple genetic factors, necessitating further research to comprehend the underlying mechanisms fully.

Days to 50% flowering
Among the parents, P_3 (-0.86), P_4 (-0.79) and P_6 (-0.44) showed significantly negative GCA effect for days to 50% flowering and were found good combiner for this trait.

Days to fruit set
Among the parents, P_3 (-1.27), P_4 (-0.07), P_6 (-1.18), P_7 (-0.70) and P_8 (-1.15) showed significantly negative GCA effect for days to fruit set and were recorded the good combiner for this trait.

Length of fruit (cm)
Among the eight parents, P_3 (0.13), P_6 (0.18), P_7 (0.28) and P_8 (0.38) showed significantly positive GCA effect for length of fruit and were found the good combiner for this trait. Similarly, Navhale *et al.* (2014) [10] and Chakrabarty *et al.* (2019) [2] observed positive effects in various parental lines

Table 1: Analysis of variance for combining ability in 8 x 8 half diallel of Chilli

Source	DF	Plant height	Number of primary branches per plant	Plant spread (cm)		Days to flower initiation	Days to 50% flowering	Days to fruit set	Length of fruit (cm)
				S-N	E-W				
Mean sum of square									
GCA	7	213.37**	0.26	63.78**	70.50**	4.29**	5.12**	18.08**	1.23**
SCA	28	54.58**	0.28*	45.43**	54.79**	6.39**	3.33**	4.77**	0.74**
Error	70	2.72	0.14	3.54	2.90	0.02	0.05	0.01	0.05

Table 1: contd….

Source	DF	Diameter of fruit (cm)	Fruit pedicel length	Number of seeds per fruit	Average weight of fruit (g)	Number of fruits per plant	Fruit yield per plant (g)	Fruit yield per plot (kg)	Fruit yield per hectare (q)
Mean sum of square									
GCA	7	0.004	0.49**	206.82**	0.41**	1744.32**	25188.22**	25.79**	7774.23**
SCA	28	0.01*	0.18**	32.95**	0.34**	1293.51**	6989.03**	7.16**	2157.12**
Error	70	0.00	0.01	2.41	0.02	434.30	1394.17	1.43	430.29

* And** significant at 5% and 1% respectively.

Table 2: Estimation of general combining ability effects for different characters of Chilli in 8 x 8 half diallel

Sr. No.	Parents	Plant height (cm)	Number of primary branches per plant	Plant spread (cm)		Days to flower initiation	Days to 50% flowering	Days to fruit set	Length of fruit (cm)
				S-N	E-W				
1.	P_1	-8.00**	-0.30**	-4.89**	-5.91**	1.16**	1.19**	2.18**	-0.12
2.	P_2	-2.69**	-0.05	-1.13*	-0.71	-0.60**	-0.01	0.56**	-0.74**
3.	P_3	0.48	-0.10	-1.07	3.01**	-0.33**	-0.86**	-1.27**	0.13*
4.	P_4	-2.72**	-0.02	1.21*	0.34	-0.96**	-0.79**	-0.07*	-0.02
5.	P_5	0.41	0.06	1.66**	0.10	0.29**	0.65**	1.64**	-0.10
6.	P_6	5.30**	0.09	-0.17	0.96	0.10**	-0.44**	-1.18**	0.18**
7.	P_7	0.79	0.23*	0.72	0.29	0.35**	-0.10	-0.70**	0.28**
8.	P_8	6.43**	0.09	3.66**	1.90**	-0.01	0.37**	-1.15**	0.38**
	S. E.±(gi)	0.48	0.11	0.55	0.50	0.04	0.06	0.03	0.06
	C. D. at 5%	0.97	0.22	1.11	1.00	0.08	0.13	0.06	0.13

Table 2: contd...

Sr. No.	Parents	Diameter of fruit (cm)	Fruit pedicel length (cm)	Average weight of fruit (g)	Number of seeds per fruit	Number of fruits per plant	Fruit yield per plant (g)	Fruit yield per plot (kg)	Fruit yield per hectare (q)
1.	P_1	0.00	0.28**	-0.23**	-6.83**	-5.79	-60.62**	-1.94**	-33.68**
2.	P_2	-0.01	0.04	-0.08*	-5.77**	-10.62	-40.92**	-1.30**	-22.73**
3.	P_3	0.02	-0.19**	-0.07	-1.05*	15.17*	14.27	0.45	7.93
4.	P_4	-0.01	0.29**	-0.01	2.30**	-18.22**	-61.52**	-1.96**	-34.18**
5.	P_5	-0.00	0.00	-0.21**	3.89**	21.54**	-4.52	-0.14	-2.51
6.	P_6	-0.00	0.05	0.06	-1.19*	4.87	45.37**	1.45**	25.20**
7.	P_7	0.03*	-0.31**	0.22**	2.88**	-3.15	40.07**	1.28**	22.26**
8.	P_8	-0.02	-0.18**	0.33**	5.77**	-3.79	67.87**	2.17**	37.70**
	S. E.±(gi)	0.01	0.02	0.04	0.45	6.16	11.04	0.35	6.13
	C. D. at 5%	0.03	0.05	0.08	0.91	12.29	22.02	0.70	12.23

* And** significant at 5% and 1% respectively.

Table 3: Estimation of specific combining ability effects for different characters of Chilli in 8 x 8 half diallel

Sr. No.	Hybrids	Plant height (cm)	Number of primary branches per plant	Plant spread (cm)		Days to flower initiation	Days to 50% flowering	Days to fruit set	Length of fruit (cm)
				S-N	E-W				
1.	$P_1 \times P_2$	1.08	-0.57	2.10	3.88*	6.31**	4.20**	0.58**	-0.07
2.	$P_1 \times P_3$	-4.45**	0.09	-7.58**	0.38	5.11**	3.39**	2.35**	-1.22**
3.	$P_1 \times P_4$	4.06**	0.21	0.36	3.60*	0.07	-0.02	-2.38**	1.31**
4.	$P_1 \times P_5$	-0.34	-0.55	1.78	3.32*	2.27**	0.93**	-0.44**	0.22
5.	$P_1 \times P_6$	-2.57	0.69*	-0.77	-6.72**	-0.54**	-0.64**	-0.67**	0.83**
6.	$P_1 \times P_7$	1.87	0.75*	3.10	-4.78**	-2.19**	-2.38**	-1.75**	0.47*
7.	$P_1 \times P_8$	-5.01**	0.02	4.30*	3.35*	-1.82**	-3.85**	-4.30**	0.70**
8.	$P_2 \times P_3$	0.20	0.78*	-2.61	-5.76**	-1.79**	1.66**	1.04**	0.83**
9.	$P_2 \times P_4$	9.65**	0.50	5.44**	1.77	-1.16**	-1.41**	-0.83**	-0.97**
10.	$P_2 \times P_5$	2.27	1.07**	8.38**	5.28**	-2.29**	0.07	-2.48**	0.08
11.	$P_2 \times P_6$	-0.98	-0.43	-3.13	9.75**	-2.04**	-1.17**	-2.58**	-0.21
12.	$P_2 \times P_7$	-3.76*	0.24	5.32**	2.42	-0.48**	-1.64**	-3.13**	-0.78**
13.	$P_2 \times P_8$	-5.41**	0.18	-11.02**	-10.18**	1.29**	1.22**	-1.01**	-0.18
14.	$P_3 \times P_4$	-3.98**	0.42	-2.36	-4.33**	0.57**	0.44*	-0.26*	-0.05
15.	$P_3 \times P_5$	15.10**	0.12	9.93**	9.88**	-2.49**	-1.01**	-0.32**	1.36**
16.	$P_3 \times P_6$	-1.15	-0.77*	1.82	7.67**	2.17**	-0.18	2.78**	-0.39
17.	$P_3 \times P_7$	-4.60**	0.09	4.51*	4.35**	-2.28**	-1.32**	-0.30**	-0.89**
18.	$P_3 \times P_8$	16.79**	0.43	8.91**	3.85*	-0.91**	0.01	-1.84**	1.12**

19.	P_4 x P_5	0.30	0.31	9.05**	8.55**	0.54**	-2.09**	-1.85**	-0.04
20.	P_4 x P_6	1.72	0.28	6.20**	7.70**	-2.01**	-0.39	-0.08	0.51*
21.	P_4 x P_7	-0.55	-0.33	-2.10	3.35*	2.55**	2.47**	0.44**	1.74**
22.	P_4 x P_8	2.41	-0.32	2.98	7.42**	-0.82**	2.27**	1.76**	-0.76**
23.	P_5 x P_6	3.07*	-0.21	-2.93	-6.07**	1.67**	1.16**	-0.74**	0.28
24.	P_5 x P_7	1.19	-0.62	-6.56**	-3.40*	0.29*	0.22	0.72**	-0.05
25.	P_5 x P_8	-6.78**	0.12	-2.78	-3.94*	-1.34**	0.21	1.04**	-0.82**
26.	P_6 x P_7	11.96**	0.49	-5.05**	-1.60	-3.26**	1.32**	0.28**	-0.57**
27.	P_6 x P_8	9.04**	0.16	7.44**	7.13**	-1.29**	-1.55**	-1.20**	0.49*
28.	P_7 x P_8	6.93**	0.02	9.82**	10.45**	1.07**	-0.23	-0.41**	0.86**
	S. E.±Sij	1.49	0.34	1.71	1.54	0.12	0.21	0.10	0.21
	C.D @ 5%	2.98	0.69	3.40	3.08	0.25	0.41	0.21	0.42
	C. D. at 5%	0.97	0.22	1.11	1.00	0.08	0.13	0.06	0.13

Table 3: contd...

Sr. No.	Hybrids	Diameter of fruit (cm)	Fruit pedicel length	Average weight of fruit (g)	Number of seeds per fruit	Number of fruits per plant	Fruit yield per plant (g)	Fruit yield per plot (kg)	Fruit yield per hectare (q)
1.	P_1 x P_2	-0.01	-0.15	0.18	0.54	-6.57	4.30	0.14	2.39
2.	P_1 x P_3	-0.06	-0.01	-0.21	-0.11	-15.37	-42.90	-1.37	-23.83
3.	P_1 x P_4	-0.04	1.16**	0.78**	2.13	-26.64	13.90	0.44	7.72
4.	P_1 x P_5	-0.02	-0.12	-0.04	-1.53	3.59	46.90	1.50	26.06
5.	P_1 x P_6	-0.04	-0.06	-0.27*	2.42	26.59	52.00	1.67	28.89
6.	P_1 x P_7	0.12*	-0.03	0.96**	1.08	-38.37*	-9.70	-0.31	-5.39
7.	P_1 x P_8	0.16**	-0.48**	0.52**	-4.54**	0.93	89.50*	2.86*	49.72*
8.	P_2 x P_3	0.13*	0.10	-0.34*	13.36**	48.46*	124.40**	3.98**	69.11**
9.	P_2 x P_4	-0.04	0.10	0.60**	-5.60**	-15.47	29.20	0.93	16.22
10.	P_2 x P_5	0.02	0.97**	0.48**	1.00	-35.57	-2.80	-0.09	-1.56
11.	P_2 x P_6	0.03	-0.16	0.49**	-3.11**	-18.91	-3.70	-0.12	-2.05
12.	P_2 x P_7	0.01	-0.16	-0.23	-1.26	12.13	3.60	0.12	2.00
13.	P_2 x P_8	-0.02	-0.19*	-0.09	-3.21*	-11.24	-80.20*	-2.57*	-44.55*
14.	P_3 x P_4	-0.06	-0.62**	-0.18	-3.98**	-2.94	-28.00	-0.90	-15.56
15.	P_3 x P_5	-0.07	0.23*	0.02	2.09	100.96**	91.00**	2.91**	50.56**
16.	P_3 x P_6	-0.05	-0.25**	0.52**	2.64	-30.04	13.10	0.42	7.28
17.	P_3 x P_7	0.10*	0.18*	0.72**	-2.04	-37.34	-2.60	-0.08	-1.45
18.	P_3 x P_8	0.25**	0.09	0.29*	-1.39	-8.37	48.60	1.55	27.00
19.	P_4 x P_5	0.22**	-0.32**	-0.20	-2.87*	-3.31	14.80	0.48	8.22
20.	P_4 x P_6	-0.01	0.42**	-0.41**	3.15*	16.69	-22.10	-0.71	-12.28
21.	P_4 x P_7	-0.07	0.29**	0.35**	-3.13*	-16.27	-31.80	-1.02	-17.67
22.	P_4 x P_8	-0.02	0.36**	0.07	-1.02	-8.97	-35.60	-1.14	-19.78
23.	P_5 x P_6	-0.02	-0.19**	0.95**	-0.11	-50.74**	5.90	0.19	3.28
24.	P_5 x P_7	-0.06	-0.09	-0.08	0.34	-21.04	-34.80	-1.12	-19.33
25.	P_5 x P_8	0.02	-0.35**	0.56**	-7.74**	-51.74**	-92.60**	-2.96**	-51.44**
26.	P_6 x P_7	0.01	-0.57**	-0.60**	-2.04	59.96**	91.30**	2.92**	50.72**
27.	P_6 x P_8	0.08	0.20**	0.26*	15.21**	31.26	173.50**	5.55**	96.39**
28.	P_7 x P_8	0.01	-0.09	0.04	10.73**	36.96	162.80**	5.21**	90.45**
	S. E.±Sij	0.05	0.09	0.13	1.41	18.90	33.86	1.08	18.81
	C.D @ 5%	0.10	0.18	0.26	2.81	37.69	67.53	2.16	37.51
	C.D @ 1%	0.14	0.24	0.35	3.76	50.45	90.40	2.89	50.22

* And** significant at 5% and 1% respectively.

Table 4: Estimation of genetic variance component for different characters in 8 x 8 half diallel Chilli

Sr. No.	Source	Plant height (cm)	Number of primary branches per plant	Plant spread (cm)		Days to flower initiation	Days to 50% flowering	Days to fruit set	Length of fruit (cm)
				S-N	E-W				
				Component of variance					
1.	σ2GCA	21.06	0.01	6.02	6.76	0.42	0.50	1.80	0.11
2.	σ2SCA	51.85	0.13	41.88	51.89	6.37	3.27	4.75	0.68
3.	σ2 a	42.13	0.02	12.04	13.51	0.85	1.01	3.61	0.23
4.	σ2 D	51.85	0.13	41.88	51.89	6.37	3.27	4.75	0.68
5.	A : D	0.81	0.17	0.29	0.26	0.13	0.31	0.76	0.34
6.	h2 (ns)%	43.60	7.70	21.00	19.80	11.80	23.40	43.10	24.10
7.	σ2GCA/σ2SCA	0.40	0.08	0.14	0.13	0.06	0.15	0.38	0.17

Table 4: Contd...

Sr. No.	Source	Diameter of fruit (cm)	Fruit pedicel length (cm)	Number of seeds per fruit	Average weight of fruit (g)	Number of fruits per plant	Fruit yield per plant (g)	Fruit yield per plot (kg)	Fruit yield per hectare (q)
Component of variance									
1.	σ2GCA	0.00	0.04	0.03	20.44	131.00	2379.40	2.43	734.39
2.	σ2SCA	0.00	0.16	0.31	30.54	859.21	5594.86	5.72	1726.82
3.	σ2 a	0.00	0.09	0.07	40.88	262.00	4758.81	4.87	1468.78
4.	σ2 D	0.00	0.16	0.31	30.54	859.21	5594.86	5.72	1726.82
5.	A : D	0.00	0.57	0.24	1.34	0.30	0.85	0.85	0.85
6.	h2 (ns)%	2.10	35.10	18.70	55.40	16.80	40.50	40.50	40.50
7.	σ2GCA/ σ2SCA	0.01	0.28	0.12	0.66	0.15	0.42	0.42	0.42

* And** significant at 5% and 1% respectively.

Diameter of fruit (cm)
Among the eight parents, P_7 (0.03) showed significantly positive GCA effect for diameter of fruit and found the good combiner for this trait. The fruit diameter is significantly influenced by the general combining ability of various parental lines, as mentioned by different studies. Further research is essential to better understand the genetic mechanisms underlying this trait.

Fruit pedicel length (cm)
Among the eight parents, P_1 (0.28) and P_4 (0.29) showed significantly positive GCA effect for fruit pedicel length and were found the good combiner for this trait.

Number of seeds per fruit
Among the eight parents, P_4 (2.30), P_5 (3.89), P_7 (2.88) and P_8 (5.77) showed significantly positive GCA effect for number of seeds per fruit and were found the good combiner for this trait.

Average weight of fruit (g)
Among the eight parents, P_7 (0.22) and P_8 (0.33) showed significantly positive GCA effect for average weight of fruit and were found the good combiner for this trait. The current findings align with previous studies on the general combining ability of fruit weight. Patel *et al*. (2003) [11], Janaki *et al*. (2017) [7] and Aiswarya *et al*. (2020) [1].

Number of fruits per plant
Among the eight parents, P_3 (15.17) and P_5 (21.54) showed significantly positive GCA effect for number of fruits per plant and were found the good combiner for this trait.

Fruit yield per plant (g)
Among the eight parents, P_6 (45.37), P_7 (40.07) and P_8 (67.87) showed significantly positive GCA effect for yield per plant (g) and were found the good combiner for this trait.

Fruit yield per plot (kg)
Among the eight parents, P_6 (1.45), P_7 (1.28) and P_8 (2.17) showed significantly positive GCA effect for yield per plot and were registered the good combiner for this trait.

Fruit yield per hectare (q)
Among the eight parents, P_6 (25.20), P_7 (22.26) and P_8 (37.70) showed significantly positive GCA effect for yield per hectare and were recorded the good combiner for this trait. Navhale *et al*. (2014) [10] reported significant general combining ability effects in the parent BC-28, for fruit yield per plant. Similarly, Chakrabarty *et al*. (2019) [2] identified high GCA effects for fruit yield per plant. These findings are highly significant, emphasizing the role of genetic variability in plant breeding programs.

Specific combining ability
Specific combining ability for different cross combinations in chilli for different growth and yield characters are presented in Table 3.

Plant height (cm)
The estimates of specific combining ability varied from -6.78 to 16.79. Among the 28 cross combinations, eight crosses were recorded significant positive SCA effects for plant height and the highest SCA effects was exhibited by cross P_3 x P_8 (16.79) followed by cross P_3 x P_5 (15.10).

Number of primary branches per plant
For the number of primary branches per plant specific combining ability effects of hybrids varied from -0.77 to 1.07. Among the 28 cross combinations, four crosses were recorded significant positive SCA effects for number of primary branches per plant and the highest SCA effects was exhibited by cross P_2 x P_5 (1.07) followed by cross P_2 x P_3 (0.78), P_1 x P_7 (0.75) and P_1 x P_6 (0.69).

Plant spread (cm) (S-N)
In case of plant spread in South-North direction specific combining ability effects of hybrids varied from -11.02 to 9.93. Among the 28 cross combinations, 11 crosses were registered significant positive SCA effects for plant spread in South-North direction and the highest SCA effects was exhibited by cross P_3 x P_5 (9.93) followed by cross P_7 x P_8 (9.82) and P_4 x P_5 (9.05).

Plant spread (cm) (E-W)
Specific combining ability effects of hybrids for the plant spread in East-West direction varied from -10.18 to 10.45. Among the 28 cross combinations, 16 crosses were found the significant positive SCA effects for plant spread in East-West direction and the highest SCA effects was exhibited by cross P_7 x P_8 (10.45) which were followed by cross P_3 x P_5 (9.88), P_2 x P_6 (9.75) and P_4 x P_5 (8.55).

Days to flower initiation
The specific combining ability effects of hybrids for days to flower initiation varied from -3.26 to 6.31. Among the 28 cross combinations, 16 crosses were mentioned significant negative SCA effects for days to flower initiation and the maximum negative SCA effects was exhibited by cross P_6 x

P_7 (-3.26) which was followed by cross P_3 x P_5 (-2.49), P_2 x P_5 (-2.29) and P_3 x P_7 (-2.28).

Days to 50% flowering

The specific combining ability effects of hybrids for days to 50% flowering varied from -3.85 to 4.20. Among the 28 cross combinations, ten crosses were recorded significant negative SCA effects for days to 50% flowering and the maximum negative SCA effects was exhibited by cross P_1 x P_8 (-3.85) which was followed by cross P_1 x P_7 (-2.38).

Janaki *et al*. (2017) [7] and Thilak *et al*. (2019) [15] also reported notable negative SCA effects and this result in accordance with present findings highlighting their potential as good specific combiners. Overall, these findings indicate that specific hybrid combinations can significantly influence the expression of desirable traits in crop plants.

Days to fruit set

For days to fruit set specific combining ability effects of hybrids varied from -4.30 to 2.78. Out of the 28 cross combinations, 18 crosses were found significant negative SCA effects for days to fruit set and the maximum negative SCA effects was exhibited by cross P_1 x P_8 (-4.30) which was followed by cross P_2 x P_7 (-3.13), P_2 x P_6 (-2.58) and P_2 x P_5 (-2.48).

Length of fruit (cm)

The estimates of specific combining ability for the length of fruit varied from -1.22 to 1.74. Among the 28 cross combinations, 11 crosses were observed significant positive SCA effects for length of fruit and the highest SCA effects was exhibited by cross P_4 x P_7 (1.74) followed by cross P_3 x P_5 (1.36) and P_1 x P_4 (1.31).

Diameter of fruit (cm)

The estimates of specific combining ability for the diameter of fruit varied from -0.07 to 0.25. Among the 28 cross combinations, 6 crosses were observed significant positive SCA effects for diameter of fruit and the highest SCA effects was exhibited by cross P_3 x P_8 (0.25) followed by cross P_4 x P_5 (0.22). The present study concurs with previous findings that have reported significant specific combining ability (SCA) effects for fruit diameter in crop plants by Navhale *et al*. (2014) [10], Singh *et al*. (2014) and Nagaraja *et al*. (2016) [9] exhibited significant positive SCA effects for fruit diameter.

Fruit pedicel length (cm)

The estimates of specific combining ability for the fruit pedicel length varied from -0.62 to 1.16. Among the 28 cross combinations, seven crosses were registered significant positive SCA effects for fruit pedicel length and the highest SCA effects was exhibited by cross P_1 x P_4 (1.16) followed by cross P_2 x P_5 (0.97).

Number of seeds per fruit

The estimates of specific combining ability for the number of seeds per fruit varied from -7.74 to 15.21. Among the 28 cross combinations, four crosses were registered significant positive SCA effects for number of seeds per fruit and the highest SCA effects was exhibited by cross P_6 x P_8 (15.21) followed by cross P_2 x P_3 (13.36) and P_7 x P_8 (10.73).

Average weight of fruit (g)

The estimates of specific combining ability for the average weight of fruit varied from -0.60 to 0.96. Among the 28 cross combinations, 13 crosses were recorded significant positive SCA effects for average weight of fruit and the highest SCA effects was exhibited by cross P_1 x P_7 (0.96) followed by cross P_5 x P_6 (0.95).

Number of fruits per plant

The estimates of specific combining ability for the number of fruits per plant varied from -51.74 to 100.96. Among the 28 cross combinations, three crosses were mentioned significant positive SCA effects for number of fruits per plant and the highest SCA effects was exhibited by cross P_3 x P_5 (100.96) followed by cross P_6 x P_7 (59.96).

Fruit yield per plant (g)

The estimates of specific combining ability for the fruit yield per plant varied from -92.60 to 173.50. Among the 28 cross combinations, six crosses were recorded significant positive SCA effects for fruit yield per plant and the highest SCA effects was exhibited by cross P_6 x P_8 (173.50) followed by cross P_7 x P_8 (162.80) and P_2 x P_3 (124.40).

Similar findings were also in accordance with those of Navhale *et al.* (2014) [10] and Chakrabarty *et al.* (2019) [2] they found significant SCA effects for this character. These findings are vital for chilli breeding, underscoring the significance of carefully selecting parental lines to develop new varieties with desirable traits.

Fruit yield per plot (kg)

The estimates of specific combining ability for the fruit yield per plot varied from -2.96 to 5.55. Among the 28 cross combinations, six crosses were observed significant positive SCA effects for fruit yield per plot and the highest SCA effects was exhibited by cross P_6 x P_8 (5.55) followed by cross P_7 x P_8 (5.21) and P_2 x P_3 (3.98).

Fruit yield per hectare (q)

The estimates of specific combining ability for the fruit yield per hectare varied from -51.44 to 96.39. Among the 28 cross combinations, six crosses were registered significant positive SCA effects for fruit yield per hectare and the highest SCA effects was exhibited by cross P_6 x P_8 (96.39) followed by cross P_7 x P_8 (90.45) and P_2 x P_3 (96.11).

Gene action

The ratio of general combining ability variance to specific combining ability variance was recorded less than unity which indicates that, predominant role of additive gene action. The data estimating GCA and SCA variance is presented in Table 4. The magnitude of σ^2GCA/σ^2SCA was found to be less than 1, indicating the predominance of non-additive gene action for all the characters such as plant height, number of primary branches per plant, plant spread (S-N), plant spread (E-W), days to flower initiation, days to 50% flowering, days to fruit set, length of fruit, diameter of fruit, fruit pedicel length, number of seeds per fruit, number of fruits per plant, fruit yield per plant, fruit yield per plot and fruit yield per hectare except for average weight of fruit which showed additive gene action.

Heritability

Data regarding with heritability was depicted in Table 4. The narrow sense heritability for all yield and yield contributing characters ranged between 2.10 to 55.40 percent. The characters recorded high heritability estimates (h^2) were average weight of fruit (g) (55.40%.), plant height (43.60%), days to fruit set (43.10%), fruit pedicel length (35.10%), fruit yield per plant (40.50%), fruit yield per plot (40.50%) and fruit yield per hectare (40.50%). The characters registered moderate heritability estimates (h^2) in the plant spread (S-N) (21.00%), plant spread (E-W) (19.80%), days to flower initiation (11.80%), days to 50% flowering (23.40%), length of fruit (24.10%), number of seeds per fruit (18.70%) and number of fruits per plant (16.80%) whereas low heritability estimates (h^2) was mentioned in the number of primary branches per plant (7.70%).

When high heritability is coupled with a high genetic advance as a percentage of the mean (GAM), it suggests the presence of additive gene effects, indicating that selection would be an effective approach for trait improvement. High heritability accompanied by low genetic advance as a percentage of the mean (GAM) suggests the predominance of non-additive gene action, where the high heritability is largely influenced by environmental factors rather than genetic factors. As a result, selection for such traits may not be effective or rewarding. Low heritability combined with high genetic advance as a percentage of the mean (GAM) suggests that the trait is governed by additive gene effects, where the low heritability is due to favorable environmental influences, making selection effective. On the other hand, low heritability along with low GAM indicates that the trait is highly influenced by environmental factors, rendering selection was ineffective.

Similar findings were reported by Janaki *et al*. (2015) [8] and Chakrabarty (2019) [2] documented high heritability for the number of fruits per plant and plant height, the high heritability values for these traits suggest that the observed variation is primarily governed by genetic factors, with minimal environmental influence.

Conclusion

Estimation of GCA effects indicated that the parents Sel.10-2, Sel. 59-2-2, Sel.64-1 and Sel.14-6-2 were found as good general combiner for most of the yield and yield contributing characters. Whereas, the cross combinations P_2 x P_3, P_3 x P_5, P_3 x P_8, P_6 x P_7, P_6 x P_8, P_7 x P_8 exhibited highest percent of positive heterosis and significant SCA effect for yield and yield contributing characters. The magnitude of dominance variance was higher than additive variance for majority of the traits which indicated that, the involvement of non-additive gene action. The magnitude of σ^2GCA/σ^2SCA was found to be less than 1, indicating the predominance of non-additive gene action for all the characters except for average weight of fruit which showed additive gene action. The narrow sense heritability for all yield and yield contributing characters ranged between 2.10 to 55.40 percent.

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