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Heterosis and combining ability studies for yield and quality traits in pepper (*Capsicum annuum* L.)

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Abstract

Pepper (*Capsicum annuum* L.) is an important vegetable and spice crop valued for its economic and nutritional significance. However, productivity is often limited due to biotic and abiotic stresses, low yielding varieties and lack of suitable hybrids. Hence, the present study was undertaken to assess heterosis and combining ability for yield and horticultural traits in chilli, with the aim of identifying superior general and specific combiners for yield improvement. The experimental material consisting of eight parental genotypes and their 28 hybrids obtained through half-diallel mating design were evaluated for yield and horticultural traits in randomized block design with two replications at College of Horticulture, Bengaluru, Karnataka during 2024-25. Significant heterosis was observed for many traits, especially for earliness, yield and its components. Among the hybrids, CH-113 × CH-18 exhibited highest significant and positive heterobeltiosis (299.58%) and standard heterosis (43.84%) for fresh fruit yield per plant. Overall, combining ability analysis revealed that CH-113 as the best general combiner and CH-113 × CH-18 as the best specific combiner for yield and contributing traits with high gca and sca effects respectively. The predominance of non-additive gene action for all the traits suggests that these traits can be improved through hybridization.

Keywords: Pepper, *capsicum*, heterosis, combining ability, diallel, capsaicin, vitamin c, chilli, chlorophyll, seed, yield, quality, pericarp thickness, pedicel length

1. Introduction

Pepper (*Capsicum* spp.) is one of the most important vegetable and spice crop having economic importance. It is likely originated in Central America and Chile and was first domesticated in Mexico. It was introduced to Europe after being found by Christopher Columbus in tropical America (Perry *et al.*, 2007) [13]. The genus *Capsicum* belongs to the family Solanaceae and includes around 30 species, of which only five viz., *Capsicum annuum* L., *Capsicum frutescens* L., *Capsicum chinense* Jacq., *Capsicum baccatum* L. and *Capsicum pubescens* Ruiz and Pav are the cultivated species. Among them *Capsicum annuum* L. is the most commonly cultivated species due to its diverse types. Chilli is diploid having chromosome number of $2n=2x=24$, a genomic size of about 2700 Mb and approximately 30,701 genes (Moscone *et al.*, 2016) [10]. It is widely cultivated in tropical and subtropical regions, with India being the important producer and exporter of chilli. It plays an important role in our daily diet as well as in the food processing industry due to its pungency and flavor (Hasan *et al.*, 2014) [8]. The pungency in peppers is due to capsaicin ($C_{18}H_{27}NO_3$), a volatile alkaloid present in the placenta and pericarp, which is also used in pharmaceutical and cosmetic industry. Besides, capsaicin provides various health benefits, such as pain relief, reduced risk of type II diabetes and obesity, cancer prevention, relief from sinus congestion, protection against ulcers and improved health. The fruits are rich source of Vitamin A, C & E. Regular intake of 50-100 g of fresh chillies can meet approximately 60-100 per cent of the daily requirements of vitamin C and A and also provides strong antioxidant properties that help combat oxidative stress. Incorporating peppers in the diet is therefore useful for improving immunity and may help in lower the risk of various health issues, including some types of cancer, cardiovascular disorders and macular degeneration (Salim *et al.*, 2014) [16]. Despite its importance, productivity remains relatively low due to

factors such as low yield potential, susceptibility to various biotic and abiotic stresses. To address these challenges, heterosis breeding has emerged as a promising strategy for enhancing yield, quality and stress tolerance. Heterosis and combining ability form the foundation of hybrid breeding in chilli. F_1 hybrids often exhibit heterosis or hybrid vigour, resulting in superior performance compared to their parents. The success of any breeding programme largely depends on the selection of diverse and superior parental genotypes. In this context, combining ability analysis serves as an effective tool to evaluate genetic potential of parental genotypes and their crosses. General combining ability (GCA) indicates additive gene effects, while specific combining ability (SCA) indicates non-additive gene effects, both of them are crucial for designing an efficient breeding programme. The use of appropriate mating design such as diallel or line $\times$ tester helps in identifying suitable parents for developing high yielding chilli hybrids. Exploiting heterosis along with combining ability analysis thus provides a strong foundation for developing high yielding and stable pepper hybrids (Nagaraju *et al.*, 2017) [11]. The present study was undertaken to identify promising general and specific combiners and to assess the extent of heterosis in pepper.

2. Materials and Methods

The study was conducted at the Vegetable Science block of the College of Horticulture, UHS Campus, Bengaluru. The experiment involved eight diverse parental genotypes crossed in a half-diallel mating design to develop 28 F_1 hybrids. Hybridization was carried out during the winter of 2024 at the College of Horticulture, Bengaluru. The F_1 hybrids along with parents and a standard check were evaluated following randomized block design with two replications during *khari*f,

2025. In each genotype, five plants were randomly selected and tagged and data on their growth and earliness parameters like plant height (cm), plant spread in North-South and East-West directions (cm), primary and secondary branches (no), days to first flowering, fifty per cent flowering and first fruit picking were recorded. Five fruits were randomly selected from each of five tagged plants and yield and attributing traits such as fruit length (cm), fruit diameter (mm), pedicel length (cm), pericarp thickness (mm), no. of fruits/plant, fresh fruit yield/plant (g), duration of harvest (days), number of seeds and their test weight (g) were recorded and their average was worked out. Besides, quality parameters like chlorophyll content (mg/100g), capsaicin content (per cent) and vitamin C content (mg/100g) in fruits was also estimated. Heterosis was assessed by comparing the F_1 mean with the better parent (BP) values and by determining the percentage superiority over the hybrid check. Combining ability analysis was done using data from parents and hybrids following Griffing's (1956) [7] Model-I and Method-II.

3. Results and Discussion

3.1 Estimates of heterosis

3.1.1 Growth and earliness traits

Growth and flowering parameters are important as they influence overall plant development, productivity. Growth and earliness traits showed a wide range of heterosis, indicating substantial variability among hybrids. The hybrid, CH-1 $\times$ CH-116 demonstrated highest significant heterobeltiosis (28.31%) for plant height, plant spread showed wide variation in both North-South (-50.02 to 30.67%) and East-West (-39.84 to 68.45%) directions. Similarly, primary and secondary branches exhibited considerable heterosis, suggesting scope for improvement through hybridization.

Table 1: Per cent heterosis over better parent and commercial check for growth parameters

Sl. No.	Cross	Plant height		Plant spread (N-S)		Plant spread (E-W)		Primary branches		Secondary branches		Days to first flowering		Days to fifty per cent flowering		Days to first picking	
		BP	CC	BP	CC	BP	CC	CC	CC	BP	CC	BP	CC	BP	CC	BP	CC
1	CH-113 $\times$ CH-114	-	-	-	-	-	-	-15.00	-10.53	-	0.00	4.86*	28.86**	7.34	36.05**	-0.32	17.18**
2	CH-113 $\times$ CH-49	9.02	37.72**	23.11**	38.10**	19.31**	21.79**	4.76	15.79	25.00**	0.00	29.25**	-7.96**	23.42**	-1.16	12.50**	1.53
3	CH-113 $\times$ CH-115	-6.19	36.77**	-14.63*	31.27**	21.87**	24.27**	-5.00	0.00	23.53**	1.96	26.08**	-6.22*	14.68**	8.14	23.42**	6.11
4	CH-113 $\times$ CH-1	17.63**	28.14**	-1.54	20.74**	20.09**	22.54**	-20.83	0.00	-14.71*	13.73	1.19	26.62**	-1.69	34.88**	25.06**	15.27**
5	CH-113 $\times$ CH-20	12.98*	21.63**	21.21**	9.30	-5.18	-8.09	5.00	10.53	19.12**	7.84	21.14**	-7.21**	21.43**	2.33	12.62**	0.38
6	CH-113 $\times$ CH-18	13.94*	34.92**	9.56	-11.80*	22.01**	24.40**	0.00	36.84*	4.41	39.22**	17.72**	12.19**	20.41**	-9.30	19.27**	-7.25*
7	CH-113 $\times$ CH-116	3.56	33.50**	-14.49*	29.94**	21.13**	23.55**	-13.04	5.26	-8.82	21.57*	30.95**	13.68**	31.78**	-15.12*	26.92**	-5.73
8	CH-114 $\times$ CH-49	-	-	-17.04*	37.86**	-13.39*	31.87**	-33.33*	-26.32	-5.66	-1.96	26.58**	-4.48	18.02**	5.81	-1.62	15.65**
9	CH-114 $\times$ CH-115	-	-	-0.99	32.20**	-9.28	36.53**	-16.67	-21.05	27.27**	-21.57*	-5.88**	19.40**	2.75	30.23**	12.67**	20.99**
10	CH-114 $\times$ CH-1	-	-	-	5.79	-	32.68**	-20.83	0.00	-11.11	-5.88	5.17*	31.59**	5.93	45.35**	21.59**	20.61**
11	CH-114 $\times$ CH-20	7.98	15.75**	16.35**	4.91	32.32**	7.50	-5.56	-10.53	14.81	21.57*	13.36**	6.47*	18.75**	5.81	12.34**	3.05
12	CH-114 $\times$ CH-18	-7.09	27.50**	-14.63*	31.83**	-3.12	22.08**	-26.92*	0.00	15.69	15.69	-7.69**	13.43**	-6.42	18.60**	-8.44**	7.63*
13	CH-114 $\times$ CH-116	-10.02*	29.79**	5.73	-13.38*	68.45**	27.46**	-13.04	5.26	28.57**	23.53*	16.62**	4.23	12.84**	10.47	25.15**	-3.44
14	CH-49 $\times$ CH-115	0.13	32.51**	-3.14	27.44**	13.60*	-10.63*	28.57	42.11*	43.64**	54.90**	27.92**	-6.22*	18.02**	5.81	32.23**	-6.11

15	CH-49 × CH-1	10.57	32.46**	-4.46	28.43**	-3.23	23.87**	4.17	31.58	24.07**	31.37**	33.84**	13.93**	26.27**	1.16	35.98**	-1.53
16	CH-49 × CH-20	8.47	24.75**	-0.17	-9.98	35.45**	10.05	47.62**	63.16**	38.89**	47.06**	13.38**	12.69**	-7.14	20.93**	-6.25*	8.78**
17	CH-49 × CH-18	22.08**	30.52**	-4.95	24.10**	5.35	15.26**	-11.54	21.05	-3.77	0.00	10.71**	16.17**	-1.80	26.74**	-7.89**	6.87*
18	CH-49 × CH-116	3.52	33.53**	18.86**	-2.63	37.85**	8.45	26.09	52.63**	30.19**	35.29**	13.00**	13.18**	-5.41	22.09**	14.79**	9.92**
19	CH-115 × CH-1	18.32**	44.95**	30.93**	52.70**	39.84**	57.91**	-27.08*	-7.89	38.18**	33.33**	31.86**	67.29**	22.03**	67.44**	-8.56**	40.65**
20	CH-115 × CH-20	-13.98*	40.33**	-13.71*	22.19**	7.71	-12.49*	82.35**	63.16**	30.91**	41.18**	38.82**	22.39**	25.89**	-3.49	29.75**	-2.67
21	CH-115 × CH-18	9.02	26.52**	22.56**	38.16**	-12.53	29.65**	3.85	42.11*	29.09**	39.22**	26.27**	-6.47*	20.18**	1.16	27.55**	0.38
22	CH-115 × CH-116	-8.03	38.01**	-11.20	27.26**	-4.53	27.76**	0.00	21.05	-9.09	-1.96	18.43**	3.48	13.76**	9.30	30.85**	-4.20
23	CH-1 × CH-20	16.15**	41.84**	38.21**	44.28**	26.37**	40.18**	50.00**	-36.84*	46.30**	43.14**	25.84**	-7.21**	26.27**	1.16	23.08**	18.32**
24	CH-1 × CH-18	21.04**	26.06**	-14.44*	31.67**	36.74**	49.12**	53.85**	-36.84*	44.44**	41.18**	-4.77*	19.15**	11.86**	20.93**	20.84**	21.76**
25	CH-1 × CH-116	28.31**	17.60**	30.67**	7.05	37.59**	4.11	29.17*	63.16**	27.78**	35.29**	11.73**	10.45**	17.80**	12.79*	35.24**	-0.38
26	CH-20 × CH-18	-8.68	36.65**	36.77**	42.99**	25.05**	39.11**	-15.38	15.79	3.70	9.80	-2.96	14.18**	-11.61*	15.12*	20.07**	23.28**
27	CH-20 × CH-116	-5.34	34.34**	20.46**	28.28**	18.19**	33.53**	43.48**	-31.58	38.89**	35.29**	-3.08	21.14**	-8.04	19.77**	-7.40**	19.47**
28	CH-18 × CH-116	-7.03	40.30**	50.02**	59.05**	27.41**	41.62**	38.46**	-15.79	31.37**	31.37**	13.23**	8.46**	-9.35	12.79*	0.59	29.77**
	S.Em±	3.26	3.26	4.49	4.49	4.01	4.01	0.78	0.78	1.24	1.24	1.06	1.06	2.60	2.60	2.07	2.07
	CD at 5%	9.46	9.46	13.03	13.03	11.63	11.63	2.26	2.26	3.60	3.60	13.03	13.03	7.54	7.54	6.00	6.00

*, ** Significant at 5% and 1% probability level, respectively

Table 2: Per cent heterosis over better parent and commercial check for fruit traits

Sl. No.	Cross	Fruit length		Fruit diameter		Pedicel length		Pericarp thickness	
		BP	CC	BP	CC	BP	CC	BP	CC
1	CH-113 × CH-114	-18.50 **	-26.39 **	-38.13**	-31.36**	0.88	-4.27	-69.01 **	-13.16
2	CH-113 × CH-49	1.84	-22.41 **	4.40	-19.79**	10.48 **	-2.77	-52.11 **	34.21 **
3	CH-113 × CH-115	-27.90 **	-45.07 **	-11.48**	-20.33**	33.92 **	1.26	-58.22 **	17.11
4	CH-113 × CH-1	2.41	-21.98 **	-24.16**	-31.13 **	36.73 **	11.40 **	-25.35 **	109.21 **
5	CH-113 × CH-20	2.24	-22.11 **	-26.09 **	-26.21 **	16.02 **	10.48 **	-30.99 **	93.42 **
6	CH-113 × CH-18	-6.92	-29.08 **	-24.32**	-31.36 **	8.38 **	4.11	-26.06 **	107.24 **
7	CH-113 × CH-116	1.55	-22.63 **	-4.71	-30.09 **	48.75 **	19.70 **	-50.47 **	38.82 **
8	CH-114 × CH-49	-7.43 *	-16.40 **	-7.62**	2.49	7.07 **	1.59	-46.93 **	13.82
9	CH-114 × CH-115	-23.24 **	-30.68 **	36.68 **	51.65**	17.67 **	11.65 **	22.91 **	189.47 **
10	CH-114 × CH-1	-26.39 **	-33.52 **	-31.10 **	-23.55 **	8.83 **	3.27	-6.44	100.66 **
11	CH-114 × CH-20	-18.28 **	-26.20 **	-6.99 **	3.18	-18.66 **	-22.55 **	-38.65 **	31.58 **
12	CH-114 × CH-18	-26.34 **	-33.48 **	-32.90 **	-25.55 **	0.70	-3.27	-44.94 **	39.47 **
13	CH-114 × CH-116	-2.47	-11.92 **	-17.70**	-8.68 **	25.80 **	19.36 **	-21.47 **	68.42 **
14	CH-49 × CH-115	-15.01 **	-38.81 **	35.86**	22.29 **	31.24 **	15.51 **	53.91 **	262.50 **
15	CH-49 × CH-1	7.47	-22.63 **	-19.38 **	-26.78 **	8.00 **	-4.95 *	-22.03 **	51.32 **
16	CH-49 × CH-20	31.83 **	-5.10	-28.21 **	-28.32 **	-3.87	-8.47 **	7.46	108.55 **
17	CH-49 × CH-18	16.71 **	-15.99 **	30.59 **	18.44 **	16.14 **	11.57 **	-46.75 **	34.87 **
18	CH-49 × CH-116	31.26 **	-5.51 *	5.85	-18.67 **	36.19 **	19.87 **	-6.10	82.24 **
19	CH-115 × CH-1	-6.80	-39.47 **	-21.07**	-28.32 **	-19.03 **	-34.03 **	-45.67 **	27.96 **
20	CH-115 × CH-20	-11.20 **	-39.14 **	3.079	2.92	12.15 **	6.79 **	-33.52 **	56.58 **
21	CH-115 × CH-18	29.16 **	-16.12 **	-2.96	-11.99**	0.00	-3.94	-13.25 **	119.74 **
22	CH-115 × CH-116	46.26 **	-5.01	-25.10 **	-32.59 **	95.42 **	57.25 **	-49.72 **	18.42 *
23	CH-1 × CH-20	9.41 *	-25.02 **	-18.39 **	-18.52 **	18.66 **	12.99 **	-20.56 **	29.61 **
24	CH-1 × CH-18	52.82 **	-22.37 **	-31.06**	-37.39 **	-11.34 **	-14.84 **	3.38	161.84 **
25	CH-1 × CH-116	28.98 **	-26.61 **	-18.95 **	-26.40 **	29.84 **	5.78 *	-6.05	53.29 **
26	CH-20 × CH-18	12.92 **	-22.61 **	-28.90**	-29.01 **	-1.66	-5.53 *	-47.79 **	32.24 **
27	CH-20 × CH-116	-15.19 **	-41.88 **	-7.50 **	-7.64**	-8.27 **	-12.66 **	-14.95 *	19.74 *
28	CH-18 × CH-116	32.17 **	-24.80 **	7.33 *	-2.65	-0.79	-4.69	-18.18 **	107.24 **
	S. Em±	0.32	0.32	0.35	0.35	0.08	0.08	0.04	0.04
	CD at 5%	0.93	0.93	1.02	1.02	0.23	0.23	0.17	0.17

*, ** Significant at 5% and 1% probability level, respectively

Table 3: Per cent heterosis over better parent and commercial check for yield and its attributing traits

Sl. No.	Cross	No. of fruits/plant		Fresh fruit yield/plant		Average fruit weight		Duration of harvest	
		BP	CC	BP	CC	BP	CC	BP	CC
1	CH-113 × CH-114	-10.90	-22.54 **	8.49	-60.95 **	-47.39**	-58.19 **	0.00	-18.25 **
2	CH-113 × CH-49	8.11	-6.01	51.42 *	-45.49 **	29.45	-32.69 **	4.65	-14.45 **
3	CH-113 × CH-115	13.16	-1.62	53.86 **	-39.45 **	-9.20	-41.22 **	4.65	-14.45 **
4	CH-113 × CH-1	-19.05 *	-19.42 *	52.81 **	-39.70 **	47.99 **	-23.67*	8.84	-11.03 **
5	CH-113 × CH-20	23.04 *	12.37	-26.17 *	-50.68 **	-13.51	-36.42 **	-8.84	-25.48 **
6	CH-113 × CH-18	166.62 **	131.79 **	299.58 **	43.84 **	12.96	-34.35 **	26.51 **	3.42
7	CH-113 × CH-116	28.86 **	12.02	90.30 **	-31.50 **	24.07	-36.00 **	11.40 *	-8.94 *
8	CH-114 × CH-49	-49.20 **	-63.12 **	7.32	-64.93 **	62.60**	29.22 **	2.35	-25.48 **
9	CH-114 × CH-115	-56.34 **	-71.33 **	15.67	-54.48 **	90.52**	51.40 **	-18.73 **	-36.50 **
10	CH-114 × CH-1	-70.96 **	-71.10 **	-44.78 *	-78.21 **	-18.75	-35.43**	-16.71 **	-36.50 **
11	CH-114 × CH-20	-65.19 **	-68.21 **	-38.46 **	-58.90 **	83.75 **	45.92 **	-14.36 **	-33.08 **
12	CH-114 × CH-18	-60.20 **	-67.75 **	-41.28	-79.54 **	-4.37	-24.00 *	-4.52	-23.76 **
13	CH-114 × CH-116	-33.61 **	-54.57 **	33.78	-58.61 **	37.70 **	9.4371	2.35	-25.48 **
14	CH-49 × CH-115	-12.58	-36.53 **	60.79 **	-36.72 **	102.43 **	31.04 **	2.19	-20.15 **
15	CH-49 × CH-1	-33.68 **	-33.99 **	-2.46	-61.51 **	30.25	-32.28 **	16.71 **	-11.03 **
16	CH-49 × CH-20	-13.80	-21.27 *	-25.61 *	-50.31 **	57.77**	15.97	15.82 **	-9.51 *
17	CH-49 × CH-18	-29.24 **	-42.66 **	94.05 **	-32.39 **	162.39 **	52.48 **	9.52 *	-12.55 **
18	CH-49 × CH-116	26.11 *	-8.44	88.44 **	-38.42 **	97.61 **	2.73	21.20 **	-11.98 **
19	CH-115 × CH-1	-62.02 **	-62.20 **	-71.84 **	-88.89 **	-46.54 **	-65.39 **	-32.65 **	-47.38 **
20	CH-115 × CH-20	-16.46	-23.70 **	-7.22	-38.02 **	27.02 *	-6.62	-4.62	-25.48 **
21	CH-115 × CH-18	-28.67 **	-42.20 **	29.93	-48.87 **	67.77 **	8.60	2.86	-17.87 **
22	CH-115 × CH-116	-10.64	-38.84 **	39.19	-45.22 **	61.12**	4.30	-4.62	-25.48 **
23	CH-1 × CH-20	-56.91 **	-57.11 **	-57.62 **	-71.69 **	-18.91	-40.39**	11.19 *	-13.12 **
24	CH-1 × CH-18	-66.32 **	-66.47 **	-44.38 *	-78.05 **	35.042 *	-21.52 *	3.33	-17.49 **
25	CH-1 × CH-116	-11.03	-11.45	79.76 **	-29.06 **	32.75	-36.92 **	34.41 **	2.47
26	CH-20 × CH-18	-58.10 **	-61.73 **	-70.52 **	-80.31 **	-42.11 **	-57.45**	7.14	-14.45 **
27	CH-20 × CH-116	-57.97 **	-61.62 **	-58.49 **	-72.28 **	-10.13	-33.94**	2.43	-19.96 **
28	CH-18 × CH-116	-43.65 **	-54.34 **	0.36	-65.03 **	38.31 *	-19.61 *	-4.29	-23.57 **
S. Em±		18.87	18.87	97.86	97.86	0.57	0.57	4.87	4.87
CD at 5%		54.75	54.75	283.94	283.94	1.65	1.65	14.13	14.13

*, ** Significant at 5% and 1% probability level, respectively

Table 4: Per cent heterosis over better parent and commercial check for seed and quality traits

Sl. No.	Cross	No. of seeds/ fruit		Seed test weight		Chlorophyll content		Capsaicin content		Vitamin C content	
		BP	CC	BP	CC	BP	CC	BP	CC	BP	CC
1	CH-113 × CH-114	-56.05 **	-59.22 **	-11.90 **	-31.07 **	-41.26 **	-21.05 **	8.05	-35.83 **	89.96 **	3.92
2	CH-113 × CH-49	97.64 **	-5.94 *	13.41 **	-11.27 **	-46.16 **	-27.63 **	-35.42 **	-49.75 **	-27.33 **	-4.53
3	CH-113 × CH-115	74.49 **	-28.89 **	-5.01	-25.68 **	-49.99 **	-32.79 **	-22.11 **	-39.80 **	-53.89 **	-37.25 **
4	CH-113 × CH-1	14.35 **	-33.34 **	-4.23	-25.07 **	-49.90 **	-32.66 **	-20.02 **	-41.24 **	-22.43 **	-22.43 **
5	CH-113 × CH-20	-20.83 **	-33.35 **	-31.34 **	-44.55 **	-29.11 **	-4.72	-31.76 **	-47.59 **	-56.60 **	-54.90 **
6	CH-113 × CH-18	-4.15	-51.85 **	-4.28	-25.11 **	-65.37 **	-53.46 **	-32.85 **	-59.91 **	-62.35 **	-37.25 **
7	CH-113 × CH-116	18.58 **	-44.39 **	11.12 *	-13.07 **	1.41	36.30 **	37.02 **	-18.63 **	42.29 **	-22.16 **
8	CH-114 × CH-49	5.94 *	-1.70	33.98 **	1.27	-15.97	-47.10 **	-17.25 **	-35.62 **	-50.75 **	-35.29 **
9	CH-114 × CH-115	29.21 **	19.90 **	44.12 **	6.57	8.48	-31.70 **	-10.77 *	-31.03 **	-61.09 **	-47.06 **
10	CH-114 × CH-1	-26.48 **	-31.78 **	15.63 **	-14.50 **	10.65	-30.34 **	-38.09 **	-54.51 **	-54.90 **	-54.90 **
11	CH-114 × CH-20	-49.35 **	-53.00 **	6.47	-14.01 **	-28.40 **	-48.64 **	-49.20 **	-60.99 **	-8.68 *	-5.10
12	CH-114 × CH-18	-2.17	-9.22 **	4.36	-22.83 **	8.16	-31.91 **	-1.81	-41.38 **	-76.47 **	-60.78 **
13	CH-114 × CH-116	-0.83	-7.98 **	45.78 **	7.80 *	12.90	-28.92 **	29.13 **	-26.87 **	78.26 **	-19.61 **
14	CH-49 × CH-115	107.10 **	-1.43	20.31 **	-9.06 *	22.28	-52.86 **	-22.82 **	-39.95 **	-63.11 **	-49.80 **
15	CH-49 × CH-1	12.85 **	-34.21 **	-2.97	-26.66 **	144.88 **	8.10	-25.42 **	-41.97 **	-7.46 **	21.57 **
16	CH-49 × CH-20	-24.47 **	-36.41 **	8.09	-12.70 **	-37.57 **	-55.22 **	-1.75	-23.55 **	-38.81 **	-19.61 **
17	CH-49 × CH-18	70.63 **	-14.29 **	50.08 **	13.43 **	-21.58	-69.77 **	-21.05 **	-38.58 **	-26.12 **	23.14 **
18	CH-49 × CH-116	81.57 **	-13.59 **	32.47 **	0.12	-0.68	-44.93 **	-16.73 **	-35.21 **	-38.75 **	-19.53 **
19	CH-115 × CH-1	-10.32 *	-47.72 **	2.10	-32.46 **	9.39	-51.71 **	-18.37 **	-36.91 **	-68.30 **	-56.86 **
20	CH-115 × CH-20	-5.74 *	-20.64 **	-0.25	-19.44 **	-22.72 **	-44.57 **	-25.41 **	-42.35 **	-46.69 **	-27.45 **
21	CH-115 × CH-18	99.16 **	0.04	23.48 **	-15.60 **	244.21 **	24.29 **	-9.83	-30.30 **	-62.82 **	-38.04 **
22	CH-115 × CH-116	116.13 **	1.35	16.55 **	-21.76 **	-1.37	-45.31 **	-52.69 **	-63.43 **	-36.31 **	-13.33 **
23	CH-1 × CH-20	-25.09 **	-36.93 **	-25.48 **	-39.81 **	-19.03 *	-41.92 **	-16.92 **	-36.20 **	15.09 **	19.61 **
24	CH-1 × CH-18	11.71 **	-34.88 **	-17.03 **	-43.28 **	241.19 **	50.62 **	-25.34 **	-45.14 **	-42.35 **	-3.92
25	CH-1 × CH-116	17.40 **	-31.56 **	16.24 **	-21.97 **	24.88 *	-30.75 **	30.61 **	-4.04	-37.73 **	-37.73 **
26	CH-20 × CH-18	-44.99 **	-53.68 **	-30.38 **	-43.77 **	9.48	-21.47 **	-30.40 **	-46.54 **	-49.41 **	-15.69 **
27	CH-20 × CH-116	-34.88 **	-45.18 **	-19.11 **	-34.67 **	-32.85 **	-51.83 **	-13.72 **	-33.74 **	-18.87 **	-15.69 **
28	CH-18 × CH-116	25.64 **	-36.89 **	9.92	-24.87 **	23.09 *	-31.74 **	2.28	-38.93 **	-49.90 **	-16.50 **
S.Em±		3.46	3.46	0.22	0.22	0.11	0.11	0.03	0.03	3.82	3.82
CD at 5%		10.04	10.04	0.64	0.64	0.32	0.32	0.09	0.09	11.08	11.08

*, ** Significant at 5% and 1% probability level, respectively

Table 5: General combining ability effects of parental genotypes for growth, earliness, yield and quality parameters

Sl. No.	Parent Parameters	CH-113	CH-114	CH-49	CH-115	CH-1	CH-20	CH-18	CH-116	S.E.m±	CD at 5%
1.	Plant height (cm)	-1.89 **	2.23**	-1.02	-1.67 *	-0.28	2.44**	-0.33	0.53	0.69	2.00
2.	Plant spread (N-S) (cm)	3.59 **	-4.65 **	1.76	-4.35**	-4.36**	7.07 **	-3.19**	4.12**	0.95	2.76
3.	Plant spread (E-W) (cm)	3.34**	1.03	5.22**	-4.88 **	-7.63 **	3.24**	-4.96 **	4.64 **	0.85	2.47
4.	Primary branches (no.)	-0.1	-0.78**	0.62**	0.08	-0.12	-0.18	0.22	0.25	0.16	0.46
5.	Secondary branches (no.)	1.09**	-0.83**	1.39 **	0.39	-1.23 **	-0.06	-0.43	-0.33	0.26	0.75
6.	Days to first flowering	-2.81 **	2.17 **	-0.88 **	0.45	3.73 **	-1.55 **	-1.36 **	0.24	0.22	0.64
7.	Days to fifty per cent flowering	-2.84 **	2.41 **	-0.44	0.96	4.66 **	-1.19 *	-2.34 **	-1.24 *	0.54	1.57
8.	Days to first picking	-3.27 **	0.63	-2.62**	1.64**	7.54 **	-2.05 **	-1.62**	-0.25	0.44	1.28
9.	Fruit length (cm)	0.05	0.50 **	0.67 **	-0.49 **	-0.64 **	-0.04	-0.24 **	0.19 **	0.07	0.20
10.	Fruit diameter (mm)	-1.59**	1.54 **	0.41 **	1.19**	-1.06 **	0.31 **	-0.12	-0.67**	0.07	0.20
11.	Pedicle length (cm)	-0.01	0	0.04 *	0.03 *	-0.15 **	-0.07 **	-0.06 **	0.21 **	0.02	0.06
12.	Pericarp thickness (mm)	0.03 **	-0.01	0.04 **	0.11 **	-0.01	-0.09 **	0.09 **	-0.16 **	0.01	0.03
13.	No. of fruits/plant	77.23 **	-56.70 **	2.13	-14.80 **	-9.95 *	-4.75	7.65	-0.80	3.91	11.34
14.	Fresh fruit yield/plant (kg/plant)	168.01 **	-128.97 **	29.86	19.38	-97.61 **	0.16	22.18	-13.01	20.28	58.84
15.	Average fruit weight (g)	-1.11 **	1.02**	0.88 **	0.52 **	-1.12 **	0.15	-0.03	-0.30 *	0.11	0.32
16.	Duration of harvest (days)	7.38 **	-9.42 **	2.88 **	-6.47 **	0.03	-0.39	4.63 **	1.36	1.03	2.98
17.	No. of seeds/fruit	-17.41 **	17.04 **	8.96 **	11.38 **	-8.88 **	-5.50 **	-3.96 **	-1.63 **	0.57	1.65
18.	Seed test weight (g)	-0.12 *	0.49 **	0.65 **	-0.27 **	-0.44 **	-0.29 **	-0.16 **	0.15 **	0.05	0.14
19.	Chlorophyll content (mg/100g)	0.42 **	-0.06 *	-0.25 **	-0.16 **	0.09 **	-0.08 **	0.04	0.00	0.02	0.06
20.	Capsaicin content (%)	-0.03 **	-0.03 **	0.03 **	0.01	0.02 **	0.00	-0.03 **	0.02 **	0.01	0.03
21.	Vitamin C content (mg/100g)	-10.51 **	-17.45 **	15.41 **	-3.33 **	3.36 **	5.88 **	16.00 **	-9.35 **	0.81	2.35

* and ** Significant at 5 and 1 per cent probability level, respectively

Early flowering is commonly associated with early yield and hence negative heterosis is desirable. It was observed from the study that many hybrids showed negative heterosis for earliness parameters. Maximum heterosis in the desired negative direction was observed over better parent (-38.82%) and standard check (-22.39%) in the cross CH-115 × CH-20. For days to fifty per cent flowering the highest negative heterobeltiosis (-31.78%) and standard heterosis (-15.12%) was manifested in CH-113 × CH-116. Early picking benefit farmers to improve their income therefore negative heterosis is desirable for this trait. In this regard, the cross CH-49 × CH-1 exhibited significant heterobeltiosis (-35.98%) followed by CH-49 × CH-115 (-32.23%), while CH-113 × CH-18 displayed standard heterosis (-7.25%) (Table 1.) These results suggest the possibility of selecting hybrids suitable for early production. Similar findings were reported in chilli (Rohini and Lakshmanan, 2017; Farwah *et al.*, 2020) [14, 6].

3.1.2 Yield and contributing traits

Fruit traits are crucial in peppers as they directly influence market quality and yield. Fruit length and diameter are significant because they determine fruit size, consumer preference and marketable yield. Fruit length showed heterobeltiosis range of -27.90 to 52.82 per cent and none among 28 hybrids showed positive heterosis over check. Among the crosses, CH-114 × CH-115 demonstrated highest and significant heterosis over better parent and check for fruit diameter (36.68%, 51.65% respectively). Pedicel length influences ease of harvest and reduces fruit damage by providing stronger support for heavier fruits therefore, highest heterosis is desirable. The hybrid combination, CH-115 × CH-116 exhibited highest significant heterosis over better parent (95.42%) and check variety (57.25%). In the study pericarp thickness showed a wide range of heterobeltiosis (-69.01% in CH-113 × CH-114 to 53.91% in CH-49 × CH-115) and twenty five crosses showed significant and positive standard heterosis was for pericarp thickness (Table 2).

Number of fruits per plant, fresh fruit yield per plant and average fruit weight are key yield-determining traits in chilli, as

they directly influence total productivity, marketability and profitability. Among the hybrids, CH-113 × CH-18 manifested highest significant heterobeltiosis and standard heterosis for number of fruits per plant (166.62%, 131.79%), fresh fruit yield per plant (299.58%, 43.84%). Wide range of heterobeltiosis (-47.39 and 162.39%) and standard heterosis (-37.39 to 51.65%) observed for average fruit weight. The heterosis over better parent varied from -32.65 to 34.41 per cent and -47.38 to 3.42 per cent for duration of harvest. Therefore, crosses with highest heterosis can be exploited for heterosis breeding (Table 3). Singh *et al.* (2014) [16] reported similar findings where heterosis relative to better parent ranged from -71.82 to 331.11 per cent for total fruit yield per plant, -79.30 to 205.95 per cent for number of fruits per plant and -28.65 to 57.52 per cent for average fruit weight. Similar findings were reported in chilli by many researchers (Sahid *et al.*, 2020 and Singh *et al.*, 2022) [15, 18].

3.1.3 Seed and quality traits

Consumers usually prefer fruits with fewer seeds, but very low seed content can make the fruits soft, reduce shelf life and transportability. So, the choice for fewer or more seeds in a fruit depends on the purpose for which it will be used. For number of seeds per fruit, the heterosis relative to better parent, the values ranged between -49.35 and 116.13 per cent and standard heterosis varied from -59.22 to 19.90 per cent. Highest significant heterobeltiosis (50.08%) and standard heterosis (13.43%) was noted in the cross, CH-49 × CH-18. Highest magnitude of heterobeltiosis for chlorophyll content (244.21%) in the fruits was manifested in the hybrid, CH-115 × CH-18 whereas, CH-1 × CH-18 displayed standard heterosis of 50.62 per cent. The cross, CH-113 × CH-116 exhibited highest significant heterobeltiosis (37.02%) and none among 28 hybrids showed positive heterosis over check for capsaicin content. The highest magnitude of heterobeltiosis (89.96%) and standard heterosis (23.14%) was observed in the cross combination, CH-113 × CH-114 and CH-49 × CH-18 respectively (Table 4). These results align with previous finding of Naresh *et al.* (2016) [12]; Aiswarya *et al.* (2020) [1].

Table 6: Specific combining ability effects of hybrids for growth and earliness parameters

Sl. No.	Cross	Plant height (cm)	Plant spread (N-S) (cm)	Plant spread (E-W) (cm)	Primary branches (no.)	Secondary branches (no.)	Days to first flowering	Days to fifty per cent flowering	Days to first picking
1.	CH-113 × CH-114	-12.75 **	-5.29	-4.03	-0.09	-1.19	8.16 **	8.77 **	6.09 **
2.	CH-113 × CH-49	-0.42	-14.56 **	-8.60 **	-0.24	-3.41 **	-3.60 **	-4.38 *	-0.91
3.	CH-113 × CH-115	1.05	-2.92	-0.40	-0.46	-2.16 *	-4.23 **	-1.78	-2.17
4.	CH-113 × CH-1	7.12 **	5.61	3.68	-0.26	0.96	5.69 **	6.02 **	-2.07
5.	CH-113 × CH-20	10.02 **	18.49 **	3.88	0.31	-0.96	-2.63 **	-2.13	-2.23
6.	CH-113 × CH-18	1.31	11.67 **	-0.42	1.16 *	3.41 **	-4.82 **	-5.98 **	-7.66 **
7.	CH-113 × CH-116	1.68	-10.31 **	-9.37 **	-0.37	1.06	-7.01 **	-9.58 **	-8.03 **
8.	CH-114 × CH-49	-1.90	-6.12 *	-14.01 **	-1.57 **	-1.74 *	-7.17 **	-6.63 **	4.44 **
9.	CH-114 × CH-115	-5.72 *	4.57	-7.49 **	-0.78	-3.24 **	1.10	2.47	3.68 **
10.	CH-114 × CH-1	-6.56 **	-16.07 **	-1.78	0.42	0.39	2.72 **	5.27 **	-2.47
11.	CH-114 × CH-20	10.97 **	23.18 **	18.14 **	-0.02	2.71 **	-2.10 **	-5.88 **	-4.38 **
12.	CH-114 × CH-18	3.59	3.71	3.67	0.08	2.34 **	0.51	0.77	-1.81
13.	CH-114 × CH-116	0.75	11.33 **	32.04 **	0.31	3.24 **	-4.78 **	-3.83 *	-10.43 **
14.	CH-49 × CH-115	3.86	2.00	8.18 **	0.82	4.29 **	-6.16 **	-5.18 **	-10.82 **
15.	CH-49 × CH-1	2.52	1.21	0.78	0.52	2.91 **	-12.54 **	-10.88 **	-13.72 **
16.	CH-49 × CH-20	6.45 **	4.71	15.90 **	2.08 **	3.74 **	3.44 **	3.47 *	2.62
17.	CH-49 × CH-18	4.24	3.54	4.71	-0.32	-1.89 *	4.65 **	7.12 **	0.94
18.	CH-49 × CH-116	0.78	13.62 **	13.28 **	1.16 *	2.51 **	1.86 *	4.02 *	1.57
19.	CH-115 × CH-1	-7.62 **	-12.31 **	-15.21 **	-0.82	-4.34 **	18.79 **	16.22 **	9.64 **
20.	CH-115 × CH-20	-6.35 **	0.95	8.73 **	2.62 **	3.99 **	-11.99 **	-8.43 **	-9.15 **
21.	CH-115 × CH-18	8.35 **	-1.72	3.78	1.22 *	4.11 **	-5.78 **	-5.28 **	-7.57 **
22.	CH-115 × CH-116	-2.44	-0.20	-4.37	0.19	-1.24	-3.37 **	-2.88	-11.95 **
23.	CH-1 × CH-20	-9.04 **	-16.92 **	-9.74 **	-1.93 **	-5.14 **	-9.17 **	-10.13 **	-1.30
24.	CH-1 × CH-18	7.36 **	3.54	-8.39 **	-2.33 **	-4.51 **	1.24	-0.48	0.53
25.	CH-1 × CH-116	13.80 **	27.56 **	22.81 **	2.39 **	5.14 **	-3.85 **	-5.08 **	-15.35 **
26.	CH-20 × CH-18	-4.51 *	-17.04 **	-11.59 **	0.23	0.81	4.52 **	2.87	11.12 **
27.	CH-20 × CH-116	-3.38	-12.44 **	-16.92 **	-2.04 **	-5.04 **	5.73 **	3.77 *	7.24 **
28.	CH-18 × CH-116	-5.76 **	-27.08 **	-14.92 **	-1.69 **	-4.16 **	0.44	1.92	13.57 **
S.E.m±		1.29	1.81	1.01	0.50	0.80	0.69	1.66	1.09
CD at 5%		3.74	5.25	2.93	1.45	2.32	2.00	4.82	3.16

* and ** Significant at 5 and 1 per cent probability level, respectively

Table 7: Specific combining ability effects of hybrids for yield and its attributing traits

Sl. No.	Cross	Fruit length (cm)	Fruit diameter (mm)	Pedicle length (cm)	Pericarp thickness (mm)	No. of fruits/plant	Fresh fruit yield/plant (g)	Average fruit weight (g)	Duration of harvest (days)
1.	CH-113 × CH-114	-0.50 *	-2.16 **	-0.10 *	-0.36 **	-2.80	-120.65	-2.24**	4.60
2.	CH-113 × CH-49	-0.21	0.46*	-0.09	-0.22 **	-25.88 *	-89.67	-0.56	-2.70
3.	CH-113 × CH-115	-1.64 **	-0.39	0.04	-0.36 **	0.55	-4.97	-0.72*	6.65 *
4.	CH-113 × CH-1	1.14 **	0.47 *	0.53 **	0.11 **	-42.80 **	108.99	1.98**	4.65
5.	CH-113 × CH-20	0.53 *	-0.27	0.41 **	0.13 **	20.75	-123.71	-0.06	-13.93 **
6.	CH-113 × CH-18	-0.06	-0.50 *	0.21 **	0.01	266.60 **	1015.25 **	0.24	19.05 **
7.	CH-113 × CH-116	0.24	0.20	0.41 **	-0.01	16.05	125.11	0.41	6.07
8.	CH-114 × CH-49	0.02	0.22	0.02	-0.26 **	-15.45	-31.40	1.04**	-0.40
9.	CH-114 × CH-115	-0.45 *	5.83 **	0.33 **	0.33 **	-16.28	107.43	2.74**	-5.55
10.	CH-114 × CH-1	-0.63 **	-1.68 **	0.27 **	0.11 **	-20.63	-67.07	-0.86*	-12.05 **
11.	CH-114 × CH-20	-0.39	0.41	-0.59 **	-0.07 **	-19.58	72.39	2.48**	-7.13 *
12.	CH-114 × CH-18	-1.01 **	-2.88 **	-0.03	-0.22 **	-30.98 *	-203.19 **	-1.26**	0.10
13.	CH-114 × CH-116	1.01 **	-0.14	0.38 **	0.14 **	5.97	89.11	1.03**	1.12
14.	CH-49 × CH-115	-1.55 **	3.14 **	0.41 **	0.57 **	0.15	166.69 *	1.64**	3.65
15.	CH-49 × CH-1	0.45 *	-0.97**	-0.02	-0.12 **	0.80	-20.78	-0.53	9.15 **
16.	CH-49 × CH-20	1.85 **	-2.55**	-0.21 **	0.17 **	23.10	19.02	1.10**	11.57 **
17.	CH-49 × CH-18	0.81 **	3.97**	0.38 **	-0.28 **	-35.55 **	217.12 **	3.49**	2.55
18.	CH-49 × CH-116	1.57 **	-0.31	0.36 **	0.15 **	46.90 **	178.26 **	0.76*	6.57 *
19.	CH-115 × CH-1	-0.32	-1.95 **	-0.88 **	-0.28 **	-43.28 **	-346.58 **	-2.17**	-29.29 **
20.	CH-115 × CH-20	-0.88 **	0.72**	0.26 **	-0.09 **	34.77 **	180.40 **	0.10	-0.07
21.	CH-115 × CH-18	1.96 **	-0.77**	-0.08	-0.03	-17.63	25.21	1.19**	4.90
22.	CH-115 × CH-116	2.79 **	-2.90**	1.48 **	-0.16 **	-1.93	105.17	1.21**	-1.82
23.	CH-1 × CH-20	0.88 **	0.19	0.63 **	-0.08 **	-42.33 **	-116.15	-0.29	9.68 **
24.	CH-1 × CH-18	1.39 **	-1.81**	-0.21 **	0.25 **	-74.98 **	-216.30 **	1.02**	-1.10
25.	CH-1 × CH-116	0.47 *	0.16	0.13 **	0.08 **	52.47 **	420.64 **	0.36	28.43 **
26.	CH-20 × CH-18	0.77 **	-2.10**	-0.02	-0.17 **	-69.93 **	-341.74 **	-2.41**	3.32
27.	CH-20 × CH-116	-1.87 **	1.21 **	-0.50 **	0.03	-61.23 **	-207.91 **	-0.72*	-0.65
28.	CH-18 × CH-116	0.28	2.31 **	-0.28 **	0.19 **	-57.88 **	-140.95 *	0.32	-10.43 **
S.E.m±		0.20	0.22	0.05	0.02	11.99	62.17	0.35	3.17
CD at 5%		0.58	0.64	0.14	0.06	34.79	180.39	1.01	9.20

* and ** Significant at 5 and 1 per cent probability level, respectively

Table 8: Specific combining ability effects of hybrids for seed and quality parameters

Sl. No.	Cross	No. of seeds/ fruit	Seed test weight (g)	Chlorophyll content (mg/100g)	Capsaicin content (%)	Vitamin C (mg/100 g)
1.	CH-113 × CH-114	-42.00 **	-0.92 **	-0.16 *	0.07 **	51.76 **
2.	CH-113 × CH-49	44.36 **	0.14	-0.10	-0.10 **	9.92 **
3.	CH-113 × CH-115	8.21 **	0.18	-0.29 **	0.00	-6.11 *
4.	CH-113 × CH-1	21.94 **	0.39 **	-0.53 **	-0.02	2.94
5.	CH-113 × CH-20	18.54 **	-0.95 **	0.18 *	-0.06 **	-34.07 **
6.	CH-113 × CH-18	-10.19 **	0.10	-0.90 **	-0.12 **	-25.44 **
7.	CH-113 × CH-116	-1.56	0.52 **	0.91 **	0.16 **	15.95 **
8.	CH-114 × CH-49	16.13 **	0.29 *	0.00	0.02	-15.82 **
9.	CH-114 × CH-115	45.44 **	1.54 **	0.22 **	0.07 **	-9.58 **
10.	CH-114 × CH-1	-10.22 **	0.42 **	0.00	-0.13 **	-24.61 **
11.	CH-114 × CH-20	-44.78 **	0.30 *	-0.20 *	-0.17 **	25.79 **
12.	CH-114 × CH-18	18.00 **	-0.37 *	0.01	0.03	-43.50 **
13.	CH-114 × CH-116	17.49 **	1.19 **	0.11	0.09 **	25.61 **
14.	CH-49 × CH-115	22.18 **	0.43 **	0.00	-0.05 *	-45.36 **
15.	CH-49 × CH-1	-5.71 **	-0.48 **	0.94 **	-0.08 **	23.78 **
16.	CH-49 × CH-20	-12.33 **	0.23	-0.13	0.09 **	-22.48 **
17.	CH-49 × CH-18	18.63 **	1.69 **	-0.54 **	0.00	12.81 **
18.	CH-49 × CH-116	17.33 **	0.56 **	-0.01	-0.03	-7.17 **
19.	CH-115 × CH-1	-27.98 **	0.08	-0.32 **	-0.02	-40.82 **
20.	CH-115 × CH-20	8.42 **	0.74 **	-0.01	-0.05 *	-12.08 **
21.	CH-115 × CH-18	37.26 **	0.83 **	1.21 **	0.09 **	-33.45 **
22.	CH-115 × CH-116	36.86 **	0.14	-0.10	-0.24 **	18.15 **
23.	CH-1 × CH-20	4.75 **	-0.35 *	-0.21 **	-0.01	31.23 **
24.	CH-1 × CH-18	6.23 **	-0.69 **	1.48 **	-0.05 *	-3.89
25.	CH-1 × CH-116	8.76 **	0.30 *	-0.07	0.23 **	-14.46 **
26.	CH-20 × CH-18	-24.79 **	-0.87 **	0.23 **	-0.04 *	-18.91 **
27.	CH-20 × CH-116	-14.62 **	-0.63 **	-0.31 **	0.01	6.44 *
28.	CH-18 × CH-116	-3.99 *	-0.16	-0.04	0.00	-4.55
S.E.m±		1.74	0.14	0.07	0.02	2.47
CD at 5%		5.05	0.40	0.20	0.06	7.17

* and ** Significant at 5 and 1per cent probability level, respectively.

Table 9: Estimates of combining ability variances for growth, earliness, yield and quality parameters

Sl. No.	Trait	GCA variance	SCA variance	GCA/SCA variance
1.	Plant height (cm)	2.15	44.17	0.05
2.	Plant spread (N-S) (cm)	20.77	158.21	0.13
3.	Plant spread (E-W) (cm)	24.63	158.26	0.16
4.	Primary branches (no.)	0.14	1.45	0.09
5.	Secondary branches (no.)	0.75	10.27	0.07
6.	Days to first flowering	6.11	43.48	0.14
7.	Days to fifty per cent flowering	11.61	73.47	0.16
8.	Days to first picking	11.84	79.65	0.15
9.	Fruit length (cm)	0.20	1.80	0.11
10.	Fruit diameter (mm)	1.17	4.62	0.25
11.	Pedicle length (cm)	0.01	0.28	0.04
12.	Pericarp thickness (mm)	0.007	0.05	0.14
13.	No. of fruits/plant	1351.50	4585.01	0.29
14.	Fresh fruit yield/plant (kg/plant)	7575.61	78344.85	0.10
15.	Average fruit weight (g)	0.65	3.22	0.20
16.	Duration of harvest (days)	29.76	131.31	0.23
17.	No. of seeds/fruit	132.59	898.13	0.15
18.	Seed test weight (g)	0.15	0.78	0.20
19.	Chlorophyll content (mg/100g)	0.04	0.30	0.13
20.	Capsaicin content (%)	0.0006	0.015	0.06
21.	Vitamin C (mg/100g)	149.66	926.41	0.16

GCA- General Combining ability

SCA- Specific Combining Ability

3.2 Combining ability analysis

Combining ability studies help in understanding the performance of parental genotypes and their hybrids and provide insights into the nature of gene action controlling different traits (Sprague and Tatum, 1942) ^[20]. Parental genotypes with significant gca effects

in desirable direction are considered good general combiners as they contribute favourable genes for the improvement of particular trait. High sca effects in specific cross combinations indicate the superior performance due to specific parental interactions.

Combining ability analysis revealed that CH-20 exhibited significant and positive gca effects for plant height (2.44) and plant spread in North-South direction (7.07), indicating its suitability as a good general combiner for these traits (Table 5). The hybrid CH-1 × CH-116 showed high sca effects for plant height (13.80) and plant spread (N-S) (27.56), suggesting its potential as a superior specific combiner as shown in Table 6.

CH-49 was identified as best general combiner for several traits, including plant spread in East-West direction (5.22), primary (0.62) and secondary branches (1.39), fruit length (0.67), pedicel length (0.04), seed test weight (0.65) and capsaicin content (0.03). The hybrid CH-1 × CH-116 also recorded high sca effects for plant spread (E-W) (22.81), primary (2.39) and secondary branches (5.14), duration of harvest (28.43) and capsaicin content (0.23).

Further, CH-113 was identified as best general combiner for earliness and yield traits, with desirable gca effects for days to first flowering (-2.81), days to fifty per cent flowering (-2.84), days to first picking (-3.27), number of fruits per plant (77.23), fruit yield per plant (168.01), duration of harvest (7.38) and chlorophyll content (0.42). The hybrid CH-49 × CH-1 exhibited high sca effects for earliness traits particularly days to first flowering (-12.54) and days to fifty per cent flowering (-10.88), indicating its suitability for developing early maturing hybrids. CH-113 × CH-18 displayed highest positive and significant sca effects for number of fruits per plant (266.60), fresh fruit yield per plant (1015.25), thus this hybrid can be exploited through hybridization for obtaining maximum yield as it was found the best specific combiner for yield (Table 7). CH-1 × CH-18 was found best specific combiner for chlorophyll content (1.48) and CH-18 was best general combiner (16.00) and CH-113 × CH-114 was best specific combiner (51.76) for vitamin C content as they displayed highest significant sca effects for these traits as in Table 8. Identification of good general and specific combiners indicates the involvement of both additive and non-additive gene actions. Similar findings have been reported earlier in chilli (Chakrabarty *et al.*, 2024 and Komala *et al.* 2024) [3,9].

The ratio of GCA to SCA variance gives information on the genetic control of characters (Falconer and Mackay, 1996) [5]. A GCA: SCA ratio value of more than one indicates predominance of additive gene action, suggesting that improvement through selection would be more effective. In such cases desirable traits can be fixed through selection in successive generations. However, when GCA to SCA ratio is less than one, non-additive gene action plays a major role in character inheritance indicating the importance of hybridization and exploitation of heterosis. If this ratio is equal to one, it indicates that both additive and non-additive gene actions are equally important in the inheritance of the trait (Singh and Chaudhary, 1985) [19]. In such cases, hybridization followed by selection in later generations may be useful for crop improvement.

Overall, for all the twenty-one characters observed, SCA variance was higher than GCA variance which resulted in low GCA to SCA variance ratio (<1.00), indicating the preponderance of non-additive gene action in the inheritance (Table 9). Hence, appropriate breeding strategies should be adopted for improved expression of these traits. Either we can exploit heterosis breeding and utilize hybrid vigour alternatively; true breeding lines with improved characters can be developed by postponing the selections to later generations for fixation of these traits. These results are in concurrence with earlier studies (Verma, 2022; Akshay, 2024 and Deep, 2025) [21, 2, 4].

4. Conclusion

The present study revealed considerable heterosis for yield and

its contributing traits in pepper, indicating good scope for hybrid development. Best general combiner with high gca effects can be utilized in breeding programmes for varietal improvement and can be used as one of the parents in hybridization. The hybrids with high sca effects for different traits are best specific combiners and can be exploited through hybridization for improvement of these traits. Non-additive component of genetic variance was higher than additive component and hence heterosis breeding is an effective approach for improving chilli productivity.

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