International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(10): 888-893
www.biochemjournal.com
Received: 19-07-2025
Accepted: 21-08-2025

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Synergizing genetics and environment: Evaluation of GCA & SCA in *Capsicum* spp. across agro-climatic zones for fruit yield and nutraceutical traits

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DOI: https://www.doi.org/10.33545/26174693.2025.v9.i10Sk.5936

Abstract
The present investigation aimed to estimate the combining ability of parents and hybrids in *Capsicum annuum* L. over the three different locations of Gujarat, under the jurisdiction of Anand Agricultural University (AAU) during *Kharif-rabi* 2024-25. The experimental materials consisted of 37 genotypes comprising 28 hybrids developed using half diallel mating design, eight parental genotypes and one standard check GAVCH-1. The analysis of variance for combining ability across three environments revealed highly significant mean squares for both GCA and SCA for all studied traits indicating the involvement of both additive and non-additive gene action to their expression. However, characters *viz.* days to 50% flowering, plant height, number of branches per plant, fruits per plant, average fruit length, average fruit girth, pedicel length, average fruit weight, fruit yield per plant, test weight, chlorophyll content and ascorbic acid content exhibited GCA/SCA ratios less than 1, showed the predominance of non-additive gene action. Based on the general combining ability analysis, the parental lines ACS-18-03, G-4, ACS-20-20 and ACS-20-22 were found to be good general combiners and hybrids G-4 × GP-20, GVC-101 × ACS-18-03, and ACS-18-03 × ACS-20-20 emerged as the top specific combiners for fruit yield per plant, suggesting the presence of favorable non-additive gene action in these combinations. The inclusion of ACS-18-03 in two of these top-performing crosses further underlines its versatility as a parental line and its potential role in enhancing yield through hybridization.

Keywords: *Capsicum annuum*, General Combining Ability (GCA), Specific Combining Ability (SCA), Additive and non-additive gene action, variance

Introduction
Vegetables play a vital role in ensuring global food security and nutrition by supplying essential vitamins, minerals, and dietary fiber. The global demand for vegetables has been steadily rising, driven by increased awareness of their health benefits and improved economic conditions. Leading producers of vegetables include countries like China, India, the United States, and Turkey (Keatinge *et al*., 2011) [8]. Despite this growth, the vegetable sector faces ongoing challenges such as significant post-harvest losses, limited storage infrastructure, and fluctuating market prices, which hinder consistent supply and profitability. Chilli peppers (*Capsicum* spp.) are widely cultivated in tropical and subtropical regions due to their adaptability and economic importance. While green chilli fruits are consumed as vegetables, the dried red fruits serve as popular spices (Kumari *et al.*, 2017) [9]. India holds the distinction of being the world's largest producer, consumer, and exporter of chillies, followed by China, Thailand, Ethiopia, and Indonesia. Among Indian varieties, the G-4 green chilli, commonly known as Guntur green chilli, dominates the export market (Anonymous, 2024) [2]. The Guntur district in Andhra Pradesh, famed as the 'Chilli Capital of India,' hosts Asia's largest red chilli market, with varieties like Guntur Sannam and Guntur Teja prized for their vibrant red color and intense heat, respectively (Enroute Indian History). Meanwhile, the Byadagi chilli from Karnataka is well-known for its oil oleoresin, an important ingredient in cosmetic products such as nail polish and lipstick (Lokeshvarappa, 2007) [10].
The chilli fruit, botanically classified as a berry, consists of three main parts: the pericarp, placenta, and seeds.

The placental tissue contains oil-rich bubbles responsible for synthesizing capsaicinoids, the group of compounds that impart pungency (Zamljen *et al.*, 2021) [12]. Pungency is a complex and highly variable trait influenced by environmental factors. Capsaicinoids include capsaicin, dihydrocapsaicin, nordihydrocapsaicin, homocapsicin, and others, with capsaicin and dihydrocapsaicin constituting about 80% of the total pungent compounds. The production of these alkaloids is genetically controlled by multiple genes (Hornero-Méndez *et al.*, 2002 [6]; Manjula *et al.*, 2011) [11].
In chilli breeding, selecting parents based solely on their individual performance may not guarantee the inheritance of desired traits in the offspring, especially for complex, polygenic traits like green fruit quality. Therefore, estimating the general combining ability (GCA) and specific combining ability (SCA) of parents and hybrids is essential. GCA primarily reflects additive gene action and guides the selection of parents, whereas SCA is associated with non-additive gene action specific to hybrid combinations. Assessing GCA and SCA not only aids in identifying superior parents and promising hybrids but also provides insight into the underlying gene action, helping breeders devise effective strategies for trait improvement.

Materials & Methods

The experimental material comprising eight parental lines (Table 1) and one standard check (GAVCH-1) were procured from Main Vegetable Research Station (MVRS), Anand Agricultural University (AAU), Anand. The parental lines were crossed in half diallel mating design at MVRS, AAU, Anand during *kharif-rabi* season of the year 2023-2024. In the present study, eight parents, 28 hybrids and one standard check formed the experimental materials for evaluation at different geographical loations *Viz.*, Main Vegetable Research Station, AAU, Anand (E_1); Agricultural Research Station, AAU, Derol (E_2) and Agricultural Research Station, AAU, Jabugam (E_3). The experimental materials consisted of 37 genotypes comprising 28 hybrids developed using half diallel mating design, eight parental genotypes and one standard check GAVCH-1. Observations were recorded for different quantitative and qualitative characters *viz.*, number of fruits per plant, average fruit length, average fruit girth, average fruit weight, fruit yield per plant, capsaicin content and ascorbic acid content.

Combining Ability Analysis

Combining ability analysis was computed on data obtained for parents and F_1s following Griffing (1956) [5] Model-I and method-II. The method -II is meant for a diallel having parents and their F_1s excluding reciprocals, while in Model - I.

Estimation of general and specific combing ability effects

General combining ability (GCA) effect of i^{th} parent.

$$g_i = \frac{1}{(P+2)} \left[\sum(X_{i.} + X_{ii}) - \frac{2}{P} X_{..} \right]$$

Specific combining ability (SCA) effect of ij^{th} cross/ hybrid

$$S_{ij} = X_{ij} - \frac{1}{(P+2)} (X_{i.} + X_{ii} + X_{.j} + X_{jj}) + \frac{2}{(P+1)(P+2)} X_{..}) \ (i \neq j)$$

Test of significance of GCA and SCA effects

Each GCA and SCA estimate was subjected to ‘t’ test, and both GCA and SCA were tested against zero for their significance.

't' test for GCA = $\frac{g_i - 0}{SE\,(g_i)}$ and 't' test for SCA = $\frac{S_{ij} - 0}{SE\,(S_{ij})}$

The ‘t’ values thus obtained were compared with the table ‘t’ value at 0.05 and 0.01 probability levels at error degree of freedom. Since the error degree of freedom is greater than 30, the value of calculated 't' is regarded as significant if it exceeds 1.96. Hence, all the GCA and SCA effects would be significant at 5 per cent level of significance, if their estimates are larger than the S.E. ($\hat{g}_i/\hat{s}_{ij}$) x 1.96. By similar analogy, any gca and sca effects greater than S.E. ($\hat{g}_i/\hat{s}_{ij}$) x 2.58 are regarded as significant at 1 per cent level of significance.

Estimation of components of genetic variances

The genetic variances $\hat{\sigma}^2$gca and $\hat{\sigma}^2$sca were calculated as under:

$$\hat{\sigma}^2_{gca} = \frac{MSg - MSe^1}{1(P+2)}$$

$\hat{\sigma}^2_{gca}$ = Variance due to general combining ability, and it was equated as V_A (Additive genetic variance) as:

$$\hat{\sigma}^2_{gca} = \frac{1}{2}\hat{\sigma}^2_A = \frac{1}{2}V_A \text{ or } \hat{\sigma}^2_A = 2\hat{\sigma}^2_{gca} = V_A$$

$$\hat{\sigma}^2_{sca} = \frac{MSs - MSe^1}{1}$$

$\hat{\sigma}^2_{sca}$ =Variance due to specific combining ability, and it has equal amount /quantity of V_D *i.e.*, Variance due to dominance deviation.

Results & Discussion

In chilli, consistent efforts have been made to improve fruit yield and other yield-contributing traits through hybridization strategies. A key step in any successful hybrid breeding program is the careful selection of parents. Not all parental lines, even if phenotypically desirable, combine well in hybrid combinations. Some lines may consistently produce superior progenies when crossed, while others may perform poorly despite appearing promising. Identifying parental lines that reliably produce high-performing hybrids is of immense value to plant breeders aiming to develop superior cultivars.

ANOVA of Combining Ability

The pooled analysis over environments demonstrated highly significant GCA and SCA effects studied traits, confirming the involvement of both additive and non-additive gene actions in the inheritance of these traits in chilli. Environmental variances were significant for fruits per plant, average fruit weight and fruit yield per plant, indicating that environment strongly influences the expression of these traits. GCA × Environment (GCA × E) interaction was significant for a subset of traits including fruits per plant, average fruit length, average fruit girth, average fruit weight and capsaicin content, suggesting that the additive genetic effects of parental lines for these traits vary with environmental conditions. SCA × Environment (SCA × E) interaction was significant for fruits per plant and average fruit girth indicates that non-additive gene effects for these traits are strongly influenced by the environment

(Table 1). In the present investigation, non-additive gene action was observed for average fruit length, average fruit girth, average fruit girth and fruit yield per plant which is in accordance with the findings of Kaur *et al.* (2017) and Chakrabarty *et al.* (2019) [3]; Janaki *et al.* (2018) [7] and Aiswarya *et al.* (2019) [1].

Table 1: Analysis of variance for combining ability over the environments for different characters

		GCA	SCA	ENV. (E)	GCA × E	SCA × E	Pooled error	σ^2_{gca}	σ^2_{sca}	$\sigma^2_{gca}/\sigma^2_{sca}$	σ^2_A	σ^2_D
	df	7	28	2	14	56	216					
1	Fruits per plant	2078.966**	1070.223**	8980.107**	622.605**	337.088**	195.399	62.791	291.614	0.222	125.583	291.614
2	Average fruit lrngth	25.261**	10.576**	3.322	2.203*	1.421	1.102	0.813	3.164	0.263	1.624	3.162
3	Average fruit girth	0.689**	0.187**	0.017	0.033**	0.028**	0.008	0.021	0.063	0.331	0.045	0.064
4	Average fruit weight	107.423**	38.794**	4.016**	1.995**	1.102	0.794	3.553	12.671	0.282	7.100	12.670
5	Fruit yield per plant	0.074**	0.024**	0.248**	0.013	0.007	0.007	0.012	0.013	0.923	0.024	0.013
6	Capsaicin content	17.681**	0.897**	0.016	0.021*	0.006	0.006	0.595	0.360	1.971	1.180	0.352
7	Ascorbic acid content	1121.861**	1619.983**	1.562	3.708	4.413	14.385	36.923	535.210	0.073	73.840	535.212

*, ** Significant at 5 and 1 percent levels, respectively

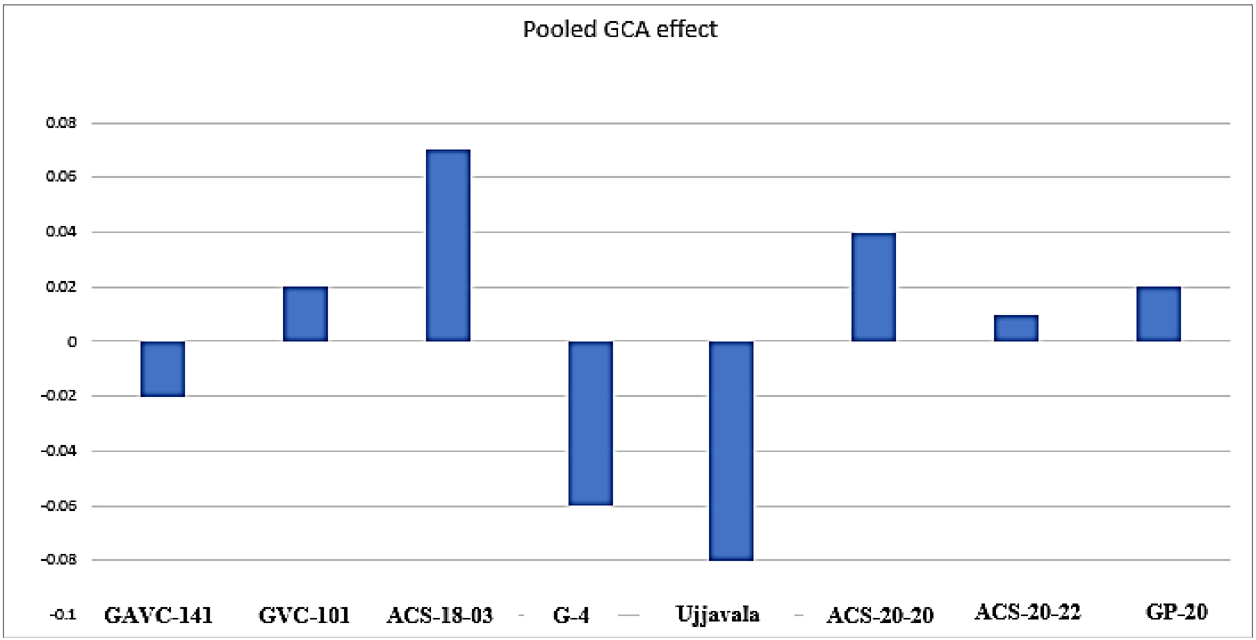

Fig 1: General combining ability effects of parents in pooled over environments for fruit yield per plant

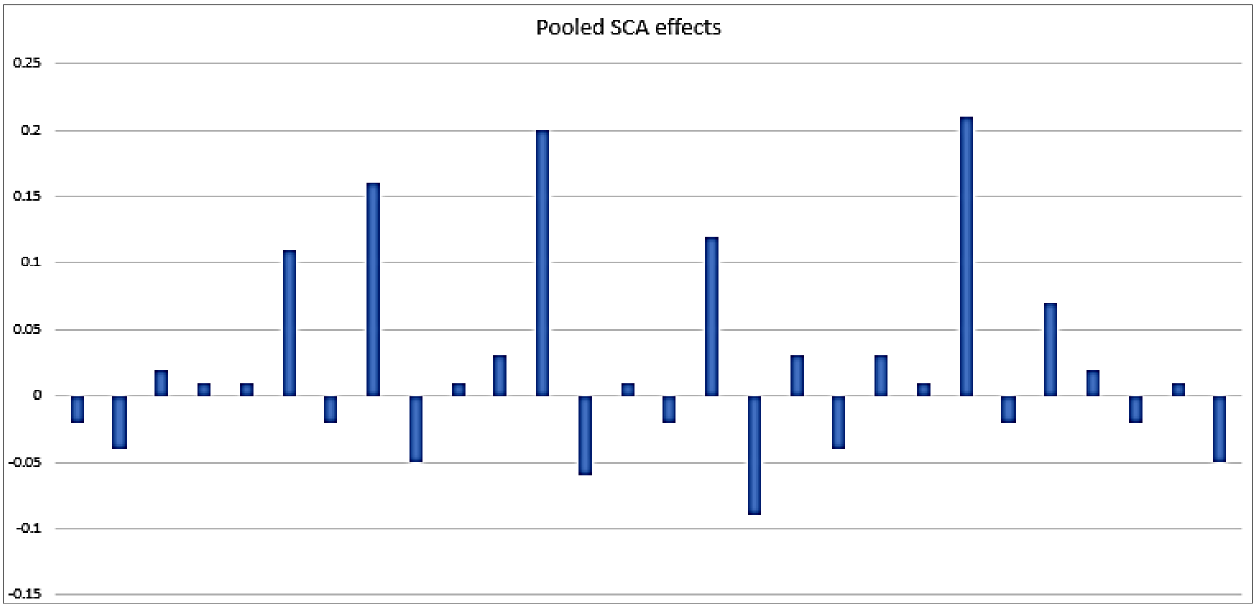

Fig 2: Specific combining ability effects of crosses in pooled over environments for fruit yield per plant

General and Specific Combining Ability

Fruit-associated attributes (Fruits per plant, Fruit length, Fruit girth, Fruit weight)

The evaluation of fruit-related traits in chilli identified key parents and hybrids with consistent combining abilities across multiple environments. ACS-20-20 and ACS-20-22 consistently emerged as good general combiners for fruit length, fruit girth, and fruit weight, with ACS-20-20 recording significant positive GCA effects for fruit weight (E1: 4.26, E2: 2.65, E3: 2.89, PEVs: 3.27), fruit length (E1: 0.97, E2: 1.36, E3: 0.60, PEVs: 0.98), and fruit girth (E1: 0.32, E2: 0.24, E3: 0.18, PEVs: 0.24). Similarly, ACS-20-22 showed positive GCA effects for fruit weight (E1: 1.59, E2: 2.46, E3: 2.46, PEVs: 2.17), fruit length (E1: 0.84, E2: 1.73, E3: 1.01, PEVs: 1.19), and fruit girth (E1: 0.17, E2: 0.29, E3: 0.12, PEVs: 0.19). In contrast, G-4 and GVC-101 were identified as excellent general combiners for fruits per plant, with G-4 showing very high positive GCA effects (E1: 30.27, E2: 8.29, E3: 10.23, PEVs: 16.26) and GVC-101 also performing well (E1: 6.09, E2: 5.36, E3: 10.23, PEVs: 7.23). However, both G-4 and GVC-101 exhibited significantly negative GCA effects for other traits. For instance, G-4 showed GCA values of -1.72 (E1), -1.41 (E2), -2.03 (E3), and -1.72 (PEVs) for fruit length, and -2.63 (E1), -2.39 (E2), -2.15 (E3), -2.39 (PEVs) for fruit weight, indicating their limited utility beyond improving fruit number. Ujjavala, GAVC-141, and GP-20 showed non-significant or mixed GCA effects and were considered average combiners across traits. Among hybrids, GVC-101 × ACS-20-20 (E1: 38.11, E2: 57.68, E3: 29.03, PEVs: 41.61), G-4 × GP-20 (E1: 39.26, E2: 21.76, E3: 40.29, PEVs: 33.77), and GVC-101 × ACS-20-22 (E1: 23.03, E2: 14.56, E3: 19.63, PEVs: 19.08) were top specific combiners for fruits per plant. For fruit length, hybrids such as ACS-18-03 × G-4 showed strong SCA effects (E2: 4.16, E3: 3.51, PEVs: 3.39), as did GAVC-141 × Ujjavala in E1 (3.59). In contrast, GAVC-141 × ACS-18-03 showed negative SCA effects (E1: -3.84, E2: -2.28, E3: -3.68, PEVs: -3.27), marking it as a poor specific combiner. For fruit girth, high SCA values were observed in GAVC-141 × ACS-20-22 (E1: 0.48, PEVs: 0.22), ACS-20-20 × GP-20 (E2: 0.26), and G-4 × Ujjavala (E3: 0.33). Regarding fruit weight, the best specific combiners were ACS-20-22 × GP-20 (E1: 5.76, E2: 3.83, PEVs: 3.74) and ACS-18-03 × G-4 (E3: 3.02), while crosses such as GVC-101 × ACS-20-20 (PEVs: -5.30), ACS-20-20 × ACS-20-22 (PEVs: -6.57), and GAVC-141 × ACS-20-20 (PEVs: -3.52) were poor specific combiners. Overall, ACS-20-20 and ACS-20-22 stand out as elite general combiners across multiple fruit traits, while specific hybrids like GVC-101 × ACS-20-20, ACS-20-22 × GP-20, and ACS-18-03 × G-4 show promise for targeted trait improvement in chilli breeding programs.

Fruit Yield per Plant

Parents exhibiting significant and positive GCA effects are considered as good general combiners, as they contribute favourably to increasing fruit yield. In this study, ACS-18-03 showed significant positive GCA effects in E_1 (0.11), E_2 (0.07) and PEVs (0.07), establishing it as a superior general combiner (Table 2). Similarly, ACS-20-20 demonstrated significant positive GCA in E_2 (0.07), E_3 (0.07) and PEVs (0.04) marking it as valuable parent for improving fruit yield. Conversely, parents with significant negative GCA effects are considered poor general combiners, as they negatively influencing fruit yield. Here, Ujjavala (E_1: -0.09, E_2: -0.09, E_3: -0.05, PEVs: -0.08) and G-4 (E_1: -0.05, E_2: -0.07, E_3: -0.06, PEVs: -0.06) showed negative significant effect in all environments. These parents may not be desirable in breeding programs aimed at increasing fruit yield.

The specific combining ability effects of crosses for fruit yield per plant varied from -0.14 to 0.34 in E_1, -0.13 to 0.17 in E_2, -0.12 to 0.28 in E_3 and -0.09 to 0.21 in PEVs. In all, five hybrids each in E_1 and PEVs, 10 in E_2 and seven in E_3 exhibited significant positive SCA effects. Notably, crosses G-4 × GP-20 (E_1: 0.34, PEVs: 0.21), GVC-101 × ACS-18-03 and GVC-101 × ACS-20-22 in E_2 (0.17) as they exhibited significant positive SCA effects in all environments and pooled data. On the other hand, hybrid ACS-18-03 × ACS-20-22 (E_2, E_3 and PEVs), had significant negative SCA effect and was identified as poor specific combiners (Table 3). Fig. 2 shows the SCA effects of hybrids in in individual as well as pooled over environments.

Table 2: Estimates of general combining ability effects for fruit yield per plant

Sr. No.	Parents	E_1	E_2	E_3	Pooled
1	GAVC- 141	-0.06 **	0.01	-0.01	-0.02
2	GVC - 101	0.05 *	-0.01	0.02 *	0.02
3	ACS- 18 -03	0.11 **	0.07 **	0.02	0.07**
4	G -4	-0.05 *	-0.07 **	-0.06 **	-0.06**
5	Ujjavala	-0.09 **	-0.09 **	-0.05 **	-0.08**
6	ACS-20-20	-0.01	0.07 **	0.07 **	0.04**
7	ACS-20-22	0.01	-0.02	0.03 **	0.01
8	GP -20	0.04 *	0.04 **	-0.02	0.02
SE (g_i) ±		0.02	0.01	0.01	0.01
Min.		-0.09	-0.09	-0.06	-0.08
Max.		0.11	0.07	0.07	0.07
No. of significant parents		6	5	5	4
No. of significant +ve parents		3	3	3	2
No. of significant -ve parents		3	2	2	2

*, ** Significant at 5 and 1 percent levels, respectively

Table 3: Estimates of specific combining ability effects for fruit yield per plant

Sr. No.	Hybrids	E_1	E_2	E_3	Pooled
1	GAVC-141 × GVC- 101	-0.04	0.05	-0.08 **	-0.02
2	GAVC-141 × ACS-18-03	-0.14 *	0.06 *	-0.04	-0.04
3	GAVC-141 × G-4	0.03	-0.02	0.04	0.02
4	GAVC-141 × Ujjavala	-0.09	0.13 **	0.01	0.01
5	GAVC-141 × ACS-20-20	0.01	0.04	-0.05 *	0.01
6	GAVC-141 × ACS-20-22	0.18 **	-0.02	0.17 **	0.11*
7	GAVC-141 × GP-20	-0.01	-0.02	0.01	-0.02
8	GVC- 101 × ACS-18-03	0.17 **	0.17 **	0.12 **	0.16**
9	GVC- 101 × G-4	-0.05	-0.10 **	-0.02	-0.05
10	GVC- 101 × Ujjavala	-0.01	-0.05	0.08 **	0.01
11	GVC- 101 × ACS-20-20	0.02	0.07 *	0.01	0.03
12	GVC- 101 × ACS-20-22	0.26 **	0.17 **	0.16 **	0.20**
13	GVC- 101 × GP-20	-0.11	-0.01	-0.06 *	-0.06
14	ACS-18-03 × G-4	0.04	0.09 **	-0.12 **	0.01
15	ACS-18-03 × Ujjavala	0.03	-0.08 **	-0.01	-0.02
16	ACS-18-03 × ACS-20-20	0.19 **	-0.11 **	0.28 **	0.12**
17	ACS-18-03 × ACS-20-22	-0.07	-0.13 **	-0.08 **	-0.09*
18	ACS-18-03 × GP-20	0.11	0.01	-0.04	0.03
19	G-4 × Ujjavala	-0.02	-0.01	-0.08 **	-0.04
20	G-4 × ACS-20-20	-0.03	0.11 **	0.03	0.03
21	G-4 × ACS-20-22	0.05	0.01	-0.04	0.01
22	G-4 × GP-20	0.34 **	0.07 *	0.23 **	0.21**
23	Ujjavala × ACS-20-20	0.01	-0.10 **	0.02	-0.02
24	Ujjavala × ACS-20-22	0.05	0.02	0.14 **	0.07
25	Ujjavala × GP-20	0.01	0.07 *	-0.01	0.02
26	ACS-20-20 × ACS-20-22	-0.07	0.06 *	-0.06 *	-0.02
27	ACS-20-20 × GP-20	0.01	0.01	-0.02	0.01
28	ACS-20-22 × GP-20	-0.09	0.01	-0.06 *	-0.05
SE (S_{ij}) ±		0.06	0.03	0.02	0.05
Min.		-0.14	-0.13	-0.12	-0.09
Max.		0.34	0.17	0.28	0.21
No. of significant crosses		6	15	15	6
No. of +ve significant crosses		5	10	7	5
No. of -ve significant crosses		1	5	8	1

*, ** Significant at 5 and 1 percent levels, respectively

Biochemical Attributes (Capsaicin content & Ascorbic Acid Content): Capsaicin and ascorbic acid contents are two important quality traits in chilli, contributing to its pungency and nutritional value, respectively. In both traits, General Combining Ability (GCA) and Specific Combining Ability (SCA) analyses were used to identify superior parents and hybrids across three environments and pooled data. For capsaicin content, parents G-4 (PEVs: 1.30), Ujjavala (PEVs: 0.73), and ACS-18-03 (PEVs: 0.45) were identified as good general combiners due to their consistently significant and positive GCA effects. In contrast, for ascorbic acid content, ACS-20-20 (PEVs: 8.36), GP-20 (PEVs: 6.37), GAVC-141, and GVC-101 showed positive and significant GCA effects, classifying them as good general combiners. Interestingly, GP-20 and ACS-20-20, which were poor general combiners for capsaicin (PEVs: -0.83 and -0.77 respectively), showed strong potential for improving ascorbic acid content, indicating trait-specific combining ability.

Among hybrids, several crosses exhibited significant and positive SCA effects for both traits across environments. For capsaicin, the highest positive SCA effects were recorded in G-4 × GP-20 (PEVs: 1.54) and ACS-18-03 × ACS-20-20 (PEVs: 0.92). In the case of ascorbic acid, top performing crosses were GAVC-141 × Ujjavala (PEVs: 47.44), ACS-20-20 × ACS-20-22 (PEVs: 33.71), and ACS-20-20 × GP-20 (PEVs: 28.94). These results suggest the potential to develop dual-purpose hybrids by selecting parental lines with complementary combining abilities for both traits, thereby improving both the pungency and nutritional value of chilli cultivars.

Conclusions

For the character fruit yield per plant, parents ACS- 18 -03 and ACS-20-20 were found good general combiners again ACS- 18 -03 was good combiner for number of fruits per plant, and capsaicin content, making it a valuable parent in breeding programs aiming to enhance both productivity and pungency. Parent ACS-20-20 was good combiner for average fruit length, average fruit girth, average fruit weight and ascorbic acid content. This parent is particularly suitable for improving both yield components and nutritional quality in hybrid development. Parent *ACS-20-22* was noted as good combiner for average fruit length**,** average fruit girth and average fruit weight emphasizing its role in improving fruit structure.

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