RESEARCH ARTICLE

Exploitation of Heterosis and Combining Ability for Total Soluble Solids, Ascorbic Acid and Flesh Thickness in Sponge Gourd (*Luffa cylindrica* (L) Roem.)

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Abstract

The present investigation was carried out to assess heterosis, combining ability and gene action for important fruit quality traits in sponge gourd (Luffa cylindrica (L) Roem.). Nine parents were crossed in a half-diallel mating design to generate 36 F_1 hybrids along with two commercial checks (Kashi Saumya and NSGH-341) and were evaluated during the Kharif seasons of 2024 and 2025 using RBD with three replications. Based on pooled analysis across seasons, Kashi Shreya × Kashi Vandana recorded the highest mid-parent heterosis (56.73%) and better-parent heterosis (48.53%) for total soluble solids. In comparison, Pusa Sneha × Kashi Vandana expressed the maximum standard heterosis over Kashi Saumya (83.44%) and NSGH-341 (47.63%), for ascorbic acid content VRSG-2/13 × VRSG-8 showed the highest mid-parent (29.12%) and better-parent heterosis (26.01%). In contrast, Pusa Sneha × Kashi Vandana registered the highest standard heterosis over Kashi Saumya (44.88%) and NSGH-341 (21.17%). For flesh thickness, the highest mid-parent (30.33%) and better-parent heterosis (23.76%) were recorded in Kashi Shreya × Kashi Jyoti, while Pusa Chikni × Kashi Shreya recorded the maximum standard heterosis over Kashi Saumya (32.62%) and NSGH-341 (19.67%). Combining ability analysis revealed Pusa Sneha (0.35) has the best general combining ability (GCA) for total soluble solids, Kashi Shreya (0.30) for ascorbic acid content and Kashi Kalyani (0.26) for flesh thickness. The hybrids Pusa Sneha × Kashi Vandana (0.91), VRSG-2/13 × VRSG-8 (0.66) and Kashi Shreya × Kashi Jyoti (0.50) exhibited the highest specific combining ability (GCA) for total soluble solids, ascorbic acid content and flesh thickness, respectively. The predominance of SCA variance over GCA variance for all quality traits indicated the major role of non-additive gene action. The identified hybrids and parental lines offer considerable potential for developing high-quality sponge gourd hybrids through heterosis breeding.

Keywords: Sponge gourd, Heterosis, Combining ability, Quality traits, Gene action

Highlights:

- The crosses Kashi Shreya × Kashi Vandana, Pusa Sneha × Kashi Vandana and Pusa Chikni × Kashi Shreya were promising for total soluble solids, ascorbic acid and flesh thickness, respectively.
- Parents Pusa Sneha, Kashi Shreya, and Kashi Kalyani showed desirable general combining ability for quality-oriented breeding.
- The relative magnitude of combining ability variances indicated an important role of non-additive genetic effects in the expression of fruit quality traits.

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Introduction

Sponge gourd (*Luffa cylindrica* (L) Roem.) is an important vegetable crop cultivated widely in tropical and subtropical regions, especially in India, and is considered to have originated in subtropical Asia, with India as one of its primary centres of origin (Swarup, 2006). It is recognized as a nutritionally rich vegetable. The fruits contain appreciable quantities of proteins, carbohydrates, vitamins, minerals and dietary fibre (Gopalan *et al*., 2012). Compared to ridge gourd, sponge gourd fruits possess higher protein and carotene content, indicating superior nutritional quality (More & Shinde, 2001). In addition to its dietary importance, sponge gourd has diverse industrial and medicinal applications. Dried mature fruits are used as natural sponges for body scrubbing, cleaning utensils, and industrial purposes (Altinsik *et al*., 2010). Medicinal uses include treatment of conjunctivitis and jaundice using leaf and fruit extracts (Manikandaselvi *et al*., 2016), while the seed oil is traditionally used for treating skin-related disorders.

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Despite its economic and nutritional importance, breeding efforts in sponge gourd are relatively limited, resulting in the availability of only a few improved varieties for commercial cultivation. In recent years, improvement of fruit quality traits has gained increasing importance due to changing consumer preferences and growing demand for nutritionally superior vegetables. Among various quality parameters, total soluble solids, ascorbic acid content and flesh thickness play an important role in determining fruit sweetness, nutritional value and consumer acceptability. Therefore, improvement of these quality attributes has become an important objective in sponge gourd breeding programmes.

Heterosis breeding is an effective approach for improving quantitative and qualitative traits in cross-pollinated crops (Chauhan, 2018; Costa *et al*., 2019). In sponge gourd, heterosis may be expressed through improved fruit quality attributes such as sweetness, nutritional value and flesh characteristics. The magnitude of heterosis depends on the genetic constitution of the parents and the gene action governing the traits. Combining ability analysis helps to assess the breeding potential of parental lines and their hybrid performance. General combining ability (GCA) is mainly associated with additive gene effects, whereas specific combining ability (SCA) reflects non-additive gene action (Ruma *et al*., 2024). Diallel analysis further partitions genetic variance into GCA and SCA components representing additive and non-additive effects (Hallauer *et al*., 2010). Knowledge of gene action is essential for selecting appropriate breeding strategies. Predominance of non-additive gene action favours heterosis breeding, while additive gene action supports selection-based breeding (Sonavane *et al*., 2022; Simranpreet *et al*., 2022).

Although several studies have reported heterosis and combining ability in sponge gourd, most of them have primarily focused on yield and yield-related traits, while information on important fruit quality parameters remains limited. Moreover, systematic evaluation of these quality traits under multi-seasonal conditions is still inadequate. Therefore, understanding the genetic architecture of fruit quality traits through heterosis and combining ability analysis is essential for effective hybrid breeding in sponge gourd.

In view of the nutritional, economic and medicinal value of sponge gourd and the limited emphasis on systematic evaluation of fruit quality traits, the present investigation was undertaken to study heterosis and combining ability for quality parameters in sponge gourd using a half-diallel mating design. The objective of the present investigation was to elucidate the genetic architecture governing these traits, to identify superior parents and promising hybrid combinations for their effective utilization in heterosis breeding and development of high-quality sponge gourd hybrids.

Material and Methods

The experimental material comprised of 9 parental lines, *viz*., Pusa Chikni (P1), Kashi Shreya (P2), Kashi Jyoti (P3), Pusa Sneha (P4), Kashi Kalyani (P5), Kashi Vandana (P6), VRSG-2/13 (P7), VRSG-8 (P8) and Local Variety (P9), and 36 F_1 hybrids developed through a half-diallel mating design excluding reciprocals, along with two standard checks, Kashi Saumya (C1) and NSGH-341 (C2). The material was evaluated in a randomized block design with three replications at the New Nursery, Adhartal, Department of Horticulture, College of Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur (M.P.) during the *Kharif* seasons of 2024 and 2025. Recommended agronomic practices were followed to maintain uniform crop growth.

The experiment was conducted on raised beds with a spacing of 2.0 m between rows and 1.0 m between plants. Each genotype was grown in a single row consisting of ten plants in each replication. Observations were recorded from five randomly selected plants per replication, and three marketable fruits from each plant were used for estimating total soluble solids (°Brix), ascorbic acid content (mg 100 g^{-1} fresh weight), and flesh thickness (cm). Total soluble solids were determined using a digital refractometer by placing a drop of juice on the prism at ambient temperature. Flesh thickness was measured at the central portion of the fruit (excluding rind) using a vernier calliper. Ascorbic acid content was estimated by the volumetric titration method described by Sadasivam and Balasubramanian (2005) using 2,6-dichlorophenol indophenol dye, and expressed on a per 100 g fresh weight basis.

Data recorded during *Kharif* 2024 and *Kharif* 2025 were analyzed separately as well as pooled over seasons. Prior to pooling the data across seasons, homogeneity of error variances was tested using Bartlett's test, and since the variances were found to be homogeneous, pooled analysis was carried out. Combining ability analysis was performed using Griffing's diallel approach (Method II, Model I) to estimate general combining ability (GCA) and specific combining ability (SCA) effects and variances. The relative magnitude of GCA and SCA variances was used to infer the nature of gene action governing the traits. Heterosis for each F_1 hybrid was computed as percentage deviation over the mid-parent, better-parent and standard checks, with standard heterosis expressed over the superior check. The significance of heterosis estimates was tested using standard errors derived from the respective error mean squares. All statistical analyses, including analysis of variance, combining ability, and heterosis estimation, were carried out using AgriANALYZE statistical software (Popat *et al*., 2024).

Results

Heterosis for total soluble solids

Highly significant heterosis for TSS was observed among several hybrids across both seasons and in pooled analysis (Table 1), indicating substantial scope for improvement of fruit sweetness through hybridization. In pooled data, mid-parent heterosis ranged from -23.91 to 56.73%. The hybrids Kashi Shreya × Kashi Vandana (56.73%), Kashi Shreya × Kashi Jyoti (50.96%), and Pusa Sneha × Kashi Vandana (49.50%) recorded the highest desirable positive heterosis, demonstrating superior transgressive performance over parental means. Better-parent heterosis for TSS was relatively lower but remained significant in a number of crosses. In pooled analysis, it varied from -33.15 to 48.53%, with Kashi Shreya × Kashi Vandana (48.53%), Kashi Shreya × Kashi Jyoti (44.84%), and Pusa Chikni × Kashi Shreya (33.43%) as the most promising combinations. The consistent superiority of these hybrids indicates favourable parental interactions contributing to enhanced TSS in sponge gourd fruits. Standard heterosis expressed over both commercial checks showed marked improvement in TSS. Pooled standard heterosis over check-1 ranged from -8.85% to 83.44%, while over check-2 it ranged from -26.65 to 47.63%. The hybrids Pusa

Table 1: Estimates of heterosis over mid-parent (MPH), better-parent (BPH) and standard checks (SH) for Total soluble solids in sponge gourd

	Total soluble solids											
	MPH			*BPH*			*SH (1)*			*SH (2)*		
Hybrids	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled
P. Chikni × K. Shreya	36.20 **	37.36 **	36.97 **	31.40 **	35.22 **	33.43 **	53.72 **	58.28 **	56.39 **	23.70 **	27.30 **	25.86 **
P. Chikni × K. Jyoti	38.36 **	44.78 **	41.41 **	29.46 **	35.36 **	32.31 **	51.46 **	58.44 **	55.08 **	21.88 **	27.43 **	24.80 **
P. Chikni × P. Sneha	5.36	7.06	6.29 *	-5.00	-3.41	-4.16	38.35 **	40.56 **	39.84 **	11.33 **	13.05 **	12.53 **
P. Chikni × K. Kalyani	32.47 **	39.48 **	35.91 **	26.97 **	33.66 **	30.21 **	48.54 **	56.46 **	52.62 **	19.53 **	25.83 **	22.82 **
P. Chikni × K. Vandana	8.97 *	12.93 *	11.04 **	0.83	4.38	2.66	17.96 **	22.19 **	20.33 **	-5.08	-1.73	-3.17
P. Chikni × VRSG-2/13	-3.31	-0.15	-1.83	-11.20 **	-8.77	-10.07 **	3.88	6.79	5.41	-16.41 **	-14.11 **	-15.17 **
P. Chikni × VRSG-8	-8.61	-8.41	-8.51 *	-14.11 **	-13.01 *	-13.57 **	0.49	1.82	1.31	-19.14 **	-18.11 **	-18.47 **
P. Chikni × Local Variety	-7.48	-8.56	-8.14 *	-11.07 **	-10.04	-10.77 **	4.05	5.30	4.59	-16.28 **	-15.31 **	-15.83 **
K. Shreya × K. Jyoti	41.94 **	60.15 **	50.96 **	37.50 **	51.97 **	44.84 **	49.51 **	72.35 **	60.98 **	20.31 **	38.62 **	29.55 **
K. Shreya × P. Sneha	14.89 **	19.69 **	17.22 **	0.33	6.48	3.26	46.12 **	54.97 **	50.66 **	17.58 **	24.63 **	21.24 **
K. Shreya × K. Kalyani	23.00 **	26.03 **	24.68 **	22.17 **	22.63 **	22.57 **	32.85 **	39.07 **	36.23 **	6.90	11.85 *	9.63 **
K. Shreya × K. Vandana	64.10 **	49.11 **	56.73 **	57.14 **	39.85 **	48.53 **	70.87 **	58.61 **	65.08 **	37.50 **	27.56 **	32.85 **
K. Shreya × VRSG-2/13	13.55 **	11.97 *	12.96 **	7.89	3.80	6.05	17.31 **	17.72 **	17.87 **	-5.60	-5.33	-5.15
K. Shreya × VRSG-8	1.53	-1.44	0	-1.19	-4.96	-3.10	7.44	7.78	7.70	-13.54 **	-13.32 **	-13.32 **
K. Shreya × Local Variety	-8.59	-12.78 *	-10.50 **	-8.93 *	-12.85 *	-10.77 **	-0.97	-1.16	-0.82	-20.31 **	-20.51 **	-20.18 **
K. Jyoti × P. Sneha	-4.84	-3.21	-4.03	-19.11 **	-17.75 **	-18.43 **	17.80 **	19.70 **	19.02 **	-5.21	-3.73	-4.22
K. Jyoti × K. Kalyani	5.49	9.58	7.51	2.87	6.79	4.89	10.36 *	14.57 *	12.62 **	-11.20 **	-7.86	-9.37 **
K. Jyoti × K. Vandana	17.11 **	21.15 **	19.02 **	15.71 **	19.67 **	17.50 **	17.96 **	21.85 **	20.00 **	-5.08	-2.00	-3.43
K. Jyoti × VRSG-2/13	3.00	3.50	3.12	0.95	0.98	0.80	2.91	2.81	2.95	-17.19 **	-17.31 **	-17.15 **
K. Jyoti × VRSG-8	-3.32	-4.56	-3.89	-3.77	-6.13	-4.87	-0.97	-1.16	-0.82	-20.31 **	-20.51 **	-20.18 **
K. Jyoti × Local Variety	-7.94	-10.85	-9.33 *	-10.49 *	-15.35 **	-12.76 **	-3.40	-4.14	-3.61	-22.27 **	-22.90 **	-22.43 **
P. Sneha × K. Kalyani	39.73 **	38.05 **	38.77 **	21.33 **	19.91 **	20.45 **	76.70 **	74.50 **	75.74 **	42.19 **	40.35 **	41.42 **
P.Sneha × K. Vandana	57.62 **	41.18 **	49.50 **	32.67 **	18.77 **	25.73 **	93.20 **	72.85 **	83.44 **	55.47 **	39.01 **	47.63 **

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P. Sneha × VRSG-2/13	-9.10 *	-3.42	-6.26	-24.00 **	-19.57 **	-21.80 **	10.68 *	17.05 **	14.10 **	-10.94 **	-5.86	-8.18 *
P. Sneha × VRSG-8	-17.58 **	-18.02 **	-17.82 **	-29.67 **	-29.35 **	-29.55 **	2.43	2.81	2.79	-17.58 **	-17.31 **	-17.28 **
P. Sneha × Local Variety	-22.65 **	-25.14 **	-23.91 **	-32.67 **	-33.45 **	-33.15 **	-1.94	-3.15	-2.46	-21.09 **	-22.10 **	-21.50 **
K. Kalyani × K. Vandana	25.82 **	23.24 **	24.56 **	21.27 **	18.67 **	20.00 **	30.10 **	27.32 **	28.85 **	4.69	2.40	3.69
K. Kalyani × VRSG-2/13	14.67 **	15.82 **	15.20 **	9.65 *	10.19	9.92 *	17.64 **	18.21 **	18.03 **	-5.34	-4.93	-5.01
K. Kalyani × VRSG-8	-6.24	-7.63	-6.74	-8.14	-8.49	-8.09 *	-1.46	-1.82	-1.31	-20.70 **	-21.04 **	-20.58 **
K. Kalyani × Local Variety	-0.15	-1.95	-0.98	-0.45	-4.53	-2.37	7.44	8.11	7.87	-13.54 **	-13.05 **	-13.19 **
K. Vandana × VRSG-2/13	-2.62	-4.64	-3.66	-3.41*	-5.83	-4.61	-3.88	-6.46	-5.08	-22.66 **	-24.77 **	-23.61 **
K. Vandana × VRSG-8	5.84	7.28	6.68	4.09	4.25	4.25*	7.12	9.77	8.69 *	-13.80 **	-11.72 *	-12.53 **
K. Vandana × Local Variety	-4.99	-8.57	-6.48	-8.70	-14.18 **	-11.13 **	-1.46	-2.81	-1.80	-20.70 **	-21.84 **	-20.98 **
VRSG-2/13 × VRSG-8	3.46	5.49	4.47	0.94	1.26	1.10	3.88	6.62	5.41	-16.41 **	-14.25 **	-15.17 **
VRSG-2/13 × Local Variety	-10.85 *	-13.95 *	-12.37 **	-14.99 **	-20.18 **	-17.51 **	-8.25	-9.60	-8.85 *	-26.17 **	-27.30 **	-26.65 **
VRSG-8 × Local Variety	-10.67 *	-15.45 **	-12.82 **	-12.74 **	-18.42 **	-15.28 **	-5.83	-7.62	-6.39	-24.22 **	-25.70 **	-24.67 **
No. of significant +ve crosses	14	14	15	11	11	12	18	18	19	9	10	10
No. of significant -ve crosses	5	5	8	12	11	11	0	0	1	20	19	20

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

K= Kashi, P= Pusa

MPH: Mid-parent heterosis, BPH: Better-parent heterosis, SH (1): Standard heterosis over check 1, SH (2): Standard heterosis over check 2

Y1: Kharif 2024 and Y2: *Kharif* 2025

Table 2: Estimates of heterosis over mid-parent (MPH), better-parent (BPH) and standard checks (SH) for Ascorbic acid in sponge gourd

Ascorbic acid	*MPH*			*BPH*			*SH (1)*			*SH (2)*		
Hybrids	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled
P. Chikni × K. Shreya	13.49 *	17.71 **	15.67 **	12.34 *	16.51 **	14.50 **	39.38 **	38.99 **	39.14 **	14.07 *	18.42 **	16.37 **
P. Chikni × K. Jyoti	6.86	12.01 **	9.40 **	4.06	9.26 *	6.65	36.25 **	37.07 **	36.48 **	11.51 *	16.78 **	14.14 **
P. Chikni × P. Sneha	8.28	9.98 *	9.08 *	6.55	8.21	7.34 *	32.19 **	29.09 **	30.43 **	8.18	9.98 *	9.08 *
P. Chikni × K. Kalyani	18.68 **	22.69 **	20.65 **	7.47	12.87 **	10.12 **	33.33 **	34.65 **	33.81 **	9.12	14.72 **	11.91 **
P. Chikni × K. Vandana	10.19	9.09 *	9.51 *	5.29	2.62	3.88	30.63 **	22.42 **	26.23 **	6.91	4.30	5.57
P. Chikni × VRSG-2/13	6.67	6.71	6.62	-4.62	-6.44	-5.56	18.33 **	11.62 *	14.75 **	-3.15	-4.91	-4.03
P. Chikni × VRSG-8	-1.01	-1.27	-1.12	-13.85 *	-14.65 **	-14.25 **	6.88	1.82	4.20	-12.53 *	-13.25 **	-12.85 **
P. Chikni × Local Variety	-0.66	-2.91	-1.77	-4.79	-8.04	-6.41	18.13 **	9.70	13.73 **	-3.32	-6.54	-4.88
K. Shreya × K. Jyoti	6.93	11.30 **	9.17 **	3.10	7.49	5.36	35.00 **	34.85 **	34.84 **	10.49	14.89 **	12.77 **
K. Shreya × P. Sneha	10.17	15.83 **	12.90 **	9.51	15.13 **	12.22 **	33.13 **	34.55 **	33.61 **	8.95	14.63 **	11.74 **
K. Shreya × K. Kalyani	18.42 **	17.45 **	17.98 **	8.23	9.08 *	8.69 *	31.56 **	27.47 **	29.41 **	7.67	8.61 *	8.23 *
K. Shreya × K. Vandana	17.76 **	29.30 **	23.45 **	13.62 *	22.82 **	18.24 **	38.13 **	43.54 **	40.78 **	13.04 *	22.29 **	17.74 **
K. Shreya × VRSG-2/13	16.24 **	16.66 **	16.32 **	4.88	3.20	3.96	27.50 **	20.61 **	23.77 **	4.35	2.75	3.51
K. Shreya × VRSG-8	12.54 *	12.69 *	12.64 **	-1.20	-1.73	-1.46	20.10 **	14.85 **	17.32 **	-1.71	-2.15	-1.89
K. Shreya × Local Variety	-3.85	-5.56	-4.83	-6.94	-9.68 *	-8.43 *	13.13	5.56	9.02 *	-7.42	-10.07 *	-8.83 *
K. Jyoti × P. Sneha	-0.17	-0.38	-0.29	-4.30	-4.35	-4.32	25.31 **	20.00 **	22.44 **	2.56	2.24	2.40
K. Jyoti × K. Kalyani	6.34	4.30	5.21	-5.97	-6.20	-6.16	23.13 **	17.68 **	20.08 **	0.77	0.26	0.43
K. Jyoti × K. Vandana	-6.75	-6.44	-6.61	-13.13 *	-14.01 **	-13.53 **	13.75 *	7.88	10.66 *	-6.91	-8.09	-7.46 *
K. Jyoti × VRSG-2/13	-12.11 *	-6.85	-9.52 *	-23.23 **	-20.05 **	-21.62 **	0.52	0.30	0.31	-17.73 **	-14.54 **	-16.11 **
K. Jyoti × VRSG-8	1.54	-1.00	0.28	-13.60 **	-16.18 **	-14.89 **	13.13	5.15	8.91 *	-7.42	-10.41 *	-8.91 *
K. Jyoti × Local Variety	-2.43	-2.70	-2.45	-8.83	-9.98 *	-9.29 **	19.38 **	12.93 *	16.09 **	-2.30	-3.79	-2.91
P. Sneha × K. Kalyani	20.15 **	20.84 **	20.45 **	10.41	12.86 **	11.59 **	32.60 **	30.30 **	31.25 **	8.53	11.02 *	9.77 **
P.Sneha × K. Vandana	29.22 **	26.65 **	27.85 **	25.41 **	21.00 **	23.17 **	50.63 **	39.70 **	44.88 **	23.27 **	19.02 **	21.17 **
P. Sneha × VRSG-2/13	10.71	13.63 **	12.07 **	0.43	1.05	0.70	20.63 **	16.67 **	18.44 **	-1.28	-0.60	-0.94
P. Sneha × VRSG-8	20.29 **	20.36 **	20.36 **	6.16	5.51	5.84	27.50 **	21.82 **	24.49 **	4.35	3.79	4.11
P. Sneha × Local Variety	-14.74 *	-10.60 *	-12.60 **	-17.00 **	-14.00 **	-15.42 **	-0.31	-0.71	-0.51	-18.41 **	-15.40 **	-16.80 **
K. Kalyani × K. Vandana	10.87	9.69 *	10.23 *	4.79	7.11	5.83	18.44 **	12.63 *	15.37 **	-3.07	-4.04	-3.51

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K. Kalyani × VRSG-2/13	20.32 **	20.51 **	20.49 **	18.63 **	14.31 **	16.55 **	19.38 **	14.55 **	16.91 **	-2.30	-2.41	-2.23
K. Kalyani × VRSG-8	20.45 **	15.92 **	18.16 **	15.22 *	8.27	11.64 **	15.94 *	8.48	11.99 **	-5.12	-7.57	-6.34
K. Kalyani × Local Variety	20.12 **	17.97 **	19.14 **	13.19 *	14.39 **	13.87 **	28.75 **	22.02 **	25.31 **	5.37	3.96	4.80
K. Vandana × VRSG-2/13	-7.81	-7.82	-7.73	-14.01 *	-14.51 **	-14.19 **	-2.81	-10.10 *	-6.45	-20.46 **	-23.41 **	-21.77 **
K. Vandana × VRSG-8	11.03	9.78	10.39 *	0.65	0.29	0.38	13.75 *	5.45	9.43 *	-6.91	-10.15 *	-8.48 *
K. Vandana × Local Variety	-12.36 *	-11.59 *	-11.97 **	-12.64 *	-12.22 *	-12.38 **	-0.63	-6.36	-3.59	-18.67 **	-20.22 **	-19.37 **
VRSG-2/13 × VRSG-8	26.52 **	31.58 **	29.12 **	22.68 **	29.44 **	26.01 **	20.00 **	16.36 **	18.14 **	-1.79	-0.86	-1.20
VRSG-2/13 × Local Variety	-13.44 *	-19.53 **	-16.44 **	-19.51 **	-25.85 **	-22.63 **	-8.44	-20.91 **	-14.86 **	-25.06 **	-32.62 **	-28.79 **
VRSG-8 × Local Variety	-9.12	-8.40	-8.69 *	-17.86 **	-16.86 **	-17.32 **	-6.56	-11.31 *	-9.02 *	-23.53 **	-24.44 **	-23.91 **
No. of significant +ve crosses	13	19	21	7	11	12	27	23	29	4	10	10
No. of significant -ve crosses	4	3	5	8	11	11	0	3	2	7	10	11

*, ** Significant at 5% and 1% level respectively.
K= Kashi, P= Pusa
MPH: Mid-parent heterosis, BPH: Better-parent heterosis, SH (1): Standard heterosis over check 1, SH (2): Standard heterosis over check 2
Y1: Kharif 2024 and Y2: *Kharif* 2025

Sneha × Kashi Vandana, Pusa Sneha × Kashi Kalyani and Kashi Shreya × Kashi Vandana consistently exhibited high positive standard heterosis over both checks, indicating their suitability for enhancing sweetness in sponge gourd.

Heterosis for ascorbic acid content

Significant heterosis for ascorbic acid content was evident in several hybrids across seasons and in pooled analysis (Table 2) reflecting substantial variability for nutritional quality improvement. In pooled data, mid-parent heterosis ranged from -16.44 to 29.12%. The crosses VRSG-2/13 × VRSG-8 (29.12%), Pusa Sneha × Kashi Vandana (27.85%) and Kashi Shreya × Kashi Vandana (23.45%) recorded the highest positive heterosis, indicating enhanced vitamin-C content in these hybrids. Better-parent heterosis for ascorbic acid was moderate but significant in selected crosses. In pooled analysis, it ranged from -22.63 to 26.01%, with superior heterotic response observed in VRSG-2/13 × VRSG-8 (26.01%) and Pusa Sneha × Kashi Vandana (23.17%). Standard heterosis over check-1 varied from -14.86 to 44.88%, while over check-2 it ranged from -28.79 to 21.17% in the pooled analysis. The hybrids Pusa Sneha × Kashi Vandana, Kashi Shreya × Kashi Vandana and Pusa Chikni × Kashi Shreya consistently expressed high positive standard heterosis. The occurrence of positive heterosis in several hybrids suggests the potential of hybridization for enhancing ascorbic acid concentration in sponge gourd fruits.

Heterosis for flesh thickness

Significant heterosis for flesh thickness was observed among several hybrids during both seasons and in pooled analysis (Table 3), suggesting the effectiveness of heterosis breeding for improving fruit flesh characteristics. In pooled data, mid-parent heterosis ranged from -13.19 to 30.33%. The highest positive heterosis was expressed by Kashi Shreya × Kashi Jyoti (30.33%), followed by Pusa Chikni × Kashi Jyoti (25.79%) and Pusa Chikni × Pusa Sneha (25.50%). Such a positive heterotic response for flesh thickness indicates enhanced tissue development in hybrid fruits compared with their parental lines. Better-parent heterosis for flesh thickness was comparatively lower, with pooled values ranging from -23.02 to 23.76%. The crosses Kashi Shreya × Kashi Jyoti (23.76%), Kashi Shreya × Pusa Sneha (21.82%) and Pusa Chikni × Kashi Shreya (16.52%) recorded superior performance over the better-parent. Standard heterosis over check-1 in pooled analysis ranged from -13.25 to 32.62%, while over check-2 it ranged from -21.72 to 19.67%. The hybrids Pusa Chikni × Kashi Shreya, Kashi Kalyani × Kashi Vandana and Kashi Kalyani × VRSG-2/13 consistently expressed high positive standard heterosis, indicating their potential for improving flesh thickness in sponge gourd.

Combining ability effects for quality traits

The general and specific combining ability effects for total soluble solids, ascorbic acid content, and flesh thickness across seasons and pooled analysis are summarized in (Table 4).

Total soluble solids

Variation in general combining ability among the parental lines for total soluble solids across seasons highlighted differences in their contribution to fruit sweetness. On a pooled basis,

Table 3: Estimates of heterosis over mid-parent (MPH), better-parent (BPH) and standard checks (SH) for Flesh thickness in sponge gourd

	Flesh thickness											
	MPH			*BPH*			*SH (1)*			*SH (2)*		
Hybrids	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled
P. Chikni × K. Shreya	24.09 **	20.47 **	22.26 **	19.11 **	14.16 **	16.52 **	32.44 **	32.43 **	32.62 **	19.57 **	19.77 **	19.67 **
P. Chikni × K. Jyoti	27.12 **	24.74 **	25.79 **	16.43 **	12.07 **	14.14 **	29.46 **	30.00 **	29.91 **	16.88 **	17.57 **	17.22 **
P. Chikni × P. Sneha	25.76 **	25.27 **	25.50 **	16.31 **	13.55 **	14.89 **	29.32 **	31.71 **	30.77 **	16.75 **	19.12 **	17.99 **
P. Chikni × K. Kalyani	-1.51	-4.40	-3.11	-6.62 **	-7.49 **	-7.22 **	15.86 **	14.71 **	15.38 **	4.60	3.75	4.11
P. Chikni × K. Vandana	4.74 *	4.07	4.41	1.43	2.76	2.16	20.40 **	22.29 **	21.51 **	8.70 **	10.59 **	9.64 **
P. Chikni × VRSG-2/13	6.87 *	3.79	5.10	-4.84	-8.99 **	-7.13 **	5.81 *	5.57	5.70	-4.48	-4.52	-4.63
P. Chikni × VRSG-8	13.75 **	12.41 **	13.01 **	1.15	-1.85	-0.50	12.46 **	13.86 **	13.25 **	1.53	2.97	2.19
P. Chikni × Local Variety	10.98 **	9.39 **	10.40 **	-2.80	-6.03 *	-4.38	8.07 **	9.00 **	8.83 **	-2.43	-1.42	-1.80
K. Shreya × K. Jyoti	29.45 **	31.00 **	30.33 **	23.27 **	23.80 **	23.76 **	26.06 **	28.57 **	27.64 **	13.81 **	16.28 **	15.17 **
K. Shreya × P. Sneha	28.01 **	26.46 **	27.09 **	23.13 **	20.63 **	21.82 **	25.92 **	25.29 **	25.64 **	13.68 **	13.31 **	13.37 **
K. Shreya × K. Kalyani	2.00	0.19	1.19	-6.96 **	-7.95 **	-7.45 **	15.44 **	14.14 **	15.10 **	4.22	3.23	3.86
K. Shreya × K. Vandana	-8.21 **	-8.59 **	-8.40 **	-14.56 **	-14.41 **	-14.49 **	1.42	1.86	1.71	-8.44 **	-7.88 *	-8.23 **
K. Shreya × VRSG-2/13	17.00 **	18.00 **	17.58 **	8.17 **	8.67 **	8.56 **	10.62 **	12.86 **	11.97 **	-0.13	2.07	1.03
K. Shreya × VRSG-8	7.28 *	6.08	6.91 *	-0.97	-2.75	-1.66	1.27	1.00	1.42	-8.57 **	-8.66 **	-8.48 **
K. Shreya × Local Variety	11.28 **	12.67 **	12.15 **	1.11	1.51	1.38	3.40	5.43	4.56	-6.65 **	-4.65	-5.66 *
K. Jyoti × P. Sneha	8.18 **	8.65 *	8.29 *	7.05 *	7.58 *	7.23 *	1.13	1.43	1.42	-8.70 **	-8.27 **	-8.48 **
K. Jyoti × K. Kalyani	-11.58 **	-11.68 **	-11.81 **	-22.83 **	-22.93 **	-23.02 **	-4.25	-4.43	-4.27	-13.56 **	-13.57 **	-13.62 **
K. Jyoti × K. Vandana	-12.68 **	-13.78 **	-13.19 **	-22.32 **	-23.41 **	-22.75 **	-7.79 **	-8.86 **	-8.12 **	-16.75 **	-17.57 **	-17.10 **
K. Jyoti × VRSG-2/13	1.58	1.35	1.27	-1.53	-1.39	-1.69	-8.92 **	-8.86 **	-8.83 **	-17.77 **	-17.57 **	-17.74 **
K. Jyoti × VRSG-8	4.91	5.19	5.00	1.53	1.85	1.54	-6.09 *	-5.86	-5.84	-15.22 **	-14.86 **	-15.04 **
K. Jyoti × Local Variety	5.23	5.69	5.50	0.15	0.46	0.15	-7.37 **	-7.14 *	-7.12 *	-16.37 **	-16.02 **	-16.20 **
P. Sneha × K. Kalyani	-0.06	1.70	0.72	-11.99 **	-10.48 **	-11.34 **	9.21 **	11.00 **	10.26 **	-1.41	0.39	-0.51
P.Sneha × K. Vandana	-10.43 **	-10.92 **	-10.61 **	-19.57 **	-20.17 **	-19.76 **	-4.53	-5.00	-4.56	-13.81 **	-14.08 **	-13.88 **
P. Sneha × VRSG-2/13	7.97 **	7.39 *	7.44 *	3.60	3.48	3.31	-2.12	-2.43	-2.28	-11.64 **	-11.76 **	-11.83 **
P. Sneha × VRSG-8	-1.25	-1.42	-1.42	-5.40	-5.45	-5.57	-10.62 **	-10.86 **	-10.68 **	-19.31 **	-19.38 **	-19.41 **
P. Sneha × Local Variety	8.67 **	9.09 *	9.05 **	2.40	2.73	2.56	-3.26	-3.14	-2.99	-12.66 **	-12.40 **	-12.47 **
K. Kalyani × K. Vandana	8.40 **	9.23 **	8.78 **	6.05 **	7.03 *	6.41 *	31.59 **	32.71 **	32.34 **	18.80 **	20.03 **	19.41 **

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K. Kalyani × VRSG-2/13	24.51 **	24.19 **	24.23 **	5.82 **	5.88 *	5.73 *	31.30 **	31.29 **	31.48 **	18.54 **	18.73 **	18.64 **
K. Kalyani × VRSG-8	10.42 **	8.82 **	9.52 **	-6.28 **	-7.60 **	-7.10 **	16.29 **	14.57 **	15.53 **	4.99 *	3.62	4.24
K. Kalyani × Local Variety	27.15 **	25.98 **	26.61 **	6.39 **	5.30	5.73 *	32.01 **	30.57 **	31.48 **	19.18 **	18.09 **	18.64 **
K. Vandana × VRSG-2/13	17.57 **	15.99 **	16.85 **	1.79	0.60	1.32	20.82 **	19.71 **	20.51 **	9.08 **	8.27 **	8.74 **
K. Vandana × VRSG-8	16.22 **	16.33 **	16.29 **	0.48	0.48	0.48	19.26 **	19.57 **	19.52 **	7.67 **	8.14 **	7.84 **
K. Vandana × Local Variety	16.53 **	16.67 **	16.76 **	-0.72	-0.84	-0.72	17.85 **	18.00 **	18.09 **	6.39 *	6.72 *	6.56 *
VRSG-2/13 × VRSG-8	-0.16	-0.33	-0.25	-0.33	-0.82	-0.65	-13.46 **	-13.29 **	-13.25 **	-21.87 **	-21.58 **	-21.72 **
VRSG-2/13 × Local Variety	6.40 *	8.28 *	7.35 *	4.40	5.72	4.89	-9.35 **	-7.57 *	-8.40 **	-18.16 **	-16.41 **	-17.35 **
VRSG-8 × Local Variety	2.25	2.27	2.43	0.49	0.33	0.49	-13.03 **	-13.14 **	-12.96 **	-21.48 **	-21.45 **	-21.47 **
No. of significant +ve crosses	23	19	20	10	9	10	20	19	19	13	12	12
No. of significant -ve crosses	5	4	4	8	10	9	7	7	7	16	15	16

*, ** Significant at 5 and 1% level, respectively.
K= Kashi, P= Pusa
MPH: Mid-parent heterosis, BPH: Better-parent heterosis, SH (1): Standard heterosis over check 1, SH (2): Standard heterosis over check 2
Y1: *Kharif* 2024 and Y2: *Kharif* 2025

Pusa Sneha recorded the highest positive GCA effect (0.35), followed by Kashi Shreya (0.24) and Pusa Chikni (0.15), whereas Local Variety (-0.33), VRSG-8 (-0.30), and VRSG-2/13 (-0.26) were identified as poor general combiners for this trait. The presence of both high positive and negative GCA effects among parents indicates contrasting parental potential for influencing TSS in hybrid combinations. At the hybrid level, specific combining ability effects highlighted distinct cross-specific responses, with Pusa Sneha × Kashi Vandana registering the maximum positive SCA effect (0.91), followed by Pusa Sneha × Kashi Kalyani (0.70) and Kashi Shreya × Kashi Jyoti (0.65). Conversely, crosses involving Local Variety, particularly Pusa Sneha × Local Variety (-0.45), Pusa Sneha × VRSG-8 (-0.37) and Kashi Shreya × Local Variety (-0.31), exhibited pronounced negative SCA effects, indicating limited scope for improving TSS through these combinations.

Ascorbic acid content

Distinct parental differences were evident for general combining ability effects for ascorbic acid content, indicating differential contribution to fruit nutritional quality. On a pooled basis, Kashi Shreya emerged as the most efficient general combiner (0.30), followed by Pusa Chikni (0.23), Pusa Sneha (0.23) and Kashi Jyoti (0.12), while Local Variety (-0.32), VRSG-2/13 (-0.31) and VRSG-8 (-0.29) showed consistently poor combining ability. The differential GCA effects among the parental lines reflect variability in their ability to transmit traits associated with ascorbic acid content to the hybrids. Among the hybrids, specific combining ability effects identified a few superior cross combinations, with Pusa Sneha × Kashi Vandana (0.73), VRSG-2/13 × VRSG-8 (0.66) and Kashi Shreya × Kashi Vandana (0.52) recording the highest positive SCA effects. In contrast, negative SCA effects were most pronounced in Pusa Sneha × Local Variety (-0.46), Kashi Vandana × VRSG-2/13 (-0.41) and VRSG-2/13 × Local Variety (-0.39), indicating inferior cross performance for ascorbic acid content.

Flesh thickness

Parents differed significantly in their general combining ability effects for flesh thickness, indicating differential contribution to flesh development and such variation reflects differences in the genetic control of fruit flesh development among the parental lines. On a pooled basis, Kashi Kalyani performed the highest as a general combiner (0.26), followed by Pusa Chikni (0.23), Kashi Vandana (0.13), and Kashi Shreya (0.11), whereas VRSG-8 (-0.20), Local Variety (-0.17), Kashi Jyoti (-0.14) and VRSG-2/13 (-0.14) showed negative effects. Evaluation of specific combining ability effects revealed that Kashi Shreya × Kashi Jyoti recorded the highest positive SCA effect (0.50), followed by Kashi Kalyani × Local Variety (0.47), Kashi Kalyani × VRSG-2/13 (0.44) and Pusa Chikni × Kashi Jyoti (0.43). On the other hand, crosses such as Kashi Jyoti × Kashi Kalyani (-0.39), Kashi Shreya × Kashi Vandana (-0.38) and Pusa Sneha × Kashi Vandana (-0.33) showed strong negative SCA effects, indicating limited suitability for improving flesh thickness.

Nature of gene action for quality traits

The combining ability analysis revealed significant variation for

Table 4: Estimates of general combining ability (GCA) effects and of specific combining ability (SCA) effects for quality traits in sponge gourd

	TSS			*Ascorbic acid*			*Flesh thickness*		
Parents (GCA)	*Y1*	*Y2*	*Pooled*	*Y1*	*Y2*	*Pooled*	*Y1*	*Y2*	*Pooled*
Pusa Chikni	0.14 **	0.17 **	0.15 **	0.22 **	0.25 **	0.23 **	0.22 **	0.24 **	0.23 **
Kashi Shreya	0.22 **	0.26 **	0.24 **	0.27 **	0.34 **	0.30 **	0.10 **	0.11 **	0.11 **
Kashi Jyoti	-0.05 **	0.00	-0.03	0.11 *	0.14 **	0.12 **	-0.14 **	-0.14 **	-0.14 **
Pusa Sneha	0.37 **	0.33 **	0.35 **	0.21 **	0.24 **	0.23 **	-0.08 **	-0.08 **	-0.08 **
Kashi Kalyani	0.11 **	0.11 **	0.11 **	0.04	0.08 *	0.06 *	0.26 **	0.25 **	0.26 **
Kashi Vandana	0.10 **	0.02	0.06 **	0.00	-0.05	-0.02	0.14 **	0.13 **	0.13 **
VRSG-2/13	-0.26 **	-0.26 **	-0.26 **	-0.29 **	-0.34 **	-0.31 **	-0.14 **	-0.14 **	-0.14 **
VRSG-8	-0.30 **	-0.30 **	-0.30 **	-0.28 **	-0.31 **	-0.29 **	-0.20 **	-0.21 **	-0.20 **
Local Variety	-0.32 **	-0.33 **	-0.33 **	-0.29 **	-0.35 **	-0.32 **	-0.17 **	-0.17 **	-0.17 **
				Hybrids (SCA)					
P. Chikni × K. Shreya	0.38 **	0.36 **	0.37 **	0.17	0.23 *	0.21 *	0.27 **	0.22 **	0.24 **
P. Chikni × K. Jyoti	0.61 **	0.63 **	0.62 **	0.23	0.37 **	0.30 **	0.44 **	0.42 **	0.43 **
P. Chikni × P.Sneha	-0.08	-0.07	-0.07	0.00	0.00	0.00	0.38 **	0.40 **	0.39 **
P. Chikni × K. Kalyani	0.38 **	0.47 **	0.43 **	0.20	0.35 **	0.27 **	-0.28 **	-0.33 **	-0.31 **
P. Chikni × K. Vandana	-0.24 **	-0.13	-0.18 **	0.16	0.07	0.11	-0.05	-0.03	-0.04
P. Chikni × VRSG-2/13	-0.17 *	-0.15	-0.16 **	0.05	0.01	0.03	-0.12 **	-0.16 **	-0.14 **
P. Chikni × VRSG-8	-0.20 **	-0.22 **	-0.21 **	-0.33 *	-0.34 **	-0.33 **	0.10 *	0.11 *	0.10 *
P. Chikni × Local Variety	-0.10	-0.12	-0.11 *	0.05	-0.04	0.00	-0.04	-0.05	-0.04
K. Shreya × K. Jyoti	0.49 **	0.81 **	0.65 **	0.13	0.21	0.17	0.48 **	0.52 **	0.50 **
K. Shreya × P. Sneha	0.00	0.13	0.06	-0.02	0.09	0.03	0.42 **	0.38 **	0.40 **
K. Shreya × K. Kalyani	-0.02	0.03	0.01	0.09	0.02	0.06	-0.17 **	-0.21 **	-0.19 **
K. Shreya × K. Vandana	0.78 **	0.51 **	0.64 **	0.35 *	0.68 **	0.52 **	-0.38 **	-0.38 **	-0.38 **
K. Shreya × VRSG-2/13	0.03	-0.03	0.01	0.29 *	0.21	0.25 **	0.11 **	0.15 **	0.13 **
K. Shreya × VRSG-8	-0.13 *	-0.19 *	-0.17 **	0.05	0.00	0.02	-0.04	-0.06	-0.05

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K. Shreya × Local Variety	-0.28 **	-0.34 **	-0.31 **	-0.17	-0.27 *	-0.22 *	-0.03	0.00	-0.01
K. Jyoti × P. Sneha	-0.31 **	-0.31 **	-0.31 **	-0.12	-0.19	-0.15	0.08	0.08	0.08
K. Jyoti × K. Kalyani	-0.21 **	-0.20 *	-0.20 **	-0.02	-0.10	-0.07	-0.39 **	-0.39 **	-0.39 **
K. Jyoti × K. Vandana	-0.04	0.04	0.00	-0.28	-0.30 **	-0.29 **	-0.35 **	-0.37 **	-0.36 **
K. Jyoti × VRSG-2/13	0.01	-0.06	-0.03	-0.42 **	-0.26 *	-0.34 **	-0.10 *	-0.11 *	-0.11 *
K. Jyoti × VRSG-8	-0.04	-0.11	-0.07	-0.02	-0.12	-0.07	0.03	0.03	0.03
K. Jyoti × Local Variety	-0.06	-0.13	-0.10	0.19	0.17	0.18 *	-0.04	-0.04	-0.04
P. Sneha × K. Kalyani	0.74 **	0.68 **	0.70 **	0.18	0.21	0.20 *	-0.13 **	-0.08	-0.11 *
P.Sneha × K. Vandana	1.09 **	0.73 **	0.91 **	0.81 **	0.65 **	0.73 **	-0.33 **	-0.34 **	-0.33 **
P. Sneha × VRSG-2/13	-0.26 **	-0.11	-0.18 **	0.13	0.18	0.15	0.00	-0.01	-0.01
P. Sneha × VRSG-8	-0.39 **	-0.36 **	-0.37 **	0.34 *	0.32 **	0.33 **	-0.14 **	-0.14 **	-0.14 **
P. Sneha × Local Variety	-0.45 **	-0.45 **	-0.45 **	-0.54 **	-0.38 **	-0.46 **	0.00	0.00	0.00
K. Kalyani × K. Vandana	0.04	0.04	0.04	-0.06	-0.08	-0.07	0.17 **	0.21 **	0.19 **
K. Kalyani × VRSG-2/13	0.15 *	0.14	0.14 *	0.26	0.27 *	0.27 **	0.44 **	0.44 **	0.44 **
K. Kalyani × VRSG-8	-0.21 **	-0.23 **	-0.22 **	0.14	0.05	0.09	0.15 **	0.12 *	0.13 **
K. Kalyani × Local Variety	0.00	0.00	0.00	0.56 **	0.53 **	0.55 **	0.48 **	0.45 **	0.47 **
K. Vandana × VRSG-2/13	-0.29 **	-0.27 **	-0.28 **	-0.41 **	-0.42 **	-0.41 **	0.32 **	0.29 **	0.31 **
K. Vandana × VRSG-8	-0.02	0.09	0.03	0.11	0.08	0.09	0.35 **	0.35 **	0.35 **
K. Vandana × Local Variety	-0.17 **	-0.13	-0.15 **	-0.34 *	-0.28 *	-0.31 **	0.28 **	0.28 **	0.28 **
VRSG-2/13 × VRSG-8	0.27 **	0.31 **	0.29 **	0.60 **	0.72 **	0.66 **	-0.15 **	-0.15 **	-0.15 **
VRSG-2/13 × Local Variety	0.05	0.01	0.03	-0.30 *	-0.47 **	-0.39 **	-0.09 *	-0.05	-0.07
VRSG-8 × Local Variety	0.13 *	0.09	0.11 *	-0.25	-0.17	-0.21 *	-0.11 **	-0.11 *	-0.11 *

*, ** Significant at 5% and 1% level respectively.
K= Kashi, P= Pusa
Y1: *Kharif* 2024 and Y2: *Kharif* 2025

Table 5: Pooled analysis of variance for combining ability for quality traits in sponge gourd

Source	*df*	*TSS*	*Ascorbic acid*	*Flesh thickness*
GCA	8	0.6637**	0.6888**	0.3623**
SCA	36	0.1476**	0.1245**	0.0758**
Error	88	0.0036	0.0101	0.0026
σ^2 gca		0.0600	0.0617	0.0327
σ^2 sca		0.1440	0.1144	0.0731
σ^2 gca / σ^2 sca		0.4168	0.5396	0.4470

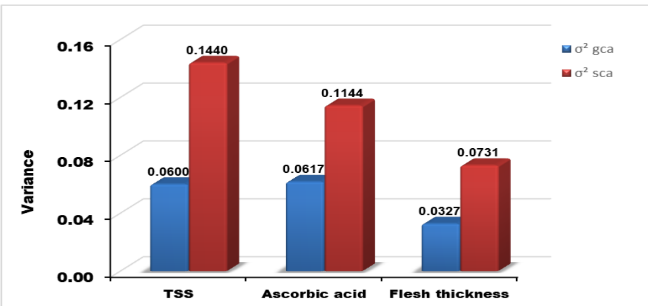

Fig. 1: Pooled estimates of GCA and SCA variances for quality traits in sponge gourd

total soluble solids, ascorbic acid content and flesh thickness, as reflected by both general combining ability (GCA) and specific combining ability (SCA) components. From (Table 5) and Fig. 1, it was evident that, for total soluble solids, the variance due to SCA (σ^2sca = 0.144) was higher than the variance due to GCA (σ^2gca = 0.060), with a σ^2gca/σ^2sca ratio of 0.4168. Similarly, for ascorbic acid content, σ^2sca (0.1144) exceeded σ^2gca (0.0617), resulting in a σ^2gca/σ^2sca ratio of 0.5396. In the case of flesh thickness, the SCA variance (0.0731) was also greater than the GCA variance (0.0327), and the corresponding σ^2gca/σ^2sca ratio was 0.447. Across all the quality traits studied, the predominance of SCA variance over GCA variance indicated a greater contribution of non-additive genetic effects in the expression of total soluble solids, ascorbic acid content and flesh thickness in sponge gourd.

Discussion

The present investigation revealed considerable heterosis and combining ability effects for total soluble solids (TSS) in sponge gourd, indicating substantial scope for improving sweetness and consumer acceptability through heterosis breeding. The superior performance of hybrids involving Pusa Sneha and Kashi Shreya suggests that these parents possess desirable genetic attributes contributing to enhanced sugar accumulation in fruits. The involvement of at least one good general combiner in several superior crosses further indicates that additive genetic effects, along with complementary interactions among parental genomes, contributed to the observed heterotic response. These findings are in agreement with earlier reports in sponge gourd by Chauhan *et al.* (2018) and Kumar and Pandit (2022), who observed improved fruit quality in heterotic combinations. Similar enhancement of TSS through heterosis has also been reported in ridge gourd by Varalakshmi *et al.* (2019) and Sarkar (2015), in bottle gourd by Yadav *et al.* (2023), and in muskmelon by Kaur *et al.* (2022), suggesting that sweetness-related traits respond positively to hybridization across cucurbit crops.

Ascorbic acid content, an important nutritional quality attribute, exhibited considerable heterosis along with significant combining ability effects in the present investigation. The enhanced ascorbic acid content observed in certain hybrids might be due to enhanced biosynthetic activity during fruit maturation, leading to increased accumulation of vitamin C in the hybrids. In addition, improved metabolic efficiency and enhanced translocation of photo assimilates to developing fruits in hybrid combinations may also contribute to increased ascorbic acid synthesis. Similar findings were earlier reported in sponge gourd by Singh (2018), who documented substantial variability and heterotic enhancement for ascorbic acid content. Comparable results were also reported in ridge gourd by Pawar *et al.* (2024), in cucumber by Kumari *et al.* (2024), Dhall *et al.* (2025), and in watermelon by Rahimi *et al.* (2022), who observed the predominance of non-additive gene action for this trait. These consistent reports across Luffa species suggest that hybridization is a reliable approach for improving ascorbic acid content in cucurbitaceous vegetables.

Flesh thickness, which influences fruit texture and cooking quality, showed significant heterosis and combining ability effects in the present investigation. The predominance of specific combining ability effects for this trait indicates the importance of non-additive gene action in its inheritance. The superior performance of specific hybrids might be due to the presence of favourable genetic factors regulating tissue development and pericarp growth. Hybrid combinations derived from parents with desirable combining ability likely facilitated enhanced cell proliferation and structural development of the fruit tissues, resulting in improved flesh thickness. Although limited information is available specifically for sponge gourd, related studies in ridge gourd by Varalakshmi *et al.* (2019), Sarkar (2015) and Sachin *et al.* (2023) reported significant heterosis and superior hybrid performance for flesh or pericarp thickness, supporting the present findings. Similar observations in bitter gourd by Triveni *et al.* (2024), Bhatt *et al.* (2023), in pumpkin by Hosen *et al.* (2022) and in snake gourd by Devi *et al.* (2017) further confirm that thickness-related quality traits can be effectively improved through heterosis breeding.

As suggested by Dey *et al.* (2010) in bitter gourd, hybrids derived from parents with favourable combining ability often outperform parental means, and a similar trend was evident in the present investigation. The consistency of these results with earlier findings in sponge gourd and other cucurbits highlights the potential of heterosis breeding for developing sponge gourd hybrids with superior nutritional and market-preferred quality attributes.

The present findings have important implications for sponge gourd breeding programmes aimed at improving fruit quality traits. The parents, Pusa Sneha, Kashi Shreya and Kashi Kalyani, which exhibited desirable general combining ability for total soluble solids, ascorbic acid content and flesh thickness, respectively, can be effectively utilized as potential parental lines in hybrid breeding programmes. Furthermore, the hybrids Pusa Sneha × Kashi Vandana, VRSG-2/13 × VRSG-8 and Kashi Shreya × Kashi Jyothi, which showed high heterosis along with significant specific combining ability effects, may serve as promising hybrids for the development of superior sponge gourd hybrids.

Conclusion

The results of the present investigation clearly concluded that fruit quality traits in sponge gourd, viz., total soluble solids, ascorbic acid content and flesh thickness, are amenable to improvement through heterosis breeding. The consistent superior performance of specific hybrids across seasons indicates the stability of heterotic response for these quality attributes. The predominance of SCA variance over GCA variance for all the traits studied highlights the major role of non-additive gene action, suggesting that direct exploitation of F_1 hybrids would be more effective than selection-based approaches for quality improvement. The identification of parents exhibiting desirable general combining ability highlights their potential use as elite parental sources, whereas the superior performance of certain cross combinations demonstrates the critical role of specific parental interactions in the manifestation of fruit quality traits. Overall, the simultaneous occurrence of high heterosis coupled with significant SCA effects provides a strong genetic basis for the development of commercially exploitable sponge gourd hybrids with enhanced nutritional attributes and consumer-preferred traits.

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Author contribution

Author 1 performed the research and prepared the manuscript. Author 2 supervised the study and revised the manuscript. Authors 3 and 4 reviewed the experimental data and the manuscript. All authors approved the final manuscript.

Conflict of interest

The authors have no conflict of interest.

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