



Heterosis and combining ability for yield attributes and quality traits in tomato (*Solanum lycopersicum*) under mid hill conditions of Himachal Pradesh

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ABSTRACT

The present investigation was undertaken to evaluate heterosis and combining ability among nine elite tomato (*Solanum lycopersicum* L.) genotypes and their 36 F₁ hybrids developed through a diallel mating design excluding reciprocals under mid-hill conditions of Himachal Pradesh during summer seasons of 2020 and 2021. The hybrids, along with parents and a commercial check hybrid, Naveen 2000+, were evaluated in a randomised block design with three replications for nine agronomic and quality traits. Significant heterosis over the better parent and standard check was observed for most of the characters studied. The crosses Arka Abha × H-7998 and Solan Lalima × BajT-4 exhibited desirable heterosis for earliness, whereas Solan Lalima × BajT-4, Solan Lalima × Arka Meghali and H-7998 × BajT-4 recorded superior performance for fruit yield/plant. The parents Solan Lalima and BajT-4 were identified as good general combiners for fruit yield and quality traits while BajT-4 also exhibited superior combining ability for number of fruits/plant, fruits/cluster and average fruit weight. High specific combining ability effects were observed in the crosses Solan Lalima × BajT-4, Solan Lalima × Arka Meghali and H-7998 × BajT-4 for fruit yield and associated traits. Predictability ratios less than unity for most traits indicated the predominance of non-additive gene action in the inheritance of these characters, suggesting the scope for exploitation of heterosis in tomato improvement programmes. The study identified promising parental combinations and hybrids for further evaluation under mid-hill conditions of Himachal Pradesh.

Keywords: Gene action, General combining ability, Hybrid vigour, Specific combining ability

Heterosis, commonly referred to as hybrid vigour, is one of the most important genetic phenomena exploited in modern plant breeding programmes. It refers to the superior performance of F₁ hybrids over their parents for economically important traits due to the favourable interaction of alleles contributed by genetically diverse parental lines. Exploitation of heterosis has significantly contributed towards enhancement in yield, earliness, stress tolerance, adaptability and overall plant vigour in several crop species. In vegetable crops, heterosis breeding has emerged as an effective approach for developing high-yielding hybrids with superior quality attributes and wider adaptability. Although the advantages of heterosis are confined mainly to the F₁ generation and require continuous hybrid seed production, its commercial success has made

it an indispensable component of crop improvement programmes worldwide.

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and economically important vegetable crops across the world owing to its high nutritional value, processing versatility and consumer preference. The crop is an important source of vitamin C (13.7 mg) and lycopene (5–10 mg/100 g fresh weight), along with minerals and antioxidants (Ali *et al.* 2020), which play a significant role in human nutrition and health. In India, tomato is cultivated over an area of approximately 808.5 thousand hectares with a productivity of 24.83 t/ha (NHB 2021). In Himachal Pradesh, tomato cultivation under mid-hill and off-season conditions contributes substantially towards farmers' income and nutritional security. The increasing demand for high-yielding hybrids possessing earliness, better fruit quality and adaptability under diverse environmental conditions necessitates the identification and development of superior hybrid combinations.

The success of heterosis breeding largely depends upon the selection of genetically diverse parents with desirable combining ability. However, superior parental performance

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does not necessarily result in superior hybrids because expression of heterosis is governed by complex genetic mechanisms involving additive and non-additive gene effects. Therefore, combining ability analysis serves as an important tool for understanding the nature and magnitude of gene action controlling different quantitative traits. General combining ability (GCA) is associated primarily with additive gene effects, whereas specific combining ability (SCA) reflects non-additive gene action including dominance and epistatic interactions. Estimation of GCA and SCA effects facilitates identification of superior parents and promising cross combinations for use in hybrid breeding programmes. Keeping these aspects in view, the present investigation was undertaken to estimate heterosis and combining ability for yield, earliness and quality traits in tomato under mid-hill conditions of Himachal Pradesh.

MATERIALS AND METHODS

Experimental material and hybridisation programme:

The parental genotypes used in the present investigation were selected based on their diverse horticultural characteristics, adaptability and genetic variability. The source and important characteristics of the parental lines are presented in Table 1.

The experimental material comprised nine genetically diverse and highly homozygous tomato genotypes selected on the basis of variation in important horticultural traits such as yield potential, fruit size, plant vigour and quality attributes. The parental lines were crossed in all possible combinations excluding reciprocals following a half-diallel mating design (Griffing's Method II, Model I) to generate 36 F_1 hybrids. The diallel mating design was adopted to estimate general combining ability (GCA) and specific combining ability (SCA) effects for economically important traits in tomato. A commercial hybrid, Naveen 2000+, was included as a standard check for estimation of commercial heterosis. The hybrid is widely cultivated under mid-hill conditions owing to its desirable horticultural characteristics such as high yield potential, uniform red fruits, firmness and medium maturity duration.

Field evaluation and data recording: The experiment was conducted during the summer season of 2020 and 2021 at Regional Horticultural Research and Training Station,

Bajaura, Kullu (32.2°N, 77°E; at an elevation of 1,090 m amsl), Himachal Pradesh. The experiment was laid out in a randomised complete block design (RCBD) with three replications. Each genotype was grown in plots measuring 3.60 m × 2.40 m following a spacing of 90 cm between rows and 30 cm between plants. Recommended agronomic and plant protection practices for tomato cultivation under mid-hill conditions were followed uniformly throughout the crop growth period to ensure healthy crop establishment and minimise environmental variation.

Observations were recorded from five randomly selected plants in each replication for nine important horticultural and quality traits, namely days to first harvest (C1), number of fruits/plant (C2), number of fruits/cluster (C3), fruit yield/plant (kg) (C4), average fruit weight (g) (C5), pericarp thickness (mm) (C6), plant height (cm) (C7), total soluble solids (°Brix) (C8) and ascorbic acid content (mg/100 g fresh weight) (C9). Heterosis was estimated over the better parent (BP) (heterobeltiosis) and standard check (SC) using the following formulae:

$$\text{Better parent heterosis (BPH): } H = [(F_1 - BP)/BP] \times 100\%$$

$$\text{Standard heterosis (SH): } H = [(F_1 - SC)/SC] \times 100\%$$

The relative importance of additive and non-additive gene action was assessed using the predictability ratio $[2\sigma^2\text{GCA} / (2\sigma^2\text{GCA} + \sigma^2\text{SCA})]$.

Statistical analysis: The experimental data were subjected to analysis of variance following the procedure described by Panse and Sukhatme (1985). Combining ability analysis for different traits was carried out according to Griffing's Method II, Model I (fixed effect model) (Griffing 1956) to estimate GCA and SCA effects. Statistical analyses were performed using OPSTAT software and Microsoft Excel.

RESULTS AND DISCUSSION

The evaluation of nine tomato parental lines and their 36 hybrid combinations revealed a broad spectrum of phenotypic variability across multiple horticultural, yield, and quality-related traits. This wide variation clearly indicated the presence of substantial genetic diversity among the experimental material, thereby providing ample

Table 1 Source and important characteristics of parental tomato genotypes used in the study

Genotype	Origin	Genetic background
Solan Lalima	Dr Yashwant Singh Parmar University of Horticulture and Forestry, Solan	Early maturity, good fruit set, adapted to mid-hill conditions
Arka Meghali	Indian Institute of Horticultural Research, Bengaluru	High yield potential, medium-sized fruits
Arka Abha	Indian Institute of Horticultural Research, Bengaluru	Disease tolerance, good fruit firmness
H-7998	World Vegetable Center, Taiwan	Bacterial wilt resistance, vigorous growth
BajT-1	RHRTS Bajaura breeding line	Good fruit quality and adaptability
BajT-4	RHRTS Bajaura breeding line	High yield, thick pericarp, prolific fruiting
BajT-10	RHRTS Bajaura breeding line	Earliness and moderate fruit size
BajT-11	RHRTS Bajaura breeding line	Large fruit size and market preference
BT-21	RHRTS Bajaura breeding line	Vigorous plant growth and high vegetative vigour

scope for effective selection and genetic improvement through hybrid breeding (Table 2). The manifestation of variability among both parents and hybrids highlights the importance of exploiting heterosis and combining ability to develop superior genotypes suited to diverse agro-climatic conditions. Such variability is particularly valuable in tomato, where both yield and quality traits must be simultaneously improved to meet the demands of growers, consumers, and processing industries.

Response of parental lines and hybrids on studied traits:

Among the parental lines, BajT-4 and Solan Lalima were identified as the earliest maturing genotypes, recording first harvest at 67.70 and 68.70 days, respectively (Table 3). Earliness is an important trait in tomato, particularly under off-season and short-duration cropping systems, where early market availability provides economic advantage to growers. Among the hybrids, Solan Lalima × BajT-4 recorded the earliest harvest (62.76 days), followed by Solan Lalima × Arka Abha (66.12 days). The negative heterotic response observed for days to first harvest in these hybrids indicated the usefulness of hybridisation in reducing crop duration and improving earliness. Similar findings for earliness through heterosis breeding in tomato were reported by Singh *et al.* (2008) and Kumar *et al.* (2013). The superior performance of these hybrids might be attributed to favourable non-additive gene interactions governing earliness traits.

Significant variability was observed among the parents and hybrids for number of fruits/plant and fruits/cluster, indicating the presence of sufficient genetic diversity for improvement of yield-contributing traits (Table 3). Among the parents, H-7998 recorded the highest number of fruits/plant (46.25), while among the hybrids, Arka Abha × H-7998 produced the maximum number of fruits/plant (47.28), followed closely by Solan Lalima × BajT-4 (46.27). Similarly, BajT-4 exhibited the highest number of fruits/cluster (5.02) among the parental lines, while the hybrid

Solan Lalima × BajT-4 recorded the highest value (5.40) among the hybrids. The enhanced fruiting ability observed in these hybrids may be due to favourable complementation of genes controlling floral initiation and fruit set. Positive heterotic effects for fruit number and related traits in tomato have also been reported by Sharma *et al.* (2019) and Meena *et al.* (2022).

Fruit yield/plant exhibited considerable variation among the genotypes (Table 3). Among the parental lines, BajT-4 recorded the highest fruit yield/plant (2.40 kg), indicating its potential as a good general combiner for yield-related traits. However, the hybrid Solan Lalima × BajT-4 significantly outperformed all other genotypes by recording the highest fruit yield/plant (3.10 kg). The superior performance of this hybrid may be attributed to the combined effect of earliness, higher fruit number and desirable fruit weight. The results further indicated that selection of genetically diverse and complementary parents can effectively enhance hybrid performance for yield and related traits. Similar enhancement in fruit yield due to heterosis has also been reported by earlier workers in tomato breeding programmes.

Average fruit weight, an important trait influencing market preference and yield, exhibited considerable variation among the parental lines and hybrids (Table 3). Among the parents, BajT-11 recorded the highest average fruit weight (77.27 g), indicating its potential usefulness in developing large-fruited hybrids. Among the hybrids, Solan Lalima × BajT-4 and Solan Lalima × BajT-11 recorded the highest average fruit weight (83.82 g and 80.18 g, respectively), surpassing their respective parental lines. The superior performance of these hybrids might be attributed to favourable heterotic effects and efficient expression of non-additive gene action governing fruit weight. Improvement in fruit weight among hybrids could also be associated with enhanced cell division, cell enlargement and efficient translocation of assimilates towards developing fruits. Similar findings for increased fruit weight through heterosis in tomato have been reported by Kumar *et al.* (2019) and Sharma *et al.* (2020).

Pericarp thickness, which is closely associated with fruit firmness, shelf life and transportability, also showed significant variation among the genotypes (Table 3). Among the parental lines, BajT-4 recorded the maximum pericarp thickness (5.97 mm), whereas the hybrid Solan Lalima × BajT-1 exhibited the highest pericarp thickness (5.87 mm) among the hybrids. Increased pericarp thickness is considered desirable in tomato as it enhances fruit firmness and reduces post-harvest losses during transportation and storage. The improved performance of certain hybrids for this trait suggested the effectiveness of hybridisation in enhancing post-harvest quality attributes. Similar observations were also reported by Garg *et al.* (2013) and Singh *et al.* (2021).

Plant height varied significantly among the parental lines and hybrids, indicating substantial genetic variability for vegetative growth traits (Table 3). Among the parents, plant height ranged from 121.92 cm in BajT-10 to 215.06 cm

Table 2 Analysis of variance for combining ability for yield and yield contributing traits in tomato

Trait	Mean sum of squares		
	GCA	SCA	Error
Days to first harvest	79.842*	12.869*	2.277
Number of fruits/plant	54.197*	12.095*	3.056
Number of fruits/cluster	0.455*	0.055*	0.032
Fruit yield/plant (kg)	0.346*	0.092*	0.02
Average fruit weight (g)	431.355*	38.889*	2.348
Pericarp thickness (mm)	0.664*	0.257*	0.006
Plant height (cm)	682.970*	370.087*	2.397
TSS (°Brix)	0.426*	0.133*	0.006
Ascorbic acid (mg/100 g)	23.520*	8.852*	0.382
df	8	36	88

*Significant at 5% level of significance. GCA, General combining ability; SCA, Specific combining ability; df, Degree of freedom.

Table 3 Top three parents and cross combinations based on their *per se* performance and heterotic response

Traits	<i>Per se</i> performance			Heterosis	
	Parents	Hybrids		Heterobeltiosis	Commercial heterosis
Days to first picking	Solan Lalima (67.67)	Solan Lalima × BajT-4 (62.76)	Solan Lalima × BajT-10 (-17.08%)	Solan Lalima × BajT-4 (-8.82%)	
	BajT-4 (68.77)	Solan Lalima × BajT-10 (66.33)	BajT-4 × BajT-11 (-15.82%)	Solan Lalima × Arka Abha (-2.94%)	
	H-7998 (68.22)	Solan Lalima × Arka Abha (66.12)	Solan Lalima × Arka Abha (-10.80%)	Solan Lalima × BajT-10 (-2.45%)	
Number of fruits/plant	H-7998 (46.25)	Arka Abha × H-7998 (47.28)	Arka Abha × H-7998 (13.45%)	Arka Abha × H-7998 (0.41%)	
	BajT-4 (45.51)	Solan Lalima × BajT-4 (46.27)	Arka Abha × BT-21 (9.37%)		
	Arka Meghali (43.24)	Solan Lalima × Arka Meghali (42.68)			
Number of fruits/cluster	BajT-4 (5.02)	Solan Lalima × BajT-4 (5.40)	Solan Lalima × BajT-4 (7.64%)	Solan Lalima × BajT-4 (15.96%)	
	Arka Abha (4.95)	Arka Meghali × BajT-4 (5.09)	Arka Meghali × BajT-1 (1.71%)	Arka Meghali × BajT-1 (9.38%)	
	H-7998 (4.91)	Solan Lalima × Arka Meghali (5.03)	Arka Meghali × BajT-4 (1.53%)	Arka Meghali × BajT-4 (6.30%)	
Fruit yield/plant (kg)	BajT-4 (2.40)	Solan Lalima × BajT-4 (3.10)	Arka Meghali × BajT-10 (37.21%)	Solan Lalima × BajT-4 (36.51%)	
	Solan Lalima (2.28)	Solan Lalima × Arka Meghali (2.89)	H-7998 × BajT-1 (34.58%)	Solan Lalima × Arka Abha (27.13%)	
	Arka Meghali (2.03)	Arka Meghali × BajT-4 (2.83)	Solan Lalima × BajT-4 (29.31%)	Solan Lalima × H-7998 (26.21%)	
Average fruit weight (g)	BajT-11 (77.27)	Solan Lalima × BajT-4 (83.82)	Arka Meghali × BajT-10 (35.69%)	Solan Lalima × BajT-4 (24.37%)	
	BajT-4 (76.25)	Solan Lalima × BajT-11 (80.18)	Solan Lalima × BajT-4 (9.92%)	Solan Lalima × BajT-11 (18.97%)	
	BajT-1 (72.74)	Arka Meghali × BajT-10 (77.97)	Solan Lalima × BajT-11 (3.77%)	Arka Meghali × BajT-10 (15.70%)	
Pericarp thickness (mm)	BajT-4 (5.97)	Solan Lalima × BajT-1 (5.87)	Arka Meghali × BajT-1 (28.33%)	H-7998 × BajT-4 (18.42%)	
	BajT-10 (5.45)	H-7998 × BajT-4 (5.73)	H-7998 × BajT-4 (18.42%)	Solan Lalima × BajT-1 (15.79%)	
	Solan Lalima (5.40)	Solan Lalima × BajT-4 (5.53)	Arka Meghali × H-7998 (13.11%)	Arka Meghali × BajT-1 (1.32%)	
Plant height (cm)	H-7998 (215.05)	BT-21 × BajT-1 (213.39)	BT-21 × BajT-1 (27.14%)	H-7998 × BajT-1 (22.37%)	
	BT-21 (206.06)	Arka Meghali × Arka Abha (210.82)	BT-21 × BajT-11 (18.18%)	BT-21 × BajT-1 (21.92%)	
	Solan Lalima (203.20)	H-7998 × BajT-1 (206.91)	BT-21 × BajT-4 (9.05%)	Arka Meghali × Arka Abha (13.70%)	
TSS (°B)	BajT-11 (5.74)	Arka Meghali × BajT-4 (5.29)	Solan Lalima × Arka Meghali (9.62%)	BajT-4 × BajT-10 (19.62%)	
	BajT-10 (5.34)	BajT-4 × BajT-10 (5.28)	Arka Meghali × H-7998 (7.72%)	BajT-4 × BajT-11 (14.79%)	
	BT-21 (5.20)	BT-21 × BajT-11 (5.20)	BT-21 × BajT-1 (5.12%)	BajT-10 × BajT-11 (14.64%)	
Ascorbic acid (mg/100 g)	BT-21 (30.10)	Solan Lalima × BajT-11 (30.46)	Solan Lalima × BajT-11 (40.57%)	Arka Abha × BajT-10 (14.24%)	
	Arka Meghali (29.36)	BT-21 × BajT-4 (30.39)	Arka Abha × BajT-10 (28.34%)	Solan Lalima × BajT-11 (13.21%)	
	BajT-4 (25.68)	BT-21 × BajT-1 (30.10)	Arka Abha × BajT-10 (25.17%)	BT-21 × BajT-4 (12.97)	

in H-7998. Among the hybrids, BT-21 × BajT-1 (213.39 cm) and Arka Meghali × Arka Abha (210.82 cm) recorded maximum plant height, indicating pronounced hybrid vigour for vegetative growth. Increased plant height may contribute towards higher photosynthetic efficiency and biomass accumulation, which could indirectly influence yield performance. However, excessive vegetative growth may create management difficulties under field conditions; therefore, maintenance of optimum plant architecture is important for practical cultivation and efficient crop management.

Heterosis and heterobeltiosis among hybrids: Heterosis analysis revealed significant hybrid vigour for most of the traits studied, thereby confirming the effectiveness of hybrid breeding for tomato improvement under mid-hill conditions (Table 3). For earliness, hybrids such as Solan Lalima × BajT-10 and BajT-4 × BajT-1 exhibited substantial negative heterobeltiosis (-17.08% and -15.82%, respectively), indicating earlier maturity compared to the better parent. Negative heterosis for days to first harvest is considered desirable in tomato as it facilitates early market availability and improved cropping intensity. Similar findings for earliness through heterosis breeding have also been reported by Singh *et al.* (2008) and Kumar *et al.* (2019).

For number of fruits/plant, hybrids such as Arka Abha × H-7998 (13.45%) and Solan Lalima × BajT-4 exhibited significant positive heterosis, indicating the importance of favourable non-additive gene effects in improving fruit set and reproductive efficiency. Enhanced fruit number in these hybrids may be attributed to better floral development and efficient assimilate partitioning towards reproductive organs.

Average fruit weight exhibited maximum heterosis in the hybrid Arka Meghali × BajT-10 (35.69%), suggesting the importance of non-additive gene action in the inheritance of this trait. Similarly, fruit yield/plant exhibited considerable heterobeltiosis in hybrids such as Solan Lalima × BajT-4 (29.31%), Arka Meghali × BajT-10 (37.21%) and H-7998 × BajT-1 (34.58%). The superior performance of these hybrids may be attributed to favourable interaction of yield-contributing traits such as fruit number, fruit weight and overall plant vigour. Substantial heterosis for fruit yield and related traits in diallel-derived hybrids suggested that exploitation of heterosis can effectively enhance productivity through favourable parental combinations. The superior performance of the present hybrids further supports the importance of utilising genetically diverse parents for yield improvement in tomato breeding programmes. Similar results for fruit yield heterosis in tomato were also reported by Khapte *et al.* (2019), Sharma *et al.* (2019) and Meena *et al.* (2022).

Significant heterotic effects were also observed for pericarp thickness in hybrids such as H-7998 × BajT-4 and Solan Lalima × BajT-1, indicating the possibility of improving post-harvest quality traits through hybridisation. Similar observations were earlier reported by Garg *et al.* (2013). Plant height exhibited maximum heterobeltiosis (27.14%) in the cross BT-21 × BajT-1, indicating pronounced

hybrid vigour for vegetative growth traits. However, these promising hybrids require further evaluation across multiple environments before their suitability for large-scale cultivation can be confirmed.

Correlation analysis: To further elucidate the relationships among different traits, Pearson's correlation analysis was conducted (Fig. 1). The analysis revealed a significant negative correlation between days to first harvest and number of fruits/cluster (-0.500), indicating that early-maturing genotypes tended to produce comparatively fewer fruits/cluster. This may be attributed to comparatively reduced vegetative growth and assimilate accumulation in early genotypes. However, days to first harvest exhibited negative correlations with fruit yield/plant, number of fruits/plant, average fruit weight, pericarp thickness and plant height, indicating that genotypes with fewer days to first harvest (earlier maturity) tended to have comparatively higher values for these yield and yield-contributing traits. This association suggests that earliness did not necessarily compromise productivity and may, in fact, be favourably associated with yield potential and other desirable fruit attributes. These findings are particularly important for tomato improvement programmes aimed at developing early-yielding hybrids with desirable yield potential, where early maturity can be combined with superior yield and associated traits.

Number of fruits/plant exhibited a strong positive correlation with fruit yield/plant (0.679) and average fruit weight (0.785), indicating the significant contribution of these traits towards overall productivity. The positive association between fruit number and yield suggested that selection for increased fruit set could effectively improve yield performance. Similarly, the positive correlation between fruit number and average fruit weight indicated the possibility of simultaneous improvement of both traits through selection and hybridisation. On the other hand, number of fruits/plant exhibited negligible association with plant height, total soluble solids (TSS) and ascorbic acid

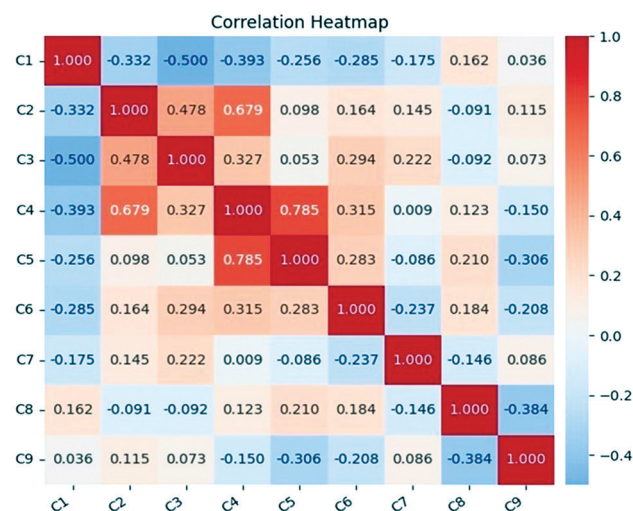


Fig. 1 Correlation coefficients among the evaluated traits. Traits details are given under Materials and Methods.

content, suggesting relative independence among these traits and providing opportunities for their separate genetic improvement.

Average fruit weight exhibited the highest positive correlation with fruit yield/plant (0.785), highlighting its important role in determining overall yield performance. Pericarp thickness showed a moderate positive correlation with fruit yield (0.315) and also exhibited positive association with days to first harvest and number of fruits/cluster. These associations suggested that improvement in pericarp thickness may contribute towards enhanced fruit firmness, yield stability and post-harvest quality. Plant height exhibited a negative association with pericarp thickness (-0.237), indicating a possible trade-off between vegetative growth and structural fruit attributes. The observed associations among yield and quality traits indicated the importance of simultaneous selection for multiple characters in tomato improvement programmes. Correlation analysis can assist breeders in identifying traits that contribute directly or indirectly to yield and quality enhancement, thereby improving selection efficiency during hybrid development. This approach has been widely recommended in tomato breeding studies.

Further, total soluble solids (TSS) and ascorbic acid content exhibited a negative correlation (-0.384), indicating the complexity involved in simultaneous improvement of sweetness and nutritional quality traits in tomato. Nevertheless, significant variability observed for these quality parameters among parents and hybrids suggested the possibility of improving both traits through appropriate parental selection and heterosis breeding. Similar associations among quality traits in tomato were also reported by earlier workers. Therefore, careful selection of parental combinations is essential for developing hybrids possessing both superior fruit quality and nutritional attributes.

Genetic variability among studied traits: Combining ability analysis provided deeper insights into the genetic control of the studied traits. General combining ability (GCA) was found to be significant for several characters, indicating the importance of additive variance in the inheritance of these traits. Among the parental lines, BajT-4 emerged as a good general combiner for earliness and yield-related traits, indicating its usefulness in tomato hybrid breeding programmes. Similarly, Arka Abha, Arka Meghali and Solan Lalima exhibited desirable GCA effects for fruit number, average fruit weight and fruit yield/plant, suggesting their potential utility in developing superior hybrid combinations (Table 4). The favourable GCA effects observed in these parents indicated the presence of desirable additive gene effects that can be effectively exploited through selection and hybridisation.

Specific combining ability (SCA), identified several promising cross combinations for yield and associated traits. For number of fruits/plant, crosses such as Arka Abha × H-7998 (5.16) and Arka Abha × BT-21 (4.31) exhibited high positive SCA effects, indicating superior performance due to

Table 4 Estimates of general combining ability effects of lines for different traits

Parents	Traits	Days to 50 per cent flowering	Days to first harvest	Number of fruits/plant	Number of fruits/cluster	Fruit yield/plant (kg)	Average fruit weight (g)	Fruit shape index	Pericarp thickness (mm)	Number of locules/fruit	Plant height (cm)	Harvest duration (days)	TSS (°Brix)	Ascorbic acid (mg/100 g)
Solan Lalima		-0.69	-5.17	2.49*	0.19*	0.21*	5.85*	0.03	0.31*	-0.34*	8.06*	-5.17*	-0.21*	-0.75*
Arka Meghali		0.36	0.11	1.47*	0.11*	0.15*	0.86	-0.05*	-0.21*	-0.09*	0.83	0.11	-0.13*	2.18*
Arka Abha		0.16	0.74	1.03*	0.04	-0.03	-4.61*	0.09*	-0.10*	0.10*	1.52*	0.74	-0.22*	1.12*
H-7998		-0.17	0.33	0.17	0.06	-0.15*	-8.46*	-0.06*	-0.05*	0.24*	9.75*	0.33	-0.12*	0.17
BT-21		0.17	2.18*	-0.56	0.01	-0.23*	-9.44*	0.01*	-0.39*	0.25*	2.06*	2.18*	-0.09*	1.58*
BajT-1		0.27	0.08	-0.77	-0.03	-0.05	3.80*	-0.02	0.10*	0.01	3.29*	0.08	0.08*	-0.03
BajT-4		-0.22	-3.39*	2.71*	0.26*	0.28*	5.87*	0.03*	0.31*	-0.46*	-4.48*	-3.39*	0.19*	-0.37*
BajT-10		-0.44	1.75*	-2.92*	-0.19*	-0.07	-0.73	0.01*	0.18*	0.19*	-16.72*	1.75*	0.25*	-1.66*
BajT-11		0.56	3.35*	-3.62*	-0.41*	-0.09*	6.86*	0.05*	-0.15*	0.09*	-4.32*	3.35*	0.24*	-2.24*
SE(Gi) ±		0.42	0.40	0.46	0.05	0.03	0.43	0.02	0.02	0.01	0.40	0.42	0.02	0.14
SE(Gi-Gj) ±		0.63	0.64	0.74	0.08	0.05	0.65	0.03	0.03	0.02	0.64	0.64	0.03	0.26
CD(p<0.05) (Gi)		0.97	0.98	1.14	0.12	0.08	1.04	0.05	0.04	0.04	1.01	0.98	0.05	0.40
CD (p<0.05) (Gi-Gj)		1.46	1.48	1.71	0.19	0.13	1.50	0.07	0.07	0.06	1.52	1.48	0.07	0.60

*Significant at 5% level of significance. Gi – Gj, Difference between the general combining ability (GCA) effects of two parents/genotypes.

Table 5 Estimates of genetic components of variance for different horticultural and quality traits in tomato

Trait	σ^2 GCA	σ^2 SCA	σ^2 a	σ^2 D	GCA/SCA ratio	Predictability ratio
Days to first harvest	7.051	10.592	14.103	10.59	0.666	0.571
Number of fruits/plant	4.649	9.039	9.298	9.039	0.514	0.507
Number of fruits/cluster	0.073	0.118	0.146	0.118	0.62	0.553
Fruit yield/plant (kg)	0.077	0.113	0.153	0.113	0.679	0.576
Average fruit weight (g)	39.001	36.541	78.001	36.54	1.067	0.681
Pericarp thickness (mm)	0.06	0.252	0.12	0.252	0.238	0.322
Plant height (cm)	61.87	367.691	123.741	367.69	0.168	0.252
TSS (°Brix)	0.038	0.126	0.076	0.126	0.301	0.376
Ascorbic acid (mg/100 g)	2.103	8.47	4.207	8.47	0.248	0.332

GCA, General combining ability; SCA, Specific combining ability; σ^2_a , Additive genetic variance; σ^2 D, Dominance genetic variance.

favourable specific parental interactions. Similarly, H-7998 $\times$ BajT-4 (12.50) and Arka Meghali $\times$ BajT-10 (13.81) were identified as promising specific combiners for this trait. For fruit yield/plant, the cross H-7998 $\times$ BajT-1 exhibited the highest SCA effect (0.54), despite involving parents with average or comparatively low GCA effects (Supplementary Table 1). This observation suggests a significant role of non-additive gene action in the expression of fruit yield and indicates that superior hybrids may be obtained even from parents with moderate combining ability when favourable gene interactions occur. Similar results have been reported by Farwah *et al.* (2024) who observed that crosses with high SCA effects frequently involved parents with contrasting combining ability, indicating the importance of non-additive gene action in the expression of yield and quality traits. These findings support the use of combining ability analysis for identifying superior hybrid combinations in tomato breeding programmes.

Variance component analysis revealed that the SCA variance (σ^2 SCA) was higher than the GCA variance (σ^2 GCA) for most of the traits studied, indicating the predominant role of non-additive gene action in their inheritance (Table 5). However, the predictability ratios indicated the involvement of both additive and non-additive gene effects. The relatively lower predictability ratios for pericarp thickness, plant height, TSS and ascorbic acid content suggested a greater influence of non-additive gene action in the inheritance of these traits. Some findings indicating the predominance of non-additive gene action for yield and related traits in tomato have also been reported by Kumar *et al.* (2013), Thakur (2014) and Yu *et al.* (2020). The predominance of non-additive gene effects suggested that exploitation of heterosis through hybrid breeding may be an effective approach for improving these economically important traits. Similar observations regarding the predominance of non-additive gene action for yield and related traits have been reported in tomato by Khapte *et al.* (2019), suggesting that hybrid breeding remains an effective strategy for exploiting heterosis and enhancing productivity. The presence of substantial SCA variance in

the present study further supports the importance of specific parental combinations in determining hybrid performance.

However, for average fruit weight, σ^2 GCA exceeded σ^2 SCA and the predictability ratio was greater than 0.5, indicating the relatively higher importance of additive gene effects in the inheritance of this trait. This suggested that improvement in fruit weight may also be achieved effectively through selection-based breeding approaches in addition to hybrid development.

Overall, the results of the present investigation demonstrated substantial genetic variability among the parental lines and hybrids for yield, earliness and quality traits under mid-hill conditions of Himachal Pradesh. Hybrids such as Solan Lalima $\times$ BajT-4, Arka Meghali $\times$ BajT-10 and H-7998 $\times$ BajT-1 exhibited superior performance for important horticultural traits and may be considered promising for further evaluation. The study also identified BajT-4, Solan Lalima and Arka Meghali as desirable general combiners for yield and related traits. The predominance of non-additive gene action for most traits suggested that exploitation of heterosis could be an effective breeding approach for improving yield and earliness in tomato. However, the relatively higher additive genetic variance observed for average fruit weight indicated the possibility of improving this trait through selection-based breeding approaches.

Thus, the findings highlighted the integration of heterosis and combining ability analysis provides useful information regarding the inheritance of important horticultural traits and identification of promising parental combinations for future tomato breeding programmes. The identified superior hybrids and combining parents may serve as valuable genetic resources for the development of high-yielding tomato cultivars suitable for mid-hill agro-climatic conditions. Further evaluation of promising hybrids across diverse environments would help in assessing their stability and wider adaptability.

REFERENCES

- Ali M Y, Sina A A I, Khabdker S S, Neesa L, Tanvir E M, Kabir A, Khalil M I and Gan S H. 2020. Nutritional composition

- and bioactive compounds in tomatoes and their impact on human health and disease: A review. *Foods* **10**(1): 45. <https://doi.org/10.3390/foods10010045>
- Farwah S, Afroza B, Dar Z A, Nazir G, Masoodi U H, Nabi A and Shamma R. 2024. Combining ability studies for maturity, growth, yield and quality traits in tomato (*Solanum lycopersicum* L.). *Journal of Scientific Research and Reports* **30**(4): 53–60. <https://doi.org/10.9734/jsrr/2024/v30i41889>
- Garg N, Cheema D S and Chawla N. 2013. Manifestation of heterosis for fruit yield, quality and shelf-life in tomato (*Solanum lycopersicum* L.). *Vegetable Science* **40**(1): 28–33.
- Griffing B. 1956. Concepts of general and specific combining ability in relation to diallel crossing systems. *Australian Journal of Biological Sciences* **9**: 463–93. <https://doi.org/10.1071/BI9560463>
- Khapte P S, Jansirani P and Saraswathi T. 2019. Heterosis in oblong fruited tomato (*Solanum lycopersicum* L.) hybrids for growth and yield traits. *The Indian Journal of Agricultural Sciences* **89**(10): 1594–98. <https://doi.org/10.56093/ijas.v89i10.94584>
- Kumar A, Singh M and Rai A K. 2019. Genetic divergence studies in tomato (*Solanum lycopersicum* L.). *Journal of Pharmacognosy and Phytochemistry* **8**(5): 232–35.
- Kumar R, Srivastava K, Singh N P, Vasistha, N K, Singh R K and Singh M K. 2013. Combining ability analysis for yield and quality traits in tomato (*Solanum lycopersicum* L.). *Journal of Agricultural Science* **5**(2): 213–18. <https://doi.org/10.5539/ijas.v5n2p213>
- Meena O P, Bahadur V and Singh A. 2022. Genetic variability, heritability and genetic advance studies in diverse genotypes of tomato (*Solanum lycopersicum* L.). *International Journal of Plant and Soil Science* **34**(22): 188–95.
- NHB. 2021. *Indian Horticulture Database*. National Horticulture Board, Ministry of Agriculture, Government of India.
- Panse, V G and Sukhatme P V. 1985. Statistical Methods for Agricultural Workers, 4th edn. Indian Council of Agricultural Research, New Delhi.
- Sharma H, Singh B and Kumar P. 2019. Assessment of genetic variability, heritability, and genetic advance for yield and quality traits in tomato (*Solanum lycopersicum* L.). *Journal of Pharmacognosy and Phytochemistry* **8**(3): 1142–46.
- Sharma N S, Dhillon M A and Singh H. 2022. Assessment of tomato (*Solanum lycopersicum* L.) hybrids for development and yield accredits under polyhouse condition in subtropical area. *The Pharma Innovation Journal* **11**(7): 366–69.
- Singh A, Singh B and Kumar S. 2021. Heterosis and combining ability analysis for yield and quality traits in tomato (*Solanum lycopersicum* L.). *The Indian Journal of Agricultural Sciences* **91**(4): 586–90.
- Singh B, Rai N, Singh R K, Singh M C, Singh A K and Chaturvedi A K. 2008. Heterosis, combining ability and gene action studies in tomato (*Solanum lycopersicum* L.). *Vegetable Science* **35**: 132–35.
- Thakur N. 2014. ‘Studies on hybrid performance, heterosis and combining ability studies under organic and in organic farming systems in tomato (*Solanum lycopersicum* L.)’. PhD Thesis, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur, Himachal Pradesh.
- Yu K C, Wang H, Liu X G, Xu C, Li Z W, Xu X J, Liu J C, Wang Z H and Xu Y B. 2020. Large-scale analysis of combining ability and heterosis for development of hybrid maize breeding strategies using diverse germplasm resources. *Frontiers in Plant Science* **11**: 660. <https://doi.org/10.3389/fpls.2020.00660>