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Heterosis and combining ability for growth and yield traits in Tomato (*Solanum lycopersicum* L.) under protected condition

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Abstract

The present study was heterosis and combining ability for growth and yield traits in tomato (*Solanum lycopersicum* L.) under protected condition. Followed half-diallel mating design involving six parental lines to develop 15 F₁ hybrids. Significant variation was observed among the genotypes for all the characters studied. Among the parents, Pusa Ruby recorded the highest plant height (227.12 cm), number of branches per plant (9.67), number of fruits per plant (23.00) and fruit yield per plot (12.90 kg). While, CHMT-4 exhibited the highest average fruit weight (64.32 g) and CHMT-1 the highest leaf area (34.70 cm²). Among the hybrids, CHMT-1 × CHMT-20 recorded the highest plant height (227.99 cm), Pusa Ruby × CHMT-4 recorded the highest number of branches per plant (9.10), number of fruits per plant (25.00), fruit yield per plot (18.70 kg) and average fruit weight (74.82 g). CHMT-4 × CHMT-1 flowered earliest (37.00 days), Arka Vikas × CHMT-1 exhibited the highest leaf area (34.50 cm²) and Pusa Ruby × CHMT-20 recorded the highest number of locules per fruit (4.52). The highest standard heterosis was observed in Pusa Ruby × CHMT-4 for fruit yield per plot (31.41%), number of fruits per plant (17.92%), average fruit weight (11.46%) and number of branches per plant (9.63%). The hybrid, Pusa Ruby × CHMT-20 for number of locules per fruit (16.79%) and Arka Vikas × CHMT-1 for leaf area (10.22%). Positive significant standard heterosis for plant height was recorded only in CHMT-1 × CHMT-20 (0.60%), whereas CHMT-4 × CHMT-1 exhibited the highest desirable negative standard heterosis for days to first flowering (-4.14%). Combining ability analysis revealed significant GCA and SCA effects for all traits, with additive gene action predominating for most yield traits and non-additive gene action for plant height, days to first flowering and leaf area. CHMT-4 and Pusa Ruby were identified as superior general combiners, while Pusa Ruby × CHMT-4, Arka Vikas × CHMT-20 and CHMT-1 × CHMT-20 emerged as promising hybrids for tomato improvement and hybrid breeding.

Keywords: Tomato, heterosis, combining ability, half diallel and protected condition

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops belonging to the family Solanaceae with a diploid chromosome number of 2n = 2x = 24 and is believed to have originated in Peru, South America (Rick, 1969). Owing to its high nutritional and economic value, tomato has become an important crop for both fresh consumption and processing. Heterosis or hybrid vigour, refers to the superior performance of F₁ hybrids over their parents for growth, yield and other economically important traits. The success of heterosis breeding largely depends on the identification of genetically superior parents through combining ability analysis, which provides information on the nature of gene action governing quantitative traits. General Combining Ability (GCA) reflects additive gene effects, whereas Specific Combining Ability (SCA) is associated with non-additive gene effects. Since growth and yield are complex quantitative traits influenced by both genetic and environmental factors, the combined assessment of heterosis and combining ability is essential for identifying superior parents and promising hybrid combinations. Therefore, the present investigation was undertaken to estimate heterosis and combining ability for growth and yield parameters in tomato under protected cultivation.

2. Material and Methods

The present investigation was conducted at the College of Horticulture, Mudigere, to develop tomato hybrids with improved growth and yield traits under protected cultivation. Six diverse parental lines were crossed using a half-diallel mating design to produce 15 F₁ hybrids, which, along with the parents and a commercial check, were evaluated in a Randomized Complete Block Design (RCBD). Standard crop management practices, including nursery raising, hybridization, transplanting, fertilization, irrigation, training and pruning, were followed throughout the experiment. Observations were recorded on important growth and parameters. The collected data were statistically analyzed using Analysis of Variance (ANOVA) and heterosis was estimated over the mid-parent, better parent and commercial check. General Combining Ability (GCA) and Specific Combining Ability (SCA) analyses were performed following Griffing's Model-I to determine the nature of gene action governing the studied traits.

2.1 Statistical analysis

2.1.1 Analysis of variance

Source	d.f.	Mean squares	Expectation of mean squares
Replications	(r-1)	Mr	$\sigma^2_e + g \sigma^2_r$
Genotypes	(g-1)	Mg	$\sigma^2_e + r \sigma^2_g$
Parents	(p-1)	Mp	-
Hybrids	(h-1)	Mh	-
Parents vs. hybrids	1	Mp vs. Mh	-
Error	(r-1)(g-1)	Me	σ^2_e
Total	(rg-1)		

Where,

r = number of replications

g = number of genotypes

p = number of parents

h = number of hybrids

2.1.2 Heterosis

$$\text{Mid-parent heterosis (\%)} = \frac{(F_1 - MP)}{MP} \times 100$$

$$\text{Better parent heterosis (\%)} = \frac{(F_1 - BP)}{BP} \times 100$$

$$\text{Standard heterosis (\%)} = \frac{(F_1 - SC)}{SC} \times 100$$

2.1.3 ANOVA for combining ability

Source of Variation	Degrees of freedom	Sum of squares	Mean sum of squares	Expectation of mean sum of squares
GCA	(P-1)	S _g	M _g	$\sigma^2_e + \frac{(P+2)}{(P-1)} \Sigma g^2$
SCA	$\frac{P(P-1)}{2}$	S _s	M _s	$\sigma^2_e + \frac{2}{P(P-1)} \Sigma S^2$
Error	(r-1)(g-1)	S _e	M _e	σ^2_e

Where,

S_g = Sum of squares due to general combining ability

$S_g = 1 / p+2 \{ \Sigma (X_i + X_{ii})^2 - 4 X^2 \}$

S_s = Sum of squares due to specific combining ability

$S_s = \Sigma \Sigma X^2_{ij} - 1 / P + 2 \Sigma (X_i + X_{ii})^2 + 2 / (P + 1) (P + 2) X^2$, $1 \leq j$

P = Number of parents

X_i = Array total involving ith recurrent parent

X_{ii} = Mean value of ith parent

X_{ij} = General total of 'P' parental line and P (P-1) / 2 progenies

X_{ij} = Mean value of ijth cross

M_e = Error mean square (M_e / r)

2.1.4 General and Specific Combining Ability effects

The general and specific combining ability effects were estimated as under,

$$\text{Population mean}(\mu) = \frac{2}{P(P+1)} Y_{..}$$

$$\text{GCA effect}(g_i) = \frac{1}{P+2} (Y_i + Y_{ii}) - \frac{2}{P} Y_{..}$$

$$\text{SCA effect}(s_{ij}) = Y_{ji} - \frac{1}{P+2} (Y_i + Y_{ii} + Y_j + Y_{jj}) - \frac{2}{(P+1)(P+2)} Y_{..}$$

Where,

P = Number of parents

g_i = General combining ability effect of ith parent

s_{ij} = Specific combining ability effect of the cross-involving ith and jth parents

Y_i = Total of array involving ith parent

Y_j = Total of array involving the jth parent

Y_{ii} = Parental value of the ith parent

Y_{j j} = Parental value of the nth parent

Y_{..} = Total of all P(P+1) 2 items of the diallel table

3. Results and Discussion

3.1 ANOVA for growth and yield parameters

The ANOVA revealed highly significant differences among genotypes for all the growth and yield traits, indicating the presence of substantial genetic variability. Significant variation among parents and hybrids suggests good potential for selecting superior genotypes. The significant parent vs. hybrid comparisons for most traits indicate the presence of heterosis, while the low error mean squares confirm the reliability and precision of the experimental results. Overall, the findings demonstrate the effectiveness of the breeding material for developing high-yielding tomato hybrids (Table 1).

3.2 Per se performance and heterosis

3.2.1 Growth parameters

Plant height varied significantly among the parental lines and hybrids. Pusa Ruby (227.12 cm) and CHMT-1 × CHMT-20 (227.99 cm) recorded the highest plant height among parents and hybrids, respectively. Mid-parent heterosis ranged from (-2.43 to 2.64%), better-parent heterosis from (-3.56 to 1.90%) and positive significant standard heterosis was observed only in CHMT-1 × CHMT-20 (0.60%) (Plate 1), indicating favourable gene interactions promoting vegetative growth. Similar findings were reported by Izzo *et al.* (2022) [3].

Significant variation was observed for number of branches per plant. Pusa Ruby (9.67) and Pusa Ruby × CHMT-4 (9.10) recorded the highest values among parents and hybrids, respectively (Table 2). Mid-parent, better-parent and standard heterosis ranged from (-36.84 to 45.74%), (-56.55 to 30.43%) and (-57.42 to 9.63%), respectively (Table

3). Enhanced branching may be attributed to favourable genetic interactions and efficient assimilate partitioning. These findings agree with Singh *et al.* (2024) [21, 22].

For days to first flowering, CHMT-4 (37.40 days) and CHMT-4 × CHMT-1 (37.00 days) were the earliest parent and hybrid, respectively. Mid-parent heterosis ranged from (-2.88 to 4.34%), better-parent heterosis from (-4.63 to 3.69%) and the maximum negative standard heterosis (-4.14%) was recorded in CHMT-4 × CHMT-1, indicating earliness due to accelerated floral initiation. Similar results were reported by, Kathimba *et al.* (2022), and Kondratenko *et al.* (2025) [5, 8].

Leaf area differed significantly among genotypes. CHMT-1 (34.70 cm²) and Arka Vikas × CHMT-1 (34.50 cm²) recorded the highest values among parents and hybrids, respectively. Mid-parent heterosis ranged from (-16.00 to 13.28%), better-parent heterosis from (-18.05 to 12.54%) and the highest standard heterosis (10.22%) was exhibited by Arka Vikas × CHMT-1, reflecting improved leaf expansion and photosynthetic capacity. Similar observations were reported by Liu *et al.* (2024) and Nnabuihe *et al.* (2026) [12, 16].

3.2.2 Yield parameters

The number of fruits per plant varied significantly among the genotypes. Pusa Ruby (23.00) and Pusa Ruby × CHMT-4 (25.00) recorded the highest values among the parents and hybrids, respectively. Mid-parent heterosis ranged from (0.77 to 38.96%), better-parent heterosis from (-11.00 to 36.05%) and the highest standard heterosis (17.92%) was observed in Pusa Ruby × CHMT-4, indicating improved fruit set and favourable yield-related gene interactions. Similar findings were reported by Lone *et al.* (2021) and Izzo *et al.* (2022) [3, 7].

Significant variation was observed for fruit yield per plot. Pusa Ruby (12.90 kg) and Pusa Ruby × CHMT-4 (18.70 kg) recorded the highest yield among the parents and hybrids, respectively. Mid-parent heterosis ranged from (-4.90 to 68.07%), better-parent heterosis from (-16.00 to 59.58%) and the highest standard heterosis (31.41%) was expressed by Pusa Ruby × CHMT-4, reflecting the combined effect of superior yield-contributing traits. Similar results were reported by Singh *et al.* (2024), Sharma *et al.* (2025) and Lalramhlimi *et al.* (2025) [11, 20, 21, 22].

Average fruit weight differed significantly among the genotypes. CHMT-4 (64.32 g) and Pusa Ruby × CHMT-4 (74.82 g) recorded the highest values among the parents and hybrids, respectively (Table 2). Mid-parent heterosis ranged from (-5.00 to 28.27%), better-parent heterosis from (-12.00 to 24.44%) and the highest standard heterosis (11.46%) was observed in Pusa Ruby × CHMT-4, suggesting efficient assimilate partitioning and favourable non-additive gene effects (Table 4). These findings agree with Nevani *et al.* (2022), and Lalramhlimi *et al.* (2025) [11, 15].

The number of locules per fruit showed significant variation among the genotypes. Pusa Ruby (4.23) and Pusa Ruby × CHMT-20 (4.52) recorded the highest values among the parents and hybrids, respectively. Mid-parent heterosis ranged from (-9.36 to 42.22%), better-parent heterosis from (-14.44 to 32.93%) and the highest standard heterosis (16.79%) was expressed by Pusa Ruby × CHMT-20, reflecting improved meristem development and carpel differentiation. Similar observations were reported by Izzo *et al.* (2022) and Singh *et al.* (2024) [3, 21, 22].

3.3 Combining ability studies

The ANOVA for combining ability revealed highly significant ($p \leq 0.01$) differences for both GCA and SCA for all the characters studied, indicating the involvement of both additive and non-additive gene effects. Higher GCA variance than SCA variance was observed for number of branches per plant, number of fruits per plant, fruit yield per plot, average fruit weight and number of locules per fruit, suggesting the predominance of additive gene action (Table 5). In contrast, plant height, days to first flowering and leaf area exhibited relatively higher SCA variance, indicating the importance of non-additive gene action. The low error variances confirmed the reliability of the experimental results. Overall, additive gene effects predominated for most yield-related traits, indicating the effectiveness of selection, while non-additive gene action can be exploited through heterosis breeding for specific traits.

General and Specific Combining Ability

3.3.1 Growth parameters

For plant height at 90 DAS, positive and highly significant GCA effects were observed in CHMT-4 (0.84) and CHMT-1 (0.53), whereas Arka Vikas (-1.01) and CHMT-20 (-0.44) exhibited highly significant negative effects (Table 6). The hybrid CHMT-1 × CHMT-20 (4.65) showed the maximum highly significant positive SCA effect, followed by Arka Vikas × CHMT-4 (4.02). On the other hand, the lowest negative SCA effects was recorded in the cross combination, Pusa Ruby × Arka Vikas (-3.25) followed by CHMT-4 × CHMT-1 (-3.09) (Table 7). Similarly, both positive and negative GCA and SCA effects were observed in parents and hybrids, respectively in the research conducted by Mishra *et al.* (2020) and Kathimba *et al.* (2022) [5, 14].

For number of branches per plant at 90 DAS, Pusa Ruby (1.30) and CHMT-4 (1.28) showed highly significant and highest positive GCA effects, while Arka Vikas (-1.42) and CHMT-20 (-0.50) recorded highest highly significant negative effects. Among the hybrids, Arka Vikas × CHMT-20 (1.79) expressed the highest positive and highly significant SCA effect, followed by Pusa Ruby × Krishna Prabha Shalmala (1.54). Significant negative SCA effects were observed in Pusa Ruby × Arka Vikas (-1.81) and Pusa Ruby × CHMT-1 (-1.40). These results align with the findings of Mishra *et al.* (2020), Soresa *et al.* (2021) and Kumar *et al.* (2023a) [9, 14, 24].

Among the parental lines, Krishna Prabha Shalmala (0.25) recorded a highly significant and highest positive GCA effect, indicating the earliness, whereas CHMT-4 (-0.22) showed a significant negative effect. Out of 15 direct crosses, two crosses showed highest and highly significant positive SCA effect in the desired direction which included the cross CHMT-4 × CHMT-20 (1.16) followed by Krishna Prabha Shalmala × CHMT-20 (0.81). Maximum highly significant negative SCA effects were observed in CHMT-4 × CHMT-1 (-1.20) followed by Pusa Ruby × Krishna Prabha Shalmala (-0.95). Farwah *et al.* (2022) and Kumar *et al.* (2023b) [10] also revealed that parents and hybrids in tomato exhibited positive and negative GCA and SCA effects.

The estimates of GCA effects revealed that CHMT-4 (0.80), CHMT-1 (0.59) and Krishna Prabha Shalmala (0.13) were good general combiners for leaf area as they exhibited highly significant positive effects. whereas, Arka Vikas (-

1.29) exhibited the highest and highly significant negative effect. Among the hybrids, Arka Vikas × CHMT-1 (3.88) and Pusa Ruby × CHMT-20 (3.04) recorded the highly significant and highest positive SCA effects. Maximum highly significant negative SCA effects were observed in Krishna Prabha Shalmala × CHMT-1 (-3.60) and CHMT-1 × CHMT-20 (-3.09). Enhanced leaf area in these hybrids may be attributed to favourable non-additive gene action contributing to greater photosynthetic surface. A similar trend was reported by Mishra *et al.* (2020) and Javed *et al.* (2022) [4, 14].

3.3.2 Yield parameters

The parents, CHMT-4 (1.65) and Pusa Ruby (1.41) were identified as the best general combiners, while Arka Vikas (-1.80) showed the highest negative GCA effect. Among the hybrids, Arka Vikas × CHMT-20 (3.53) and Pusa Ruby × Krishna Prabha Shalmala (2.19) exhibited the highest positive SCA effects, indicating favourable dominance and epistatic interactions for fruit production. Similar findings were reported by Liu *et al.* (2021), Khojah *et al.* (2022) [6] and Javed *et al.* (2022) [4, 13]. The parents, CHMT-4 (1.96) and Pusa Ruby (1.09) were the best general combiners, whereas Arka Vikas (-1.90) recorded the highest negative

GCA effect. Arka Vikas × CHMT-20 (3.60) showed the highest positive SCA effect, followed by Pusa Ruby × Krishna Prabha Shalmala (3.42), suggesting the importance of non-additive gene action for fruit yield. These results are in agreement with Kathimba *et al.* (2022), Pham *et al.* (2022) and Reddy *et al.* (2023) [5, 17, 18].

The parents, CHMT-4 (5.12) and Pusa Ruby (2.37) were identified as superior general combiners, while Arka Vikas (-4.90) exhibited the highest negative GCA effect. Arka Vikas × CHMT-20 (8.85) and Pusa Ruby × Krishna Prabha Shalmala (7.54) recorded the highest positive SCA effects, indicating favourable dominance and epistatic interactions governing fruit development (Table 7). Similar observations were reported by Chandel *et al.* (2021) and Javed *et al.* (2022) [1, 4].

Among the parents, CHMT-20 (0.15) and Arka Vikas (0.12) were the best general combiners, whereas CHMT-1 (-0.41) recorded the highest negative GCA effect. Krishna Prabha Shalmala × CHMT-4 (0.79) and Pusa Ruby × CHMT-20 (0.66) exhibited the highest positive SCA effects, indicating the role of non-additive gene action in locule development. Similar findings were reported by Reddy *et al.* (2023) and Singh *et al.* (2025) [18, 23].

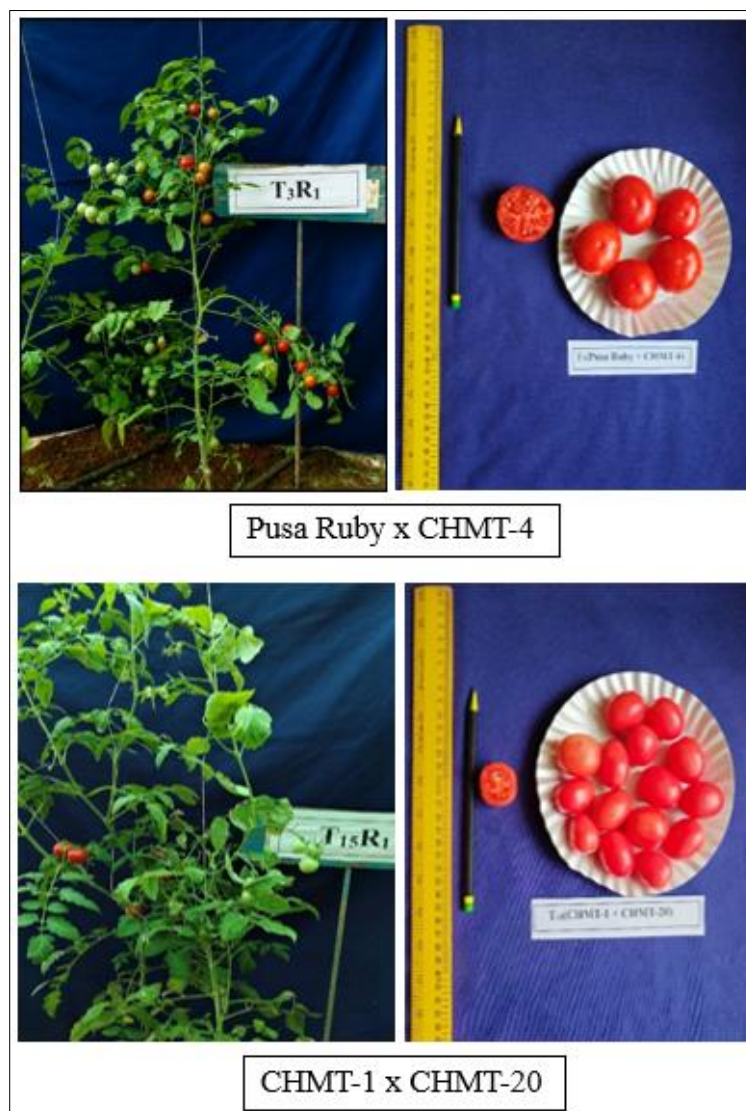


Plate 1: Best performing hybrids

Table 1: Analysis of Variance (ANOVA) for growth and yield parameters

Character	Replication	Genotypes	Parents	Hybrid	Parent vs Hybrid	Check vs Hybrid	Error
DF	2	21	5	14	1	1	42
Plant height (cm) at 90 DAS	0.29	23.31**	30.77**	21.59**	0.48**	31.20**	0.10
No. of branches per plant at 90 DAS	0.01	10.07**	16.29**	8.19**	1.98**	14.56**	0.007
Days to first flowering	0.10	1.20**	0.78**	1.46**	0.70**	0.05	0.08
Leaf area (cm ²)	0.02	12.63**	16.31**	13.11**	0.001	0.0002	0.009
Number of fruits per plant	0.16	19.72**	22.98**	12.12**	129.31**	3.86	3.33
Fruit yield per plot (kg)	0.08	26.51**	8.93**	21.96**	204.21**	1.55	1.43
Average fruit weight (g)	1.08	146.0**	73.18*	126.21**	904.68**	1.58**	30.00
Number of locules per fruit	0.01	0.73**	1.23**	0.48**	2.28**	0.04**	0.003

DAS- Days after sowing

* and ** indicates significance at 5% and 1% level, respectively

Table 2: Per se value of parents, hybrids and check for growth and yield parameters

Genotypes	1	2	3	4	5	6	7	8
Pusa Ruby (P R)	227.12	9.67	38.47	29.90	23.00	12.90	61.85	4.23
Krishna Prabha Shalmala (K P S)	221.89	5.10	38.33	33.00	18.00	10.56	57.20	3.20
Arka Vikas (A V)	219.19	3.63	38.53	28.20	16.00	8.63	50.94	4.13
CHMT-4 (C-4)	226.19	8.10	37.40	31.70	21.50	12.83	64.32	3.37
CHMT-1(C-1)	223.96	7.40	38.80	34.70	20.00	11.40	59.46	2.20
CHMT-20 (C-20)	220.26	4.60	37.87	30.30	16.72	9.60	54.18	3.40
Pusa Ruby × Krishna Prabha Shalmala (P R × K P S)	222.16	8.60	37.67	31.40	24.68	18.13	73.45	4.00
Pusa Ruby × Arka Vikas (P R × A V)	219.02	4.20	38.13	28.90	20.41	12.23	59.92	4.19
Pusa Ruby × CHMT-4 (P R × C-4)	221.12	9.10	38.53	33.20	25.00	18.70	74.82	3.75
Pusa Ruby × CHMT-1 (P R × C-1)	223.26	5.77	39.07	30.60	22.40	14.82	66.18	3.51
Pusa Ruby × CHMT-20 (P R × C-20)	223.32	6.43	38.17	34.10	23.05	15.85	68.75	4.52
Krishna Prabha Shalmala × Arka Vikas (K P S × A V)	225.52	3.80	39.20	29.70	19.26	10.94	56.78	3.55
Krishna Prabha Shalmala × CHMT-4 (K P S × C-4)	224.82	7.27	38.73	32.80	24.35	17.75	72.91	4.48
Krishna Prabha Shalmala × CHMT-1 (K P S × C-1)	226.19	4.60	39.17	28.43	20.93	12.94	61.84	3.84
Krishna Prabha Shalmala × CHMT-20 (K P S × C-20)	220.32	5.36	39.40	31.90	21.98	14.28	64.95	4.36
Arka Vikas × CHMT-4 (A V × C-4)	227.09	6.73	38.67	30.10	23.38	16.34	69.87	3.65
Arka Vikas × CHMT-1 (A V × C-1)	220.06	3.53	38.33	34.50	18.14	9.52	52.46	3.66
Arka Vikas × CHMT-20 (A V × C-20)	224.46	6.00	37.80	29.20	22.72	15.32	67.42	3.76
CHMT-4 × CHMT-1 (C-4 × C-1)	221.52	7.03	37.00	32.30	24.02	17.22	71.68	3.10
CHMT-4 × CHMT-20 (C-4 × C-20)	222.52	6.93	39.27	33.80	23.70	16.81	70.94	3.71
CHMT-1 × CHMT-20 (C-1 × C-20)	227.99	5.00	37.87	28.70	21.55	13.73	63.73	3.50
Arka Abhed- Check (A A)	226.62	8.30	38.60	31.30	21.20	14.23	67.13	3.87

1-Plant height (cm) @ 90 DAS

2- No. of branches @ 90 DAS

3- Days to first flowering

4- Leaf area (cm²)

5- No. of fruits per plant

6- Fruit yield per plot (kg)

7- Average fruit weight (g)

8- No. of locules per fruit

Table 3: Heterosis percentage of hybrids for growth parameters

Hybrids	Plant height @ 90 DAS			No. of branches @ 90 DAS			Days to first flowering			Leaf area (cm ²)		
	MP	BP	SC	MP	BP	SC	MP	BP	SC	MP	BP	SC
P R × K P S	-1.04**	-2.18 **	-1.97 **	16.47**	-11.03**	3.61 **	-1.90 **	-2.07 **	-2.41 **	-0.15	-4.84 **	0.31
P R × A V	-1.84 **	-3.56 **	-3.35 **	-36.84**	-56.55 **	-49.39 **	-0.95	-1.03	-1.20 *	-0.51	-3.34 **	-7.66 **
P R × C-4	-2.43 **	-2.63 **	-2.42 **	2.43**	-5.86 **	9.63 **	1.58 **	0.17	-0.17	7.79 **	4.73 **	6.07 **
P R × C-1	-1.01 **	-1.69 **	-1.48 **	-32.42**	-40.34 **	-30.52**	1.12	0.68	1.20 *	-5.26 **	-11.81 **	-2.23 **
P R × C-20	-0.16	-1.67 **	-1.45 **	-9.81 **	-33.44 **	-22.49 **	-1.90	-0.77	-1.12	13.28 **	12.54 **	8.94 **
K P S × A V	2.26 **	1.63 **	-0.48 **	-12.97 **	-25.49 **	-54.21 **	1.99 **	1.73 **	1.55 **	-2.94**	-10.00 **	-5.11 **
K P S × C-4	0.35 **	-0.60 **	-0.79 **	10.10 **	-10.28 **	-12.44 **	2.28 **	1.04	0.34	1.39 **	-0.60 *	4.79 **
K P S × C-1	1.46 **	0.99 **	-0.19	-26.40 **	-37.83 **	-44.57**	1.55 **	0.94	1.46 *	-16.00 **	-18.05 **	-9.15 **
K P S × C-20	-0.33 **	-0.70 **	-2.77 **	10.65**	5.22 **	-35.34**	3.41 **	2.78 **	2.07 **	0.78 **	-3.33 **	1.91 **
A V × C-4	1.97 **	0.39 **	0.20	14.77 **	-16.87 **	-18.87**	1.84 **	0.34	0.17	0.50	-5.04 **	-3.83 **
A V × C-1	-0.68 **	-1.74 **	-2.89 **	-35.95 **	-52.25**	-57.42 **	-0.86	-1.20 *	-0.69	9.69 **	-0.57 *	10.22 **
A V × C-20	2.15 **	1.90 **	-0.95 **	45.74 **	30.43**	-27.71 **	-1.04	-1.90 **	-2.07 **	-0.17	-3.63 **	-6.70 **
C-4 × C-1	-1.57 **	-2.06 **	-2.25 **	-9.24**	-13.16 **	-15.26 **	-2.88 **	-4.63 **	-4.14 **	-2.71 **	-6.91 **	3.19 **
C-4 × C-20	-0.31 **	-1.61 **	-1.80 **	9.18**	-14.40**	-16.46 **	4.34 **	3.69 **	1.72 **	9.03 **	6.62 **	7.98 **
C-1 × C-20	2.64 **	1.79 **	0.60 **	-16.66 **	-32.43 **	-39.75 **	-1.21 *	-2.40 **	-1.89 **	-11.69 **	-17.29 **	-8.30 **
S. E m ±	0.22	0.18	0.18	0.03	0.04	0.04	0.11	0.16	0.16	0.04	0.05	0.05

C.D@5%	0.62	0.51	0.51	0.09	0.13	0.13	0.32	0.45	0.45	0.11	0.15	0.15
C.D@1%	0.84	0.69	0.69	0.13	0.18	0.18	0.43	0.61	0.61	0.15	0.21	0.21

MP- Mid parent, BP- Better parent, SC- Standard check

DAS - Days after sowing

* and ** indicates significance at 5% and 1% level, respectively

Table 4: Heterosis percentage of hybrids for yield parameters

Hybrids	No. of fruits per plant			Fruit yield per plot (kg)			Average fruit weight (g)			No. of locules per fruit		
	MP	BP	SC	MP	BP	SC	MP	BP	SC	MP	BP	SC
P R × K P S	20.39 **	7.30	16.42 *	54.56 **	40.54 **	27.41 **	23.39 **	18.76 **	9.41	0.97	-5.45 **	-10.42 **
P R × A V	4.66	-11.00	-3.70	13.61	-5.20	-14.00 *	6.25	-3.10	-11.00	-9.36**	-14.44 **	-8.69 **
P R × C-4	12.36	8.70	17.92 *	45.36 **	44.96 **	31.41 **	18.60 **	16.32 *	11.46	-0.52	-4.54 **	-9.56 **
P R × C-1	4.18	-2.60	5.66	21.98 **	14.88 *	4.15	9.11	7.00	-1.40	22.72 **	-1.81	-6.97 **
P R × C-20	16.12 *	0.22	8.73	40.89 **	22.87 **	11.38	18.50 *	11.16	2.41	27.92 **	23.27 **	16.79 **
K P S × A V	13.29	7.00	-9.20	14.02	3.60	-23.00 **	5.01	-0.73	-15.00 *	-3.13 *	-14.04 **	-8.26 **
K P S × C-4	23.29 **	13.26	14.86 *	51.77 **	38.35 **	24.74 **	20.00 **	13.36	8.61	36.37**	32.93 **	15.76 **
K P S × C-1	10.15	4.65	-1.30	17.85 *	13.51	-9.10	6.02	4.00	-7.90	42.22 **	20.00 **	-0.77
K P S × C-20	26.68 **	22.11 **	3.68	41.67 **	35.23 **	0.35	16.63 *	13.55	-3.20	32.12 **	28.23 **	12.66 **
A V × C-4	24.69 **	8.74	10.28	52.28 **	27.36 **	14.83 *	21.24 **	8.63	4.08	-2.66 *	-11.62 **	-5.68 **
A V × C-1	0.77	-9.30	-14.00 *	-4.90	-16.00	-33.00 **	-5.00	-12.00	-22.00 **	15.63 **	-11.38 **	-5.42 **
A V × C-20	38.96 **	36.05 **	7.17	68.07 **	59.58 **	7.66	28.27 **	24.44 **	0.43	-0.13	-8.95**	-2.84 *
C-4 × C-1	15.75 *	11.72	13.30	42.14 **	34.22 **	21.01 **	15.82 *	11.44	6.78	11.31 **	-8.01 **	-19.89 **
C-4 × C-20	24.08**	10.23	11.79	49.89 **	31.02 **	18.13 **	19.73 **	10.29	5.68	9.60**	9.11 **	-4.13 **
C-1 × C-20	17.43 *	7.75	1.65	30.76 **	20.44 *	-3.50	12.16	7.18	-5.10	25.00 **	2.94 *	-9.56 **
S. E m ±	1.02	1.05	1.05	0.67	0.69	0.69	3.15	3.15	3.15	0.02	0.03	0.03
C.D@5%	2.91	3.00	3.00	1.91	1.97	1.97	9.01	9.01	9.01	0.06	0.09	0.09
C.D@1%	3.89	4.01	4.01	2.55	2.63	2.63	2.04	12.04	12.04	0.08	0.12	0.12

MP- Mid parent, BP- Better parent, SC- Standard check

* and ** indicates significance at 5% and 1% level, respectively

Table 5: Analysis of Variance (ANOVA) for combining ability

Characters	GCA	SCA	Error
Plant height (cm) at 90 DAS	3.59**	8.95**	0.03
No. of branches per plant at 90 DAS	9.44**	1.26**	0.002
Days to first flowering	0.20**	0.49**	0.03
Leaf area (cm ²)	4.37**	4.43**	0.003
Number of fruits per plant	13.54**	4.68**	1.10
Fruit yield per plot (kg)	14.78**	7.43**	0.47
Average fruit weight (g)	94.99**	35.84**	9.79
Number of locules per fruit	0.36**	0.22**	0.001

DAS- Days after sowing

* and ** indicates significance at 5% and 1% level, respectively

Table 6: General Combining Ability (GCA) effects of parents for different characters

Parents	Pusa Ruby	Krishna Prabha Shalmala	Arka Vikas	CHMT-4	CHMT-1	CHMT-20	S. E m ±	C.D@5%	C.D@1%
Plant height (cm) at 90 DAS	0.05	0.017	-1.01 **	0.84 **	0.53 **	-0.44 **	0.06	0.17	0.22
Number of branches per plant at 90 DAS	1.30 **	-0.39 **	-1.42 **	1.28 **	-0.27 **	-0.50 **	0.02	0.05	0.06
Days to first flowering	-0.03	0.25 **	0.05	-0.22 **	0.02	-0.07	0.06	0.15	0.19
Leaf area (cm ²)	-0.14 **	0.13 **	-1.29 **	0.80 **	0.59 **	-0.10 **	0.02	0.05	0.07
Number of fruits per plant	1.41 **	-0.38	-1.80 **	1.65 **	-0.40	-0.48	0.19	0.56	0.73
Fruit yield per plot (kg)	1.09 **	-0.21	-1.90 **	1.96 **	-0.73 **	-0.21	0.10	0.29	0.38
Average fruit weight (g)	2.37 *	-0.44	-4.90 **	5.12 **	-1.60	-0.47	0.27	0.75	0.99
Number of locules per fruit	0.06 **	0.08 **	0.12 **	-0.02 *	-0.41 **	0.15 **	0.01	0.03	0.04
Stem girth (cm)	0.03 *	0.01	0.002	0.03 *	-0.03	-0.05 **	0.02	0.04	0.06

DAS- Days after sowing

* and ** indicates significance at 5% and 1% level, respectively

Table 7: Specific Combining Ability (SCA) effects of hybrids for different characters

Hybrids	Plant height (cm) at 90 DAS	Number of branches per plant at 90 DAS	Days to first flowering	Leaf area (cm ²)	Number of fruits per plant	Fruit yield per plot (kg)	Average fruit weight (g)	Number of locules per fruit
P R × K P S	-1.15 **	1.54 **	-0.95 **	0.10 *	2.19 *	3.42 **	7.54 **	-0.31 **
P R × A V	-3.25 **	-1.81 **	-0.27	-0.97 **	-0.67	-0.79	-1.50	-0.29 **
P R × C-4	-3.02 **	0.36 **	0.39 **	1.22 **	0.48	1.82 **	3.35	-0.17 **

P R × C-1	-0.57 **	-1.40 **	0.67 **	-1.16 **	-0.07	0.63	1.46	0.31 **
P R × C-20	0.47 **	-0.51 **	-0.12	3.04 **	0.66	1.14	2.87	0.66 **
K P S × A V	3.28 **	-0.51 **	0.49 **	-0.44 **	-0.03	-0.78	-1.80	-0.29 **
K P S × C-4	0.71 **	0.23 **	0.30 *	0.55 **	1.62	2.17 **	4.25	0.79 **
K P S × C-1	2.40 **	-0.86 **	0.48 **	-3.60 **	0.25	0.04	-0.07	0.53 **
K P S × C-20	-2.48 **	0.12 **	0.81 **	0.56 **	1.38	0.86	1.88	0.48 **
A V × C-4	4.02 **	0.73 **	0.44 **	-0.72 **	2.06 *	2.45 **	5.71 *	-0.07 *
A V × C-1	-2.69 **	-0.89 **	-0.14	3.88 **	-1.10	-1.70 **	-4.90	0.31 **
A V × C-20	2.67 **	1.79 **	-0.57 **	-0.70 **	3.53 **	3.60 **	8.85 **	-0.15 **
C-4 × C-1	-3.09 **	-0.11 *	-1.20 **	-0.41 **	1.31	2.16 **	4.21	-0.08 **
C-4 × C-20	-1.12 **	0.01	1.16 **	1.79 **	1.07	1.23 *	2.30	-0.04
C-1 × C-20	4.65 **	-0.35 **	-0.49 **	-3.09 **	0.97	0.83	1.85	0.12 **
S. E m ±	0.16	0.04	0.14	0.05	0.19	0.10	0.27	0.03
C.D@5%	0.46	0.13	0.41	0.14	0.55	0.29	0.74	0.09
C.D@1%	0.60	0.17	0.54	0.19	0.73	0.38	0.99	0.11

DAS- Days after sowing

* and ** indicates significance at 5% and 1% level, respectively

4. Conclusion

The present investigation revealed significant genetic variability among the parental lines and F₁ hybrids for all the growth and yield parameters, indicating good scope for tomato improvement through hybrid breeding. Superior heterotic performance was observed in crosses such as Pusa Ruby × CHMT-4 for yield-related traits and CHMT-1 × CHMT-20 for plant height, highlighting their potential for commercial exploitation. Combining ability analysis indicated that both additive and non-additive gene actions governed the studied traits, with additive effects predominating for most yield attributes, while non-additive effects were important for specific growth traits. Overall, the identified superior parents and hybrids can be effectively utilized in future tomato breeding programmes aimed at developing high-yielding and productive hybrids.

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