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Heterosis Studies for Growth and Flowering Characters in Brinjal (*Solanum melongena* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

This study evaluated heterosis and selected genetic parameters for 14 quantitative traits in brinjal (eggplant). Eight lines and three testers were crossed in a line × tester design to produce 24 F1 hybrids, which were evaluated during the rabi and kharif seasons of 2022–23. The experiment was conducted at the College Farm, College of Horticulture, Jagudan, and the Fruit Research Station, Dehgam, using a randomised block design with three replications. Standard agronomic practices were followed, and observations were recorded from six selected plants per treatment across replications for plant height, plant spread, flowering and picking traits, fruit yield, phenolic content and related characters. Heterosis was expressed as the percentage increase

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or decrease relative to the better parent (heterobeltiosis) and the standard check (standard heterosis). For plant height at 90 DAT, several crosses exhibited positive heterosis, with L5 × T1 and L7 × T2 recording the highest pooled standard heterosis values. L5 × T1 also performed best for plant height at the last picking and showed consistently favourable heterosis for plant spread in both the E–W and N–S directions. Desirable negative heterosis for days to first flower initiation and days to first picking was recorded in L3 × T1, L2 × T1 and L5 × T1. L3 × T1 and L5 × T1 exhibited desirable positive heterosis for days to last picking. These crosses may be useful for improving growth and flowering traits in brinjal, subject to further evaluation for yield, quality and stability.

Keywords: Brinjal; heterosis; heterobeltiosis; standard heterosis; flowering earliness; hybrid evaluation.

1. Introduction

Brinjal (*Solanum melongena* L.) is an important tender-fruited vegetable crop grown in India during the rainy (kharif), winter (rabi) and spring (summer) seasons (Vora, 2019). It is a non-tuber-bearing species. Although brinjal is generally classified as a self-pollinated crop, natural out-crossing has been reported and varies among varieties and environments. The average out-crossing rate is approximately 6–7 per cent; therefore, brinjal is also regarded as an often cross-pollinated crop. Under hot and humid conditions, out-crossing from surrounding plants may reach 20 per cent through insect- or wind-mediated pollination. The relatively high level of cross-pollination in brinjal is associated with heterostyly (Choudhury, 1976).

India possesses considerable genetic diversity in brinjal for agro-morphological traits, providing substantial scope for yield improvement through heterosis breeding. F1 hybrids are popular among farmers because of their earliness, high yield potential, uniform maturity and favourable economic returns. Compared with other solanaceous crops, relatively few breeding efforts have focused on developing potential brinjal hybrids through the exploitation of local germplasm (Anjana et al., 2023). Estimating heterosis for fruit yield and quality traits can assist in identifying superior hybrid combinations for commercial exploitation. Recent studies have demonstrated exploitable heterosis in brinjal for plant height, flowering time and yield-related traits and have indicated that parental genetic divergence can influence hybrid performance (Rajan et al., 2023; Swamy et al., 2025). Associations among plant height, flowering and fruit-yield components, together with differences in the performance of eggplant hybrids across selection criteria, further support the combined assessment of growth and flowering traits during hybrid evaluation (Chaudhary et al., 2024; Quamruzzaman et al., 2026). However, the pooled heterotic performance of the specific set of eight lines, three testers and their 24 F1 hybrids for growth and flowering traits across four test environments has not been documented. Therefore, the present study aimed to assess heterosis for growth and flowering characters in brinjal.

2. Materials and Methods

The investigation evaluated heterosis and selected genetic parameters for 14 quantitative traits in brinjal. The experimental material comprised eight lines, three testers and their 24 F1 hybrids generated through a line × tester design. The genotypes were evaluated in a randomised block design with three replications at the College Farm, College of Horticulture, Jagudan, District Mehsana, and the Fruit Research Station, Dehgam, District Gandhinagar, during the rabi and kharif seasons of 2022–23. Standard cultivation and crop-management practices were followed. Data were recorded from six selected plants in each treatment across replications for plant height at 90 DAT and at the last picking (cm), plant spread at the last picking in the E–W and N–S directions (cm), days to first flower initiation, days to first picking after transplanting and days to last picking after transplanting. The magnitude of heterosis in the hybrids was expressed as the percentage increase or decrease relative to the better parent and the standard check in the desirable direction and was calculated using the formulae given by Hayes *et al.* (1955).

$$\text{Heterobeltiosis } = \frac{\overline{\text{F1}} - \overline{\text{BP}}}{\overline{\text{BP}}} \times 100$$

$$\text{Standard heterosis} = \frac{\overline{\text{F1}} - \overline{\text{SC}}}{\overline{\text{SC}}} \times 100$$

Where,

$\overline{F1}$ = Mean performance of hybrid
$\overline{BP}$ = Mean value of the better parent
$\overline{SC}$ = Mean value of the standard check hybrid (GJBH-4)

3. Results and Discussion

The ranges of heterosis observed for the growth and flowering traits are presented in Table 1.

Table 1. The estimation of heterobeltiosis and standard heterosis in pooled environment of growth and flowering characters of brinjal

Hybrids	Plant height at 90DAT(cm)		Plant height at Last Pickings (cm)		Plant spread at last picking (E-W) (cm)		Plant spread at last picking (N-S) (cm)	
	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis
$L_1 \times T_1$	-7.4**	-17.9**	0.3	-17.5**	-16.0**	-5.6*	-17.8**	-1.7
$L_1 \times T_2$	-10.4**	-15.9**	-13.2**	-22.7**	-20.1**	-13.9**	-6.9**	11.4**
$L_1 \times T_3$	-24.8**	-22.8**	-14.2**	-20.4**	4.3	-3.8	-14.4**	2.4
$L_2 \times T_1$	6.2*	-5.9*	-0.6	-12.2**	-5.8*	5.7*	-1.1	3.4
$L_2 \times T_2$	-8.8**	-14.4**	-5.5*	-15.8**	-15.4**	-8.9**	3.4	4.9
$L_2 \times T_3$	-16.7**	-14.5**	-11.1**	-17.5**	-2.6	-3.2	-5.7*	-4.4
$L_3 \times T_1$	-1.6	-12.8**	-5.7*	-17.3**	2.1	14.6**	20.1**	25.4**
$L_3 \times T_2$	-13.3**	-18.7**	-14.1**	-23.4**	-8.4**	-1.3	11.5**	6.6*
$L_3 \times T_3$	-26.4**	-24.4**	-21.3**	-27.0**	-9.2**	-8.5**	21.2**	20.3**
$L_4 \times T_1$	-9.6**	-19.9**	-4.1	-18.8**	-29.0**	-20.3**	-5.1*	23.5**
$L_4 \times T_2$	-23.1**	-27.8**	-13.9**	-23.3**	-17.7**	-11.3**	-23.3**	-0.1
$L_4 \times T_3$	-25.6**	-23.6**	-16.2**	-22.3**	-0.2	-9.8**	-2.6	26.8**
$L_5 \times T_1$	11.5**	14.0**	3.0	4.9*	4.0	16.8**	0.6	33.5**
$L_5 \times T_2$	-4.2	-2.0	-8.7**	-7.0**	-11.2**	-4.3	-7.9**	22.3**
$L_5 \times T_3$	0.0	2.7	-2.6	-0.9	0.8	3.5	-24.2**	0.7
$L_6 \times T_1$	-0.8	-12.1**	-1.5	-12.7**	-28.0**	-19.1**	5.6*	19.3**
$L_6 \times T_2$	-12.0**	-17.4**	-8.0**	-18.1**	-15.5**	-9.0**	4.0	17.5**
$L_6 \times T_3$	-21.0**	-18.9**	-9.0**	-15.6**	5.9*	-4.3	-13.4**	-2.2
$L_7 \times T_1$	-2.9	-1.4	-8.3**	-9.2**	-2.9	9.0**	-20.5**	5.2
$L_7 \times T_2$	2.2	3.8	-0.7	-1.7	-6.8**	0.4	-14.1**	13.6**
$L_7 \times T_3$	-9.0**	-6.5**	-3.2	-4.2	-2.7	-3.3	-5.2*	25.3**
$L_8 \times T_1$	6.8*	-5.3*	5.8*	-5.6*	-22.1**	-12.5**	-21.9**	-13.7**
$L_8 \times T_2$	-5.4*	-11.2**	-2.9	-13.4**	-19.0**	-12.8**	-15.9**	-7.1*
$L_8 \times T_3$	-19.9**	-17.8**	-10.1**	-16.6**	-1.7	-6.4*	-12.0**	-2.7
Min.	-26.4	-27.8	-21.3	-27.0	-29.0	-20.3	-24.2	-13.7
Max.	11.5	14.0	5.8	4.9	5.9	16.8	21.2	33.5
Significant + ve crosses	3	1	1	1	0	3	4	12
Significant - ve crosses	15	19	14	19	14	11	12	2
S.Ed ±	1.693	1.693	1.984	1.984	1.900	1.900	1.791	1.791
CD @ 5 %	2.814	2.814	3.297	3.297	3.157	3.157	2.976	2.976
CD @ 1 %	4.011	4.011	4.700	4.700	4.500	4.500	4.242	4.242

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

(Table 1 Conti..)

Hybrids	Days to first flower initiation		Days taken to first picking after transplanting		Days taken to last picking after transplanting	
	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis
$L_1 \times T_1$	-3.6*	1.5	-0.1	-1.4	-4.8**	-3.5*
$L_1 \times T_2$	-2.2	0.8	1.7	-1.3	-4.0*	-3.3
$L_1 \times T_3$	-1.6	1.5	-4.4*	-7.2**	1.4	1.7
$L_2 \times T_1$	-15.6**	-11.1**	-11.5**	-12.7**	0.6	2.0
$L_2 \times T_2$	1.3	-6.4**	1.1	-10.6**	-0.7	0.1
$L_2 \times T_3$	-1.6	-9.0**	3.2	-8.8**	-0.4	-0.1
$L_3 \times T_1$	-15.9**	-11.4**	-13.9**	-15.1**	4.8**	6.2**
$L_3 \times T_2$	-0.7	-4.1*	3.0	-3.8	0.2	1.4

Hybrids	Days to first flower initiation		Days taken to first picking after transplanting		Days taken to last picking after transplanting	
	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis	Heterobeltiosis	Standard Heterosis
$L_3 \times T_3$	1.9	-1.7	-1.1	-7.6**	0.8	2.0
$L_4 \times T_1$	-1.3	3.9*	-0.4	2.4	-4.0*	-2.4
$L_4 \times T_2$	1.3	5.8**	3.8	6.6**	-3.6*	-2.0
$L_4 \times T_3$	-2.6	1.7	-2.9	-0.3	-4.7*	-3.1
$L_5 \times T_1$	-13.1**	-8.4**	-10.8**	-12.0**	0.7	3.9*
$L_5 \times T_2$	0.8	-0.6	2.5	-5.2*	-2.3	0.9
$L_5 \times T_3$	0.0	-1.3	8.1**	-0.1	-2.7	0.4
$L_6 \times T_1$	-0.3	5.0**	2.2	2.2	-6.5**	-5.2**
$L_6 \times T_2$	4.9**	9.5**	4.2*	4.2*	-4.1*	-3.4*
$L_6 \times T_3$	0.8	5.1**	-1.7	-1.7	-2.9	-2.6
$L_7 \times T_1$	-10.1**	-5.3**	-6.0**	-7.2**	-3.9*	-2.6
$L_7 \times T_2$	-0.8	-0.5	-6.1**	-8.7**	0.0	1.2
$L_7 \times T_3$	-4.3*	-4.0*	-5.0*	-7.6**	-0.9	0.3
$L_8 \times T_1$	-0.9	4.4*	3.8	4.1*	-4.7*	-3.4*
$L_8 \times T_2$	4.9**	7.5**	4.1*	4.4*	-5.4**	-4.7*
$L_8 \times T_3$	7.0**	9.6**	6.6**	6.9**	-8.4**	-8.2**
Min.	15.9	-11.4	-13.9	-15.1	-8.4	-8.2
Max.	7.0	9.6	8.1	6.9	4.8	6.2
Significant +ve crosses	3	8	4	5	1	2
Significant -ve crosses	6	8	7	11	11	6
S.Ed ±	1.095	1.095	1.828	1.828	3.266	3.266
CD @ 5 %	1.820	1.820	3.038	3.038	5.427	5.427
CD @ 1 %	2.594	2.594	4.330	4.330	7.736	7.736

3.1 Plant Height at 90 DAT (cm)

Positive heterosis is desirable for this trait. Heterobeltiosis ranged from -25.6 per cent (L3 × T3) to 10.4 per cent (L5 × T1) in E1, -35.1 per cent (L8 × T3) to 15.3 per cent (L5 × T1) in E2, -32.3 per cent (L1 × T3) to 25.8 per cent (L8 × T1) in E3 and -33.4 per cent (L4 × T3) to 19.2 per cent (L8 × T1) in E4. Significant positive heterobeltiosis was recorded for two, two, three and two crosses in E1, E2, E3 and E4, respectively. Standard heterosis ranged from -22.9 per cent (L4 × T2) to 17.3 per cent (L5 × T3) in E1, -38.1 per cent (L8 × T3) to 10.3 per cent (L5 × T1) in E2, -32.8 per cent (L1 × T3) to 15.9 per cent (L7 × T2) in E3 and -26.0 per cent (L4 × T3) to 18.8 per cent (L7 × T2) in E4. Significant positive standard heterosis was recorded for three, one, two and two crosses in E1, E2, E3 and E4, respectively. In the pooled analysis, standard heterosis ranged from -27.8 per cent (L4 × T2) to 14.0 per cent (L5 × T1). The two highest positive pooled standard heterosis values were recorded by L5 × T1 (14.0%) and L7 × T2 (3.8%). Comparable findings have been reported by Das et al. (2009), Chowdhury et al. (2010), Dubey et al. (2014), Biswas et al. (2013) and Sharma et al. (2016). Similar results were also documented by Khapte et al. (2017), Patidar et al. (2017), Kalaiyarasi et al. (2018), Bhatt et al. (2019) and Bagade et al. (2020), as well as by Jivani et al. (2020) and Susmitha et al. (2023).

3.2 Plant Height at the Last Picking (cm)

Positive heterosis is desirable for this trait. Heterobeltiosis ranged from -29.6 per cent (L4 × T2) to 16.2 per cent (L5 × T1) in E1, -31.1 per cent (L8 × T3) to 0.4 per cent (L4 × T3) in E2, -27.2 per cent (L1 × T2) to 8.2 per cent (L5 × T1) in E3 and -24.6 per cent (L4 × T3) to 13.7 per cent (L1 × T1) in E4. Significant positive heterobeltiosis was observed for two crosses in E1 and one cross in E4, whereas no cross showed significant positive heterobeltiosis in E2 or E3. Standard heterosis ranged from -33.2 per cent (L4 × T2) to 11.9 per cent (L5 × T1) in E1, -36.1 per cent (L8 × T3) to -0.7 per cent (L5 × T1) in E2, -32.7 per cent (L1 × T2) to 1.5 per cent (L7 × T1) in E3 and -22.0 per cent (L4 × T3) to 10.38 per cent (L5 × T1) in E4. Significant positive standard heterosis was observed for one cross in E1, whereas no cross showed significant positive standard heterosis in E2, E3 or E4. In the pooled analysis, standard heterosis ranged from -27.0 per cent (L3 × T3) to 4.9 per cent (L5 × T1). L5 × T1 was the only hybrid that recorded significant positive pooled standard heterosis in the desirable direction (4.9%). Comparable findings were reported by Joshi et al. (2008), Chowdhury et al. (2010), Dubey et al. (2014), Boddepalli et al. (2016) and Shahjahan et al. (2016). Similar observations were made by Khapte et al. (2017), Patidar et al. (2017), Sujin et al. (2018), Chaurasia et al. (2018) and Makasare et al. (2020), as well as by Jivani et al. (2020) and Susmitha et al. (2023).

3.3 Plant Spread at the Last Picking (E–W) (cm)

Positive heterosis is desirable for this trait. Heterobeltiosis ranged from -35.8 per cent (L4 × T1) to 7.3 per cent (L1 × T3) in E1, -34.3 per cent (L6 × T1) to 12.7 per cent (L6 × T3) in E2, -27.1 per cent (L6 × T1) to 5.9 per cent (L5 × T1) in E3 and -23.1 per cent (L8 × T1) to 8.5 per cent (L3 × T1) in E4. Significant positive heterobeltiosis was observed for one cross in E2, whereas no cross showed significant positive heterobeltiosis in E1, E3 or E4. Standard heterosis ranged from -25.2 per cent (L4 × T1) to 24.2 per cent (L5 × T1) in E1, -23.7 per cent (L6 × T1) to 15.9 per cent (L5 × T1) in E2, -21.3 per cent (L6 × T1) to 14.3 per cent (L5 × T1) in E3 and -16.0 per cent (L8 × T1) to 18.5 per cent (L3 × T1) in E4. Significant positive standard heterosis was recorded for five, two, two and three crosses in E1, E2, E3 and E4, respectively. In the pooled analysis, standard heterosis ranged from -20.3 per cent (L4 × T1) to 16.8 per cent (L5 × T1). The three best hybrids for significant positive pooled standard heterosis were L5 × T1 (16.8%), L3 × T1 (14.6%) and L7 × T1 (9.0%). Comparable findings were reported by Boddepalli et al. (2016), Shahjahan et al. (2016), Khapte et al. (2017), Jivani et al. (2020) and Singh et al. (2021).

3.4 Plant Spread at the Last Picking (N–S) (cm)

Positive heterosis is desirable for this trait. Heterobeltiosis ranged from -35.5 per cent (L4 × T2) to 33.2 per cent (L3 × T3) in E1, -31.7 per cent (L4 × T2) to 28.1 per cent (L3 × T3) in E2, -26.2 per cent (L8 × T2) to 16.8 per cent (L3 × T1) in E3 and -27.7 per cent (L7 × T1) to 27.5 per cent (L3 × T1) in E4. Significant positive heterobeltiosis was recorded for four, two, one and three crosses in E1, E2, E3 and E4, respectively. Standard heterosis ranged from -24.3 per cent (L8 × T1) to 31.3 per cent (L5 × T1) in E1, -23.4 per cent (L8 × T1) to 21.8 per cent (L5 × T1) in E2, -9.5 per cent (L8 × T2) to 35.0 per cent (L5 × T1) in E3 and -0.6 per cent (L2 × T3) to 48.3 per cent (L5 × T1) in E4. Significant positive standard heterosis was recorded for eleven, five, eleven and sixteen crosses in E1, E2, E3 and E4, respectively. In the pooled analysis, standard heterosis ranged from -13.7 per cent (L8 × T1) to 33.5 per cent (L5 × T1). The three best hybrids for significant positive pooled standard heterosis were L5 × T1 (33.5%), L4 × T3 (26.8%) and L3 × T1 (25.4%). Comparable findings were reported by Boddepalli et al. (2016), Shahjahan et al. (2016), Khapte et al. (2017), Jivani et al. (2020) and Singh et al. (2021).

3.5 Days to First Flower Initiation

Negative heterosis is desirable for this trait. Heterobeltiosis ranged from -12.7 per cent (L2 × T1) to 8.0 per cent (L1 × T3) in E1, -16.2 per cent (L3 × T1) to 17.4 per cent (L8 × T3) in E2, -19.8 per cent (L2 × T1) to 7.7 per cent (L8 × T3) in E3 and -19.3 per cent (L3 × T1) to 13.9 per cent (L8 × T2) in E4. Significant negative heterobeltiosis was recorded for five, three, nine and twelve crosses in E1, E2, E3 and E4, respectively. Standard heterosis ranged from -8.5 per cent (L2 × T1) to 11.3 per cent (L6 × T2) in E1, -16.3 per cent (L3 × T1) to 8.7 per cent (L6 × T2) in E2, -15.2 per cent (L2 × T1) to 13.5 per cent (L8 × T3) in E3 and -9.6 per cent (L3 × T1) to 14.9 per cent (L8 × T2) in E4. Significant negative standard heterosis was recorded for three, seven, eight and three crosses in E1, E2, E3 and E4, respectively. In the pooled analysis, standard heterosis ranged from -11.4 per cent (L3 × T1) to 9.6 per cent (L8 × T3). The three best hybrids for significant negative pooled standard heterosis were L3 × T1 (-11.4%), L2 × T1 (-11.1%) and L2 × T3 (-9.0%). Comparable findings were reported by Boddepalli et al. (2016), Pramila et al. (2017), Rani et al. (2018), Chaurasia et al. (2018) and Deshmukh et al. (2020). Similar results were reported by Timmareddygari et al. (2021) and Gill et al. (2022).

3.6 Days to First Picking after Transplanting

Negative heterosis is desirable for this trait. Heterobeltiosis ranged from -12.6 per cent (L3 × T1) to 7.9 per cent (L6 × T3) in E1, -17.3 per cent (L5 × T1) to 12.5 per cent (L8 × T3) in E2, -12.4 per cent (L2 × T1) to 19.5 per cent (L5 × T3) in E3 and -17.6 per cent (L3 × T1) to 16.4 per cent (L8 × T2) in E4. Significant negative heterobeltiosis was recorded for one, four, seven and ten crosses in E1, E2, E3 and E4, respectively. Standard heterosis ranged from -17.7 per cent (L3 × T1) to 7.6 per cent (L8 × T3) in E1, -21.3 per cent (L5 × T1) to 4.6 per cent (L4 × T2) in E2, -12.5 per cent (L2 × T1) to 13.5 per cent (L8 × T3) in E3 and -9.6 per cent (L3 × T1) to 15.3 per cent (L8 × T2) in E4. Significant negative standard heterosis was recorded for six, ten, ten and six crosses in E1, E2, E3 and E4, respectively. In the pooled analysis, standard heterosis ranged from -15.1 per cent (L3 × T1) to 6.9 per cent (L8 × T3). The three best hybrids for significant negative pooled standard heterosis were L3 × T1 (-15.1%), L2 × T1 (-12.7%) and L5 × T1 (-12.0%). Comparable findings were reported by

Chowdhury et al. (2010), Biswas et al. (2013), Shahjahan et al. (2016), Pramila et al. (2017) and Rani et al. (2018). Similar observations were documented by Chaurasia et al. (2018), Deshmukh et al. (2020), Timmareddygari et al. (2021) and Gill et al. (2022).

3.7 Days to Last Picking after Transplanting

Positive heterosis is desirable for this trait. Heterobeltiosis ranged from -12.5 per cent (L4 × T2) to 6.9 per cent (L5 × T3) in E1, -13.6 per cent (L1 × T2) to 3.4 per cent (L3 × T1) in E2, -12.6 per cent (L8 × T3) to 5.7 per cent (L3 × T1) in E3 and -12.5 per cent (L5 × T3) to 4.5 per cent (L3 × T1) in E4. Standard heterosis ranged from -13.4 per cent (L4 × T2) to 4.1 per cent (L3 × T1) in E1, -8.6 per cent (L8 × T3) to 6.9 per cent (L5 × T1) in E2, -12.3 per cent (L8 × T3) to 4.8 per cent (L3 × T1) in E3 and -3.9 per cent (L5 × T3) to 11.4 per cent (L3 × T1) in E4. Significant positive standard heterosis was recorded for two and five crosses in E2 and E4, respectively. In the pooled analysis, standard heterosis ranged from -8.2 per cent (L4 × T2) to 6.2 per cent (L3 × T1). The two best hybrids for significant positive pooled standard heterosis were L3 × T1 (6.2%) and L5 × T1 (3.9%). These findings were consistent with those of Chowdhury et al. (2010), Boddepalli et al. (2016), Shahjahan et al. (2016), Bhatt et al. (2019) and Deshmukh et al. (2020). Similar observations were reported by Timmareddygari et al. (2021) and Gill et al. (2022).

4. Conclusions

Substantial variation in heterobeltiosis and standard heterosis was observed among the 24 brinjal hybrids for growth and flowering traits across the four environments. In the pooled analysis, L5 × T1 recorded favourable standard heterosis for plant height at 90 DAT (14.0%), plant height at the last picking (4.9%), plant spread in the E–W direction (16.8%) and plant spread in the N–S direction (33.5%). L3 × T1 showed desirable negative standard heterosis for days to first flower initiation (-11.4%) and days to first picking (-15.1%), while L2 × T1 also expressed earliness for these traits (-11.1% and -12.7%, respectively). For days to last picking, L3 × T1 and L5 × T1 recorded desirable positive standard heterosis of 6.2% and 3.9%, respectively. These results demonstrate that the relative advantages of individual crosses differed across traits and environments. L5 × T1 was notable for vegetative growth and plant spread, whereas L3 × T1 and L2 × T1 were associated with earlier flowering and picking. The identified crosses should be evaluated further for fruit yield, fruit quality, pest response and stability across additional environments before their breeding or commercial value is established.

5. Limitations

The study was restricted to eight lines, three testers and 24 F1 hybrids evaluated at two locations during two seasons. Although four environments were considered, complete environment-wise means, genotype × environment interaction and stability analyses were not presented. Consequently, the identified crosses require further multilocation testing using complete yield, quality, pest-response and stability data before their broader breeding or commercial usefulness can be determined.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgement of the author(s). All AI-assisted outputs, including content, references and interpretations, were carefully reviewed, revised, verified and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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