International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(12): 1697-1702
www.biochemjournal.com
Received: 01-10-2025
Accepted: 05-11-2025

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Heterosis in tomato (*Solanum lycopersicum*) hybrids for fruit morphological and processing traits

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DOI: https://www.doi.org/10.33545/26174693.2025.v9.i12St.6931

Abstract
In the present study, sixteen parents were crossed in a half-half half-diallel mating design to produce 120 F_1 hybrids. The experiment was carried out at the Division of Vegetable Crops, Indian Institute of Horticultural Research, Bengaluru. Heterobeltiosis, relative heterosis and standard heterosis were estimated for growth, fruit yield and processing traits in F_1 hybrids. Heterosis studies revealed that hybrids IIHR-2957 X IIHR-Sel.57, IIHR-Sel.19 X Arka Ashish and IIHR-Sel.19 X CLN3916D had significant desirable relative heterosis. While the hybrids IIHR-2821 X IIHR-Sel.22, IIHR-2834 X IIHR-Sel.57, Arka Ashish X CLN3916D had the highest positive and significant standard heterosis (SH) for shelf life, dry matter content and viscosity.

Keywords: Heterosis, heterobeltiosis, relative heterosis, standard heterosis

1. Introduction
Tomato (*Solanum lycopersicum* L.; 2n = 24) is a versatile, widely planted and significant tropical and subtropical vegetable crop. Cultivars with different growth habits and fruit quality traits are used in these two distinct production segments. A ripe tomato is used in the manufacture of a wide range of processed products, including puree, paste, powder, ketchup, sauce, soup and canned whole fruits. Although fresh tomatoes are consumed widely, more than 80% of tomato consumption comes from processed tomatoes (Takeoka *et al.*, 2001) [13]. The development of processing-type hybrids is seen as a promising approach to meet the needs of processing industries, though the creation of such hybrids in India is currently in an infant stage due to the non-availability of suitable genetic stock (Kumar *et al.*, 2024) [9].
In plant breeding programme, heterosis plays a vital role where hybrid vigour depends on the direction and magnitude of heterosis involved. Heterosis for yield, yield components, and quality attributes was extensively studied (Ahmad *et al.*, 2011) [1]. Through heterosis breeding, Koutisika *et al.* (2008) [8] observed improvement in many quantitative and qualitative parameters in tomato. A crucial requirement for selecting crosses with a high degree of exploitable heterosis is knowledge of the magnitude of heterosis in different cross combinations.

2. Material and Methods
The study was undertaken during 2019-20 and 2020-21. The experiment was carried out at the ICAR-Indian Institute of Horticultural Research (IIHR), Bangalore, Karnataka. The experimental field is located 890 meters above MSL, 130.58' N latitude and 770.37' E longitude.
Experimental material and hybrid development: Sixteen superior parents having higher total soluble solids content were used for the hybridization program. One hundred twenty half diallel cross hybrids developed from the hybridization programme (16x 16 half diallel), 16 parental lines and four check cultivars (Arka Vishesh, Arka Apeksha, Arka Samrat and Arka Rakshak) were used in the experiment. The list of F_1 hybrids used in this experiment is presented in Tables 1 and 2. In the field, all the selected parental lines were transplanted with a 1m x 0.5m spacing. The crop was grown according to the tomato package of practices. The emasculation was done one day before the anthesis using forceps during the evening. The next day, pollen from a male parent was collected in the morning and used for pollination.

The crossed fruits were kept on the plant until maturity. Five randomly selected plants from each row in each replication were tagged for the purpose of recording the parameters.
The data were recorded on days to 50 percent flowering, days to first fruit ripening, number of fruits per cluster, fruit length (cm), fruit width (cm), pericarp thickness (mm), number of locules per fruit, TSS (°Brix), fruit firmness (kg/cm^2), size of the core in fruit cross section (mm), peduncle scar size (mm), number of seeds per fruit, average fruit weight (g), number of fruits per plant, yield per plant (Kg), shelf life (days), pulp recovery (%), P^H, titrable acidity (%), moisture content (%), dry matter content (%) and viscosity (mPa). The magnitude of heterosis was assessed at about mid-parent and a better-parent. Using the methodology of Turner (1953) [15] and Hayes *et al.* (1956) [6], they were calculated as a percentage increase or decrease in F_1 hybrids over the mid-parent (MP) and better parent (BP). The F_1 hybrids and their parents were evaluated in the field replications in an augmented block design (ABD) to estimate heterosis for yield and other quality parameters. Data were analyzed by Indostat Services, Hyderabad.

3. Results
The estimates of heterosis were computed for all the 22 traits studied in the 120 hybrids of tomato and expressed in percentage over mid-parental value (MPH-relative heterosis), better parental value (BPH-heterobeltiosis) and standard heterosis (SH) over check hybrids of Arka Vishesh, Arka Apeksha, Arka Samrat and Arka Rakshak (Tables 3).

3.1 Days to 50 percent flowering
The negative relative heterosis (MPH) for days to 50 percent flowering ranged from-20.00 percent (IIHR-Sel.57 × IIHR-Sel.22) to 0.92 percent (IIHR-2784 × IIHR-Sel.22) and 115 hybrids registered negative and significant relative heterosis values. The heterobeltiosis (BPH) for days to 50 percent flowering was the lowest in the hybrid IIHR-Sel. 57 x PED (-28.81 percent) and 118 hybrids registered negative and significant (BPH) values. Hybrids with the lowest standard heterosis may be preferred. Almost all the hybrids showed significantly negative standard heterosis over the standard check. The lowest heterosis over all standard checks (SH) was observed in the hybrid PED × CLN3916C, which was lowest in Arka Vishesh (-29.72 percent).

3.2 Days to first fruit ripening
The negative relative heterosis (MPH) for days to first fruit ripening ranged from-13.44 percent (IIHR-2327-1 × IIHR-Sel.57) to 5.93 percent (IIHR-Sel.19 × IIHR-2955) and 110 hybrids registered negative and significant relative heterosis values. The heterobeltiosis (BPH) for days to first fruit ripening was the lowest in the hybrid IIHR-2847 × PED (-21.05 percent) and 117 hybrids registered negative and significant (BPH) values. Hybrids with the lowest standard heterosis may be preferred. Almost all the hybrids showed significantly negative standard heterosis over all standard checks used under the study, particularly IIHR-2847 × PED recorded the best significant heterosis (-22.75) over all the checks. The lowest heterosis overall standard checks (SH) was observed in the hybrid IIHR-2847 × PED, in which it was lowest in Arka Apeksha (-22.75 percent).

3.3 Number of fruits per cluster
A total of thirty hybrids recorded significant and positive relative heterosis (MPH) values for fruits per cluster, with a range from-23.66 percent (IIHR-2784 × IIHR-2847) to 11.11 percent (IIHR-2955 × PED). The heterosis over better parents (BPH) ranged from-30.00 percent (IIHR-2784 × IIHR-2847) to 12.50 percent (IIHR-2821 × IIHR-2955 and IIHR-2955 × IIHR-2834). The highest heterosis values over the standard checks, such as Arka Vishesh, Arka Samrat and Arka Rakshak, were registered by the hybrid IIHR-2955 × PED as 15.47 percent.

3.4 Fruit length (cm)
A total of 68 hybrids recorded significant and positive relative heterosis (MPH) values for fruit length, with a general range value from-19.47 percent (IIHR-2821 × CLN3916D) to 37.30 percent (IIHR-Sel.19 × IIHR-2955). The heterosis over better parents (BPH) ranged from-26.29 percent (IIHR-2957 × CLN3916D) to 32.59 percent (IIHR-Sel.19 × IIHR-2955). The highest heterosis values over standard checks (SH), Arka Vishesh, Arka Samrat and Arka Samrat were registered by the hybrid IIHR-Sel. 41-1 × IIHR-2833 as 63.59 percent.

3.5 Fruit width (cm)
The relative heterosis (MPH) for fruit width ranged from-21.72 percent (IIHR-2847 × IIHR-2833) to 40.72 percent (IIHR-Sel.19 × IIHR-2955), and a total of 72 hybrids were found to be significant and positive. The heterosis over better parents (BPH) ranged from-22.30 percent (IIHR-2847 × IIHR-2833) to 39.15 percent (IIHR-Sel.19 × IIHR-2955), and 39 hybrids exhibited positive heterobeltiosis value. Hybrid IIHR-Sel. 19 × IIHR-2327-1 showed significantly positive highest heterosis over all standard checks under the study (Table 4.29).

3.6 Pericarp thickness (mm)
The relative heterosis (MPH) for pericarp thickness of 120 tomato hybrids of the present study ranged from-34.78 percent (IIHR-Sel.41-1 × PED) to 80.09 percent (IIHR-2955 × CLN3916D) and a total of 71 hybrids were found to be significant and positive. The heterosis over better parents (BPH) ranged from-45.33 percent (IIHR-Sel.41-1 × PED) to 57.66 percent (IIHR-2327-1 × IIHR-2955) and 56 hybrids exhibited positive significant heterobeltiosis value. The hybrid IIHR-2327-1 × IIHR-2833 recorded the highest heterosis values over all the standard checks except Arka Vishesh

3.7 Number of locules per fruit
The heterosis for mid-parent (MPH) for the number of locules per fruit of 120 tomato hybrids of the study ranged from-24.35 percent (IIHR-2847 × IIHR-2833) to 66.67 percent (PED × IIHR-Sel.22) and a total of 65 hybrids exhibited positive and significant heterotic values. The heterosis for better parents (BPH) ranged from-48.36 percent (IIHR-2327-1 × Arka Ashish) to 57.51 percent (IIHR-2784 × IIHR-Sel.22). The highest positive and significant heterosis (SH) values over standard checks were recorded in the hybrid IIHR-Sel. 19 × IIHR-2327-1 and 14 hybrids exhibited positive and significant standard heterosis values over Arka Apeksha and Arka Rakshak.

3.8 TSS (°Brix)
The heterosis for mid-parent (MPH) for TSS of 120 tomato hybrids of the study showed a range from-15.60 percent (IIHR-2957 × Arka Ashish) to 7.08 percent (IIHR-2833 × IIHR-2821) and a total of 65 hybrids exhibited positive and significant heterotic values. The heterosis for better parents (BPH) ranged from-15.63 percent (IIHR-2833 × Arka Ashish) to 5.87 percent (IIHR-2784 × IIHR-Sel.57). The heterosis (SH) values over all the standard checks were highest positive and significant in the hybrid (IIHR-2957 × CLN3916D) except Arka Vishesh.

3.9 Fruit firmness (kg/cm^2)
A total of 57 hybrids recorded significant and positive relative heterosis (MPH) values for firmness with a range from-28.23 percent (IIHR-2784 × IIHR-2833) to 31.74 percent (IIHR-2327-1 × IIHR-2955). The heterosis over better parents (BPH) ranged from-39.58 percent (IIHR-2784 × IIHR-2833) to 28.60 percent (IIHR-2327-1 × IIHR-2957). The highest heterosis values over all the standard checks (SH) were registered by the hybrid IIHR-2784 × IIHR-Sel. 22.

3.10 Size of the core in fruit cross-section (mm)
The relative heterosis (MPH) for size of the core in fruit cross-section of 120 tomato hybrids of the present study ranged from-30.77 percent (IIHR-2833 x Arka Ashish) to 252.7 percent (IIHR-2847 × CLN3916C) and a total of 71 hybrids were found to be significant and positive. The heterosis over better parents (BPH) ranged from-36.72 percent (IIHR-2833 x Arka Ashish) to 248.37 percent (IIHR-2847 × CLN3916C) and 51 hybrids exhibited positive significant heterobeltiosis value. Hybrid (IIHR-2847 × CLN3916C) showed a significantly positive highest heterosis over all the standard checks.

3.11 Peduncle scar size (mm)
The relative heterosis (MPH) for peduncle scar size ranged from-54.75 percent (IIHR-2957 × IIHR-Sel.57) to 116.39 percent (PED × CLN3916C) and a total of 79 hybrids were found to be significant and positive. The heterosis over better parents (BPH) ranged from-62.16 percent (IIHR-2957 × IIHR-Sel.57) to 105.38 percent (PED × CLN3916C) and 56 hybrids exhibited a significantly positive significant heterobeltiosis value. Twelve hybrids showed significantly positive standard heterosis over the standard check. The hybrid IIHR-2327-1 × IIHR-2821 recorded the positive highest significant heterosis values over all the standard checks except Arka Samrat (Table 4.35).

3.12 Number of seeds per fruit
The heterosis for mid-parent (MPH) values for the number of seeds per fruit showed a range from-46.39 percent (IIHR-2821 × CLN3916D) to 180.16 percent (IIHR-Sel.19 × PED) and a total of 64 hybrids exhibited positive and significant heterotic values. The heterosis for better parents (BPH) ranged from-59.75 percent (IIHR-Sel.19 × CLN3916D) to 171.46 percent (IIHR-Sel.19 × PED). The heterosis (SH) values over all the standard checks were the highest negative and significant in the hybrid IIHR-2784 x IIHR-2955 (Table 4.36).

3.13 Average fruit weight (g)
The heterosis for mid-parent (MPH) values for average fruit weight showed a range from-40.65 percent (IIHR-Sel.19 × IIHR-2833) to 108.12 percent (IIHR-Sel.41-1 × CLN3916D) and a total of 93 hybrids exhibited positive and significant heterotic values. The heterosis for better parents (BPH) ranged from-42.25 percent (IIHR-Sel.19 × IIHR-2833) to 83.61 percent (IIHR-Sel.41-1 × CLN3916D). The heterosis (SH) values over all the standard check hybrids were the highest positive and significant in the hybrid (IIHR-Sel.41-1 × CLN3916D).

3.14 Number of fruits per plant
The relative heterosis for the number of fruits per plant ranged from-55.53 percent (IIHR-2327-1 × CLN3916C) to 110.24 percent (IIHR-Sel.41-1 × IIHR-Sel.57) and 74 hybrids recorded significant and positive (MPH) values, respectively. The heterobeltiosis (BPH) values ranged from-69.54 (IIHR-Sel.19 × IIHR-2327-1) to 108.08 (IIHR-Sel.41-1 × IIHR-Sel.57) and a total of 48 hybrids recorded positive and significant heterobeltiosis values. The hybrid IIHR-2327-1 × Arka Ashish recorded the highest standard heterosis (SH) over Arka Apeksha and Arka Rakshak.

3.15 Yield per plant (Kg)
The heterotic values (MPH) for yield per plant of 120 tomato hybrids of the study varied from-38.58 percent (IIHR-2784 × IIHR-Sel.57) to 79.58 percent (IIHR-2957 × Arka Ashish) and 86 hybrids exhibited positive and significant heterosis over mid-parental values. Heterobeltiosis (BPH) values for this trait ranged between-39.75 percent (IIHR-2784 × IIHR-Sel.57) to 71.90 percent (IIHR-2784 × IIHR-2834) and a total of 70 hybrids recorded positive and significant heterobeltiosis values. When the hybrids were compared with all the standard checks hybrid IIHR-2327-1 × IIHR-2955 had the highest heterosis (SH) value.

3.16 Shelf life (days)
Shelf life of 120 tomato hybrids evaluated for this study revealed that 79 hybrids exhibited positive and significant heterosis over mid-parental value (MPH), which varied from-55.74 percent (IIHR-2784 × IIHR-2327-1) to 97.22 percent (Arka Ashish × IIHR-Sel.22). The values of heterobeltiosis (BPH) ranged from-61.97 percent (IIHR-2784 × IIHR-2327-1) to 71.15 percent (IIHR-2847 × IIHR-Sel.19) and a total of 62 hybrids registered positive and significant heterobeltiosis values. When the hybrids were compared with all the standard checks, the highest significantly positive significant heterosis (SH) was observed in the hybrid IIHR-2847 × IIHR-Sel. 19.

3.17 Pulp recovery (%)
The pulp recovery of 120 tomato hybrids evaluated in this study revealed that seventeen hybrids exhibited positive and significant heterosis over mid-parental value (MPH), which varied from-8.45 percent (IIHR-2784 × IIHR-2847) to 32.85 percent (IIHR-2327-1 × IIHR-2821). The range of heterobeltiosis (BPH) values was noted between-9.57 percent (IIHR-2784 × IIHR-2847) to 32.07 percent (IIHR-2327-1 × IIHR-2821) and a total of 103 hybrids registered positive and significant heterobeltiosis values. When the hybrids were compared with all the standard checks, the highest significantly positive significant heterosis (SH) was observed in the hybrid IIHR-2821 × CLN3916D.

3.18 P^H

For the pH, sixty-two tomato hybrids exhibited positive and significant heterosis over mid-parental value (MPH), which varied from-14.42 percent (IIHR-Sel.41-1 × IIHR-Sel.22) to 13.11 percent (IIHR-Sel.41-1 × IIHR-2821). The range of heterobeltiosis (BPH) was between-15.12 percent (IIHR-Sel.41-1 × IIHR-Sel.22) to 12.97 percent (IIHR-Sel.41-1 × IIHR-2821). When the hybrids were compared with all the standard checks, the highest positive significant standard heterosis (SH) values were observed in the hybrid (IIHR-2847 × IIHR-Sel.19).

3.19 Titrable acidity (%)

The relative heterosis for titrable acidity of 120 tomato hybrids ranged from-60.47 percent (IIHR-Sel.57 × PED) to 52.94 percent (Arka Ashish × CLN3916C) and 23 hybrids recorded significant and positive (MPH) values respectively. The heterobeltiosis (BPH) ranged from-69.09 percent (IIHR-Sel.57 × PED) to 35.00 percent (IIHR-2847 × IIHR-2327-1) and a total of 20 hybrids recorded positive and significant heterobeltiosis values. When the hybrids were compared with all the standard checks (SH), the highest positive and significant heterosis was observed in the hybrid IIHR-2847 × IIHR-2327-1.

3.20 Moisture content (%)

Among the 120 tomato hybrids evaluated, total sixty-five hybrids recorded significant and positive relative heterosis (MPH) for moisture content with a range of-9.64 percent (IIHR-Sel.41-1 × IIHR-2957) to 4.28 percent (Arka Ashish × IIHR-Sel.22). The heterosis over better parents (BPH) ranged from-11.75 percent (IIHR-Sel.57 × CLN3916D) to 2.76 percent (IIHR-Sel.19 × IIHR-Sel.22) and 41 hybrids exhibited positive and significant values. Hybrid PED × Arka Ashish recorded positive significant heterosis value over Arka Apeksha and Arka Samrat.

3.21 Dry matter content (%)

The relative heterosis (MPH) value for dry matter content ranged from-92.24 percent (IIHR-Sel.19 × IIHR-2327-1) to 409.13 percent (IIHR-2834 × IIHR-Sel.57) and 62 hybrids recorded positive and significant values. The heterobeltiosis (BPH) for this trait ranged from-94.27 percent (IIHR-Sel.19 × IIHR-2327-1) to 282.68 percent (IIHR-Sel.41-1 × IIHR-2957) and 47 hybrids exhibited positive and significant heterobeltiosis values. The highest positive and significant standard heterosis (SH) over all the standard checks was registered in the hybrid (IIHR-Sel.57 × CLN3916D) for dry matter content.

3.22 Viscosity (mPa)

The relative heterosis (MPH) for viscosity ranged from-84.18 percent (IIHR-2847 × IIHR-2957) to 417.64 percent (IIHR-2821 × IIHR-Sel.22) and 52 hybrids had positive and significant relative heterosis values for this trait. The heterosis over the better parent (BPH) ranged from-88.65 percent (IIHR-2834 × IIHR-Sel.22) to 363.15 percent (IIHR-2821 × IIHR-Sel.22) and a total of 32 hybrids had the highest positive and significant BPH value. The highest positive and significant standard heterosis (SH) was noted in the hybrid Arka Ashish × CLN3916C over all the standard checks except Arka Vishesh.

Similar results were also recorded in the first and second season data.

4. Discussion

In the present study, heterosis over the better parent for each trait was computed over pooled environments. The results revealed a wide range of heterotic patterns for all the traits studied. Maximum range of heterosis was observed for most of the traits. Negative heterosis is preferred for days to fifty percent flowering and days to first fruit ripening. A total of 60 hybrids registered negative and significant relative heterosis values for days to fifty percent flowering and 58 hybrids registered negative and significant relative heterosis values for days to first fruit ripening. These results were in accordance with the results of Asima *et al.* (2017) [4], Chauhan *et al.* (2014) [5], Angadi and Dharmatti (2012) [2] and Shankla *et al.* (2016) [11].

Among the 120 tomato hybrids evaluated, a total of 30 hybrids recorded significant and positive mid-parent heterosis (MPH) values for fruits per cluster, and the highest heterosis values over all the standard checks (SH) were registered by the hybrid IIHR-2955 x PED. A total of 68 hybrids recorded significant and positive relative heterosis (MPH) values for fruit length and the highest heterosis values over standard check (SH) Arka Apeksha was registered by the hybrid IIHR-Sel. 41-1 x IIHR-2833. Totally 72 hybrids were found to be significant and positive for fruit width, Hybrid IIHR-Sel. 19 x IIHR-2327-1 showed significantly positive highest heterosis overall standard checks. 71 hybrids were found to have significant and positive MPH for pericarp thickness, hybrid IIHR-2327-1 x IIHR-2833 recorded the positive highest significant heterosis values over all the standard checks. 65 hybrids exhibited positive and significant heterotic values for the number of locules per fruit, the hybrid IIHR-Sel. 19 x IIHR-2327-1 recorded the highest positive and significant heterosis values over all the standard checks.

Totally 65 hybrids exhibited positive and significant heterotic values for TSS. The hybrid IIHR-2957 x CLN3916D recorded the highest positive significant heterosis values over all the standard checks. 57 hybrids exhibited positive and significant heterosis over mid-parental values in the case of fruit firmness, the hybrid IIHR-2784 x IIHR-Sel. 22 had the highest heterosis (SH) value. 93 hybrids exhibited positive and significant heterosis over mid-parental values in the case of average fruit weight, the hybrid IIHR-Sel. 41-1 x CLN3916D had the highest heterosis (SH) value. 74 hybrids exhibited positive and significant heterosis over mid-parental values in the case of number of fruits per plant, the hybrid IIHR-2955 x Arka Ashish had the highest heterosis (SH) value. 86 hybrids exhibited positive and significant heterosis over mid-parental values. In the case of the number of fruits per plant, the hybrid IIHR-2957 x Arka Ashish had the highest heterosis (SH) value.

The hybrids, such as IIHR-2847 x IIHR-Sel.19, IIHR-2327-1 x IIHR-2821, IIHR-2847 x IIHR-Sel.19, IIHR-Sel. 57 x CLN3916C, PED x Arka Ashish, IIHR-Sel. 57 x CLN3916D and Arka Ashish x CLN3916C had the highest positive and significant standard heterosis (SH) for shelf life, pulp recovery, P^H, titrable acidity, moisture content, dry matter content and viscosity, respectively. These results indicate that these hybrids are preferred for improving quality parameters in tomato. The combination of a higher number of fruits, fruit size and thick flesh is the main reason for heterosis of yield. Significant and desirable heterosis of variable magnitude for maturity and yield traits has been reported by several studies, such as Singh *et al.* (2005) [12], Joshi *et al.* (2006) [7], Asati *et al.* (2007) [3] and Rao *et al.* (2007) [10].

Table 1: List of parents selected for hybridization in this study

Sl. No.	Genotype
1	IIHR-2957
2	IIHR-2834
3	IIHR-2833
4	IIHR-2327-1
5	IIHR-2847
6	IIHR-2955
7	IIHR-2821
8	IIHR-2784
9	IIHR-Sel.19
10	IIHR-Sel.22
11	IIHR-Sel.57
12	IIHR-Sel.41-1
13	Arka Ashish
14	Pusa Early Dwarf
15	CLN3916C
16	CLN3916D

Table 2: List of different cross combinations included in the study

Sl. No.	Cross/Hybrid
1	IIHR-Sel.22 x CLN3916D
2	CLN3916C x CLN3916D
3	CLN3961C x IIHR-Sel.22
4	Arka Ashish x CLN3916D
5	Arka Ashish x IIHR-Sel.22
6	Arka Ashish x CLN3916C
7	PED x CLN3916D
8	PED x IIHR-Sel.22
9	PED x CLN3916C
10	PED x Arka Ashish
11	IIHR-Sel.57 x CLN3916D
12	IIHR-Sel.57 x IIHR-Sel.22
13	IIHR-Sel-57 x CLN3916C
14	IIHR-Sel.57 x Arka Ashish
15	IIHR-Sel.57 x PED
16	IIHR-2834 x CLN3916D
17	IIHR-2834 x IIHR-Sel.22
18	IIHR-2834 x CLN3916C
19	IIHR-2834 x Arka Ashish
20	IIHR-2834 x PED
21	IIHR-2834 x IIHR-Sel.57
22	IIHR-2955 x CLN3916D
23	IIHR-2955 x IIHR-Sel.22
24	IIHR-2955 x CLN3916C
25	IIHR-2955 x Arka Ashish
26	IIHR-2955 x PED
27	IIHR-2955 x IIHR-Sel.57
28	IIHR-2955 x IIHR-2834
29	IIHR-2957 x CLN3916D
30	IIHR-2957 x IIHR-Sel.22
31	IIHR-2957 x CLN3916C
32	IIHR-2957 x Arka Ashish
33	IIHR-2957 x PED
34	IIHR-2957 x IIHR-Sel.57
35	IIHR-2957 x IIHR-2834
36	IIHR-2957 x IIHR-2955
37	IIHR-2821 x CLN3916D
38	IIHR-2821 x IIHR-Sel-22
39	IIHR-2821 x CLN3916C
40	IIHR-2821 x Arka Ashish
41	IIHR-2821 x PED
42	IIHR-2821 x IIHR-Sel.57
43	IIHR-2821 x IIHR-2834
44	IIHR-2821 x IIHR-2955
45	IIHR-2821 x IIHR-2957
46	IIHR-2833 x CLN3916D
47	IIHR-2833 x IIHR-Sel.22
48	IIHR-2833 x CLN3916C
49	IIHR-2833 x Arka Ashish
50	IIHR-2833 x PED
51	IIHR-2833 x IIHR-Sel.57
52	IIHR-2833 x IIHR-2834
53	IIHR-2833 x IIHR-2955
54	IIHR-2833 x IIHR-2957
55	IIHR-2833 x IIHR-2821
56	IIHR-2327-1 x CLN3916D
57	IIHR-2327-1 x IIHR-Sel.22
58	IIHR-2327-1 x CLN3916C
59	IIHR-2327-1 x Arka Ashish
60	IIHR-2327-1 x PED
61	IIHR-2327-1 x IIHR-Sel.57
62	IIHR-2327-1 x IIHR-2834
63	IIHR-2327-1 x IIHR-2955
64	IIHR-2327-1 x IIHR-2957
65	IIHR-2327-1 x IIHR-2821
66	IIHR-2327-1 x IIHR-2833
67	IIHR-Sel.19 x CLN3916D
68	IIHR-Sel.19 x IIHR-Sel.22
69	IIHR-Sel.19 x CLN3916C
70	IIHR-Sel.19 x Arka Ashish
71	IIHR-Sel.19 x PED
72	IIHR-Sel.19 x IIHR-Sel-57
73	IIHR-Sel.19 x IIHR-2834
74	IIHR-Sel.19 x IIHR-2955
75	IIHR-Sel.19 x IIHR-2957
76	IIHR-Sel.19 x IIHR-2821
77	IIHR-Sel.19 x IIHR-2833
78	IIHR-Sel.19 x IIHR-2327-1
79	IIHR-Sel. 41-1 x CLN3916D
80	IIHR-Sel. 41-1 x IIHR-Sel.22
81	IIHR-Sel. 41-1 x CLN3916C
82	IIHR-Sel. 41-1 x Arka Ashish
83	IIHR-Sel. 41-1 x PED
84	IIHR-Sel 41-1 x IIHR-Sel.57
85	IIHR-Sel. 41-1 x IIHR-2834
86	IIHR-Sel. 41-1 x IIHR-2955
87	IIHR-Sel. 41-1 x IIHR-2957
88	IIHR-Sel 41-1 x IIHR-2821
89	IIHR-Sel. 41-1 x IIHR-2833
90	IIHR-Sel. 41-1 x IIHR-2327-1
91	IIHR-Sel. 41-1 x IIHR-Sel-19
92	2847 x CLN3916D
93	2847 x IIHR-Sel-22
94	IIHR-2847 x CLN3916C
95	IIHR-2847 x Arka Ashish
96	IIHR-2847 x PED
97	IIHR-2847 x IIHR-Sel.57
98	IIHR-2847 x IIHR-2834
99	IIHR-2847 x IIHR-2955
100	IIHR-2847 x IIHR-2957
101	IIHR-2847 x IIHR-2821
102	IIHR-2847 x IIHR-2833
103	IIHR-2847 x IIHR-2327-1
104	IIHR-2847 x IIHR-Sel.19
105	IIHR-2847 x IIHR-Sel. 41-1
106	IIHR-2784 x CLN3916D
107	IIHR-2784 x IIHR-Sel.22
108	IIHR-2784 x CLN3916C
109	IIHR-2784 x Arka Ashsh
110	IIHR-2784 x PED
111	IIHR-2784 x IIHR-Sel.57
112	IIHR-2784 x IIHR-2834
113	IIHR-2784 x IIHR-2955
114	IIHR-2784 x IIHR-2957
115	IIHR-2784 x IIHR-2821
116	IIHR-2784 x IIHR-2833
117	IIHR-2784 x IIHR-2327-1
118	IIHR-2784 x IIHR-Sel.19
119	IIHR-2784 x IIHR-Sel. 41-1
120	IIHR-2784 x IIHR-2847

Table 3: List of best heterotic hybrids for important traits in tomato

Sl. No.	Trait/character	Heterobeltiosis (BPH)	Standard heterosis (SH)
1	Days to 50 % flowering	IIHR-Sel.57 x PED	PED × CLN3916C
2	Days to first fruit ripening	IIHR-2847 × PED	IIHR-2847 × PED
3	Fruit firmness (kg/cm^2)	IIHR-2327-1 × IIHR-2957	IIHR-2784 × IIHR-Sel.22
4	Number of seeds per fruit	IIHR-Sel.19 × CLN3916D	IIHR-2784 * IIHR-2955
5	Number of fruits per plant	IIHR-Sel.41-1 × IIHR-Sel.57	IIHR-2327-1 × Arka Ashish
6	Yield per plant (kg)	IIHR-2784 × IIHR-2834	IIHR-2327-1 x IIHR-2955
7	TSS (°Brix)	IIHR-2784 × IIHR-Sel.57	IIHR-2957 × CLN3916D
8	Pulp recovery (%)	IIHR-2327-1 × IIHR-2821	IIHR-2821 × CLN3916D
9	Dry matter (%)	IIHR-Sel.41-1 × IIHR-2957	IIHR-Sel.57 × CLN3916D
10	Viscosity (mPa)	IIHR-2821 × IIHR-Sel.22	Arka Ashish × CLN3916C

5. Conclusion

Heterosis studies revealed that hybrids IIHR-2957 X IIHR-Sel.57, IIHR-2847 X IIHR-2834, IIHR-Sel.41-1 X CLN3916C, IIHR-Sel.19 X Arka Ashish, and IIHR-Sel.19 X CLN3916D had significant desirable relative heterosis. While the hybrids IIHR-2821 X IIHR-Sel.22., IIHR-2821 X IIHR-2955, IIHR-Sel.41-1 X IIHR-Sel.19, IIHR-2847 X IIHR-Sel.41-1, IIHR-2834 X PED, IIHR-2834 X IIHR-Sel.57, Arka Ashish X CLN3916D had the highest positive and significant standard heterosis (SH) for shelf life, pulp recovery, pH, titrable acidity, moisture content, dry matter content and viscosity, respectively.

6. Disclaimer (Artificial Intelligence)

Authors hereby declare that no generative AI technologies such as large language models (Chat GPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of manuscripts.

7. Acknowledgement

We would like to express our sincere thanks to the Division of Vegetable Crops, ICAR-Indian Institute of Horticultural Research, Bengaluru, Karnataka (India), for providing all the necessary facilities and valuable suggestions during the investigation.

8. Competing interests

The authors have declared that no competing interests exist.

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