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Analysis of combining ability for morphological and biochemical traits in half-diallel crosses of tomato

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Abstract
Combining ability analysis, primarily conducted through designs like the diallel cross, provides a genetic blueprint by elucidating the nature and magnitude of gene action involved in economically important traits in tomato. Significant GCA effects were found for each of the 22 traits, including yield, fruit weight, and shelf life, in the current 16 × 16 half-diallel cross population. The study also showed that no parent behaved as a good general combiner for all characters at a time. But there were parents with high GCA for specific traits: IIHR-2327-1 was found to be an excellent general combiner for yield per plant (0.933) and average fruit weight (37.166), whereas Pusa Early Dwarf was outstanding for earliness attributes like no of days taken to 50% flowering and fruit ripening. Genotypes IIHR-2957 for shelf life and TSS were also the superior parents, along with Arka Ashish for pulp recovery. The results of the present study revealed that the extent of SCA variance was greater than GCA variance for all the characters under study, indicating that non-additive gene action played a predominant role in the expression of yield and quality components. Some of the promising hybrids with high SCA effects were IIHR-2327-1 x IIHR-2955 for yield per plant (2.479), IIHR-2847 x IIHR-Sel 19 for shelf life (14.534) and Pusa Early Dwarf x Arka Ashish for earliness and fruit firmness. The non-additive traits need to be exploited/bred through heterosis breeding or selection in subsequent segregating generations in order to realize an economically significant improvement. The findings of this study indicate that while parental lines such as IIHR-2327-1 and IIHR-Sel. 41-1 are effective for improving morphological traits in general, the development of specialized F1 hybrids remains the most effective strategy for optimizing tomato productivity and processing quality.

Keywords: combining ability, tomato, breeding, hybrid vigour

1. Introduction

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop worldwide, second in production and consumption to potato. The conventional selection of pure lines over the years has greatly reduced the genetic bases of cultivated tomatoes, although great success has been achieved by modern breeding (Gonias *et al*., 2019) [4]. The total genetic variance can be decomposed into these specific components using biometrical designs such as diallel and half-diallel crossing systems. Phenotypic observation alone is not sufficient to succeed in a breeding program; it is mandatory to gain knowledge of the nature and operation of genes controlling economic traits. This comes from the combination of ability analysis, a biometrical method for testing the relative performance of parental lines and their hybrids. It is known that diallel analysis involves the crossing of a group of parental lines in all possible combinations, thus enabling a holistic view of GCA for the parents and SCA for all hybrids produced. Such analyses enable GCA/SCA ratio estimation, and they provide a scientific principle to assess how much a character is controlled by additive or non-additive genes. Traits such as fruit weight and diameter often possess a GCA/SCA ratio in the higher range, which indicates an additive-dominance type of gene action, whereas metabolites and most of the quality traits have lower ratio values, indicating predominance of non-additive gene effects (Temesgen, 2021) [22].

The assessment of the parents by the combining ability analysis is a basic approach in tomato breeding to check and nominate effective genotypes worthy of lines for hybridization. The general combining ability (GCA) is the basic genetic value of a parent, defined as the average performance of a line in all cross combinations. Considerable GCA effects are mainly due to additive gene action and additive × additive interactions, which are estimable genetic components that can be fixed through regular selection procedures. On the other hand, SCA (Specific Combining Ability) occurs when a given hybrid combination has a response higher or lower than expected on account of GCA of the parents. SCA involves non-additive gene effects, such as dominance, overdominance and epistasis (Ranga *et al*., 2024) [14]. By characterizing the contributions of these genetic effects, breeders can decide whether to emphasize fixing desirable traits in homozygous lines or heterotic breeding to maximize productivity and fruit quality in modern tomato production.

2. Materials and Methods

The experiment was carried out at ICAR-Indian Institute of Horticultural Research (IIHR) Bengaluru, Division of Vegetable Crop during 2019-20 and 2020-21. Sixteen parental genotypes were selected from an initial set of 220 diverse tomato lines, recognized for their superior processing attributes and overall quality. Half-diallel mating system comprised of the 16 selected parent plants that has been established to produce 120 F_1 hybrids. Hybridization was performed by emasculation one day before anthesis of the female parent with forceps and manual pollination using pollen masses of the male parent the next morning. The matured crossed fruits were harvested, seeds extracted using a standard fermentation method and sown in pro-trays and transplanted at 1m x 0.5 m spacing. Hybrids, parents, and four commercial checks derived from hybrids involving the two new populations were tested in field trials during two separate seasons.

Field evaluation was conducted in an Augmented Block Design (ABD) and 22 quantitative and biochemical traits, including yield, fruit firmness and total soluble solids, were measured. To understand the genetic control of these traits, combining ability analysis was performed using Griffing (1956) [5] method II, Model I (fixed-effect statistical model). This technique dissects the total genetic variance into General Combining Ability (GCA), which is fixable and represents additive gene action and Specific Combining Ability (SCA), which contributes with non-additive gene effects. All the statistical analysis was performed with the Indo-Stat software, which allowed for to estimation of the variance ratio and thus identify the best breeding options. This biometric method enabled researchers to have superior general combiners for selection improvement and identify the best specific crosses for the increase of tomato yield and industry quality.

3. Results and Discussion

Analysis of variance (ANOVA) for general and specific combining ability in tomato showed that variation due to both GCA and SCA was highly significant for all twenty-two quantitative and processing characters studied (Table 1). These characters included several growth, yield and quality variables such as days to 50% flowering, average fruit weight and lycopene content. One important point that was observed in all data sets was that SCA variance exceeded GCA variance for all the traits studied (Table 2). Therefore, the GCA/SCA ratio was less than one for all traits, suggesting that non-additive gene action, which includes dominance (absence of heterosis following the projection of genotypical dissimilarity), overdominance and various forms of epistasis, predominantly controls inheritance of these characters. Plant yield exhibited 0.173 GCA variance compared to the much more significant SCA variance of 1.325. Corroborative findings were reported by Vekariya *et al*. (2019) [24], Singh *et al*. (2022) [18] and Sharma *et al*. (2025) [17]. Although additive effects contribute a heritable component of the genetic architecture that can be addressed by standard breeding techniques, the predominance of non-additive variance implies that the phenotypic performance of a genotype is largely determined by unique epistatic interactions among particular parental genomes.

General Combining Ability (GCA) indicated the internal genetic values of parental lines and their potential to pass on the desirable fixable traits to their progeny through additive gene effects (Table 3). The results indicated that no one parent was the best general combiner parent for all 22 characters at once, but strategic selection of parents depending on the breeding objective. Genotype IIHR-2327-1 was identified as the best general combiner for yield since it had maximum positive GCA effects for yield per plant (0.933), average fruit weight (37.166) and peduncle scar size (1.918). Findings that align with each other have been documented by Mishra *et al*. (2020) [12], Farwah *et al*. (2024) [2]. In the context of breeding for early generation yield and earliness, the parent PED (Pusa Early Dwarf) has been recognized as the superior general combiner. It demonstrates the most significant negative general combining ability (GCA) for both the number of days to reach 50% flowering (-2.149) and the number of days to the onset of first fruit ripening (-5.035). Research conducted by Bharathkumar and Sadashiva (2017) [1], Kumar *et al*. (2020) [8], Soresa *et al*. (2021) [20], Umesh *et al*. (2021) [23] has produced findings that substantiate these results. General combining ability estimates for shelf life were highest for IIHR-2957 (6.885), Arka Ashish for pulp recovery (1.859) and IIHR-2847 for total soluble solids (0.137). Concordant findings have been reported by Kaushik and Dhaliwal (2018) [7], Reddy *et al*. (2020) [15], Singh *et al*. (2021) [19], Nayana *et al*. (2021) [13], Ibirinde *et al*. (2022) [6]. Due to their significant general combining ability (GCA) effects, these parents are considered essential for developing superior pure lines, as they facilitate the accumulation of beneficial additive alleles in subsequent segregating generations.

Analysis of SCA revealed the existence of superior cross-combinations for important genotypes over their parents, thus suggesting potentially promising hybrids in heterosis breeding (Table 4). The crosses IIHR-2327-1 x IIHR-2955 (SCA 2.479) and IIHR-2955 x CLN3916C (SCA 2.479) were found to be positively significant for SCA of yield per plant among the hybrids studied, which can be exploited to enhance total productivity. Similar findings have been documented by Srivastava *et al*. (2019) [21], Mahmoud and El-Mansy (2020) [11] and Liu *et al*. (2021) [9]. The hybrid Pusa Early Dwarf x Arka Ashish was adjudged as the best combiner for maturity traits, recording significantly low SCA effects for days to 50% flowering -24.144 and good SCA effect for fruit firmness (17.283). Desirable traits targeted for the fresh market, such as shelf-life, were most effectively enhanced in cross IIHR-2847 x IIHR-Sel. 19 with an SCA effect of 14.534. Furthermore, the hybrid IIHR-Sel. The hybrid 41-1 x CLN3916D presented the highest SCA (99.603) for average fruit weight. Research by Yu *et al*. (2020) [25], Fortuny *et al*. (2021) [3], Manjunath *et al*. (2025) [11] and Rudas and Torbaniuk (2025) [16] has yielded comparable results. This emphasizes that often the most promising hybrids include at least one parent with a high GCA value, thus enabling breeders to exploit the "chemistry" of non-additive relationships while benefiting from a good additive genetic background.

Non-additive gene action (SCA) was observed to be the predominant genetic component for yield and its characters, suggesting that breeding of F_1 hybrids is still the most effective method for harnessing their potential vigor. Analysis of the allelic interactions exposed as well as duplicate epistasis in some traits, which mainly involved those types when dominance effects and dominance × dominance actions had an antagonistic type. This genetic phenomenon may well mask the speed of progress through selection by reducing variation in early segregating generations. Conclusively, combining ability analysis is an important biometrical technique for researchers to select superior genotypes like IIHR-2327-1 and Pusa Early Dwarf with respect to their contribution towards tomato yield and processing quality in diverse environments.

Table 1: Analysis of variance for growth, yield and quality traits in tomato under half diallel design

Sl. No.	Source	Treatments	Parents	Hybrids	Parent v/s Hybrids	GCA	SCA
	DF	135	15	119	1	15	120
1	Days to 50% flowering	2.87	3.57	2.02	93.46	10.79	1.88
2	Days to first fruit ripening	12.32	25.14	9.62	141.38	73.78	4.64
3	Number of fruits per cluster	0.12	0.18	0.11	1.12	0.50	0.07
4	Fruit length (cm)	0.60	0.46	0.62	0.57	3.15	0.29
5	Fruit width (cm)	0.31	0.27	0.31	0.42	1.08	0.21
6	Pericarp thickness (mm)	1.73	1.17	1.79	3.03	2.25	1.67
7	Number of locules per fruit	0.45	0.62	0.44	0.03	1.47	0.33
8	TSS	0.04	0.02	0.05	0.01	0.10	0.04
9	Firmness (kg/ cm^2)	0.59	1.17	0.52	0.05	2.64	0.33
10	Size of the core in fruit cross section (mm)	51.58	20.39	55.46	57.05	105.48	44.84
11	Peduncle scare size (mm)	10.33	7.17	10.63	22.29	14.79	9.78
12	Number of seeds per fruit	720.02	531.06	738.57	1347.09	1829.74	581.31
13	Average fruit weight (g)	890.27	333.46	925.15	5092.09	3189.69	602.84
14	Number of fruits per plant	267.44	384.66	253.85	125.55	679.12	215.98
15	Yield per plant (Kg)	1.52	0.51	1.58	9.67	3.11	1.33
16	Shelf life (days)	75.40	45.73	79.05	84.89	273.58	50.62
17	Pulp recovery (%)	29.20	64.39	13.60	1358.60	27.69	29.39
18	P^H	0.03	0.02	0.04	0.02	0.03	0.03
19	Titrable acidity (%)	0.01	0.00	0.01	0.08	0.01	0.01
20	Moisture (%)	5.72	2.70	6.13	2.14	8.40	5.39
21	Dry matter (%)	5.72	2.70	6.13	2.14	8.41	5.39
22	Viscosity (mPa)	6337840.00	8177754.00	6157231.00	231534.00	20308670.00	4591486.00

Table 2: Variance due to general and specific combining ability effects for growth, yield and quality traits in tomato for pooled season

Source of variation	DF	Days to 50% 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	Firmness (kg/cm^2)	Size of the core in fruit cross section (mm)	Peduncle scar size (mm)
GCA Variance	15	0.600	4.099	0.028	0.175	0.060	0.125	0.082	0.006	0.147	5.860	0.822
SCA Variance	120	1.878	4.637	0.073	0.285	0.208	1.669	0.325	0.037	0.331	44.841	9.776
GCA/SCA Ratio	135	0.319	0.884	0.381	0.613	0.290	0.075	0.251	0.157	0.443	0.131	0.084
VA		1.199	8.198	0.056	0.350	0.120	0.250	0.163	0.012	0.294	11.719	1.643
VD		1.878	4.637	0.073	0.285	0.208	1.669	0.325	0.037	0.331	44.841	9.776

Source of variation	DF	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 (%)	Dry matter (%)	Viscosity (mPa)
GCA Variance	15	101.652	177.205	37.729	0.173	15.199	1.538	0.002	0.000	0.467	0.467	1128259.167
SCA Variance	120	581.309	602.843	215.976	1.325	50.623	29.392	0.033	0.007	5.387	5.387	4591486.139
GCA/SCA Ratio	135	0.175	0.294	0.175	0.130	0.300	0.052	0.055	0.042	0.087	0.087	0.246
VA		203.304	354.410	75.458	0.345	30.397	3.077	0.004	0.001	0.934	0.934	2256518.334
VD		581.309	602.843	215.976	1.325	50.623	29.392	0.033	0.007	5.387	5.387	4591486.139

Table 3: General combining ability effects of parents for growth, yield and quality parameters in tomato for pooled season

Sl. No.	Parents	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	Firmness (kg/cm^2)	Size of the core in fruit cross section (mm)	Peduncle scar size (mm)
1	IIHR- 2784	1.212 **	3.938 **	-0.146 **	0.546 **	0.083 **	0.351 **	-0.426 **	0.033 **	0.541 **	-1.711 **	-0.788 **
2	IIHR- 2847	0.128 **	0.965 **	0.075 **	-0.214 **	-0.005 **	0.055 **	-0.086 **	0.137 **	-0.131 **	3.688 **	-0.002 **
3	IIHR- Sel.41-1	0.545 **	1.354 **	-0.230 **	0.864 **	0.234 **	-0.517 **	0.144 **	-0.097 **	0.475 **	2.580 **	-0.019 **
4	IIHR- Sel.19	0.156 **	0.604 **	-0.220 **	0.341 **	0.114 **	0.113 **	0.127 **	0.072 **	0.269 **	2.275 **	0.342 **
5	IIHR- 2327-1	0.823 **	2.021 **	0.075 **	-0.149 **	0.594 **	-0.028 **	0.359 **	0.112 **	-0.048 **	3.403 **	1.918 **
6	IIHR- 2833	-0.066 **	-0.507 **	-0.092 **	-0.041 **	-0.266 **	0.514 **	-0.288 **	-0.038 **	-0.098 **	-2.380 **	0.297 **
7	IIHR- 2821	0.378 **	-0.063 **	0.010 **	-0.290 **	0.133 **	0.037 **	-0.049 **	-0.018 **	-0.317 **	0.859 **	-0.622 **
8	IIHR- 2957	0.073 **	-1.757 **	0.065 **	-0.793 **	-0.027 **	-0.474 **	0.386 **	0.034 **	-0.317 **	-0.182 **	1.262 **
9	IIHR- 2955	-0.149 **	0.243 **	0.204 **	-0.084 **	-0.198 **	-0.216 **	-0.086 **	0.001 **	-0.071 **	-1.341 **	0.490 **
10	IIHR- 2834	0.767 **	0.993 **	0.057 **	-0.096 **	-0.167 **	0.456 **	-0.355 **	0.025 **	0.224 **	-3.549 **	-0.951 **
11	IIHR- Sel.57	0.045 **	1.604 **	-0.147 **	0.279 **	0.123 **	-0.007 **	0.341 **	0.028 **	0.061 **	1.693 **	1.106 **
12	PED	-2.149 **	-5.035 **	0.371 **	-0.661 **	-0.162 **	-0.572 **	0.443 **	-0.083 **	-1.071 **	-0.761 **	-1.532 **
13	Arka Ashish	-0.927 **	-2.063 **	0.205 **	0.081 **	-0.432 **	0.153 **	-0.354 **	-0.165 **	-0.078 **	-3.621 **	-0.768 **
14	CLN3916C	-0.205 **	-1.063 **	-0.055 **	0.116 **	0.163 **	-0.170 **	0.098 **	-0.008 **	0.149 **	2.242 **	-0.032 **
15	IIHR- Sel.22	-0.427 **	-0.229 **	-0.146 **	0.300 **	-0.248 **	-0.231 **	-0.235 **	-0.031 **	0.028 **	-2.061 **	-0.731 **
16	CLN3916D	-0.205 **	-1.007 **	-0.027 **	-0.198 **	0.063 **	0.537 **	-0.020 **	-0.001 **	0.382 **	-1.136 **	0.031 **

Table 3: Contd…

Sl. No.	Parents	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 (%)	Dry matter	Viscosity (mPa)
1	IIHR- 2784	-17.689 **	4.035 **	-1.729 **	0.000 **	1.747 **	0.505 **	-0.049 **	0.024 **	-0.143 **	0.142 **	-1173.396 **
2	IIHR- 2847	-7.926 **	1.156 **	3.597 **	0.430 **	0.747 **	-0.029 **	0.021 **	0.035 **	-0.542 **	0.542 **	-541.674 **
3	IIHR- Sel.41-1	-9.336 **	15.850 **	-6.692 **	0.212 **	-4.420 **	0.498 **	0.020 **	-0.003 **	-0.139 **	0.139 **	-484.341 **
4	IIHR-Sel.19	-0.892 **	7.711 **	-6.217 **	-0.435 **	2.274 **	-1.641 **	0.106 **	-0.017 **	0.566 **	-0.567 **	-562.118 **
5	IIHR- 2327-1	14.690 **	37.166 **	3.536 **	0.933 **	-2.142 **	-2.203 **	-0.043 **	-0.007 **	-0.339 **	0.339 **	-985.066 **
6	IIHR- 2833	8.962 **	-14.909 **	2.960 **	-0.104 **	1.024 **	0.579 **	0.056 **	-0.017 **	0.598 **	-0.597 **	-673.638 **
7	IIHR- 2821	5.604 **	-7.954 **	-0.996 **	-0.287 **	2.024 **	-1.936 **	0.002 **	-0.001 **	0.389 **	-0.390 **	-440.730 **
8	IIHR- 2957	9.377 **	-7.630 **	-0.489 **	0.001 **	6.885 **	1.613 **	-0.055 **	0.006 **	-0.732 **	0.733 **	-357.507 **
9	IIHR- 2955	4.778 **	-5.927 **	12.522 **	0.570 **	-1.003 **	-0.221 **	0.011 **	-0.028 **	0.603 **	-0.602 **	-102.541 **
10	IIHR- 2834	-7.532 **	-3.602 **	0.992 **	0.109 **	-2.476 **	-1.050 **	0.008 **	0.000 **	-0.053 **	0.053 **	870.854 **

11	IIHR-Sel.57	-0.684 **	5.655 **	-7.657 **	-0.563 **	-0.392 **	0.861 **	0.028 **	0.019 **	-0.619 **	0.619 **	711.215 **
12	PED	13.116 **	-18.307 **	3.587 **	-0.510 **	-6.781 **	0.674 **	-0.022 **	-0.007 **	1.375 **	-1.376 **	-981.980 **
13	Arka Ashish	-17.855 **	-11.427 **	9.340 **	0.199 **	4.385 **	1.859 **	-0.017 **	-0.015 **	1.027 **	-1.027 **	2017.326 **
14	CLN3916C	0.008 **	5.378 **	-6.543 **	-0.116 **	1.247 **	1.319 **	-0.052 **	0.026 **	-0.470 **	0.470 **	2261.565 **
15	IIHR-Sel.22	-2.803 **	-5.029 **	2.617 **	0.045 **	-7.198 **	-0.890 **	0.001 **	-0.012 **	-0.519 **	0.518 **	-626.296 **
16	CLN3916D	8.183 **	-2.167 **	-8.827 **	-0.486 **	4.080 **	0.062 **	-0.016 **	-0.004 **	-1.002 **	1.002 **	1068.326 **

Table 4: Specific combining ability effects for growth, yield and quality parameters in tomato for pooled season

Sl. No.	Crosses	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
1	IIHR- 2784*IIHR- 2847	-0.851	-2.704 **	-0.399	-0.123	-0.098	-0.041	-0.065	-0.032
2	IIHR- 2784*IIHR-Sel.41-1	-1.268	3.907 **	-0.424	0.149	-0.367	-0.398	-0.136	0.152
3	IIHR- 2784*IIHR-Sel.19	-0.379	-2.343 **	0.066	0.223	0.053	0.882	-0.619	0.174 *
4	IIHR- 2784*IIHR- 2327-1	-0.046	-1.760 *	-0.229	-0.187	-0.347	0.042	-0.18	-0.066
5	IIHR- 2784*IIHR- 2833	-0.657	-2.232 *	-0.062	0.085	0.692 **	-1.53	-0.334	-0.086
6	IIHR- 2784*IIHR- 2821	-0.601	0.824	0.166	-0.296	-0.087	0.077	-0.103	0.114
7	IIHR- 2784*IIHR- 2957	-0.796	0.018	-0.219	-0.064	0.784 **	1.488	0.462	-0.289 **
8	IIHR- 2847*IIHR-Sel.41-1	0.315	0.379	0.185	-0.141	0.431	-0.203	-0.476	0.138
9	IIHR- 2847*IIHR-Sel.19	-0.796	1.629	0.005	0.613	-0.159	-0.333	-0.119	0
10	IIHR- 2847*IIHR- 2327-1	-0.462	-1.288	-0.45	-0.077	0.511 *	1.588	-0.19	-0.07
11	IIHR- 2847*IIHR- 2833	-0.574	-1.760 *	-0.284	-0.355	-0.820 **	-1.884	-0.544	0.01
12	IIHR- 2847*IIHR- 2821	-2.018 *	-1.204	0.445	-0.336	-0.249	-0.827	-0.283	0.12
13	IIHR- 2847*IIHR- 2957	-0.212	-0.51	-0.111	1.076	-0.738 **	1.254	-0.048	-0.043
14	IIHR-Sel.41-1*IIHR-Sel.19	-1.212	0.24	-0.02	0.315	0.212	-1.16	-0.189	-0.136
15	IIHR-Sel.41-1*IIHR- 2327-1	-0.879	-0.676	-0.145	-0.535	-0.178	-0.12	-0.251	0.094
16	IIHR-Sel.41-1*IIHR- 2833	0.01	0.351	0.022	1.497 **	0.111	0.939	-0.434	0.144
17	IIHR-Sel.41-1*IIHR- 2821	-0.935	-0.093	-0.25	0.066	-0.158	-0.025	0.156	-0.476 **
18	IIHR-Sel.41-1*IIHR- 2957	-1.629	-0.899	0.195	-0.332	-0.377	0.107	-0.449	0.141
19	IIHR-Sel.19*IIHR- 2327-1	0.51	-0.426	-0.155	0.848	0.952 **	-2	1.596 **	-0.074
20	IIHR-Sel.19*IIHR- 2833	0.399	-1.899 *	0.012	-1.05	-0.319	-1.041	0.243	-0.194 *
21	IIHR-Sel.19*IIHR- 2821	-1.046	-3.843 **	-0.09	-0.441	-0.048	0.815	0.674	0.106
22	IIHR-Sel.19*IIHR- 2957	-1.24	-2.649 **	-0.145	-0.529	-0.337	1.727	-0.761	0.073
23	IIHR- 2327-1*IIHR- 2833	-1.268	-1.815 *	0.377	-0.24	0.401	3.599 **	0.181	0.106
24	IIHR- 2327-1*IIHR- 2821	1.288	1.24	-0.055	0.329	0.432	0.356	1.112 *	-0.084

Table 4: Contd…

Sl. No.	Crosses	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
25	IIHR- 2327-1*IIHR- 2957	0.593	0.435	0.06	-0.039	-0.267	-0.953	-0.323	-0.107
26	IIHR- 2833*IIHR- 2821	-1.324	-1.732	-0.218	0.021	-0.058	1.484	0.419	0.386 **
27	IIHR- 2833*IIHR- 2957	0.982	1.462	0.386	0.054	0.272	-0.155	0.324	0.183 *
28	IIHR- 2821*IIHR- 2957	-0.462	-0.482	-0.045	0.403	0.173	0.232	0.084	0.043
29	IIHR- 2784*IIHR- 2955	-2.074 *	-2.982 **	0.302	0.378	0.075	-1.15	-0.066	-0.095
30	IIHR- 2784*IIHR- 2834	1.01	-0.232	-0.21	0.42	0.564 *	1.578	-0.137	-0.08
31	IIHR- 2784*IIHR-Sel.57	-0.268	3.657 **	-0.177	0.145	-0.506 *	1.102	0.008	0.098
32	IIHR- 2784*PED	-0.074	-1.204	-0.195	0.734	-0.422	-1.334	0.066	0.059
33	IIHR- 2784*Arka Ashish	-0.796	-1.176	0.141	-0.207	0.028	-0.889	0.533	0.241 **
34	IIHR- 2784*CLN3916C	-0.018	-0.176	0.061	0.847	0.154	1.584	-0.25	0.153
35	IIHR- 2784*IIHR-Sel.22	2.204 *	0.49	-0.008	-0.057	-0.035	1.615	1.083 *	-0.044
36	IIHR- 2784*CLN3916D	0.482	0.268	0.203	0.161	0.183	0.047	-0.132	0.076
37	IIHR- 2847*IIHR- 2955	0.51	-1.01	-0.25	-0.052	-0.127	0.696	0.594	-0.069
38	IIHR- 2847*IIHR- 2834	-0.907	-0.76	-0.432	0.22	-0.228	0.804	0.363	-0.104
39	IIHR- 2847*IIHR-Sel.57	-0.185	0.129	-0.228	0.775	1.062 **	0.167	0.998	-0.056
40	IIHR- 2847*PED	0.01	-2.732 **	-0.417	-0.436	-0.454	-0.498	-0.274	0.235 **
41	IIHR- 2847*Arka Ashish	-1.212	-0.704	0.25	-0.247	0.156	1.337	0.193	0.307 **
42	IIHR- 2847*CLN3916C	-1.435	-1.704	-0.321	-0.763	0.452	-0.52	0.07	-0.09
43	IIHR- 2847*IIHR-Sel.22	0.788	0.462	-0.229	0.843	-0.038	-0.689	-0.257	-0.328 **
44	IIHR- 2847*CLN3916D	-0.435	-2.760 **	0.481	0.371	0.221	1.403	-0.472	0.172 *
45	IIHR-Sel.41-1*IIHR- 2955	0.093	-0.399	-0.274	-0.31	-0.126	-0.181	0.524	0.045
46	IIHR-Sel.41-1*IIHR- 2834	-1.324	-1.649	0.203	-0.878	-0.267	-0.603	0.293	0.1
47	IIHR-Sel.41-1*IIHR-Sel.57	-1.101	-2.760 **	0.407	0.517	0.023	-1.03	0.767	0.098
48	IIHR-Sel.41-1*PED	-0.407	-0.121	-0.111	-0.494	0.077	-1.626	-0.165	-0.241 **

Table 4: Contd…

Sl. No.	Crosses	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
49	IIHR-Sel.41-1*Arka Ashish	-0.129	-0.093	-0.275	0.095	0.027	0.829	-0.368	0.121
50	IIHR-Sel.41-1*CLN3916C	1.649	-1.593	-0.185	0.559	0.353	-0.427	-0.16	-0.287 **
51	IIHR-Sel.41-1*IIHR-Sel.22	-0.129	0.574	0.076	-0.295	-0.437	0.194	0.173	-0.084
52	IIHR-Sel.41-1*CLN3916D	1.149	-1.149	-0.043	0.804	0.852 **	0.565	1.128 *	0.086
53	IIHR-Sel.19*IIHR- 2955	-0.018	3.851 **	0.046	1.443 *	1.034 **	0.569	1.211 *	0.036
54	IIHR-Sel.19*IIHR- 2834	1.565	-1.399	0.193	-0.025	0.383	-0.153	-0.35	-0.058
55	IIHR-Sel.19*IIHR-Sel.57	1.788 *	0.99	-0.103	-1.05	-0.307	0.36	-0.216	-0.04
56	IIHR-Sel.19*PED	-1.018	2.129 *	-0.121	0.43	-0.103	-0.226	-0.317	0.071
57	IIHR-Sel.19*Arka Ashish	-0.24	0.657	0.215	0.248	0.197	-1.671	-0.351	0.072
58	IIHR-Sel.19*CLN3916C	0.038	1.657	-0.025	0.133	0.633 *	-0.777	0.197	-0.055
59	IIHR-Sel.19*IIHR-Sel.22	-0.24	0.824	-0.104	1.009	0.413	3.354 **	-0.31	0.018
60	IIHR-Sel.19*CLN3916D	-0.462	0.601	-0.053	-0.683	-0.348	-0.265	-0.685	0.038
61	IIHR- 2327-1*IIHR- 2955	2.815 **	5.935 **	0.081	-0.177	0.384	1.839	-0.191	0.076
62	IIHR- 2327-1*IIHR- 2834	-2.101 *	-2.315 **	0.228	0.065	0.423	1.887	-0.582	0.172 *
63	IIHR- 2327-1*IIHR-Sel.57	-0.379	-4.426 **	0.102	-0.17	-0.437	-0.6	-1.117 *	0.05
64	IIHR- 2327-1*PED	-0.185	0.212	-0.246	0.12	-0.323	-0.835	-1.379 *	-0.119
65	IIHR- 2327-1*Arka Ashish	-0.907	-1.760 *	-0.25	-0.312	-0.353	1.67	-0.582	0.162 *
66	IIHR- 2327-1*CLN3916C	-0.629	-0.26	-0.16	0.883	0.083	-1.257	-0.375	0.015
67	IIHR- 2327-1*IIHR-Sel.22	-1.407	-2.593 **	0.101	-0.031	-0.167	-0.606	0.128	0.058
68	IIHR- 2327-1*CLN3916D	-1.629	-1.815 *	-0.018	-0.113	-0.458	-1.894	-0.257	-0.082
69	IIHR- 2833*IIHR- 2955	1.204	0.462	-0.413	-0.885	-0.727 **	-1.342	-0.704	-0.084
70	IIHR- 2833*IIHR- 2834	-0.212	0.712	-0.265	0.708	-0.188	-1.075	0.395	-0.098
71	IIHR- 2833*IIHR-Sel.57	-0.99	-0.399	0.099	-0.647	-0.198	-1.161	-0.631	0.190 *
72	IIHR- 2833*PED	0.704	-0.76	0.081	-0.328	0.227	0.543	0.268	0.031

Table 4: Contd…

Sl. No.	Crosses	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
73	IIHR- 2833*Arka Ashish	0.482	1.268	-0.083	-0.4	-0.333	-0.382	0.894	-0.638 **
74	IIHR- 2833*CLN3916C	-1.24	0.268	-0.324	-0.165	-0.148	-0.258	0.272	-0.125
75	IIHR- 2833*IIHR-Sel.22	-0.018	1.435	0.598	0.481	0.013	-0.937	-0.395	0.208 *
76	IIHR- 2833*CLN3916D	-0.74	-0.788	-0.352	-0.021	-0.208	0.684	-0.27	-0.002
77	IIHR- 2821*IIHR- 2955	-0.74	0.018	0.316	0.384	0.195	1.444	-0.784	0.056
78	IIHR- 2821*IIHR- 2834	-0.157	-0.232	-0.037	-0.524	-0.007	-1.408	-0.015	0.122
79	IIHR- 2821*IIHR-Sel.57	-0.435	-1.843 *	0.167	0.631	0.773 **	-0.885	0.13	-0.03
80	IIHR- 2821*PED	0.26	0.796	0.149	0.181	0.388	0.3	-0.142	-0.169 *
81	IIHR- 2821*Arka Ashish	1.038	0.324	-0.515	0.429	-0.122	1.795	0.155	-0.288 **
82	IIHR- 2821*CLN3916C	-0.685	-0.176	0.075	-0.106	-0.667 **	-1.152	0.033	-0.185 *
83	IIHR- 2821*IIHR-Sel.22	-0.962	-0.01	0.166	-0.29	0.104	-0.691	-0.295	0.088
84	IIHR- 2821*CLN3916D	1.315	0.768	0.047	-0.692	-0.497	-2.039	-0.18	0.008
85	IIHR- 2957*IIHR- 2955	-0.435	-0.788	0.09	0.086	0.085	0.075	-0.049	-0.147
86	IIHR- 2957*IIHR- 2834	-0.351	-0.038	-0.092	-0.101	0.254	-0.617	0.05	0.029
87	IIHR- 2957*IIHR-Sel.57	-0.629	-3.649 **	-0.388	0.334	-0.916 **	-1.433	-0.645	0.067
88	IIHR- 2957*PED	1.065	0.99	0.263	-0.007	-0.612 *	-0.789	-0.747	-0.392 **
89	IIHR- 2957*Arka Ashish	-0.157	0.518	0.09	-0.149	0.208	-0.494	0.22	-0.540 **
90	IIHR- 2957*CLN3916C	0.621	-0.982	-0.311	-0.534	0.114	0.189	0.768	-0.088
91	IIHR- 2957*IIHR-Sel.22	-1.157	-0.315	-0.219	0.052	0.435	-0.53	-0.73	0.135
92	IIHR- 2957*CLN3916D	-1.879 *	-0.538	-0.009	-0.32	0.373	-0.728	0.885	0.395 **
93	IIHR- 2955*IIHR- 2834	-1.129	-3.538 **	0.269	-0.48	-0.605 *	-2.805 *	-0.307	0.032
94	IIHR- 2955*IIHR-Sel.57	-0.907	-2.149 *	-0.027	0.465	-0.065	-0.341	-0.333	0.08
95	IIHR- 2955*PED	-0.712	1.49	0.455	0.065	0.27	1.233	0.895	0.211 **
96	IIHR- 2955*Arka Ashish	0.565	0.518	0.121	-0.287	-0.42	-0.842	0.522	-0.027

Table 4: Contd…

Sl. No.	Crosses	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
97	IIHR- 2955*CLN3916C	-0.157	-0.482	0.05	-0.262	0.875 **	-0.268	-0.26	-0.014
98	IIHR- 2955*IIHR-Sel.22	-0.435	-0.815	-0.028	0.304	-0.074	0.843	-0.097	-0.212 **
99	IIHR- 2955*CLN3916D	-0.157	0.462	0.022	-0.148	0.035	3.174 **	-0.142	0.038
100	IIHR- 2834*IIHR-Sel.57	-0.324	6.101 **	0.121	0.808	1.174 **	1.387	0.436	0.056
101	IIHR- 2834 x PED	-3.160 **	-0.327	-0.549	1.118	-0.716	1.784 *	6.840 **	4.840 **
102	IIHR- 2834 x Arka Ashish	0.675	-0.638	0.342	-0.094	0.602	-0.354	-0.263	-0.374
103	IIHR- 2834 x CLN3916C	-0.379	1.127 **	-1.083 **	-0.842 **	-0.385	2.760 **	1.043 **	0.137
104	IIHR- 2834 x IIHR-Sel.22	-0.48	0.743	0.644	0.858	-0.146	0.354	-0.341	-0.829
105	IIHR- 2834 x CLN3916D	2.175 **	-0.831 **	-0.714 **	0.855 **	1.071 **	0.598 **	-0.015	0.650 **
106	IIHR-Sel.57 x PED	-0.85	0.315	1.637	0.58	-0.256	-0.77	0.149	-0.646
107	IIHR-Sel.57 x Arka Ashish	-0.683 **	-0.499 *	0.594 *	-0.144	0.285	0.268	0.04	0.303
108	IIHR-Sel.57 x CLN3916C	-0.007	0.888	0.679	-0.912	-0.753	0.113	0.666	0.453
109	IIHR-Sel.57 x IIHR-Sel.22	-4.686	6.859	2.695	2.033	-7.155	-1.001	-4.399	-5.078
110	IIHR-Sel.57 x CLN3916D	-3.064	5.582	-1.12	2.769	-3.879	1.614	3.495	-4.067
111	PED x Arka Ashish	-24.144 **	-16.966 **	28.224 **	-3.426	0.535	24.243 **	-22.535 **	-33.315 **
112	PED x CLN3916C	2.248	25.901	18.03	20.547	6.699	32.118	3.383	12.364
113	PED x IIHR-Sel.22	24.352	8.659	-2.391	14.251	-20.391	-5.816	-2.983	17.389
114	PED x CLN3916D	1.831 *	1.223	-0.748	0.527	-1.311	-0.352	-0.806	1.408
115	Arka Ashish x CLN3916C	0.964	-6.314 **	12.575 **	3.742 **	3.575 **	0.443	-17.480 **	-12.647 **
116	Arka Ashish x IIHR-Sel.22	0.536	4.306	0.861	5.328	1.487	-1.748	-0.865	-1.875
117	Arka Ashish x CLN3916D	-0.109 *	-0.282 **	0.028	-0.092 *	0.032	0.015	-0.198 **	0.162 **
118	CLN3916C x IIHR-Sel.22	-0.046 **	-0.046 **	-0.056 **	-0.037 **	-0.032 *	-0.021	-0.011	0.053 **
119	CLN3916C x CLN3916D	1.149	0.658	-3.237 **	1.466	-0.992	0.642	1.641 *	0.174
120	IIHR-Sel.22 x CLN3916D	-0.32	1.118	-0.094	-0.842 **	0.858	0.855 **	0.58	-0.144

4. Conclusion

Combining ability analysis for tomato is consistent with dominance gene action, as observed in the higher SCA variance than GCA variance in all twenty-two quantitative and processing traits. General Combining Ability (GCA) helps in recognizing fixable additive gene effects, which are basic for the construction of superior cultivars; however, no single parent was identified as a good combiner for all traits and simultaneously. Elite parents such as IIHR-2327-1 performed well for yield and fruit weight and, PED was the best for earliness. On the other hand, Dominance and epistasis effects (SCA) are primarily responsible for bringing about heterosis of hybrids that showed the highest cross performance, such as IIHR-2327-1 x IIHR-2955 (on total productivity and maturity stage) and Pusa Early Dwarf x Arka Ashish. Finally, as yield is controlled mostly by non-additive effects, the most effective breeding strategy for immediate improvement is to develop F_1 hybrids.

5. 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.

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7. Competing interests

The authors have declared that no competing interests exist.

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