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Combining ability studies for different characters in tomato (*Solanum lycopersicum* L.)

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Abstract
In this comprehensive study, the assessment of General Combining Ability (GCA) and Specific Combining Ability (SCA) was conducted using six distinct tomato lines (*Solanum lycopersicum* L.) and three carefully chosen testers. Following a systematic line x tester breeding methodology, the research aimed to identify superior general combiners for crucial agronomic traits. Notably, parental lines like LE-56 showcased significant GCA effects in a favorable direction for traits such as days to 50% flowering, number of flowers per cluster, number of fruits per cluster, and overall fruit yield per plant. LE-64, on the other hand, stood out for its substantial GCA effects in terms of fruit length and average fruit weight. Among the testers, Pusa Gaurav, Pant T-3, and Punjab Chhuhara demonstrated high GCA effects for specific traits, positioning them as superior general combiners. Furthermore, specific combinations, such as LE-64 × Pusa Gaurav, LE-62 × Pant T-3, LE-56 × Punjab Chhuhara, and LE-67 × Pant T-3, emerged as the most promising with exceptional SCA effects, thereby holding substantial potential for future heterosis breeding strategies in tomato cultivation. These findings contribute valuable insights to tomato breeding programs, aiding in the selection of optimal parental lines and specific crosses to enhance the efficiency and success of breeding initiatives.

Keywords: General combining ability, specific combining ability, gene action, line and tester, tomato

Introduction
Tomato (*Solanum lycopersicum* L.), a globally significant vegetable crop, holds prominence not only as a fresh produce but also in various processing applications. In the pursuit of enhancing tomato breeding programs, the evaluation of combining ability emerges as a pivotal tool. This approach furnishes valuable genetic insights, aiding breeders in the strategic selection of parent plants based on the anticipated performance of their hybrids (Chezhian *et al.*, 2000) [1]. While the per se performance of individual lines serves as a benchmark, its reliance alone may not ensure the attainment of desired outcomes, as emphasized by Allard in 1960 [2]. Thus, discerning the combining ability of genotypes becomes imperative for effective breeding programs, facilitating the optimal transfer of desirable genes in ensuing progenies. This investigation is directed towards the identification of optimal parental combinations, a crucial step in the meticulous breeding of tomatoes, with the aim of enhancing key traits and overall crop performance.

Materials and Methods
The research was conducted at the experimental farm of Vegetable Research Station, Dr. Y.S. R. Horticultural University, Rajendranagar, Hyderabad, during the period 2010-2011. The study employed a line x tester model, utilizing a set of six lines, namely EC-165749, LE-56, LE-62, LE-64, LE-65, LE-67, and three testers, namely Punjab Chhuhara, Pant T-3, and Pusa Gaurav. Crossbreeding was executed manually, adhering to standard hand emasculation and pollination procedures. To assess the resulting 18 hybrids, alongside their respective nine parental lines and three standard checks (Lakshmi, US-618, and Arka Vikas), a randomized block design with three replications was employed, following the recommendation of Panse and Sukhatme (1967) [3]. Combining ability analysis was conducted in accordance with Kempthorne's methodology (1957) [4]. The study focused on observing traits such as days to 50% flowering, number of flowers per cluster, number of fruits per cluster, fruit length, fruit width, average fruit weight, and fruit yield per plant. These observations facilitated the exploration of gene action, as well as the assessment of general combining ability (GCA) effects of parents and specific combining ability (SCA) effects of hybrids in the context of tomato breeding.

Results and Discussion

The results of the combining ability analysis for various traits in tomato are presented in Table 1. The analysis of variance demonstrated highly significant differences among treatments, indicating substantial variability in the studied characters. Both parental lines and their crosses exhibited significant differences for all traits under consideration. Furthermore, the interaction effects between Lines and Testers were found to be significant for all traits, underscoring the influence of the specific combinations of parental lines on trait expression. These findings suggest a robust basis for investigating the genetic factors influencing the traits of interest and highlight the importance of understanding the combining ability for effective tomato breeding strategies.

Combining ability variances and gene action.

The assessment of general combining ability (GCA) and specific combining ability (SCA) variances, along with their ratios and gene action, is outlined in Table 2. Generally associated with additive gene action, GCA represents the additive effects of alleles contributed by a parent. In contrast, SCA is influenced by dominance and epistasis. The study revealed that, for traits such as days to 50% flowering, number of flowers per cluster, number of fruits per cluster, fruit length, fruit width, average fruit weight, and fruit yield per plant, the variance due to SCA was consistently higher in magnitude than the variance due to GCA. This observation suggests the predominance of non-additive gene action in the genetic control of these traits. The prevalence of non-additive gene action highlights the significance of dominance and epistasis in shaping the expression of key characteristics in the studied tomato population.

Combining Ability effects

The combining ability effects were estimated for all the characters as they had significant contributions in total variance. The effects due to general and specific combining ability are presented under following sub heads.

General Combining Ability Effects

The general combining ability (GCA) effects of the nine parents for different characters are outlined in Table 3. GCA effects represent numerical values assigned to parents based on their average performance in a series of cross combinations.

Days to 50% Flowering

Negative GCA effects, indicative of earliness, are considered desirable. Among the lines tested, only LE-56 (-2.111) exhibited a significant negative GCA effect, suggesting it as a favorable general combiner for earliness. Conversely, LE-65 (2.222) recorded a significant positive GCA effect, indicating poor general combining ability for earliness. Notably, none of the testers exhibited significant GCA effects for this trait.

Number of flowers per cluster

In the context of the number of flowers per cluster, noteworthy combining ability effects were observed. Among the lines, LE-56 (0.336) demonstrated a positive general combining ability (GCA), indicating its potential for increased flower production. However, LE-62(-0.168) exhibited a negative GCA effect, suggesting limited effectiveness for enhancing flower numbers. Among the testers, Pant T-3 (0.268) displayed a positive GCA effect, while Pusa Gaurav (-0.241) showed a negative GCA effect, implying differing abilities in contributing to flower numbers.

Number of fruits per cluster

Positive *gca* effects would be desirable for this trait. Among the lines only, LE-56 (0.568) showed significantly positive *gca* effect, while EC-165749 (-0.658) and LE-65 (-0.312) recorded significant negative *gca* effects.

All the testers exhibited significant *gca* effects. However Punjab Chhuhara and Pusa Gaurav recorded positive *gca* effects of 0.179 and 0.146 respectively. While Pant T-3 (-0.325) exhibited negative *gca* effect indicating poor general combining ability for fruits per cluster.

Fruit length (cm)

Among the lines, LE-56 (0.255) and LE-64 (0.397) recorded significant positive *gca* effects, while LE-62 (-0.276) and LE-67 (-0.184) recorded negative significant *gca* effect. The tester Punjab Chhuhara showed the significant positive *gca* effect of 0.489, while Pant T-3 and Pusa Gaurav showed significant negative *gca* effects of -0.175 and -0.314 respectively.

Fruit width (cm)

Three out of six lines recorded significant positive *gca* effects. They were EC-165749 (0.172), LE-65 (0.225) and LE-67 (0.291) while, LE-62 (-0.317) and LE-64 (-0.381) recorded significantly negative *gca* effects for this trait. Among the testers, only Pusa Gaurav (0.119) showed positive significant *gca* effect for fruit width.

Average fruit weight (g)

Among the lines only, LE-64 (4.266) recorded significant positive *gca* effect for average fruit weight, while LE-65 (-11.998) recorded significantly negative *gca* effect for this trait. Among the testers, Punjab Chhuhara (3.457) showed positive significant *gca* effect for fruit weight.

Fruit yield per plant (kg)

Among all the parents, the line LE-56 (0.549) and the tester Punjab Chhuhara (0.230) exhibited highly significant and positive *gca* effects and are adjudzed as good general combiners for fruit yield. However three lines *viz*., EC-165749 (-0.186), LE-62 (-0.153) and LE-64 (-0.212) and two testers *viz*., Pant T-3 (-0.144) and Pusa Gaurav (-0.086) exhibited highly significant negative *gca* effects for fruit yield and they are presumed to be poor general combiners for fruit yield per plant.

Specific Combining Ability (SCA) effects for yield, yield-contributing, and quality traits were analyzed across 18 cross combinations. The results, presented in Table 4, offer insights into specific interactions between parental lines and testers, providing crucial information for breeders to optimize combinations for targeted trait improvement in tomato breeding programs.

Days to 50% flowering

In the analysis of 18 cross combinations, LE-62 × Pant T-3 exhibited a significantly negative specific combining ability (SCA) effect (-2.167) for days to 50% flowering, indicating potential earliness. Conversely, LE-62 × Pusa Gaurav showed

a significant positive SCA effect (1.833), suggesting delayed flowering. These insights assist breeders in selecting specific parental combinations to achieve desired flowering traits in tomato breeding programs.

Number of flowers per cluster

Significant and positive *sca* effects for this trait was noticed in four crosses which ranged from 0.312 (EC-165749 × Punjab Chhuhara) to 0.784 (LE-62 × Pant T-3) and considered to be good specific combiners for number of flowers per cluster. However significant negative *sca* effects were exhibited by three crosses ranging from -0.621 in LE-62 × Pusa Gaurav to -0.447 in LE-67 × Pant T-3.

Number of fruits per cluster

Among the crosses, significant positive *sca* effects, which indicates good specific combining ability for number of fruits per cluster were observed in five crosses and the top three specific cross combinations with highly significant *sca* effects were LE-67 × Pant T-3, LE-67 × Pusa Gaurav and LE-65 × Pusa Gaurav with the *sca* effects of 0.575, 0.468 and 0.431 respectively. However, five crosses recorded significant negative *sca* effects for number of fruits per cluster, ranging from -0.600 (LE-67 × Pant T-3) to -0.355 (LE-56 × Pusa Gaurav).

Fruit length (cm)

In the assessment of fruit length across 18 tomato cross combinations, nine crosses showed significance. Four of these exhibited positive specific combining ability (SCA) effects, ranging from 0.382 to 0.536, making them effective specific combiners for increasing fruit length. However, five crosses displayed significant negative SCA effects, ranging from -0.476 to -0.328, indicating limited effectiveness in improving fruit length.

Fruit width (cm)

Significant and positive *sca* effects for this trait was noticed in five crosses which ranged from 0.274 (LE-65 × Punjab Chhuhara) to 0.534 (LE-67 × Pant T-3). Top three significant and positive *sca* effects 0.534, 0.409 and 0.394 were recorded in cross combinations of LE-67 × Pant T-3, LE-64 × Pusa Gaurav and LE-56 × Pant T-3, respectively. However, significant and negative *sca* effects were exhibited by five crosses ranging from -0.586 (LE-67 × Pusa Gaurav) to -0.307 (LE-62 × Punjab Chhuhara).

Average fruit weight (g)

Positive *sca* effects were desirable for average fruit weight. Among the crosses, significant positive *sca* effects were recorded in seven crosses ranging from 6.409 (EC-165749 × Punjab Chhuhara) to 18.481(LE-64 × Pusa Gaurav). Five superior crosses for average fruit weight were LE-64 × Pusa Gaurav (18.481), LE-56 × Pant T-3 (15.608), LE-67 × Pant T-3 (10.143), LE-64 × Pusa Gaurav (10.142) and LE-67 × Punjab Chhuhara (8.974).

Fruit yield per plant (kg)

Among the crosses significant and positive *sca* effects which indicates good specific combining ability for fruit yield were observed in five crosses and the best specific cross combinations with highly significant positive *sca* effects (Fig. 4) were LE-64 × Pusa Gaurav (0.373), LE-62 × Pant T-3 (0.349), LE-56 × Pant T-3 (0.257), LE-65 × Pusa Gaurav (0.245) and LE-67 × Pant T-3 (0.188). However, four crosses recorded significantly negative *sca* effects for fruit yield ranged from -0.556 (LE-64 × Pant T-3) to -0.326 (LE-56 × Punjab Chhuhara) and thus considered to be poor specific cross combinations for fruit yield per plant.

The assessment of general combining ability (GCA) is crucial in identifying suitable parents for hybridization in tomato breeding. The study observed significant variations in the GCA of nine parents across various growth, earliness, and yield-related traits. High GCA effects indicate potential as parents for desired traits, aiding in the selection of outstanding individuals with favorable alleles for yield components. This information is valuable for optimizing hybridization programs and enhancing specific traits in tomato crops.

The study underscores that parents exhibiting high general combining ability (GCA) effects for fruit yield per plant likely possess favorable traits contributing to yield. This finding aligns with previous research by Shankar (2010) [5]. The superior general combiners, specifically LE-56 and Punjab Chhuhara, are recommended for breeding programs to introduce genetic variability for effective selection. LE-56, in particular, stands out as a superior general combiner for various traits, including days to 50% flowering, number of flowers per cluster, number of fruits per cluster, and fruit length. Punjab Chhuhara, another identified superior general combiner, excels in traits like number of fruits per cluster, fruit length, and average fruit weight. These parent varieties can serve as valuable contributors in commercial breeding programs for improved yield and quality.

Specific combining ability (SCA) aids in identifying superior cross combinations (specific combiners) for exploiting commercial heterosis. In the current investigation, parents of different cross combinations exhibited critical trends in their general combining ability (GCA) effects for various traits. Notably, for fruit yield per plant, the top five crosses with significantly positive SCA effects involved different combinations of low x low general combining parents. The third-ranking cross, LE-56 × Pant T-3, stood out by involving high x low general combining parents. Similar patterns were observed for other studied traits, where the most successful crosses featured combinations of high x high, high x low, and low x low general combiners as parents. These findings highlight the importance of specific combiner selection for achieving desirable traits in commercial breeding programs.

Overall, the most successful cross combinations included high × high, high × low, and low × low general combiners for different traits studied. This indicates that favorable cross combinations do not always originate from strong general combiners. Therefore, high general combining ability (GCA) effects of parents may not reliably predict high specific combining ability (SCA) effects. The superior performance of these crosses may be attributed to additive × additive (high × high), additive × dominance (high × low), or dominance × dominance (low × low) epistatic interactions. These findings align with studies by Pandey *et al.* (2006) [6] and Hannan *et al.* (2007a) [7] but differ from Premalakshmi *et al.* (2005) [8], who observed good specific combiners from low × low general combiners. The excellence of cross combinations involving high × low or low × low general combiners may be linked to the genetic diversity in terms of the number of heterozygous loci in the parents, as highlighted by Gaikwad *et al.* (2002) [9].

The analysis comparing estimates of heterosis in crosses and

general combining ability (GCA) effects of parents showed that high heterosis in the desired direction was associated with crosses involving high × high general combiners for fruit length and fruit width, high × low general combiners for days to 50% flowering, number of flowers per cluster, average fruit weight, fruit yield per plant, and low × low general combiners for the number of fruits. These findings are at variance with the findings of Shankar (2010) [5], who found promising hybrids resulting from high x medium combinations.

In conclusion, the study highlights that the superior general and specific combiners identified can be valuable resources in breeding programs to enhance genetic variability for desired traits. It underscores the notion that high General Combining Ability (GCA) effects may not consistently predict high Specific Combining Ability (SCA) effects, emphasizing the role of various genetic interactions in determining cross performance.

Table 1: Analysis of variance for combining ability for different characters in Tomato.

Source	df	Mean Sum of Squares						
		Days to 50% flowering	No. of flowers/ cluster	No. of fruits/ cluster	Fruit length (cm)	Fruit width (cm)	Average fruit weight (g)	Fruit yield/ plant (kg)
Replications	2	1.5926	0.1194	0.1384	0.1390	0.0195	5.3625	0.0673
Treatments	26	9.7778**	0.7292**	0.8214**	0.8925**	0.5710**	512.7922**	0.6108**
Parents	8	8.2500**	0.8328**	0.2726**	0.5947**	0.1119**	141.4461**	0.1212**
Parents (Line)	5	11.7889**	1.2064**	0.2470*	0.7006**	0.1317**	38.6058	0.1097**
Parents (Testers)	2	1.4444	0.2693*	0.4699**	0.4287**	0.0988	225.1284**	0.0917*
Parents (L vs T)	1	4.1667	0.0913	0.0060	0.3970*	0.0384	488.2827**	0.2373**
Parents vs Crosses	1	22.2222**	2.1494**	1.6826**	2.6170**	4.4667**	3738.9147**	5.6485**
Crosses	17	9.7647**	0.5970**	1.0290**	0.9312**	0.5578**	497.7713**	0.5449**
Line Effect	5	17.9111	0.2817	1.6474	0.6321	0.7397	330.8525	0.7466
Tester Effect	2	7.1667	1.1728	1.4322	3.3166*	0.2850	186.7713	0.7269
Line * Tester Eff.	10	6.2111**	0.6394**	0.6391**	0.6037**	0.5215**	643.4308**	0.4076**
Error	52	2.2977	0.0606	0.0816	0.0564	0.0328	23.0987	0.0254
Total	80	4.7111	0.2794	0.3235	0.3302	0.2073	181.8057	0.2167

* Significant at 5% level
** Significant at 1% level

Table 2: Analysis of variance for combining ability for different characters in Tomato

S. No.	Character	σ^2 *GCA*	σ^2 *SCA*	σ^2*GCA*/ σ^2*SCA*
1	Days to 50% flowering	0.7586	1.3045	0.5815
2	No. of flowers / cluster	0.0494	0.1930	0.2559
3	No. of fruits / cluster	0.1080	0.1858	0.5812
4	Fruit length (cm)	0.1421	0.1824	0.7788
5	Fruit width (cm)	0.0355	0.1629	0.2181
6	Avg. fruit wt. (g)	17.4602	206.7774	0.0844
7	Fruit yield per plant (kg)	0.0527	0.1274	0.4136

Table 3: Estimates of general combining ability (*gca*) effects of parents for different characters in tomato

	Days to 50% flowering	No. of flowers/ cluster	No. of fruits/ cluster	Fruit length (cm)	Fruit width (cm)	Average fruit weight (g)	Fruit yield/ plant (kg)
Lines							
EC - 165749	0.222	-0.033	-0.658**	-0.106	0.172**	3.014	-0.186**
LE - 56	-2.111**	0.336**	0.568**	0.255**	0.011	-0.079	0.549**
LE - 62	0.222	-0.168*	0.149	-0.276**	-0.317**	3.123	-0.153**
LE - 64	-0.667	0.029	0.063	0.397**	-0.381**	4.266*	0.072
LE - 65	2.222**	-0.067	-0.312**	-0.084	0.225**	-11.998**	-0.070
LE - 67	0.111	-0.097	0.191	-0.184*	0.291**	1.675	-0.212**
$SE_{(i)}$	0.505	0.082	0.095	0.079	0.060	1.602	0.053
SE (i-j)	0.715	0.116	0.135	0.112	0.085	0.266	0.075
Testers							
Punjab Chhuhara	0.444	-0.027	0.179*	0.489**	0.014	3.457**	0.230**
Pant T - 3	0.278	0.268**	-0.325**	-0.175**	-0.132**	-0.539	-0.144**
Pusa Gaurav	-0.722	-0.241**	0.146*	-0.314**	0.119**	-2.918*	-0.086*
$SE_{(i)}$	0.357	0.058	0.067	0.056	0.043	1.133	0.038
SE (i-j)	0.505	0.082	0.095	0.079	0.060	1.602	0.053

* Significant at 5% level
** Significant at 1% level

Table 4: Estimates of specific combining ability (*sca*) effects of hybrids for different characters in tomato

Crosses	Days to 50% flowering	No. of flowers/ cluster	No. of fruits/ cluster	Fruit length (cm)	Fruit width (cm)	Average fruit weight (g)	Fruit yield/ plant (kg)
EC -165749 × Punjab Chhuhara	0.000	0.312*	0.365*	-0.462**	0.008	6.409*	-0.097
EC -165749 × Pant T-3	1.500	-0.450**	0.002	0.185	-0.077	-3.089	0.116
EC -165749 × Pusa Gaurav	-1.500	0.138	-0.366*	0.278	0.069	-3.320	-0.019
LE-56 × Punjab Chhuhara	1.000	0.086	0.002	0.536**	-0.031	-2.081	-0.326**
LE-56 × Pant T-3	-1.167	-0.026	0.353*	-0.406**	0.394**	15.608**	0.257**
LE-56 × Pusa Gaurav	0.167	-0.061	-0.355*	-0.130	-0.363**	-13.527**	0.069
LE-62 × Punjab Chhuhara	0.333	-0.164	-0.362*	0.241	-0.307**	3.927	0.169
LE-62 × Pant T-3	-2.167*	0.784**	0.575**	-0.265	-0.028	-11.268**	0.349**
LE-62 × Pusa Gaurav	1.833*	-0.621**	-0.213	0.024	0.335**	7.341*	-0.519**
LE-64 × Punjab Chhuhara	0.222	-0.217	-0.203	0.428**	0.004	-18.313**	0.184
LE-64 × Pant T-3	0.389	0.254	0.167	0.048	-0.414**	-0.168	-0.556**
LE-64 × Pusa Gaurav	-0.611	-0.037	0.036	-0.476**	0.409**	18.481**	0.373**
LE-65 × Punjab Chhuhara	0.000	-0.342	0.066	-0.415**	0.274*	1.084	0.109
LE-65 × Pant T-3	-0.167	-0.117	-0.497**	0.493**	-0.410**	-11.227**	-0.354**
LE-65 × Pusa Gaurav	0.167	0.458**	0.431*	-0.078	0.136	10.142**	0.245*
LE-67 × Punjab Chhuhara	-1.556	0.325*	0.132	-0.328*	0.052	8.974**	-0.039
LE-67 × Pant T-3	1.611	-0.447**	-0.600**	-0.054	0.534**	10.143**	0.188*
LE-67 × Pusa Gaurav	-0.056	0.122	0.468**	0.382**	-0.586**	-19.118**	-0.150
SE(i)	0.875	0.142	0.165	0.137	0.105	2.775	0.092
SE(ij-kl)	1.238	0.201	0.233	0.194	0.148	3.924	0.130
SE (ij-ik)	1.891	0.307	0.356	0.296	0.226	5.994	0.199

* Significant at 5% level
** Significant at 1% level

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