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Studies of combining ability in tomato (*Solanum lycopersicum* L.) for vegetative growth, yield and quality traits

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Abstract
The present investigation was undertaken to study the combining ability of parents and crosses for fruit yield and quality components in tomato using 45 hybrids involving 10 parents in half diallel fashion. Forty-five crosses along with ten parents were evaluated in randomized block design with three replications at research farm, Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, during Rabi season of 2015-16, 2016-17 and 2017-18.

Analysis of variance for combining ability and the estimates of variance components indicated that the mean squares due to parents were significant for all characters which revealed significant contribution of parents towards general combining ability variance components for most of traits. The mean sums of squares were significant for all traits indicating the significant contribution of hybrids for specific combining ability variance components. This indicated the involvement of additive as well as non-additive type of gene actions in the inheritance of these traits.

The best general combiners for various traits were BT-507-2-2 for plant height, branches plant^{-1}, flowers cluster^{-1}, fruits cluster^{-1}, yield plant^{-1}, yield plot^{-1}. Similarly, BT-22-4-1 for number of cluster plant^{-1}, fruits plant^{-1}, diameter of fruit, average fruit weight. Utkal Deepti for days to 1st flowering, TLCV incidence while BT-317 for days to 50% flowering, acidity content; BT-21 for fruit length; BT-19-1-1-1 for pericarp thickness; BT-1 for number of locules fruit^{-1}, total soluble solid content, ascorbic acid content and BT-17-2 for bacterial wilt incidence.

Best cross combinations *viz*., Utkal Kumari x BT-22-4-1, BT-19-1-1-1 x BT-3, Utkal Kumari x BT-19-1-1-1, BT-22-4-1 x BT-3 and BT-19-1-1-1 x BT-507-2-2 were found to be best specific combiners for yield plant^{-1}.

Keywords: General combining ability, specific combining ability, gene action, tomato

Introduction
Tomato (*Solanum lycopersicum* L.) a member of *Solanaceae* family, is the most widely grown vegetable throughout the World because of its wider adaptability, high yielding potential and suitability for variety of uses in fresh as well as processed food industries. Tomato in large quantities is used to produce soup, juice, ketchup, puree, paste and powder; it supplies ascorbic acid and adds variety of colours and flavors to the food. It has commercial value in the extraction of tomatine, a steroidal hormone, which is used as a substitute of diosgenin [1, 2]. Its increasing consumption makes it a high value crop for generating income to the farmers.

Tomato can be exploited for hybrid seed production because of its easy crossing and growing under varied climatic conditions, fruit containing large number of seeds and possessing high degree of heterosis for growth, yield and earliness. The choice of parents for hybridization needs to be based upon complete genetic information, the knowledge of heterosis and their combinations for the improvement of characters under consideration. Exploitation of hybrid vigour is one of the important means, by which, the crop yield can be increased.

All fruit quality attributes were expressions of genotypic and environmental effect of interactions. Hence quality attributes have to be considered together for future genetic improvement of tomato quality. Total soluble solids (TSS) and ascorbic acid content have been recognized as the most desirable attributes in tomato for processing industry. The increase of 1% TSS in fruits results to increase 20% recovery of processed products [3]. High ascorbic acid content in addition to improving the nutrition also helps in the better retention of natural colour and flavour of the tomato products. The red pigment in tomato (lycopene) is now being considered as the “world’s most powerful natural antioxidant” [4]. Therefore, tomato is one of the most important ‘protective foods’ because of its special nutritive value.

The shelf life is an important quality trait for marketing, transportation and domestic use. This trait is controlled by genetic factors as well as environmental factors such as temperature. Characters like whole fruit firmness, number of locules per fruit and pericarp thickness are the important parameters contributing towards shelf life besides biochemical changes [5]. However, pericarp thickness alone accounts for 64% of fruit firmness [6]. Hence, development of firm tomato is the basic need for longer shelf life. However, the average national productivity is very low (19.5 tonnes/ ha as compared to other countries like USA (81 t/ha), Spain (74 t/ha) and Brazil (60.7 t/ha) [7].

This indicates that there is a need to increase the productivity of this crop by developing high yielding varieties through appropriate breeding work to meet the demand of domestic and export markets. The ultimate objective in any crop improvement programme is to identify the best parent(s) and hybrid(s). Combining ability analysis is a common biometrical tool used in the breeding programme for testing the performance of lines in hybrid combinations and also for characterizing the nature and magnitude of gene action involved in the expression of traits. In view of the above facts, the efforts were made to develop F_1 hybrids for high yield, qualitative and quantitative traits.

Materials and Methods

The present investigation was conducted during *Rabi* season of 2015-16 (crossing), 2016-17 and 2017-18 (Evaluation of F_1) at Vegetable Research Farm, Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture & Technology, Bhubaneswar, Odisha, India. Ten genetically diverse lines (Utkal Pallavi, Utkal Deepti, Utkal Kumari, BT-19-1-1-1, BT-317, BT-22-4-1, BT-3, BT-17-2, BT-507-2-2 and BT-21) were crossed in half diallel mating design. The resultant 45 F_1s were evaluated along with their parents in randomized block design which was replicated thrice. Each entry was grown in one plot with 18 plants in each by adopting inter row spacing of 60 cm and intra row spacing of 45 cm.

The observations were recorded on five randomly selected plants for *viz*., plant height (cm), number of branches plant^{-1}, days to first flowering, days to 50% flowering, number of flowers cluster^{-1}, number of clusters plant^{-1}, number of fruits cluster^{-1}, number of fruits plant^{-1}, length of fruit (cm), diameter of fruit (cm), average fruit weight (g), pericarp thickness (mm), number of locules fruit^{-1}, total soluble solids (^{0}Brix), ascorbic acid content (mg/100g), acidity content (%), yield plant^{-1}, total yield plot^{-1}, TLCV affected plants plot^{-1} and bacterial wilt affected plants plot^{-1}. Data collected during the two years for above characters were pooled and analysis of variance and combining ability analysis were done.

Results and Discussion

The pooled results obtained in the present study pertaining to combining ability, gene action and ANOVA for yield and quality characters are discussed here under. Analysis of variance for combining ability (Table 1) showed significant GCA and SCA effects for all the characters under study. Environmental effects were found to be highly significant for all the characters except fruit length, diameter of fruit, pericarp thickness, TSS, fruit acidity content, TLCV incidence and wilt incidence. The interactions of GCA with environment were significant in case of the characters branches plant^{-1}, days to first flowering, days to 50% flowering, fruits plant^{-1}, fruit length, fruit diameter, pericarp thickness and total yield plot^{-1}. The interactions of SCA with environment were significant in case of the characters branches plant^{-1}, days to first flowering, days to 50% flowering, number of flowers cluster^{-1}, number of fruits cluster^{-1}, fruits plant^{-1}, fruit length, fruit diameter, pericarp thickness and number of locules fruit^{-1}.

Table 1 also shows the estimates for σ^2gca and σ^2sca which were further used in deriving predictability factor 2 σ^2gca/(2 σ^2gca+σ^2sca) following Baker (1978). Predictability factor close to 1.0 suggests that transmission of characters could be predicted primarily on the basis of GCA or additive gene effects; values close to 0.5 indicate equal importance of both additive and non-additive gene effects in the inheritance of characters, while values lower than 0.5 suggest preponderance of non-additive gene effect.

From Table Predictability factor, it is evident that in the characters plant height, number of cluster plant^{-1} and fruit weight transmission of characters can be predicted on the basis of additive gene effects. In case of number of fruits cluster^{-1}, fruit yield plant^{-1} and fruit yield plot^{-1}, both additive and non-additive gene effects are equally important while in characters like fruit length, pericarp thickness, number of locules fruit^{-1}, TSS, ascorbic acid content, acidity content and TLCV incidence, there was preponderance of non-additive gene effects. The results of the present studies are in accordance with the earlier workers Kumari and Sharma (2012) [21], Kumari *et al*. (2013) [25], Shankar *et al*. (2014) [34], Shankar (2014) [34], Biswas *et al*. (2016) [13] and Amin *et al*. (2018) [8].

Plant height (cm)

Among all the parents, significant positive GCA effects were exhibited by BT-507-2-2 (7.289), BT-19-1-1-1 (7.184), BT-22-4-1 (6.245) and BT-3 (2.287) indicating their good general combining ability. The estimates of specific combining ability effects for plant height revealed that eight hybrid combinations *viz.*, 2x4 (9.261), 6x10 (6.823), 8x9 (5.174), 2x6 (5.035), 2x7 (4.358), 1x10 (4.166), 1x9 (3.787) and 6x8 (3.525) exhibited significant positive values, which indicated their good specific combining ability. Similar findings were also obtained by C. Indu Rani and D. Veeraragavathatham (2011) [14], Izge and Garba (2012) [20], EI-Garby *et al*. (2014), Pujer *et al*. (2014) [29], Singh *et al*. (2014) [36] and Zengin *et al*. (2015) [40].

Branches per plant

For this trait, four parents *viz.*, BT-507-2-2 (17.549), BT-22-4-1 (16.822), BT-19-1-1-1 (12.140) and Utkal Kumari (3.015) revealed significant positive GCA effects indicating their good general combining ability. The SCA effects revealed that 16 hybrid combinations exhibited significant positive values, which indicated that these crosses were good specific combiners. Among the crosses, 6x7 (18.742), 4x7 (14.923), 4x9 (13.828), 3x6 (13.680) and 6x9 (12.646) were the top five combinations. Similar results have also been found in their studies by Prabuddha *et al*. (2008) [28], Saidi *et al*. (2008) [32], Singh *et al*. (2008) [37], EI-Gabry *et al*. (2014) [17], Vilas *et al*. (2015b) [39] and Amin *et al*. (2018) [8].

Days to first flowering

Among all the parents, BT-317 (-2.494), Utkal Deepti (-0.394), BT-3 (-0.215) and BT-22-4-1 (-0.213) were good general combiners as these exhibited significant negative GCA effects. Among the total forty-five cross combinations, twenty eight crosses exhibited negative SCA effects indicating their good specific combining ability out of which three were significant 2x9 (-3.849), 1x2 (-3.649) and 6x9 (-3.131). Similar results have been reported by Singh *et al*. (2008) [37], Kumari *et al*. (2010) [21] and Zengin *et al*. (2015) [40].

Table 1: Pooled analysis of variance for combining ability of 20 characters of tomato in a 10 x 10 half diallel set of F_1s and parents over two years

Source	Df	Mean sum of squares																			
		Plant height (cm)	Branches/ plant	Days to first flowering	Days to 50% flowering	No. of flowers/ cluster	No. of cluster/ plant	No. of fruits/ cluster	No. of fruits/ plant	Fruit length (cm)	Fruit diameter (cm)	Fruit weight (g)	Pericarp thickness (mm)	No. of locules/ fruit	TSS (^{0}Brix)	Ascorbic acid content (mg/100g)	Acidity content (%)	Yield/ plant (kg)	Total yield / plot (kg)	TLCV incidence (%)	Bacterial wilt incidence (%)
GCA	9	786.31**	3550.84**	28.79**	29.30**	376.58**	46.48**	365.43**	469.96**	41.23**	26.87**	3354.76**	132.12**	32.41**	120.78**	182.06**	7.30**	410.69**	134.33**	59.44**	172.50**
SCA	45	33.42**	190.27**	11.13**	14.60**	52.79**	2.06**	63.60**	45.97**	23.14**	6.58*	112.31**	80.56**	21.00**	85.97**	175.70**	5.13**	49.72**	24.08**	39.70**	31.09*
Envi.	1	55.83**	7497.60**	282.72**	194.31**	8032.73**	405.89**	8273.78**	16357.15**	21.38	1.18	52.20*	4.40	438.60**	0.34	1.66*	0.27	30.85**	25.05**	27.50	3.64
GCA x Env.	9	11.19	53.20**	27.28**	50.81**	6.04	0.23	4.16	54.96**	26.33**	8.45*	9.37	29.39*	8.40	0.07	0.33	0.02	0.68	2.01**	1.57	5.28
SCA x Env.	45	5.19	36.06**	16.42**	24.90**	17.60*	0.13	21.27**	16.13*	18.64**	8.25**	4.00	20.20*	17.95**	0.18	0.28	0.02	0.50	0.78	2.69	6.09
Pooled error	108	7.32	18.54	4.33	5.76	11.49	0.95	11.63	9.27	8.33	4.25	8.45	12.29	6.67	1.05	0.38	0.27	1.00	0.59	9.93	19.12
V GCA		32.46	147.18	1.02	0.98	15.21	1.90	14.74	19.20	1.37	0.94	139.43	4.99	1.07	4.99	7.57	0.29	17.07	5.57	2.06	6.39
V SCA		13.05	85.87	3.40	4.42	20.65	0.56	25.98	18.35	7.41	1.16	51.93	34.14	7.17	42.46	87.66	2.43	24.36	11.74	14.88	5.98
Predictability factor		0.83	0.77	0.38	0.31	0.60	0.87	0.53	0.68	0.27	0.62	0.84	0.23	0.23	0.19	0.15	0.19	0.58	0.49	0.22	0.68

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

Table 2: General combining ability effects for twenty characters of parents in 10x10 half diallel set of crosses in tomato

Parents	Plant height (cm)	Branches/ plant	Days to 1st flowering	Days to 50% flowering	No. of flowers/ cluster	No. of cluster/ plant	No. of fruits/ cluster	No. of fruits/ plant	Fruit length (cm)	Fruit diameter (cm)	Average fruit weight (g)	Pericarp thickness (mm)	No. of locules/ fruit	TSS (^{0}Brix)	Ascorbic acid content (mg/100g)	Acidity content (%)	Yield/ plant (kg)	Total yield / plot (kg)	TLCV incidence (%)	Bacterial wilt incidence (%)
Utkal Pallavi	-0.741	-8.047**	0.275	0.147	-1.483*	-0.287	-1.104	-1.408*	-0.244	-1.078**	-6.241**	0.075	-1.411**	4.896**	3.796**	-1.262**	-2.345**	-1.088**	-0.042	1.750*
Utkal Deepti	-6.065**	-15.797**	-0.394*	-0.778	3.442**	-1.433**	-3.354**	-3.828**	-1.448*	0.189	-12.030**	-0.967	-0.522	0.555**	0.317**	-0.193	-4.033**	-2.838**	-1.917**	0.708
Utkal Kumari	0.007	3.015**	-0.023	-0.015	-0.754	0.215	-1.000	-1.359*	-1.967**	-0.995*	0.313	0.013	-0.286	-1.341**	3.604**	-0.037	-0.103	0.373*	-1.917**	0.292
BT-19-1-1-1	7.184**	12.140**	1.767**	1.605**	4.621**	1.478**	3.896**	3.028**	-0.117	-0.147	5.530**	4.138**	1.089*	-2.641**	1.029**	0.068	3.326**	1.824**	3.083**	1.542
BT-317	-2.212**	-6.672**	-2.494**	-2.303**	-3.150**	-0.764**	-3.042**	-3.467**	-0.196	0.641	-7.362**	1.471*	-1.063*	2.048**	0.325**	0.861**	-2.735**	-1.120**	0.792	3.833**
BT-22-4-1	6.245**	16.822**	-0.213*	0.001	5.413**	2.007**	5.667**	7.344**	0.204	1.553**	20.092**	2.804**	0.193	0.903**	-4.446**	0.551**	6.134**	3.069**	1.417*	2.792**
BT-3	2.287**	1.453	-0.215*	-0.003	0.163	0.228	0.083	0.184	0.181	-1.401**	0.154	0.388	1.818**	-2.006**	0.554**	0.134	1.445**	0.591**	0.792	-1.167
BT-17-2	-5.297**	-7.599**	0.119	-0.305	-1.983**	-0.993**	-1.917**	-3.489**	-0.625	0.866*	-9.220**	-2.133**	0.005	-1.712**	-1.575**	0.088	-3.860**	-2.160**	-0.250	-4.500**
BT-507-2-2	7.289**	17.549**	1.050*	1.541**	5.871**	1.688**	6.000**	7.240**	2.243**	1.249**	19.587**	-2.967**	1.526**	-0.235	0.496**	-0.172	6.411**	3.920**	-0.667	-3.250**
BT-21	-8.696**	-12.864**	0.127	0.110	-5.254**	-2.137**	-5.229**	-4.243**	1.970**	-0.878*	-10.823**	-2.821**	-1.349**	-0.466*	-4.100**	-0.039	-4.241**	-2.572**	-1.292*	-2.000*
SE(g_i) ±	0.524	0.834	0.403	0.465	0.656	0.189	0.660	0.590	0.559	0.399	0.563	0.679	0.500	0.199	0.119	0.101	0.194	0.149	0.610	0.847
CD (0.05)	1.550	2.487	1.200	1.380	1.957	0.560	1.953	1.680	1.661	1.197	1.675	2.030	1.478	0.579	0.345	0.300	0.575	0.447	1.760	2.522

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

GCA and SCA effects

The pooled GCA and SCA effects are presented in Table 2 and Table 3 respectively.

Table 3: Overall Specific combining ability effects for 20 characters of tomato in a 10x10 half diallel set in the F_1 over two years

Hybrids	Plant Height (cm)	Branches/plant	Days to 1st flowering	Days to 50% flowering	No. of flowers/cluster	No. of cluster/ plant	No. of fruits/cluster	No. of fruits/plant	Fruit length (cm)	Fruit diameter (cm)
1x2	3.403	5.111	-3.649**	-3.904*	5.398*	1.645*	4.958*	0.220	-2.967	-2.432
1x3	-2.674	-2.952	-0.270	-2.292	-4.790*	0.398	-4.396	-0.948	3.602	0.526
1x4	-0.278	-5.327	0.190	0.063	1.835	-0.665	3.458	-0.160	4.102*	-2.097
1x5	-1.798	1.986	-0.999	-1.704	-1.394	0.127	-1.354	4.135*	-0.869	1.916
1x6	-0.717	-8.008**	-0.081	0.092	1.044	-1.494*	2.188	-1.402	2.706	2.453
1x7	1.034	-9.389**	-1.154	-1.679	1.544	-0.315	1.771	-1.141	-5.396**	1.057
1x8	1.180	-7.337*	5.513**	5.098**	-0.061	-0.144	0.021	2.757	-1.490	0.191
1x9	3.787*	10.015**	1.307	2.102	4.835*	0.800	4.604*	2.352	2.866	-3.293*
1x10	4.166*	7.678**	1.680	2.433	4.170*	-0.050	4.333	5.336**	0.639	1.659
2x3	0.918	4.298	-0.402	-1.167	-1.331	-0.307	-1.146	-2.041	4.081*	0.334
2x4	9.261**	2.923	2.909*	2.688	-0.206	-0.119	1.208	-3.365	0.631	-0.813
2x5	0.224	-6.514*	1.369	-0.129	7.314**	0.998	7.396**	1.829	1.960	0.824
2x6	5.035**	-5.258	-2.512	-2.983	3.002	-0.848	3.688	0.818	2.660	1.137
2x7	4.358*	6.361*	0.090	1.071	4.002	-0.369	3.771	1.528	-1.267	-0.684
2x8	-1.990	12.413**	3.182*	3.198*	1.898	1.377*	1.271	7.301**	-1.136	-0.326
2x9	2.299	-4.235	-3.849**	-4.073*	-2.456	0.145	-2.646	-0.875	-3.230	1.816
2x10	-4.919**	-3.822	2.323	2.708	0.669	-0.455	-0.417	9.755**	1.043	1.393
3x4	3.192	9.111**	-2.462	-2.750	4.606*	0.233	6.354**	8.541**	-2.575	0.520
3x5	-0.098	-0.327	3.898**	3.383*	2.377	-0.625	2.292	-3.139	1.529	-1.068
3x6	1.613	13.680**	-1.558	-2.096	5.564*	0.654	6.833**	5.675**	-0.221	-0.230
3x7	-1.701	-10.202**	-1.806	0.208	-3.686	-0.167	-3.333	-2.740	0.552	-0.026
3x8	1.205	-3.649	-0.764	1.385	4.210	-0.496	4.667*	-1.717	1.408	0.457
3x9	0.992	10.953**	1.830	4.415**	4.856*	0.823	6.250**	5.553**	2.889	2.199
3x10	1.931	0.615	-1.372	-2.679	-1.269	0.898	-1.021	-0.488	-4.213*	-0.849
4x5	2.425	0.048	-1.366	-0.338	-3.248	-0.413	-2.854	2.249	2.579	-0.391
4x6	-0.291	11.555**	-1.522	-2.117	4.939*	0.941	4.438*	2.613	-4.321*	0.747
4x7	2.664	14.923**	-1.745	-1.288	4.939*	0.545	5.771*	7.473**	-1.023	1.876
4x8	-3.122	-2.524	-2.629	-3.360*	0.585	1.166	1.271	-3.604	-1.017	-1.966
4x9	0.665	13.828**	4.440**	3.494*	5.981**	0.110	4.604*	4.867*	1.314	2.101
4x10	-3.970*	-3.010	-2.162	-1.750	-5.894**	-0.140	-5.167*	-3.772	0.712	0.878
5x6	1.284	-2.313	0.188	0.867	-3.540	-0.992	-3.625	-0.117	-2.492	3.334*
5x7	0.442	-1.014	-2.560	-3.804*	-2.540	-0.063	-2.292	-4.257*	2.956	-2.686*
5x8	-1.084	6.288*	-1.543	-2.327	4.356	-0.017	4.208	2.966	2.637	4.322**
5x9	3.240	6.640*	-0.499	-0.373	4.252	0.852	4.792*	4.112*	1.168	-0.961
5x10	2.932	6.303*	-1.177	0.683	3.377	1.327*	3.271	-0.005	-2.284	-1.634
6x7	0.896	18.742**	0.059	-0.958	6.898**	1.616*	7.250**	4.482*	2.156	0.401
6x8	3.525*	1.919	-2.074	-2.431	1.544	-0.738	2.250	1.305	3.462	-1.591
6x9	-1.526	12.646**	-3.131*	-2.852	2.939	2.781**	4.083	3.600	4.043*	1.426
6x10	6.823**	-0.391	1.867	1.504	-3.686	-0.344	-3.438	-4.816*	2.291	0.078
7x8	2.600	6.913*	0.678	1.373	0.294	0.766	-0.417	-0.835	6.835**	0.814
7x9	-1.020	-9.735**	-0.104	0.927	-3.561	-0.590	-3.083	-6.689**	-3.284	0.205
7x10	0.384	-6.322*	-1.581	-2.342	2.814	0.285	2.396	6.744**	3.764*	-2.368
8x9	5.174**	-1.433	-1.362	-3.296*	0.085	-1.044	0.417	-2.341	-9.527**	-2.086
8x10	0.528	3.980	0.611	3.060	5.210*	1.606*	5.146*	3.992*	0.595	0.941
9x10	2.035	1.982	-0.545	-2.110	3.106	-2.275**	3.479	-4.637**	4.452*	-2.268
SE (S_{ij})±	1.579	2.514	1.215	1.401	1.979	0.569	1.991	1.778	1.685	1.203
CD (0.05)	4.576	7.512	3.634	4.160	5.904	1.694	5.933	5.310	4.987	3.589

Hybrids	Fruit weight (g)	Pericarp thickness (mm)	No. of locules/fruit	TSS (⁰Brix)	Ascorbic acid (mg/100g)	Acidity content (%)	Yield/plant (kg)	Yield/plot (kg)	TLCV Incidence (%)	Wilt Incidence (%)
1x2	6.192**	2.496	-1.993	7.159**	14.203**	-0.533	0.699	1.559**	-1.723	-3.277
1x3	-1.551	-4.483	-0.228	3.655**	-10.091**	-1.339**	-2.680**	-0.788	-1.723	2.140
1x4	-3.768*	-2.108	5.147**	-0.045	1.384**	-0.144	2.291**	-1.138*	-6.723**	3.390
1x5	0.374	5.559*	0.299	8.090**	11.738**	-2.037**	-1.374*	0.272	0.568	1.098
1x6	-2.804	-3.275	3.292	9.236**	1.509**	-1.102**	0.207	-0.439	-5.057*	-2.860
1x7	1.483	7.642**	3.417*	2.569**	4.709**	0.565	2.597**	0.399	8.068**	-6.402*
1x8	3.882*	5.163*	-5.020**	-5.475**	-1.112**	-0.064	-0.724	0.302	-3.390	-0.568
1x9	3.576	2.496	0.209	-3.052**	24.767**	-0.329	5.230**	4.858**	2.027	-1.818
1x10	3.260	-7.900**	2.584	4.180**	1.363**	0.313	0.732	1.648**	5.152*	-3.068
2x3	3.463	4.059	5.132**	2.346**	-10.862**	-1.333**	-1.143	0.945	0.152	-4.318
2x4	-1.899	-5.566*	-3.493*	-3.204**	-5.087**	-1.087**	-1.422*	-0.293	0.152	-5.568

2x5	0.738	6.100**	1.834	-1.043	4.417**	1.394**	0.288	1.300*	-2.557	2.140
2x6	-7.440**	-2.733	1.403	-3.448**	5.288**	0.079	0.245	0.839	1.818	3.182
2x7	2.722	5.684*	-0.472	1.611*	12.588**	0.246	2.934**	0.035	2.443	4.640
2x8	6.471**	-5.795*	-1.910	6.517**	-5.683**	0.492	4.488**	0.463	-1.515	0.473
2x9	-2.860	6.038**	4.820**	5.440**	13.797**	0.427	0.643	-0.052	1.402	-3.277
2x10	3.850*	-7.858**	-6.055**	-1.979**	4.492**	-1.181**	0.345	0.813	-0.473	0.473
3x4	8.828**	3.955	1.022	6.142**	29.676**	2.331**	6.774**	5.630**	5.152*	4.848
3x5	1.145	8.121**	1.924	2.002**	11.530**	0.363	-0.891	-0.542	-2.557	2.557
3x6	11.916**	-6.712**	1.417	3.198**	6.301**	0.848*	7.466**	4.642**	-3.182	3.598
3x7	-0.621	8.705**	0.042	4.107**	6.551**	0.740*	0.355	-1.987**	-2.557	-2.443
3x8	-3.947*	-3.775	-0.895	-5.387**	-9.770**	-1.139**	-1.966**	0.151	0.985	-1.610
3x9	12.871**	1.559	0.584	1.386*	-11.841**	-0.704*	6.113**	3.726**	-1.098	2.140
3x10	-1.444	-8.087**	-2.291	6.667**	-7.195**	-1.587**	-0.784	-1.274*	-0.473	-4.110
4x5	-0.222	8.996**	-5.451**	4.202**	-6.745**	-2.341**	-1.770**	0.083	-0.057	-1.193
4x6	9.724**	7.663**	-3.208	-2.602**	-9.524**	-1.456**	5.311**	3.539**	-0.682	-0.152
4x7	12.562**	-8.420**	0.167	-4.593**	-2.974**	0.436	7.401**	5.508**	-2.557	-6.193*
4x8	-5.789**	-11.400**	0.980	3.413**	-2.395**	0.481	-1.970**	-0.737	-6.515**	-2.860
4x9	12.054**	-7.066**	1.790	-4.364**	-6.916**	2.117**	6.459**	2.966**	11.402**	0.890
4x10	-2.711	-4.212	-1.166	4.967**	1.480**	3.409**	-2.264**	-1.592**	-0.473	-5.360
5x6	-1.283	-6.170**	3.945*	7.409**	0.730	1.100**	1.372*	0.380	4.110*	-2.443
5x7	3.904*	-10.754**	3.820*	-6.133**	-5.820**	1.092**	0.611	-0.072	-2.765	4.015
5x8	3.228	4.267	1.132	-4.877**	2.259**	2.813**	2.491**	1.281*	15.777**	-5.152
5x9	1.697	-7.900**	-6.389**	-0.754	-7.912**	1.098**	4.420**	4.782**	-3.807	-6.402*
5x10	3.579	-2.045	-2.014	-0.873	1.184**	0.740*	1.672*	1.307*	-3.182	2.348
6x7	14.801**	6.913**	-2.687	4.863**	4.901**	1.077**	6.743**	4.567**	-5.890**	-2.443
6x8	2.175	-6.066**	0.626	0.619	-6.920**	0.048	-1.103	1.553**	0.152	-4.110
6x9	3.243	0.267	2.105	4.292**	5.009**	-0.391	4.351**	1.748**	3.068	-5.360
6x10	-4.547*	3.121	1.230	0.273	2.405**	-0.925**	2.403**	0.866	-1.307	3.390
7x8	-0.263	-1.150	1.001	6.577**	6.030**	-1.010**	2.386**	1.201*	5.777**	-0.152
7x9	-10.504**	-0.816	-4.270*	4.325**	0.259	-1.700**	-5.284**	-0.744	-3.807	6.098*
7x10	-1.860	4.038	-4.395*	2.132**	-2.145**	-2.133**	-0.207	0.906	1.818	-0.152
8x9	-3.095	0.705	2.292	6.907**	-1.062**	2.096**	0.220	0.149	-2.765	6.932*
8x10	8.465**	6.809**	4.167*	12.638**	3.234**	2.013**	0.347	1.509**	-2.140	0.682
9x10	-1.247	5.142*	2.897	-5.839**	-1.037*	-3.077**	2.651**	1.124*	-1.723	-0.568
SE (S_{ij})±	1.697	2.047	1.507	0.599	0.360	0.305	0.585	0.449	1.840	2.553
CD (0.05)	5.022	6.014	4.499	1.751	1.080	0.887	1.705	1.336	5.463	7.632

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

Days to 50% flowering

Among all the parents, only one BT-317 (-2.303) exhibited significant negative GCA effects, hence designated as good general combiners. Amongst all cross combinations, five crosses *viz*., 2x9 (-4.073), 1x2 (-3.904), 5x7 (-3.804), 4x8 (-3.360) and 8x9 (-3.296) exhibited significant negative SCA effects indicating their good specific combining ability. Similar findings have also been observed in the studies conducted by Saidi *et al*. (2008) [32], Kumari *et al*. (2010) [21] and Vinay *et al*. (2012) [41].

Number of flowers per cluster

Data pertaining to estimates of GCA effects for number of flowers cluster^{-1} revealed that four parents *viz*., BT-507-2-2 (5.871), BT-22-4-1 (5.413), BT-19-1-1-1 (4.621) and Utkal Deepti (3.442) were found to good general combiners. Out of 45 hybrid combinations, 12 were found good specific cross combinations due to their significant positive SCA effects. The crosses, 2x5 (7.314), 6x7 (6.898), 4x9 (5.981), 3x6 (5.564), 1x2 (5.398), 8x10 (5.210), 4x6 (4.939) and 4x7 (4.939) were the top seven best combinations. Similar results were reported earlier by Izge and Garba (2012) [20] and EI-Gabry *et al*. (2014) [17].

Number of cluster per plant

Significant positive GCA effects among the parents were exhibited by BT-22-4-1 (2.007), BT-507-2-2 (1.688) and BT-19-1-1-1 (1.478) revealing their good general combining ability. The estimates of specific combining ability effects for number of clusters plant^{-1} revealed that six hybrid combinations 6x9 (2.781), 1x2 (1.645), 6x7 (1.616), 8x10 (1.606), 2x8 (1.377) and 5x10 (1.327) exhibited significant positive values depicting good specific crosses. These results find support from Kumari *et al*. (2010) [21], Souza *et al*. (2012) [38] and Vilas *et al*. (2015b) [39].

Number of fruits per cluster

Significant positive GCA effects among the parents were exhibited by BT-507-2-2 (6.000), BT-22-4-1 (5.667) and BT-19-1-1-1 (3.896) indicated their good general combining ability. Thirteen hybrids were observed as good specific combiners exhibiting significant positive SCA effects. The crosses 2x5 (7.396), 6x7 (7.250), 3x6 (6.833), 3x4 (6.354) and 3x9 (6.250) were the top five combinations. Similar results were also obtained by Prabuddha *et al*. (2008) [28], Souza *et al*. (2012) [38] and Pujer *et al*. (2014) [29].

Number of fruits per plant

For number of fruits plant^{-1}, the parents BT-22-4-1 (7.344), BT-507-2-2 (7.240) and BT-19-1-1-1 (3.028) exhibited significant positive GCA effects and qualified for the category of good general combiners. Out of the 45 cross combinations, thirteen were rated as good specific combiners due to their significant positive SCA effects. Top five cross combinations were 2x10 (9.755), 3x4 (8.541), 4x7 (7.473), 2x8 (7.301) and 7x10 (6.744). These results are in conformity with those of Izge and Garba (2012) [20], Souza *et al*. (2012) [38], EI-Gabry *et al*.

(2014) [17], Pujer *et al*. (2014) [29], Enang *et al*. (2015), Vilas *et al*. (2015b) [39] and Amin *et al*. (2018) [8].

Fruit length (cm)

Two parents namely BT-21 (1.970) and BT-507-2-2 (2.243) showed significant positive GCA effects for fruit length and were rated as good general combiners while Utkal Kumari (-1.967) and Utkal Deepti (-1.448) exhibited significant negative effects and hence were designated as poor general combiners. Among all the cross combinations, 28 hybrids exhibited positive effects with respect to fruit length, out of which six were significant i.e. 7x8 (6.835), 9x10 (4.452), 1x4 (4.102), 2x3 (4.081), 6x9 (4.043) and 7x10 (3.764) revealing good specific combinations. Similar results were reported earlier by Kumari *et al*. (2010) [21], Vinay *et al*. (2012) [41] and Souza *et al*. (2012) [38].

Fruit diameter (cm)

Out of all parents, three BT-22-4-1 (1.553), BT-507-2-2 (1.249) and BT-17-2 (0.866) exhibited positive significant effects revealing that those are good general combiners. Among all cross combinations, twenty six were found to have positive effects out of which two were significant *viz*., 5x8 (4.322) and 5x6 (3.334) and hence proved to be good specific combiners. These results find support from Vinay *et al*. (2012) [41] and Souza *et al*. (2012) [38].

Average fruit weight (g)

Data pertaining to estimates of GCA effects for average fruit weight revealed that three parents *viz*., BT-22-4-1 (20.092), BT-507-2-2 (19.587) and BT-19-1-1-1 (5.530) were found to be good general combiners as they exhibited the significant and positive GCA effects. Out of forty five hybrid combinations, thirteen were found to be good specific cross combinations due to their significant positive SCA effects. The crosses, 6x7 (14.801), 3x9 (12.871), 4x7 (12.562), 4x9 (12.054) and 3x6 (11.916) were the top five best combinations. These results find support from EI-Gabry *et al*. (2014) [17], Agarwal *et al*. (2014) [9], Kumar *et al*. (2015) [24], Zengin *et al*. (2015) [40], Dagade *et al*. (2015) [16] and Amin *et al*. (2018) [8].

Pericarp thickness (mm)

Significant positive GCA effects among the parents were exhibited by BT-19-1-1-1 (4.138), BT-22-4-1 (2.804) and BT-317 (1.471) indicated their good general combining abilities. The estimates of specific combining ability effects for pericarp thickness revealed that thirteen hybrid combinations exhibited significant positive values, which indicated that these crosses were good specific cross combiners. The top five cross combinations were 4x5 (8.996), 3x7 (8.705), 3x5 (8.121), 1x7 (7.642) and 4x6 (7.663). These results find support from Vinay *et al*. (2012) [41], Souza *et al*. (2012) [38], EI-Gabry *et al*. (2014) [17], Kumar *et al*. (2015) and Dagade *et al*. (2015) [16].

Number of locules per fruit

Among the parents, Utkal Pallavi (-1.411), BT-21 (-1.349) and BT-317 (-1.063) revealed significant negative GCA effects, indicating their good combining ability, whereas, seven crosses *viz*., 5x9 (-6.389), 2x10 (-6.055), 4x5 (-5.451), 1x8 (-5.020), 7x10 (-4.395), 7x9 (-4.270) and 2x4 (-3.493) exhibited significant negative SCA effects and indicated that these crosses were good specific cross combiners. Similar results have also been found in their studies by Souza *et al*. (2012) [38], EI-Gabry *et al*. (2014) [17], Kumar *et al*. (2015) [24] and Dagade *et al*. (2015) [16].

Total soluble solids (^{0}Brix)

The perusal of data for total soluble solids revealed that significant positive GCA effects among the parents were exhibited by Utkal Pallavi (4.896), BT-317 (2.048), BT-22-4-1 (0.903) and Utkal Deepti (0.555) depicting their good general combining ability. Further, out of 45 cross combinations, 26 exhibited significant positive values, which indicated that these were good specific cross combiners. The crosses, 8x10 (12.638), 1x6 (9.236), 1x5 (8.090), 5x6 (7.409) and 1x2 (7.159) were the top five cross combinations. Similar results were also obtained by EI-Gabry *et al*. (2014) [17], Pujer *et al*. (2014) [29], Mahmoud and EI-Eslamboly (2014) [26], Agarwal *et al*. (2014) [9] and Kumar *et al*. (2015) [24].

Ascorbic acid content (mg/100g)

Significant positive GCA effects among the parents were exhibited by Utkal Pallavi (3.796), Utkal Kumari (3.604), BT-19-1-1-1 (1.029), BT-3 (0.554), BT-507-2-2 (0.496), BT-317 (0.325) and Utkal Deepti (0.317), revealing their good general combining ability. The estimates of SCA effects for ascorbic acid content revealed that 24 hybrid combinations exhibited significant positive values indicating that these were good specific crosses. The top five cross combinations were 3x4 (29.676), 1x9 (24.767), 1x2 (14.203), 2x9 (13.797) and 2x7 (12.588). The studies get the support of EI-Gabry *et al*. (2014) [17], Pujer *et al*. (2014) [29] and Mahmoud and EI-Eslamboly (2014) [26].

Acidity content of fruit (%)

Two parents namely BT-317 (0.861) and BT-22-4-1 (0.551), were designated as good general combiners, due to their significant positive GCA effects. Further, 14 cross combinations exhibited significant positive SCA values, which indicated that these crosses have good specific combining abilities. The crosses, 4x10 (3.409), 5x8 (2.813), 3x4 (2.331), 4x9 (2.117) and 8x9 (2.096), were the top five combinations. These results find support from the studies of Souza *et al*. (2012) [38], Mahmoud and EI-Eslamboly (2014) [26] and Kumar *et al*. (2015) [24].

Yield per plant (kg)

Among the parents, BT-507-2-2 (6.411), BT-22-4-1 (6.134), BT-19-1-1-1 (3.326) and BT-3 (1.445) were considered as good general combiners due to their significant positive GCA effects. Out of all cross combinations, 20 crosses revealed significant positive SCA effects, indicating their good specific combining ability. The top five cross combinations were 3x6 (7.466), 4x7 (7.401), 3x4 (6.774), 6x7 (6.743) and 4x9 (6.459). These results find support from Pemba *et al*. (2014) [27], Pujer *et al*. (2014) [29], Rajan *et al*. (2014) [42], Singh *et al*. (2014) [36], Mahmoud and EI-Eslamboly (2014) [26], Zengin *et al*. (2015) [40], Habu *et al*. (2016) [19], Basavaraj *et al*. (2016) [11],and Amin *et al*. (2018) [8].

Yield per plot (kg)

The perusal of data for yield plot^{-1} revealed that among the parents, BT-507-2-2 (3.920), BT-22-4-1 (3.069), BT-19-1-1-1 (1.824), BT-3 (0.591) and Utkal Kumari (0.373) were regarded as good general combiners due to their significant positive GCA effects. Among all cross combinations, 19 crosses were found to be good specific combiners due to their significant positive SCA effects. The crosses, 3x4 (5.630), 4x7 (5.508), 1x9 (4.858), 5x9 (4.782) and 3x6 (4.642) were the top five combinations. Similar findings were also obtained by EI-Gabry *et al*. (2014) [17], Agarwal *et al*. (2014) [9], Kumar *et al*. (2015)

[24], Habu *et al*. (2016) [19], Bhakti *et al*. (2016) [12], Kumar and Gowda (2016) [23] and Amin *et al*. (2018) [8].

TLCV Incidence (%)
Among all the parents, Utkal Deepti (-1.917), Utkal Kumari (-1.917) and BT-21 (-1.292) were designated as good general combiners due to their significant GCA effects. Twenty seven cross combinations exhibited negative SCA values, out of which four namely 1x4 (-6.723), 4x8 (-6.515), 6x7 (-5.890) and 1x6 (-5.057) were significant which indicated that these crosses have good specific combining ability. Similar reports have been obtained by Prabuddha *et al*. (2008) [28] and Chattopadhyay *et al*. (2011) [15].

Bacterial wilt incidence (%)
The perusal of data for this trait revealed that significant negative GCA effects among the parents were exhibited by BT-17-2 (-4.500), BT-507-2-2 (-3.250) and BT-21 (-2.000), which indicated their good general combining ability. The estimates of SCA effects for this trait revealed that twenty five cross combinations exhibited negative SCA effects, out of which three, 5x9 (-6.402), 1x7 (-6.402) and 4x7 (-6.193), were significant indicating that these crosses were good specific cross combinations. The results were in conformity with those of Rattan *et al*. (2007) [30] and Singh and Asati (2011) [35].

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