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Heterosis in tomato (*Solanum lycopersicum*) hybrids for growth, yield and quality traits

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Abstract
In the present investigation, ten tomato lines were crossed in half diallel mating design to produce 45 F_1 hybrids. The experiment was carried out at research farm, Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha. Heterobeltiosis and standard heterosis were estimated for growth, fruit yield and quality traits in F_1 hybrids. The parental lines, *viz.* BT-22-4-1, BT-507-2-2 and BT-19-1-1-1 were found most promising for exploiting heterosis. Appreciable amount of heterobeltosis and standard heterosis was noticed for majority of the traits studied. Considering all the cross combinations individually, the hybrid combinations that out fielded their parents for a maximum number of components for heterobeltiosis and standard heterosis coupled with high *per se* values were; BT-19-1-1-1 x BT-22-4-1, BT-22-4-1 x BT-507-2-2 and BT-19-1-1-1 x BT-3. However, hybrids those performed better for yield parameters were not heterotic significantly for quality parameters.

Keywords: Heterosis over mid-parent, heterosis over better-parent, heterobeltiosis, relative heterosis, tomato, hybrids

Introduction
Plant breeders have extensively explored and utilized heterosis to boost yield levels in several cross-pollinated crops in the recent past. However, tomato being a highly self-pollinated species, the scope for exploitation of hybrid vigour depends on the direction and magnitude of heterosis, and ease with which hybrid seeds can be produced. Tomato is an extremely popular, economically important and widely grown vegetable crop in India as well as in the world. Commercial exploitation of hybrid vigour in tomato has received greater importance on account of several advantages of hybrids over pure line varieties with resistance/tolerance to biotic and abiotic stresses. Tomato has achieved a spectacular status of functional food because of its rich nutritional composition and widespread consumption (Singh *et al*. 2010) [49].
Hence, identification of high yielding and stable varieties and the development of F_1 hybrids will help the farmers to adopt variety/hybrid for successful commercial cultivation of tomato. Heterosis in tomato was first observed by Hedrick and Booth (1908) [22] for higher yield and more number of fruits. The reproductive biology and production of appreciable quantity of seeds per fruit provide plentiful opportunity for manifestation of heterosis in tomato (Singh and Singh, 1993) [54]. The hybrids available in the market do not have good processing qualities, leading to limited development of value added products (Pandiarana *et al*. 2015) [37]. Since then, heterosis for yield, its components and quality traits were extensively studied (Ahmad *et al*. 2011) [3]. Present investigation was undertaken to ascertain the nature and extent of heterosis for yield and its component characters in tomato.

Materials and Methods
The present investigation was carried out at the Experimental Farm of Department of Vegetable Science, Odisha University of Agriculture and Technology, Bhubaneswar, during winter season of 2015-16, 2016-17 and 2017-18. The experimental farm is located at Bhubaneswar which is about 60 kms away from the Bay of Bengal and situated at an altitude of 25.5 meters above mean sea level, lying between latitude of 20^0 15’ North and longitude of 85^0 52’ East.
Experimental material: Ten superior tomato lines based on fruit yield *viz*., Utkal Pallavi (P1), Utkal Deepti (P2), Utkal Kumari (P3), BT-19-1-1-1 (P4), BT-317 (P5), BT-22-4-1 (P6), BT-3 (P7), BT-17-2 (P8), BT-507-2-2 (P9) and BT-21 (P10) were selected based on their *per se*

performance and genetic divergence from previously screened tomato genotypes (Likhita *et al*. 2017).

In the first season, parental lines were grown to obtain their selfed seed for further hybridization programme. In the following seasons these ten parental lines were crossed in half diallel mating design and 45 F_1s were obtained. Seeds of 10 parental lines and 45 F_1 hybrids were sown. One month old seedlings were transplanted in a randomized block design with three replications spacing at 60 cm × 45 cm for evaluation trial. Five randomly selected competitive plants from each row in each replication were tagged for the purpose of recording the observations on different characters.

The data were recorded on days to first flowering, days to 50% flowering, number of flower clusters per plant, number of flowers per cluster, number of fruits per cluster, number of fruits per plant, fruit length (cm), fruit diameter (cm), number of locules per fruit, pericarp thickness of fruit (mm), plant height (cm), total number of branches per plant, average fruit weight (g), fruit yield per plant (kg), total soluble solids content of fruit (^{0}Brix), ascorbic acid content of fruit (mg $100g^{-1}$) and acid content of fruit (%). Analysis of variance was performed according to Gomez and Gomez (1984) [19]. Heterosis over better parent and mid parent for different characters under study were calculated as per standard procedures.

Results and Discussion

Analysis of variance: In the pooled analysis of variance (Table 1), effects due to the genotype and its three components, P, F_1 and heterosis were significant. Genotype x Season interaction was significant in characters such as branches plant^{-1}, days to 1st flowering, days to 50% flowering, number of fruits cluster^{-1}, number of fruits plant^{-1}, fruit length, fruit diameter, pericarp thickness, number of locules fruit^{-1} and total yield plot^{-1}. The P x S (Parent x Season) was significant only in the character days to 50% flowering at the 5% level. F_1 x S (Hybrid x Season) was significant in case of branches plant^{-1}, days to first flowering, days to 50% flowering, number of fruits plant^{-1}, fruit length, fruit diameter, pericarp thickness, number of locules fruit^{-1} and total yield plot^{-1}, while Heterosis x Season was significant in branches plant^{-1}, days to 1st flowering, days to 50% flowering, number of flowers cluster^{-1}, number of fruits cluster^{-1} and average fruit weight. In all, the variance due to environment versus the genotypes was apparently clear to support the need for evaluation over seasons.

Heterosis: The estimates of heterosis were computed for all the traits studied in the 45 cross combinations of tomato and expressed in percentage over better parental value (heterobeltiosis) and mid parent value (relative heterosis).

Days to first flowering

Earliness is important to fetch premium prices in a market and in tomato hybrids being early are preferred over pure line varieties. Therefore, days to first flowering are primary indicator to predict earliness in a crop like tomato. Negative mid-parent heterosis was expressed in case of 34 hybrids, while negative better parent heterosis was shown by 38 hybrids. The hybrids 5x7 (-9.53% over mid-parent and -15.12% over better parent) and 6x9 (-9.87% over mid-parent and -10.56% over better parent) were significantly heterotic (Table 2). Early flowering in hybrids has also been reported by Ahmad *et al*. (2011) [3], Islam *et al*. (2012) [23],

Table 1: Pooled analysis of variance for 20 characters of tomato in a 10X10 half diallel set of F_1 hybrids plus parents over two years

Source	df	Mean sum of squares for									
		Plant height (cm)	Branches/ plant	Days to first flowering	Days to 50% flowering	No. of flowers/ cluster	No. of clusters/ plant	No. of fruits/ cluster	No. of fruits/ plant	Fruit length (cm)	Fruit diameter (cm)
Season (S)	1	111.66**	14995.20**	565.44**	388.63**	16065.45**	811.78**	16547.56**	32714.31**	42.77	2.36
Reps. in season	2	168.50**	61.60	23.99	22.99	3.09	0.40	5.91	36.59	33.72	66.71**
Genotype (G)	54	317.80**	1500.72**	28.15**	34.09**	213.51**	18.93**	227.81**	233.27**	52.31**	19.91**
Parent (P)	9	497.70**	1225.44**	31.58**	37.16**	201.24**	30.67**	148.50**	343.73**	40.04*	11.76
Hybrid (H)	44	254.58**	1485.88**	26.28**	32.05**	164.03**	16.35**	172.20**	186.95**	50.48**	21.66**
P vs F_1 (Het.)	1	1480.36**	4631.48**	79.39**	96.51**	2500.91**	26.92**	3388.28**	1277.18**	243.57**	16.67
G x S	54	12.38	77.84**	36.46**	58.43**	31.35	0.29	36.83*	45.21**	39.84**	16.57**
P x S	9	15.74	71.23	12.39	24.01*	14.84	0.43	6.28	17.08	14.76	6.59
F_1 x S	44	11.82	75.85**	37.48**	62.96**	11.72	0.27	12.14	50.82**	45.03**	18.82**
Het x S	1	6.65	224.75*	208.61**	168.97**	1043.71**	0.05	1398.13**	51.48	37.29	7.39
Pooled error	108	14.63	37.07	8.65	11.51	22.97	1.90	23.26	18.55	16.65	8.50

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

Table 1: Contd.....

Source	df	Mean sum of squares for									
		Average fruit weight (g)	Pericarp thickness (mm)	No. of locules/ fruit	TSS content of fruit (^{0}Brix)	Ascorbic acid content of fruit (mg/100g)	Acidity content of fruit (%)	Yield/ plant (kg)	Total yield / plot (kg)	TLCV Incidence (%)	Bacterial wilt Incidence (%)
Season (S)	1	104.40*	8.80	877.20**	0.69	3.31*	0.54	61.69**	50.10**	55.00	7.27
Reps. in season	2	249.09**	14.27	30.23	209.66**	0.05	16.54**	1.55	21.24**	2.27	134.55*
Genotype (G)	54	1305.43**	178.31**	45.81**	183.54**	353.52**	10.98**	219.76**	84.91**	85.98**	109.31**
Parent (P)	9	1847.66**	205.36**	53.82**	96.96**	175.09**	6.68**	66.00**	22.37**	56.94**	156.67**
Hybrid (H)	44	1137.46**	175.97**	44.63**	128.40**	381.75**	12.11**	206.83**	70.28**	93.86**	94.12**
P vs F_1 (Het.)	1	3815.86**	37.82	25.76	3388.65**	717.49**	0.24	2172.49**	1291.32**	0.23	351.62**
G x S	54	9.79	43.46**	32.72**	0.32	0.57	0.04	1.06	1.98*	5.00	11.90
P x S	9	16.75	13.69	20.16	0.06	0.00	0.07	0.89	1.45	5.83	0.00
F_1 x S	44	4.99	50.53**	35.70**	0.37	0.69	0.03	1.04	2.06*	4.87	14.57
Het x S	1	158.55**	0.03	14.62	0.12	0.26	0.41	3.38	3.19	3.05	1.62
Pooled error	108	16.90	24.58	13.33	2.10	0.76	0.55	2.01	1.18	19.87	38.25

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

Table 2: Pooled heterosis percentage of F_1 hybrids for different growth parameters of tomato studied in 10 x 10 half diallel cross

Hybrid	Plant height (cm)		Branches/plant (Nos.)		Days to 1st flowering (Nos.)		No. of flowers/cluster (Nos.)		No. of fruits/cluster (Nos.)	
	Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over	
	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent
1x2	2.46	12.79**	-7.99	8.17	-5.94	-5.77	17.54*	24.65**	19.44*	26.16**
1x3	-0.82	0.79	-3.54	0.43	-2.52	-0.65	-0.42	1.93	6.48	6.73
1x4	-2.89	4.66	-4.75	3.25	5.70	-0.45	3.62	13.49*	12.85	20.86**
1x5	0.90	2.48	-0.89	3.40	-4.59	-1.96	6.14	8.28	8.33	10.38
1x6	0.64	5.97	-10.57	0.65	-6.71	-2.88	5.15	14.40*	11.42	20.43**
1x7	3.08	6.13	-14.59*	-9.93	-8.03	-4.50	8.54	12.66	11.16	15.37*
1x8	0.78	6.34	-13.02	-6.67	11.84*	12.00*	10.53	14.03	12.96	16.47*
1x9	3.62	10.47**	4.27	18.52**	-0.73	2.59	10.99	20.96**	13.51	23.79**
1x10	0.30	11.07**	-1.48	9.72	2.96	4.04	13.16	18.89*	14.81	20.10*
2x3	-2.75	8.62*	-4.09	16.56**	-3.93	-2.27	2.09	10.66	8.84	14.71
2x4	1.27	19.22**	-4.25	20.25**	-2.34	2.92	-2.17	12.97	5.62	19.00*
2x5	0.18	8.74*	-12.90	-1.28	-1.83	1.06	22.83*	27.79**	25.00**	29.68**
2x6	1.08	16.56**	-15.17**	9.82	-11.95*	-8.49	5.15	20.68**	10.24	25.28**
2x7	0.91	14.03**	-6.10	15.31*	-7.05	-3.65	9.35	20.09**	10.73	21.13**
2x8	1.61	6.28	17.12**	29.30**	6.26	6.31	17.76	21.15**	18.23	21.21*
2x9	-3.27	12.79**	-15.51**	10.26	-10.72*	-7.90	-2.56	12.00	-1.16	13.27
2x10	2.46	3.14	-4.83	1.19	2.92	3.80	13.59	14.71	11.68	12.82
3x4	1.27	7.51*	20.75**	25.95**	-10.54*	-7.27	8.70	16.50*	17.67*	26.29**
3x5	0.42	3.62	0.82	9.31	-0.04	4.62	8.79	13.54	15.81	17.73*
3x6	3.83	7.65*	19.54**	29.68**	-9.71	-7.73	12.87	20.16**	18.90*	28.78**
3x7	0.92	2.27	-3.71	-2.42	-9.64	-7.90	1.22	2.68	2.58	6.70

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

Table 2: Contd.....

Hybrid	Plant height (cm)		Branches/plant (Nos.)		Days to 1st flowering (Nos.)		No. of flowers/cluster (Nos.)		No. of fruits/cluster (Nos.)	
	Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over	
	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent
3x8	-1.57	5.45	-3.81	7.13	-3.66	-10.5	13.81	20.09**	22.33*	25.84**
3x9	1.55	6.63	15.06**	26.11**	-0.34	1.09	12.09	19.53**	16.22*	27.00**
3x10	-4.56	7.22	-4.90	9.75	-4.72	-3.89	-0.84	6.52	5.58	10.19
4x5	-1.68	7.50*	2.00	14.93*	-12.80**	-5.55	-6.16	4.65	-0.40	8.53
4x6	3.99	6.58	25.98**	31.26**	-9.31	-7.99	18.12*	18.98**	22.83**	24.06**
4x7	3.00	7.98*	25.00**	28.70**	-9.68*	-8.12	10.51	16.86**	18.47*	22.41**
4x8	-10.19**	1.70	-1.50	13.87*	-10.58*	-5.73	1.09	13.88*	8.03	19.03*
4x9	5.96	7.20	25.84**	32.54**	2.54	4.82	20.29**	20.95**	21.24**	23.62**
4x10	-14.39**	1.34	-7.25	10.91	-9.80*	-5.72	-13.04	-0.41	-7.63	3.14
5x6	1.19	8.13*	-3.91	12.21*	-10.94*	-4.83	-4.04	6.31	-0.79	9.09
5x7	0.84	5.40	-4.24	5.09	-15.12**	-9.53*	-0.81	4.95	0.86	6.58
5x8	-0.46	3.48	14.19	17.61*	-6.13	-3.41	20.09*	21.48**	21.63*	23.11**
5x9	1.58	9.88**	2.47	20.79**	-8.58	-3.00	7.69	19.51**	10.81	22.91**
5x10	0.28	9.49*	7.42	15.03*	-7.14	-3.61	12.33	15.76*	13.46	16.54*
6x7	5.45	7.93*	22.76**	31.53**	-7.31	-7.05	16.18*	22.01**	21.26**	26.49**
6x8	0.31	11.13**	-1.03	18.43**	-10.35*	-6.78	5.15	17.70*	10.24	22.54**
6x9	5.31	6.70	28.99**	30.45**	-10.56*	-9.87*	18.32*	18.53**	23.17**	24.37**
6x10	0.21	16.19**	-8.00	13.69*	-3.67	-0.72	-7.35	5.44	-3.94	8.20
7x8	-0.17	8.28*	3.18	16.29*	-5.18	-1.67	5.69	13.04	6.01	13.30
7x9	1.82	5.56	-4.94	2.92	-4.93	-4.46	1.10	6.36	3.47	8.94
7x10	-6.27	6.52	-16.45**	-2.48	-8.87	-6.46	4.47	13.72	5.15	13.95
8x9	0.41	12.56**	-5.62	13.98*	-5.57	-2.54	3.30	15.81*	5.79	18.61*
8x10	1.47	6.79	9.59	14.08*	0.76	1.68	20.56*	22.86**	22.17*	24.00**
9x10	-6.19	9.98*	-7.28	15.57*	-4.16	-1.95	2.93	17.33*	5.41	19.74**

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

Singh *et al*. (2012a) [52], Patwary *et al*. (2013) [38], Shalaby (2013) [43], Shankar *et al*. (2014) [44], Tasisa *et al*. (2017) [59], Kumar *et al*. (2017) [26] and Gautam *et al*. (2018) [18].

Number of flowers per cluster

Heterosis over mid-parent was found to be positive and significant in case of 26 hybrids while heterosis over better parent was positive and significant in 8 hybrids. Highest significantly positive value was shown by 2x5 for both mid-parent (27.79%) and better parent (22.83%) followed by 8x10 (22.86% and 20.56%), 4x9 (20.95% and 20.29%), 5x8 (21.48% and 20.09%) and 6x9 (18.53% and 18.32%)

respectively (Table 2). Positive heterosis over better parent for this trait has also been reported by Gul *et al*. (2011) [20], Islam *et al*. (2012) [23], Droka *et al*. (2013) [13], Patwary *et al*. (2013) [38], Pemba *et al*. (2014) [39], Enang *et al*. (2015) [15] and Hamisu *et al*. (2018) [21].

Number of fruits per cluster

Thirty F_1 hybrids exhibited positive and significant heterosis over mid-parent while 13 exhibited positive significant heterosis over better parent. The promising ones were 2x5 (29.68% over mid-parent and 25.00% over better parent), 3x8 (25.84% over mid-parent and 22.33% over better parent), 4x6 (24.06% over mid-parent and 22.83% over better parent), 4x9 (23.62% over mid-parent and 21.24% over better parent) and 6x9 (24.37% over mid-parent and 23.17% over better parent) (Table 2). Positive heterosis for this trait has also been reported by Gul *et al*. (2011) [20], Kumari and Sharma (2011) [34], Islam *et al*. (2012) [23], Kumar *et al*. (2012), Singh *et al*. (2012b) [53], Droka *et al*. (2013) [13], Patwary *et al*. (2013) [38], Sharma and Sharma (2013) [45, 46], Pemba *et al*. (2014) [39], Ahmad *et al*. (2015) [2], Marbhal *et al*. (2016) [35], Kumar *et al*. (2016) [29, 33], Tasisa *et al*. (2017) [59], Veena *et al*. (2017) [61], Raj *et al*. (2018a) [41] and Hamisu *et al*. (2018) [21].

Plant height

More plant height is considered desirable, because it leads to more number of branches and ultimately results in increased productivity. All 45 hybrids exhibited positive heterosis over mid-parent out of which 22 were significant. Similarly, positive heterosis over better parent was observed in 32 hybrids. The promising hybrids with high magnitude of significant, positive, mid-parent heterosis were 2x4 (19.22%), 2x6(16.56%) and 6x10 (16.19%). Thirteen hybrids exhibited negative heterosis over better parent (Table 2). Positive heterosis for this trait has also been reported by Singh and Asati (2011) [48], Kumari and Sharma (2011) [34], Chattopadhyay *et al*. (2012a) [9], Islam *et al*. (2012) [23], Negi *et al*. (2012) [36], Singh *et al*. (2012a) [52], Singh *et al*. (2012b) [53], Solieman *et al*. (2013) [55], Ebenezer and Babu (2014) [14], Ahmad *et al*. (2015) [2], Enang *et al*. (2015) [15], Marbhal *et al*. (2016) [35], Kumar *et al*. (2016) [29, 33], Amin *et al*. (2017) [4], Triveni *et al*. (2017b) [60] and Gautam *et al*. (2018) [18].

Branches per plant

More number of branches plant^{-1} is considered desirable as it leads to increase in productivity. Plant architecture is largely determined by shoot branching. Five hybrids, 1x7 (-9.93%), 1x8 (-6.67%), 2x5 (-1.28%), 3x7 (-2.42%) and 7x10 (-2.48%) showed negative heterosis over mid parent while 25 hybrids showed significant positive heterosis. Nine hybrids exhibited significant positive heterosis over better parent whereas twenty-eight hybrids exhibited negative heterosis over better parent, out of which 1x7 (-14.59%), 2x6 (-15.17%), 2x9 (-15.51%) and 7x10 (-16.45%) were significant (Table 2). Significant positive heterosis for number of branches plant^{-1} has been reported by Droka *et al*. (2013) [13], Shalaby (2013) [43], Amin *et al*. (2017) [4] and Hamisu *et al*. (2018) [21].

Number of fruits per plant

Number of fruits plant^{-1} is the most important component trait which is directly related to increased fruit yield plant^{-1}. Positive and significant heterosis was noticed in 19 hybrids over mid-parent and 4 hybrids over better parent. Among these hybrids 2x8 (26.74% over mid-parent and 22.68% over better parent), 2x10 (33.59% over mid-parent and 32.65% over better parent), 3x4

Table 3: Pooled heterosis percentage of F_1 hybrids for different fruit parameters of tomato studied in 10 x 10 half diallel cross

Hybrid	No. of fruits/plant (Nos.) Heterosis % over		Fruit length (cm) Heterosis % over		Fruit diameter (cm) Heterosis % over		Average fruit weight (g) Heterosis % over	
	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent
1x2	6.04	12.97	-4.79	-3.26	-6.49	-4.57	12.08	28.14**
1x3	5.86	7.10	6.46	12.06	1.32	2.19	14.31	17.94*
1x4	4.49	10.68	7.53	9.15	-5.54	-4.08	-1.86	11.15
1x5	13.70	16.23*	1.44	3.26	4.30	6.10	9.66	13.86
1x6	-5.59	6.88	8.83	11.58	7.89	9.50	-17.57**	9.01
1x7	-0.72	4.72	-6.27	-6.10	1.48	1.54	11.40	19.07*
1x8	11.19	14.79*	-0.51	-0.46	-2.81	0.79	13.14	21.06*
1x9	-4.30	10.07	1.21	6.74	-11.96*	-7.31	-14.91**	14.14**
1x10	14.46	21.13**	3.42	5.79	0.80	2.41	8.44	17.79*
2x3	-0.28	7.39	8.54	12.51	-0.47	2.42	12.78	32.42**
2x4	-4.45	7.40	-0.90	2.19	-1.11	-0.61	-8.20	16.65*
2x5	10.02	14.77*	7.87	8.08	4.01	4.34	6.04	17.23
2x6	-5.87	12.56*	9.98	10.99	6.59	7.19	-28.84**	2.84
2x7	-0.32	11.61	-0.47	0.95	-3.48	-1.56	3.03	24.67**
2x8	22.68**	26.74**	-2.00	-0.47	-1.28	0.36	22.40*	31.46**
2x9	-11.84*	7.06	-10.95	-4.66	0.64	3.90	-27.58**	5.88
2x10	32.65**	33.59**	2.00	5.97	2.00	2.46	15.84	22.55*
3x4	18.41**	24.03**	-7.62	-1.37	0.21	2.62	29.10**	42.18**
3x5	-1.57	1.77	6.45	10.14	-1.86	0.68	17.43*	25.65**
3x6	4.19	16.75**	5.38	8.26	2.35	4.75	5.44	36.42**
3x7	-3.21	0.96	1.96	7.13	-0.71	0.19	19.59*	24.03**

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

Table 3: Contd.....

Hybrid	No. of fruits/plant (Nos.)		Fruit length (cm)		Fruit diameter (cm)		Average fruit weight (g)	
	Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over	
	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent
3x8	0.87	5.32	1.77	7.07	-2.09	2.37	3.67	14.18
3x9	-0.10	13.86*	-1.62	8.90	-0.94	5.14	1.52	33.30**
3x10	1.71	8.82	-8.26	-1.34	-4.36	-2.02	5.45	17.84*
4x5	5.05	13.59*	4.87	8.34	1.38	1.57	2.06	19.41**
4x6	6.01	13.80*	-6.85	-3.10	6.13	6.18	8.71	30.28**
4x7	19.17**	19.69**	-0.95	0.73	2.24	3.76	34.88**	43.56**
4x8	-4.29	4.45	-2.39	-0.87	-5.31	-3.26	-9.94	8.13
4x9	4.79	14.52**	-1.17	2.75	0.54	4.31	6.08	29.28**
4x10	-5.76	5.27	3.77	4.59	1.12	1.17	-7.56	12.43
5x6	-6.66	7.71	2.89	3.64	12.90*	13.17*	-17.14**	12.40*
5x7	-9.03	-2.03	9.75	11.52	-6.16	-4.59	13.79	25.95**
5x8	12.79	13.93	7.35	9.23	9.13	11.29*	18.12	21.87*
5x9	-4.79	11.67*	-1.54	5.61	-3.95	-0.54	-18.02**	12.71*
5x10	5.81	9.63	-1.69	2.33	-2.81	-2.68	15.26	20.79*
6x7	4.67	12.82*	9.00	11.55	2.83	4.30	8.39	36.50**
6x8	-4.74	10.86	9.63	12.35	-1.07	1.12	-15.41**	17.06**
6x9	8.81	10.94*	3.92	12.21	2.57	6.46	12.04**	14.42**
6x10	-14.17*	2.04	7.15	12.31	3.03	3.14	-24.41**	5.64
7x8	-3.57	4.82	15.86*	16.02*	-2.19	1.37	2.71	16.90*
7x9	-14.22*	-5.88	-8.33	-3.15	-5.68	-0.75	-22.87**	-1.35
7x10	7.38	19.48**	9.72	12.44	-8.46	-7.05	-3.17	11.74
8x9	-13.33*	2.50	-20.07**	-15.67*	-5.73	-4.24	-24.91**	5.26
8x10	15.57	18.57*	2.66	5.06	-0.87	1.22	30.18**	32.29**
9x10	-17.36**	-0.20	7.54	10.96	-9.54	-6.20	-24.66**	6.63

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

(24.03% over mid-parent and 18.41% over better parent) and 4x7 (19.69% over mid-parent and 19.17% over better parent) were significantly superior. The hybrids 2x9 (-11.84%), 6x10 (-14.17%), 7x9 (-14.22%), 8x9 (-13.33%) and 9x10 (-17.36%) showed significant negative heterosis over better parent (Table 3). The variation in number of fruits plant^{-1} may be due to genetic differences among the crosses since they were grown under the same environmental conditions. Positive heterosis over better parent for this trait has also been reported by Kumari and Sharma (2011) [34], Angadi *et al.* (2012a) [5], Chattopadhyay *et al.* (2012a) [8], Islam *et al.* (2012) [23], Negi *et al.* (2012) [36], Singh *et al.* (2012a) [52], Singh *et al.* (2012b) [53], Souza *et al.* (2012) [56], Droka *et al.* (2013) [13], Garg *et al.* (2013) [17], Solieman *et al.* (2013) [55], Patwary *et al.* (2013) [38], Ebenezer and Babu (2014) [14], Ahmad *et al.* (2015) [2], Enang *et al.* (2015) [15], Kumar and Singh (2016) [29, 33], Biswas *et al.* (2016) [7], Amin *et al.* (2017) [4], Tamta and Singh (2017), Veena *et al.* (2017) [61], Kumar *et al.* (2017) [26], Gautam *et al.* (2018) [18], Raj *et al.* (2018a) [40] and Hamisu *et al.* (2018) [21].

Fruit length

The development of fruit size depends on a number of factors such as the leaf-fruit ratio, genetic and climatic factors, position in the plant and the branch, plant age, number of seeds and water and nutrient supply (Dennis, 1996). Thirty four hybrids showed positive heterosis over mid-parent while twenty seven hybrids expressed positive heterosis over better parent. Among the hybrids showing positive heterosis, 7x8 (16.02% and 15.86%) exhibited significantly higher value over mid-parent and better parent respectively. Other hybrids which exhibited high, positive, mid-parent heterosis were 1x3 (12.06%), 1x6 (11.58%), 2x3 (12.51%), 5x7 (11.52%), 6x7 (11.55%), 6x8 (12.35%), 6x9 (12.21%), 6x10 (12.31%) and 7x10 (12.44%) (Table 3). Positive heterosis for this trait has also been reported by Gul *et al.* (2011) [20], Chattopadhyay *et al.* (2012b) [9], Islam *et al.* (2012) [23], Singh *et al.* (2012b) [53], Kumar and Singh (2016) [29, 33] and Kumar *et al.* (2016) [29, 33].

Fruit diameter

Positive mid-parent heterosis was observed for fruit diameter with respect to 31 hybrids, out of which two were significant 5x6 (13.17%) and 5x8 (11.29%). Similarly, positive better parent heterosis was shown by 22 hybrids out of which 5x6 (12.90%) was significant. Negative significant heterosis over better parent was shown by 1x9 (-11.96%) (Table 3). Positive heterosis for this trait has also been reported by Gul *et al.* (2011) [20], Islam *et al.* (2012) [23], Singh *et al.* (2012b) [53], Droka *et al.* (2013) [13], Kumar and Singh (2016) [29, 33] and Kumar *et al.* (2016) [29, 33].

Average fruit weight

Average fruit weight has direct contribution to yield. Significant positive heterosis was noticed in thirty one hybrids over mid-parent and 7 hybrids over better parent. The hybrids 2x8 (31.46% over mid-parent and 22.40% over better parent), 3x4 (42.18% over mid-parent and 29.10% over better parent), 3x7 (24.03% over mid-parent and 19.59% over better parent), 4x7 (43.56% over mid-parent and 34.88% over better parent), 6x9 (14.42% over mid-parent and 12.04% over better parent) and 8x10 (32.29% over mid-parent and 30.18% over better parent) exhibited high significant positive heterosis over both the parents. The hybrids 1x6 (-17.57%), 1x9 (-14.91%), 2x6 (-28.84%), 2x9 (-27.58%), 5x6 (-17.14%), 5x9 (-18.02%), 6x8 (-15.41%), 6x10 (-24.41%), 7x9 (-22.87%), 8x9 (-24.91%) and 9x10 (-24.66%) showed negative, significant better parent heterosis (Table 3). The studies corroborate with the findings of Ahmed *et al.* (2011) [3], Gul *et al.* (2011) [20], Angadi *et al.* (2012a) [5], Chattopadhyay *et al.* (2012a) [8], Islam *et al.* (2012) [23], Kumar *et al.* (2012), Negi *et al.* (2012) [36], Singh *et al.* (2012a) [52], Singh *et al.* (2012b) [53], Garg *et al.* (2013) [17], Solieman *et al.* (2013) [55], Agarwal *et al.* (2014) [1], Ahmad *et al.* (2015) [2], Marbhal *et al.* (2016) [35], Kumar and

Singh (2016) [29, 33], Biswas *et al*. (2016) [7], Kumar *et al*. (2016) [29, 33], Amin *et al*. (2017) [4], Kumar *et al*. (2017) [26], Triveni *et al*. (2017b) [60], Tamta and Singh (2017) [58], Veena *et al*. (2017) [61], Gautam *et al*. (2018) [18] and Raj *et al*. (2018a) [41].

Number of locules per fruit

Lesser number of locules in a fruit is considered desirable. In tomato, locule number influences fruit shape and size. The locules are directly derived from the carpels in the flower. Positive mid-parent heterosis was observed for number of locules fruit^{-1} with respect to 29 hybrids among which 1x6 (19.86%) and 2x3 (16.83%) were found to be significant. Negative better parent heterosis was exhibited by 24 crosses out of which 2x4 (-15.76%), 2x10 (-18.67%), 4x5 (-21.20%) and 7x10 (-19.68%) were significant (Table 4). Significant negative heterosis has been reported by Chattopadhyay *et al*. (2012b) [9], Singh *et al*. (2012a) [52], Singh *et al*. (2012b) [53], Garg *et al*. (2013) [17], Solieman *et al*. (2013) [55] and Tamta and Singh (2015) [57].

Table 4: Pooled heterosis percentage of F_1 hybrids for yield and different quality parameters of tomato studied in 10 x 10 half diallel cross

Hybrid	Pericarp thickness (mm)		No. of locules /fruit (Nos.)		TSS content of fruit (⁰Brix)		Ascorbic acid content of fruit (mg/100g)		Yield/plant (kg)	
	Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over	
	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent
1x2	11.64	12.41	-7.93	-0.66	33.54**	36.74**	-34.58**	-33.61**	16.84	32.06**
1x3	-7.33	-6.08	5.30	9.28	22.20**	38.78**	-25.04**	-14.71**	10.49	15.30
1x4	-26.99**	-11.29	1.09	14.81	11.71**	16.44**	12.63**	23.58**	36.45**	54.14**
1x5	18.59	22.52	-1.25	5.33	29.27**	33.79**	78.04**	88.49**	11.62	14.31
1x6	-19.69	-8.55	15.13	19.86*	38.64**	49.21**	14.07**	50.28**	23.97**	47.48**
1x7	29.45*	34.04**	-3.19	10.98	18.53**	29.96**	49.04**	82.03**	44.17**	54.53**
1x8	4.32	9.74	-12.96	-6.62	2.26	14.96**	-11.33**	0.19	8.42	14.69
1x9	6.16	11.51	-1.75	8.04	10.45**	11.94**	134.33**	156.78**	37.85**	68.80**
1x10	-26.92**	-24.50*	0.00	8.50	25.14**	37.64**	14.93**	37.32**	15.66	27.46**
2x3	12.67	14.97	12.20	16.83*	15.75**	28.72**	-38.77**	-31.22**	9.57	28.51**
2x4	-34.96**	-20.54*	-15.76*	-10.92	0.66	2.52	-22.28**	-15.86**	8.43	36.16**
2x5	17.31	22.00	2.26	3.52	2.89	8.94**	28.16**	37.56**	16.96	29.42**
2x6	-20.73*	-9.20	4.27	8.23	7.93*	13.59**	12.01**	49.04**	16.40*	52.75**
2x7	22.92	26.43*	-9.57	-3.41	12.67**	20.85**	62.94**	101.28**	36.30**	63.60**
2x8	-25.31*	-20.92	-4.27	-3.68	24.12**	36.61**	-37.77**	-30.59**	48.39**	59.23**
2x9	14.58	19.57	11.11	13.43	22.44**	23.71**	67.70**	86.21**	11.09	49.39**
2x10	-29.49*	-26.67*	-18.67*	-18.18*	8.15*	16.39**	10.14**	33.17**	24.79*	28.37**
3x4	-16.37	0.53	-5.43	3.88	21.49**	32.88**	94.51**	102.52**	71.34**	86.19**
3x5	25.00	27.45*	5.63	8.68	5.14	22.99**	33.60**	59.65**	19.14*	27.18**
3x6	-26.94**	-17.78	13.16	13.53	31.50**	39.38**	1.29	45.48**	67.55**	92.24**
3x7	28.67*	34.97**	-7.98	2.06	31.85**	37.09**	18.26**	59.48**	44.17**	48.28**

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

Table 4: Contd......

Hybrid	Pericarp thickness (mm)		No. of locules /fruit (Nos.)		TSS content of fruit (⁰Brix)		Ascorbic acid content of fruit (mg/100g)		Yield/plant (kg)	
	Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over		Heterosis % over	
	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent	Better parent	Mid-parent
3x8	-17.90	-14.74	0.00	3.51	14.69**	16.02**	-41.36**	-40.88**	5.56	16.23
3x9	0.67	7.09	1.75	8.07	9.60**	23.00**	-41.36**	-27.83**	51.17**	78.81**
3x10	-27.56*	-26.14*	-9.04	-4.73	43.30**	48.49**	-41.20**	-22.14**	10.49	26.50**
4x5	-4.87	12.57	-21.20**	-15.70*	6.90*	15.16**	-28.07**	-16.92**	13.36	30.74**
4x6	-4.87	2.63	-13.59	-5.36	6.63*	10.25**	-54.56**	-36.29**	73.39**	84.05**
4x7	-37.61**	-22.10*	-4.79	-3.76	-4.57	0.60	-14.04**	12.77**	82.62**	93.27**
4x8	-47.35**	-38.66**	-4.89	1.16	14.40**	23.81**	-24.63**	-22.14**	6.49	26.31**
4x9	-41.15**	-25.70**	0.00	3.66	-5.61	-2.89	-28.07**	-14.32**	67.27**	83.62**
4x10	-35.84**	-24.08**	-12.50	-8.00	20.80**	27.77**	-14.74**	9.71**	2.98	26.53**
5x6	-22.80*	-14.61	11.88	14.74	20.12**	33.44**	7.91	36.36**	27.52**	54.66**
5x7	-22.44	-17.12	-1.60	6.32	-12.09**	-0.58	0.48	17.04**	30.32**	42.81**
5x8	5.56	7.55	3.09	3.73	-9.06**	5.36	-11.66**	4.87	33.75**	38.26**
5x9	-23.72	-17.36	-16.37	-13.60	1.91	6.85**	-9.83*	-6.47	32.73**	65.56**
5x10	-8.33	-8.33	-10.24	-8.59	1.22	14.83**	11.75**	27.15**	25.27*	35.05**
6x7	2.07	19.76	-12.77	-3.53	33.94**	36.66**	79.93**	98.52**	71.33**	91.78**
6x8	-30.05**	-23.94*	4.94	8.28	24.28**	30.30**	-57.47**	-39.20**	11.01	38.19**
6x9	-18.65	-3.38	6.43	12.69	20.71**	28.29**	39.28**	71.11**	70.26**	76.46**
6x10	-12.44	-3.15	0.60	5.03	26.48**	29.49**	25.00**	41.32**	25.34**	61.21**
7x8	-10.49	-2.68	-5.32	1.71	37.20**	41.06**	1.48	36.12**	34.11**	51.44**
7x9	5.15	6.72	-13.30	-9.19	14.51**	24.01**	40.57**	58.60**	9.17	26.11**
7x10	4.49	11.64	-19.68*	-14.69*	29.04**	29.50**	27.85**	31.38**	16.76*	36.92**

8x9	-14.20	-5.44	6.43	9.31	20.71**	34.09**	-22.00**	-4.62	10.02	40.70**
8x10	1.23	3.14	7.23	8.54	57.67**	61.55**	-22.99**	1.41	15.50	20.63*
9x10	-1.28	6.94	4.68	6.23	-4.10	4.19	9.82*	20.91**	18.76**	56.68**

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

Pericarp thickness of fruit

Pericarp thickness is an important component of keeping quality and shelf life in tomato. Negative significant heterosis were exhibited by 9 hybrids over both mid-parent and better parent respectively 1x10 (-24.50% and -26.92%), 2x4 (-20.54% and -34.96%), 2x10 (-26.67% and -29.49%), 3x10 (-26.14% and -27.56%), 4x7 (-22.10% and -37.61%), 4x8 (-38.66% and -47.35%), 4x9 (-25.70% and -41.15%), 4x10 (-24.08% and -35.84%) and 6x8 (-23.94% and -30.05%). Positive and significant heterosis were noticed in 2 hybrids 1x7 (34.04% and 29.45%) and 3x7 (34.97% and 28.67%) over both the parents (Table 4). The potential cross combinations must have produced greater pericarp thickness than the parents involved in the respective crosses. These results were in agreement of Islam *et al.* (2012) [23], Garg *et al.* (2013) [17], Solieman *et al.* (2013) [55], Singh *et al.* (2013) [51], Ebenezer and Babu (2014) [14], Tamta and Singh (2015) [57], Kumar and Paliwal (2016) [29, 33], Kumar *et al.* (2017) [26], Veena *et al.* (2017) [61] and Raj *et al.* (2018b) [40].

Total soluble solids content of fruit

Total soluble solids content is one of the most important quality parameters for the processing industry. It represents the sum total of all fruit components other than water and volatile compounds. Negative heterosis over better parent was observed in case of 5 hybrids out of which two i.e. 5x7 (-12.09%) and 5x8 (-9.06%) were significant. Promising hybrids showing positive significant heterosis over mid-parent were 1x2 (36.74%), 1x3 (38.78%), 1x5 (33.79%), 1x6 (49.21%), 1x10 (37.64%), 2x8 (36.61%), 3x4 (32.88%), 3x6 (39.38%), 3x7 (37.09%), 3x10 (48.49%), 5x6 (33.44%), 6x7 (36.66%), 7x8 (41.06%), 8x9 (34.09%) and 8x10 (61.55%) whereas over better parent were 1x2 (33.54%), 1x6 (38.64%), 3x6 (31.50%), 3x7 (31.85%), 3x10 (43.30%), 6x7 (33.94%), 7x8 (37.20%) and 8x10 (57.67%) (Table 4). This confirms to the findings Islam *et al.* (2012) [23], Shende *et al.* (2012), Garg *et al.* (2013) [17], Solieman *et al.* (2013) [55], Gul *et al.* (2013), Kumar *et al.* (2013) [30], Singh *et al.* (2013) [51], Agarwal *et al.* (2014) [1], Dagade *et al.* (2015a), Vilas *et al.* (2015a), Tamta and Singh (2015) [57], Kumar and Paliwal (2016) [29, 33], Kumar *et al.* (2017) [26], Amin *et al.* (2017) [4], Veena *et al.* (2017) [61], Kumar *et al.* (2018) and Raj *et al.* (2018b) [40].

Ascorbic acid content of fruit (mg/100g)

Ascorbic acid is the major component of the nutritional quality in tomato. The heterosis over better parent for ascorbic acid content ranged from -57.47% (6x8) to 134.33% (1x9) while mid-parent heterosis varied from -40.88% (3x8) to 156.78% (1x9). Other promising hybrids exhibiting positive significant heterosis over mid-parent were 1x5 (88.49%), 1x6 (50.28%), 1x7 (82.03%), 2x7 (101.28%), 2x9 (86.21%), 3x4 (102.52%), 3x5 (59.65%), 3x7 (59.48%), 6x7 (98.52%), 6x9 (71.11%) and 7x9 (58.60%). Similarly, promising hybrids with positive and significant heterosis over better parent were 1x5 (78.04%), 2x7 (62.94%), 2x9 (67.70%), 3x4 (94.51%) and 6x7 (79.93%) (Table 4). Positive heterosis for ascorbic acid over both the parents has also been reported by Garg *et al.* (2013) [17], Solieman *et al.* (2013) [55], Kumar *et al.* (2013) [30], Singh *et al.* (2013) [51], Dagade *et al.* (2015a), Vilas *et al.* (2015a), Kumar *et al.* (2017) [26], Amin *et al.* (2017) [4], Veena *et al.* (2017) [61], Kumar *et al.* (2018) and Raj *et al.* (2018b) [40].

Fruit yield per plant

The ultimate goal of any breeding programme is to achieve more marketable yield per unit of area. Fruit-set in tomato influences yield through effects on both fruit number and fruit size (Bertin,1995). Twenty seven hybrids showed significantly positive better parent heterosis while forty one hybrids exhibited positive significant mid-parent heterosis. Among these hybrids, 3x4 (86.19% over mid-parent and 71.34% over better parent), 3x6 (92.24% over mid-parent and 67.55% over better parent), 3x9 (78.81% over mid-parent and 51.17% over better parent), 4x6 (84.05% over mid-parent and 73.39% over better parent), 4x7 (93.27% over mid-parent and 82.62% over better parent),4x9 (83.62% over mid-parent and 67.27% over better parent), 6x7 (91.78% over mid-parent and 71.33% over better parent) and 6x9 (76.46% over mid-parent and 70.26% over better parent) were found to be more promising than others (Table 4). Higher heterosis for fruit yield per plant in some crosses may be due to the production of higher number of fruits with greater average fruit weight as compared to their respective set of parents. Positive heterosis for fruit yield was reported earlier by Kapur (2011), Singh and Asati (2011) [48], Gul *et al.* (2011) [20], Angadi *et al.* (2012a) [5], Chattopadhyay *et al.*(2012a) [8], Gaikwad and Cheema (2012), Islam *et al.* (2012) [23], Negi *et al.* (2012) [36], Singh *et al.* (2012a) [52], Singh *et al.* (2012b) [53], Shende *et al.* (2012), Souza *et al.* (2012) [56], Droka *et al.* (2013) [13], Garg *et al.* (2013) [17], Patwary *et al.* (2013) [38], Sharma and Sharma (2013) [45], Chauhan *et al.* (2014), Pemba *et al.* (2014) [39], Ahmad *et al.* (2015) [2], Marbhal *et al.* (2016) [35], Kumar and Singh (2016) [29, 33], Kumar *et al.* (2017) [26], Triveni *et al.* (2017a), Triveni *et al.* (2017b) [60], Tamta and Singh (2017) [58], Veena *et al.* (2017) [61], Kumar *et al.* (2017) [26], Triveni *et al.* (2017c), Kumar *et al.* (2018), Raj *et al.* (2018a) [41], Ramana *et al.* (2018) and Hamisu *et al.* (2018) [21].

Conclusion

On the basis of *per se* performance, it is concluded that the hybrids BT-22-4-1 x BT-507-2-2, BT-19-1-1-1 x BT-22-4-1 and BT-19-1-1-1 x BT-3 were found promising for most of the yield and yield associated traits, whereas, for earliness Utkal Deepti x BT-507-2-2, BT-22-4-1 x BT-507-2-2 and BT-19-1-1-1 x BT-17-2 were found best, hence multilocational testing can be done for further evaluation of promising crosses and recommendation for release, notification and commercial cultivation. On the basis of heterobeltiosis, the crosses BT-19-1-1-1 x BT-3, BT-19-1-1-1 x BT-22-4-1 and Utkal Kumari x BT-19-1-1-1 were found to be best. The cross combinations, BT-22-4-1 x BT-3, BT-22-4-1 x BT-507-2-2 and Utkal Kumari x BT-19-1-1-1 were found promising for the quality traits.

Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

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