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Research Article

Study on gene action and heterotic manifestation of important growth and yield related traits in tomato (*Solanum lycopersicum* L.) under terai condition of West Bengal

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Abstract
A field experiment was conducted in the Department of Vegetable and Spice Crops, Uttar Banga Krishi Viswavidyalaya, Cooch Behar, West Bengal, during the autumn-winter season of 2023-24 to study the nature and magnitude of gene action in the manifestation of important traits and identify promising cross combinations. Seven parental lines and their 10 F_{1s} produced by Line × Tester mating were evaluated for 14 traits. Analysis of variance revealed the existence of significant intra-germplasm diversity among lines, testers, and their combinations, as well as the manifestation of significant desired hybrid vigour among the cross combinations due to heterotic effects. Predictability ratio revealed preponderance of non-additive gene action in inheritance of most of the traits and were governed by over-dominance phenomena. Based on GCA estimate B Mut-3 and BCT 115 *dg* among the lines and Berika among the testers, were observed to be the best combiners with better yield potential. Based on *per se* performance, combining ability and heterosis the crosses B Mut-3 x Berika, AC *Aft* x Berika and BCT-115 *dg* x Berika were observed to be desirable

Keywords: Combining ability, heterosis, tomato, gene action

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) (2n=2x=24) is an important solanaceous vegetable crop next to potato. It originated from Peru and Ecuador (Rick, 1969), and is cultivated in tropical and subtropical regions of the world. It is referred as the “poor man’s orange” due to its attractive colour and high nutritional composition (Bose *et al*., 2002). It is a rich source of lycopene, vitamin A, vitamin C, flavonoids, and other minerals essential for human health. (Bhowmik *et al*., 2012; Akhtar and Hazra, 2013). Globally, it is cultivated in an area of 5.0 m.ha., with production of about 186.82 million tonnes and productivity of 36.97 t/ha. In India, Andhra Pradesh ranks first in tomato production (27.44 mt) with highest productivity (44.50 t/ha), followed by Madhya Pradesh with production of 24.19 mt. (FAOSTAT, 2022). Despite its economic importance, intensive selection and artificial genetic alterations have diminished genetic diversity over a period, resulting in inconsistent productivity and limited adaptability (Zorzoli *et al*., 2007; Chattopadhyay *et al*., 2007). To address these challenges, it is essential to investigate nature and extent of genes involve in manifestation of important traits through hybridization to improve yield, fruit quality and resilience against biotic and abiotic stresses (Tesi *et al*., 1970). Combining ability analysis which is defined by Sprague and Tatum (1942) is one of the most effective methods for estimating the effects of combining ability and helps to choose the desirable parents and crosses for the exploitation of heterosis. It is vital to analyse combining ability, which illustrates both additive and non-additive gene effects, to identify superior parent lines and improve hybrid performance (Troyer, 2006; Costa *et al*., 2018). Hence, knowledge on gene action controlling the expression of traits is essential to design effective breeding scheme to meet desired goal. The concept of "Heterosis" describes the superior performance of F_1 hybrids compared to their homozygous parent lines. This phenomenon is crucial for enhancing yield potential, encouraging early maturity, and increasing stress resistance (Fageria *et al*., 2001; Duhan *et al*., 2005). Although heterosis has been employed to surpass yield plateaus and enhance fruit quality (Thakur *et al*., 2004), the success of these methods can differ based on the genetic background, and so systematic assessments of hybrids is necessary to evaluate the genetic stability and yield potential (Brajendra *et al*., 2012). The Line × Tester mating design is frequently used in tomato breeding, enabling breeders to effectively evaluate multiple lines while examining heterotic potential and parent effectiveness (Kempthorne, 1957; Fernie *et al*., 2006). In areas such as the Terai tracts of West Bengal, tomato productivity faces challenges, including limited access to high-yielding disease-resistant hybrids, reliance on outdated cultivars, and vulnerability to environmental stresses (Sigei *et al*., 2014). This situation underscores the need for targeted breeding programs focused on creating high-yielding, stress-resistant, and climate-adaptive hybrids (Kenneth, 2016). Various research has shown significant variation in both General Combining Ability (GCA) and Specific Combining Ability (SCA) related to yield and quality traits, emphasizing the role of both additive and non-additive genetic factors in hybrid development (Ochilo *et al*., 2019). Hence, the present investigation was laid out with the main objective to study the detailed nature and magnitude of gene action involved in expression of important growth and yield attributing traits and manifestation of heterosis for identification of promising cross combination.

MATERIALS AND METHODS

A total of 10 hybrids were synthesised by crossing 5 lines and 2 testers (**Table 1**) during rabi, 2022-23. The hybrids generated were raised along with their parents in a Randomized Block Design (RBD) with three replicatons, during October to April, 2023–2024 at the experimental field of Department of Vegetable Science, Uttar Banga Krishi Viswavidyalaya, Cooch Behar, West Bengal. The experimental site is located at 26°40′ N latitude and 89°38′ E longitude, at an elevation of 43 meters above mean sea level (MSL). The soil of the experimental site was sandy loam in texture, with low pH, moderate water retention capacity, and high organic matter content. The region experiences a subtropical climate with annual rainfall of 2,500–3,300 mm during June–September and temperature ranging from 5–6°C in winter to 24–34°C in summer

All the standard package of practices were followed for maintenance of good crop. Observations on yield attributing traits *viz*., plant height (cm), number of primary branches, days to first flowering (days), days to 50% flowering (days), flowers per truss, trusses per plant, fruits per plant, polar diameter (mm), equatorial diameter (mm), pericarp thickness (mm), locule number, fruit weight (g), yield per plant(kg/plant) and yield per hectare (t/ha), were recorded from 10 randomly selected healthy plants from each replication under each treatment. Combining ability analysis was carried out as per the method proposed by Kempthorne (1957) using the R-package 4.4.3 Agricolae. Predictability ratio was estimated by calculating the proportion of additive variance to dominance variance. Potence ratio was estimated as per the method described by Smith (1952) to estimate the nature and magnitude of dominance. Additionally, the extent of heterosis was evaluated following the methodology proposed by Wynne *et al*. (1970).

Table 1. Tomato Genotypes and Mutant Lines Utilized in the Present Study

Genotype	Description	Source
Lines		
BCT 115 *dg*	Possesses *dg* (dark green) gene	USDA, United States of America
AC *Aft*	Isogenic line of *Alisa Craig* with *Aft* (Anthocyanin fruit) gene	Institute of Genetics, Bulgarian Academy of Sciences, Sofia, Bulgaria
P Mut-5	Mutant of "Patharkuchi" developed by 150 Gy gamma radiation	Department of Vegetable Science, UBKV, West Bengal, India
P Mut-11	Mutant of "Patharkuchi" developed by 200 Gy gamma radiation	Department of Vegetable Science, UBKV, West Bengal, India
B Mut-3	Mutant of "Berika" developed from BCKV	Department of Vegetable Science, UBKV, West Bengal, India
Testers		
Berika	High lycopene-containing cultivar	Institute of Physiology and Genetics, Bulgarian Academy of Sciences, Bulgaria
Patharkutchi	Highly adapted local cultivar widely grown in West Bengal	Department of Vegetable Crops, B.C.K.V., Mohanpur, West Bengal, India

RESULTS AND DISCUSSION

Analysis of variance: The analysis of variance (**Table 2)** indicated that the mean sum of squares due to replication was non-significant for all the characters studied, indicating a high degree of homogeneity among the germplasms and their cross combinations evaluated in the experiment. Further variance due to genotypes was partitioned into parents, hybrids and parent *vs.* hybrids components. The presence of significant and very high genetic diversity among the genotypes, parents used, and their derived off-springs was depicted for all the important traits under study, suggesting the availability of high genetic diversity among the parents and their cross combinations. The analysis demonstrated highly significant differences between parents *vs*. hybrids for most traits except flowers per truss suggested exhibited desired hybrid vigour among the cross combination as a result of heterotic effects in the examined yield attributing traits. The existence of enormous diversity among the parents and significant contribution of hybrids derived from them towards specific combining ability for all the traits under study was demonstrated by the highly significant variances due to lines *vs* testers; hence suggested relative significance of non-additive genetic variance in the inheritance of those traits. Highly significant variances due to lines were recorded for plant height, polar diameter, equatorial diameter, number of locules, fruit weight, yield per plant, and total yield. Significant variance due to testers was recorded for polar diameter, equatorial diameter, fruit weight yield per plant, and total yield. Such significant estimates for lines as well as testers combined for traits like plant height, polar diameter, equatorial diameter, number of locules, fruit weight, yield per plant, and total yield revealed the influence of general combining ability in their inheritance. Hence, the present experiment revealed the significance of both additive as well as non-additive components in the manifestation of the important growth, yield-attributing traits, and yield. The results obtained herein confirmed the earlier findings of Bhatt *et al*. (2001), Shankar *et al*. (2013) and Longjam *et al*. (2021) for plant height and primary branches, Bhatt *et al*. (2001) and Longjam *et al*. (2021) for flowering traits, Shankar *et al*. (2013) and Longjam *et al*. (2021) for yield-related traits *viz*., fruit number, fruit weight, fruits per plant, yield per plant and yield per hectare.

*Gene action:*To develop an effective advanced breeding strategy, understanding the gene action controlling yield-related traits is critical. The predictability ratio, proportion of additive genetic variance to dominant genetic variance, was used to study the involvement of additive and non-additive gene effects for the manifestation of the traits under study, as depicted in Table 2. In this study estimate of the predictability ratio obtained for plant height (0.802), number of primary branches (0.078), days to first flowering (0.042), days to 50% flowering (0.021), trusses per plant (0.302), flowers per truss (0.043), fruits per plant (0.484), yield per plant (0.159) and yield per hectare (0.156) were considerably less than unity which indicated preponderance of non-additive gene action in the inheritance of these traits and heterotic manifestation for those traits could be rewarding. The findings were in agreement with earlier finding of Sharma and Sharma (2010) and Singh and Asati (2011) for plant height, Bhatt *et al*. (2001) for plant height, flowers per truss, fruits per plant, and yield, Yadav *et al*. (2013) for number of fruits per plant, yield per plant, and yield per hectare, Shankar *et al*. (2013) for yield per plant. On the other hand, polar diameter (4.320), equatorial diameter (2.457), number of locules (1.432), and fruit weight (1.249) had predictability ratio estimate greater than unity suggested preponderance of additive gene action for manifestation of these traits and continuous selection in successive generation could upregulate the expression. Similarly, Hannan *et al*. (2007) emphasized effective enhancement of fruit weight through repeated selection cycles.

Proportional contribution: To estimate the proportional contribution, total variance was partitioned into variance due to lines, testers, and line × tester interactions as depicted in **Table 2**. Predominant maternal contribution towards total variance was recorded for most of the traits *viz*., plant height (87.21%), days to first flower (57.80%), trusses per plant (75.52%), polar diameter (85.68%), equatorial diameter (71.20%), Locule number per fruit (90.83%), fruit weight (64.49%) and fruits per plant (83.15%); paternal influence found predominant yield per plant (40.34%) and yield per hectare (40.40%); and their interaction played significant role in manifestation of flowers per truss (52.53%) and days to 50% flowering (41.89%). However, maternal as well as parental interaction exhibited equal influence in the inheritance of primary branches, fruit per truss, and pericarp thickness.

Nature and degree of dominance: In the present experiment potence ratio estimate which utilized to estimate the nature and degree of dominance *i.e*., partial to complete dominance (**Table 3)**, was more than the unity either in positive or negative direction in majority cross combination for almost all the traits excepting truss per plant, polar diameter, fruit weight and fruits per plant suggested preponderance of over dominance phenomena in inheritance of those ten remained traits. Similar partial dominance for fruit weight and polar diameter, along with overdominance for fruit yield per plant, was evident in the investigation of Sherpa *et al*. (2014). Solieman *et al*. (2013) reported partial to overdominance for traits such as yield per plant, number of flowers per cluster, and number of fruits per plant. Maximum negative dominance estimates were recorded for days to first as well as 50 % flowering and fruits per plant, indicating involvement of high degree recessiveness might be due to asymmetrical distribution of dominant and recessive alleles in manifestation of these traits. Whereas complete positive dominance estimates were registered by primary branches and pericarp thickness. Complete dominance

Table 2. Analysis of variance for parents-hybrids, estimates of genetic components and proportional contribution to total variance for growth and yield contributing characters

Source of Variation (d.f.)	Mean Sum of Square for parents and hybrids for different yield contributing characters													
	PH	PB	DFF	FPF	TPP	FPT	PD	ED	PT	L	FW	FPP	YPP	YPH
Replication (2)	0.03	0.06	2.43	12.49	0.01	0.18	2.46	0.08	0.06	0.34	7.1	0.01	0.05	2.46
Genotypes (16)	1641.94**	20.58**	88.37**	89.35**	31.16**	32.26**	132.22**	156.46**	3.59**	2.67**	857.63**	248.33**	0.47**	108.13**
Parents (6)	1053.73**	29.66**	71.30**	105.71**	38.43**	62.93**	166.57**	84.27**	2.80**	3.55**	660.28**	310.00**	0.39**	89.53**
Hybrids (9)	1645.69**	11.49**	101.02**	76.98**	27.84**	15.34**	122.79**	211.64**	2.55**	2.27**	1049.64**	232.23**	0.50**	113.39**
Parents *vs* Hybrids (1)	5137.44**	47.94**	76.91**	102.53**	17.47*	0.42	10.93**	93.06**	17.73**	0.98**	313.75**	23.13**	0.72**	172.35**
Lines (4)	3229.12*	9.97	131.38	63.25	47.31	16.35	236.72**	339.05*	2.25	4.64*	1523.11*	434.48	0.34**	78.58**
Testers (1)	97.2	27.46	26.13	149.63	7.01	0.13	125.38*	457.63*	4.95	0.03	2567.99*	7.83	1.8**	412.26**
Lines *vs* Testers (4)	449.38**	9.01**	89.38**	72.55**	13.58**	18.14**	8.21**	22.72**	2.26**	0.46**	196.58*	86.08**	0.32**	73.48**
Error (32)	36.41	0.25	12.47	15.32	0.49	0.29	0.87	1.43	0.1	0.11	7.5	2.48	0.03	2.58
Components of genetic variation														
σ^2 GCA	55.21	0.11	0.54	0.20	0.66	0.13	5.29	8.72	0.014	0.083	39.37	6.75	0.008	1.84
σ^2 A	110.43	0.23	1.07	0.41	1.32	0.26	10.58	17.44	0.027	0.17	78.74	13.49	0.016	3.68
σ^2 SCA (σ^2 D)	137.65	2.92	25.64	19.08	4.36	5.95	2.45	7.10	0.72	0.12	63.03	27.87	0.10	23.63
Predictability ratio	0.802	0.078	0.042	0.021	0.302	0.043	4.320	2.457	0.038	1.432	1.249	0.484	0.159	0.156
Proportional contribution to the total variance (%)														
Lines	87.21	38.59	57.80	36.52	75.52	47.37	85.68	71.20	39.14	90.83	64.49	83.15	30.59	30.80
Testers	0.66	26.56	2.87	21.60	2.80	0.10	11.35	24.03	21.52	0.13	27.18	0.37	40.34	40.40
Line x Tester	12.14	34.86	39.32	41.89	21.68	52.53	2.97	4.77	39.34	9.05	8.32	16.47	29.07	28.80

**=Significance at 1% level; *= Significance at 5% level; PH – Plant height (cm), PB – Number of primary branches, DFF – Days to first flowering, FPF – Days to 50% flowering, TPP – Trusses per plant, FPT – Flowers per truss, PD – Polar diameter (mm), ED – Equatorial diameter (mm), PT – Pericarp thickness (mm), L – Locule number, FW – Fruit weight (g), FPP – Fruits per plant, YPP – Yield per plant (kg/plant), YPH – Yield per hectare (t/ha).

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was evident only by single cross for days to first flowering by B mut 3 x Patharkutchi. Seven crosses out of ten crosses registered over-dominance for days to first flowering (1.39 to -15.0), yield per plant (8.87 to -13.67), and yield per hectare (9.02 to -19.18). Whereas a total of six crosses for the plant height, days to 50% flowers, flowers per truss, equatorial diameter, and pericarp thickness registered over-dominance which ranged from 21.39 to -13.78, 0.27 to -10.0, 32.74 to -3.38, 95.30 to -1.64 and 5.99 to 0.02, respectively. However, equal importance of over-dominance and partial dominance were depicted for number of primary branches. Abundant partial dominance was noted for the traits *viz*., truss per plant with 6 crosses ranging from 0.82 to -0.26, polar diameter with 7 crosses ranging from 0.82 to -0.63, fruit weight for 7 crosses ranging from 0.78 to -0.58, and fruit per plant for 6 crosses ranging from 0.85 to -0.41.

General combining ability (GCA): Estimates for the general combining ability (GCA) (Table 3) highlighted the genetic potential of the parental lines to identify the best combiner. Among the maternal lines, B Mut-3 exhibited the maximum significant GCA estimates at desired direction for primary branches (1.8), days to 50% flowering (-3.0), flowers per truss (2.85), numbers of locules per fruit (-1.0), fruit per plant (14.64), yield per plant (0.25) and yield per hectare (3.79). BCT 115 *dg* recorded significant and maximum positive magnitude for polar diameter (6.78), equatorial diameter (7.08), and fruit weight (21.53). P Mut-5 recorded maximum positive and significant GCA estimate for pericarp thickness (0.63), while the same for P Mut-11 was demonstrated for trusses per plant (3.45). However, AC *Aft* exhibited maximum estimate at desired direction for the plant height (-29.63), days to first flowering (-4.27), and days to 50% flowering (-3.0). Hence, B Mut-3 and BCT 115 *dg* could be considered as the best combiner lines for most of the desirable traits under study. Among the pollen parent Berika displayed the maximum significant estimate of GCA at desired direction for Plant height (-1.8), primary branches (0.96), days to 50% flowering (-2.23), trusses per plant (0.48), polar diameter (2.04), equatorial diameter (3.91), pericarp thickness (0.41), fruit weight (9.25), fruits per plant (0.51), yield per plant (0.25) and yield per hectare (3.71); thereby Berika considered to be best combiner as tester.

Average performance of lines and testers: As depicted in **Table 2**, among the maternal lines, B Mut-3 emerged as a top performer, exhibiting the significantly highest estimates for most yield-attributing traits *viz*., primary branches (11.60), flowers per truss (18.60), fruits per plant (49.85). Whereas AC *Aft* found significantly superior for growth traits *viz*., recorded the minimum days to first flowering (31.33 days), 50% flowering (41.00 days) and maximum equatorial diameter (58.49 mm). BCT 115 *dg* stood out for its exceptional fruit weight (96.60 g), while P Mut-11 demonstrated superiority in trusses per plant (16.47) and polar diameter (60.86 mm). However, with respect to yield per plant and yield per hectare, significant estimate was recorded for B Mut-3 (2.55kg/ha and 38.47t/ha, respectively) followed by AC *Aft* (2.30kg/ha and 34.69 t/ha, respectively) and P Mut-11 (2.20 kg/ha and 33.23 t/ha, respectively). However, among the paternal lines, Berika exhibited significant desired manifestation for most of the traits *viz*., reduced plant height (66.84 cm), minimum days to first and 50% flowering (32 and 43.62 days, respectively), minimum locule number (2.0), maximum trust per plant (8.60), flower per truss (7.12), polar diameter (60.86 mm), equatorial diameter (58.49 mm), pericarp thickness (7.17 mm), fruit weight (91.61 g), yield per plant and per hectare (2.15 kg and 32.44 t/ha, respectively).

Specific combining ability (SCA): The *sca* effects of ten cross combinations for all studied traits (**Table 3**) reveal the influence of parental combinations on the manifestation of key growth and yield contributing traits. Among the crosses, maximum desired significant SCA effect exhibited by B Mut-3 × Berika for plant height (-13.17), flower per truss (2.04) and fruit per plant (5.65); BCT-115 *dg* × Berika for primary branches (1.88), equatorial diameter (2.91), pericarp thickness (0.91) and fruit weight (8.48); BCT-115 *dg* × Patharkutchi for locule numbers (-0.41); AC *Aft* × Patharkutchi for trusses per plant (2.55); P Mut-11 × Patharkutchi for days to first flower (-6.43) and days to 50% flower (-5.40); and P Mut-5 × Patharkutchi for polar diameter (1.82). With respect to yield per plant and yield per hectare maximum positive and significant magnitude was recorded P Mut-5 × Patharkutchi (0.28 and 4.23, respectively) followed by B Mut-3 × Berika (0.23 and 3.39, respectively), P Mut-11 × Patharkutchi (0.22 and 3.29, respectively) and AC *Aft* × Berika (0.16 and 2.42, respectively); thereby These hybrids demonstrated superior performance, making them ideal for further evaluation and commercial exploitation.

Average performance of cross combinations: As presented in Table 4, the cross combination *BCT-115 dg × Berika* exhibited significantly superior fruit characteristics, including the highest values for polar diameter (62.87 mm), equatorial diameter (67.86 mm), pericarp thickness (8.59 mm), and fruit weight (124.19 g). Whereas B Mut-3 × Berika was associated with significantly maximum fruit quantity, viz., flower per truss (13.28) and number of fruits per plant (53.34). However, significant and maximum yield per plant and hectare were recorded in B Mut-3 × Berika (3.06 kg and 46.19 t/ha, respectively) followed by AC *Aft* × Berika (2.89 kg and 43.71 t/ha, respectively) and BCT-115 *dg* × Berika (2.72 kg and 41.06 t/ha, respectively).

Heterotic performance of cross combinations: Based on *per se* performance, the best cross combinations for all fourteen traits, along with their relative heterosis (over mid-parent), heterobeltiosis (over the better parent), and nature of combining ability, are presented in **Table 5**. The results revealed that several traits—such as plant height, number of primary branches, days to first flowering, days to 50% flowering, number of flowers per truss, number of

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Table 3. GCA effect (*gca*) and average performance (*μ*) of Lines and Testers for growth and yield contributing characters

Genotypes		PH	PB	DFF	FPF	TPP	FPT	PD	ED	PT	L	FW	FPP	YPP	YPH
Lines															
BCT-115 *dg* (L1)	*gca*	3.51	-0.65**	-2.43*	-0.83	-4.09**	-0.57**	6.78**	7.08**	0.42**	0.53**	21.53**	-6.80**	0.02	0.35
	μ	60.46^{d}	2.87^{e}	37.67^{b}	51.33^{a}	9.23^{cd}	5.91^{cd}	59.76^{a}	52.3^{c}	5.75^{b}	4.63^{a}	96.6^{a}	16.36^{e}	1.39^{c}	21.02^{e}
AC *Aft* (L2)	*gca*	-29.63**	-1.62**	-4.27**	-3.00*	1.11**	-0.2	-3.05**	5.49**	-0.87**	0.82**	3.59**	-0.81	0.15*	2.28**
	μ	66.42^{d}	3.63^{e}	31.33^{d}	41^{c}	12.2^{b}	8.87^{b}	49.18^{b}	58.49^{a}	6.02^{b}	4.61^{a}	84.67^{c}	30.81^{c}	2.3^{ab}	34.69^{b}
P Mut-5 (L3)	*gca*	14.68**	-0.12	3.73**	3.17*	0.68*	-1.41**	-4.17**	3.47**	0.63**	0.57**	-2.73**	-4.92**	-0.37**	-5.67**
	μ	85.82^{b}	7.03^{c}	41^{ab}	50.33^{ab}	16.3^{a}	8.51^{b}	50.44^{b}	55.54^{b}	4.99^{c}	4.47^{a}	84.37^{c}	28.62^{cd}	2.12^{b}	32.11^{c}
P Mut-11 (L4)	*gca*	-5.84*	0.60**	6.23**	3.67*	3.45**	-0.67**	6.74**	-6.45**	0.17	-0.91**	0.66	-2.12**	-0.05	-0.75
	μ	76.30^{c}	9.82^{b}	44^{a}	57.33^{a}	16.47^{a}	5.64^{d}	60.86^{a}	46.77^{d}	5.68^{b}	4.47^{a}	83.4^{c}	29.96^{c}	2.2^{ab}	33.23^{bc}
B Mut-3 (L5)	*gca*	-9.72**	1.80**	-3.27*	-3.00*	-1.14**	2.85**	-6.3**	-9.6**	-0.35**	-1.00**	-23.05**	14.64**	0.25**	3.79**
	μ	64.24^{d}	11.6^{a}	33.67^{cd}	43^{bc}	10.2^{c}	18.6^{a}	46.91^{c}	42.54^{e}	5.92^{b}	3.2^{b}	58.04^{d}	49.85^{a}	2.55^{a}	38.47^{a}
S.E. (g_l)		2.46	0.203	1.442	1.598	0.285	0.22	0.381	0.488	0.129	0.137	1.118	0.643	0.065	0.656
Testers															
Berika (T1)	*gca*	-1.8	0.96**	-0.93	-2.23*	0.48**	-0.07	2.04**	3.91**	0.41**	-0.03	9.25**	0.51	0.25**	3.71**
	μ	66.84^{d}	5.63^{d}	32^{cd}	43.67^{bc}	8.6^{de}	7.12^{c}	60.13^{a}	51.97^{c}	7.17^{a}	2.66^{c}	91.61^{b}	26.63^{d}	2.15^{b}	32.44^{bc}
Patharkutchi (T2)	*gca*	1.8	-0.96**	0.93	2.23*	-0.48**	0.07	-2.04**	-3.91**	-0.41**	0.03	-9.25**	-0.51	-0.25**	-3.71**
	μ	114.16^{a}	6.20^{cd}	40^{ab}	52^{a}	7.83^{e}	5.84^{d}	42.19^{d}	50.86^{c}	4.03^{d}	2^{d}	60.62^{d}	35.98^{b}	1.96^{b}	29^{d}
S.E. (g_t)		1.55	0.128	0.912	1.011	0.18	0.139	0.241	0.309	0.082	0.866	0.707	0.406	0.041	0.415

Note: ***=Significance at 1% level; *= Significance at 5% level PH – Plant height (cm), PB – Number of primary branches, DFF – Days to first flowering, FPF – Days to 50% flowering, TPP – Trusses per plant, FPT – Flowers per truss, PD – Polar diameter (mm), ED – Equatorial diameter (mm), PT – Pericarp thickness (mm), L – Locule number, FW – Fruit weight (g), FPP – Fruits per plant, YPP – Yield per plant (kg/plant), YPH – Yield per hectare (t/ha).*

Table 4. SCA effect (*sca*), average performance (*μ*) and potence ratio (*P*) of hybrids for growth and yield contributing characters

Genotype		PH	PB	DFF	FPF	TPP	FPT	PD	ED	PT	L	FW	FPP	YPP	YPH
	sca	6.45*	1.88**	-2.9	-2.77	-0.3	1.75**	0.32	2.91**	0.91**	0.41*	8.48**	-0.4	0.12	1.70*
L1 x T1	*μ*	131.87^{a}	10.83^{a}	28.33^{cd}	39.67^{de}	8.83^{e}	9.57^{b}	62.87^{a}	67.86^{a}	8.59^{a}	4.92^{a}	124.19^{a}	25.86^{f}	2.72^{b}	41.06^{a}
	P	*21.39*	*4.76*	*-2.29*	*-2.04*	*-0.26*	*5.06*	*15.81*	*95.3*	*3*	*31.79*	*12.06*	*0.85*	*2.5*	*2.51*
	sca	-6.45*	-1.88**	2.9	2.77	0.3	-1.75**	-0.32	-2.91**	-0.91**	-0.41*	-8.48**	0.4	-0.12	-1.70*
L1 x T2	*μ*	122.58^{ab}	5.17^{d}	36^{b}	49.67^{ab}	8.47^{e}	6.21^{e}	58.14^{b}	54.22^{d}	5.95^{e}	4.15^{b}	88.74^{c}	25.63^{f}	2^{e}	30.24^{e}
	P	*1.31*	*0.38*	*-2.43*	*-6*	*-0.1*	*10*	*0.82*	*3.67*	*1.23*	*2.98*	*0.56*	*-0.06*	*1.14*	*1.31*
	sca	-1.55	0.44	-2.73	-3.27	2.55**	-1.05**	1.22*	-1.33*	0.33*	0.01	0.74	1.12	0.16*	2.42**
L2 x T1	*μ*	63.74^{e}	8.43^{c}	26.67^{d}	37^{e}	16.87^{a}	7.14^{d}	53.94^{c}	62.02^{b}	6.71^{cd}	4.8^{ab}	98.52^{b}	33.36^{c}	2.89^{ab}	43.71^{ab}
	P	*-13.78*	*3.8*	*-15*	*-4*	*3.59*	*-0.97*	*-0.13*	*2.08*	*0.2*	*10.46*	*2.99*	*2.22*	*8.87*	*9.02*
	sca	1.55	-0.44	2.73	3.27	-2.55**	1.05**	-1.22*	1.33*	-0.33*	-0.01	-0.74	-1.12	-0.16*	-2.42**
L2 x T2	*μ*	70.43^{e}	5.63^{d}	34^{bc}	48^{ab}	10.8^{d}	9.37^{b}	47.41^{d}	56.87^{c}	5.24^{f}	4.84^{a}	78.54^{d}	30.11^{de}	2.08^{de}	31.45^{de}
	P	*-0.83*	*0.56*	*-0.38*	*0.27*	*0.36*	*1.33*	*0.49*	*0.58*	*0.22*	*2.66*	*0.49*	*-1.27*	*-0.29*	*-0.14*
	sca	9.03**	-0.69**	0.6	0.9	-0.07	-1.52**	0.65	0.97	-0.31*	0.07	1.35	-4.55**	-0.28**	-4.23**
L3 x T1	*μ*	118.62^{b}	8.8^{c}	38^{b}	47.33^{ab}	13.83^{b}	5.46^{f}	52.24^{c}	62.3^{b}	7.58^{b}	4.61^{ab}	92.81^{c}	23.59^{f}	1.93^{e}	29.11^{e}
	P	*4.46*	*3.52*	*0.33*	*0.1*	*0.36*	*-3.38*	*-0.63*	*4.78*	*1.38*	*3.48*	*1.33*	*-4.06*	*-13.67*	*-19.18*
	sca	-9.03**	0.69**	-0.6	-0.9	0.07	1.52**	-0.65	-0.97	0.31*	-0.07	-1.35	4.55**	0.28**	4.23**
L3 x T2	*μ*	104.16^{c}	8.27^{c}	38.67^{b}	50^{ab}	13^{bc}	8.64^{c}	46.85^{d}	52.55^{d}	7.39^{b}	4.53^{ab}	71.61^{e}	31.66^{c-e}	2^{e}	30.15^{e}
	P	*0.29*	*3.96*	*-3.67*	*-1.4*	*0.22*	*1.1*	*0.13*	*-0.28*	*5.99*	*-0.05*	*-0.07*	*-0.17*	*-0.5*	*-0.26*
	sca	-0.76	-0.32	6.43**	5.40**	-0.9*	-1.22**	-0.37	-1.86**	-0.59**	-0.32	-4.54**	-1.83*	-0.22*	-3.29**
L4 x T1	*μ*	88.31^{d}	9.88^{b}	46.33^{a}	52.33^{a}	15.77^{a}	6.51^{e}	62.14^{a}	49.55^{e}	6.84^{cd}	2.74^{d}	90.32^{c}	29.11^{e}	2.31^{c}	34.97^{c}
	P	*3.54*	*1.03*	*1.39*	*0.27*	*0.82*	*0.17*	*4.5*	*0.07*	*0.56*	*0.13*	*0.69*	*0.49*	*5.4*	*5.41*
	sca	0.76	0.32	-6.43**	-5.40**	0.90*	1.22**	0.37	1.86**	0.59**	0.32	4.54**	1.83*	0.22*	3.29**
L4 x T2	*μ*	93.44^{cd}	8.62^{c}	35.33^{b}	46^{bc}	16.6^{a}	9.07^{bc}	58.78^{b}	45.46^{g}	7.21^{bc}	3.43^{c}	80.89^{d}	31.74^{cd}	2.26^{cd}	34.14^{cd}
	P	*-0.09*	*0.34*	*-3.33*	*-3.25*	*1.03*	*32.74*	*0.78*	*-1.64*	*2.85*	*-0.57*	*0.78*	*-0.41*	*1.5*	*1.43*
	sca	-13.17**	-1.31**	-1.4	-0.27	-1.28**	2.04**	-1.82**	-0.7	-0.34*	-0.18	-6.02**	5.65**	0.23**	3.39**
L5 x T1	*μ*	72.02^{e}	10.1^{ab}	29^{cd}	40.00^{c-e}	10.8^{d}	13.28^{a}	47.64^{d}	47.57^{f}	6.56^{d}	2.8^{cd}	65.12^{f}	53.34^{a}	3.06^{a}	46.19^{a}
	P	*4.99*	*0.5*	*-4.6*	*-10*	*1.75*	*0.07*	*-0.89*	*0.07*	*0.02*	*2.73*	*-0.58*	*1.3*	*3.55*	*3.56*
	sca	13.17**	1.31**	1.4	0.27	1.28**	-2.04**	1.82**	0.7	0.34*	0.18	6.02**	-5.65**	-0.23**	-3.39**
L5 x T2	*μ*	101.96^{c}	10.8^{a}	33.67^{bc}	45.00^{b-d}	12.4^{c}	9.33^{b}	47.2^{d}	41.15^{h}	6.43^{de}	3.21^{cd}	58.66^{g}	41.01^{b}	2.12^{c-e}	31.99^{c-e}
	P	*0.51*	*0.7*	*-1*	*-0.56*	*2.86*	*-0.45*	*1.12*	*-1.33*	*1.54*	*-0.87*	*-0.52*	*-0.27*	*-0.46*	*-0.37*
S.E. (S_{ij})		3.483	0.287	2.039	2.26	0.403	0.311	0.539	0.69	0.182	0.194	1.581	0.909	0.092	0.928

Note: **=Significance at 1% level; *= Significance at 5% level PH – Plant height (cm), PB – Number of primary branches, DFF – Days to first flowering, FPF – Days to 50% flowering, TPP – Trusses per plant, FPT – Flowers per truss, PD – Polar diameter (mm), ED – Equatorial diameter (mm), PT – Pericarp thickness (mm), L – Locule number, FW – Fruit weight (g), FPP – Fruits per plant, YPP – Yield per plant (kg/plant), YPH – Yield per hectare (t/ha).

Table 5. Superior cross combinations, heterosis (%) over mid parent & better parent and nature of combining ability for growth and yield contributing characters

Characters	Cross combination	Heterosis (%)		GCA	SCA
		Relative	*Heterobeltiosis*		
Plant height	AC *Aft* x Berika	-4.34	-4.64	Low x Medium	High
	AC *Aft* x Patharkutchi	-22.00	-38.31	Low x Medium	Medium
	B Mut-3 x Berika	9.89	7.75	Low x Medium	Low
Number of primary branches	BCT-115 *dg* x Berika	154.90	92.31	Low x High	High
	B Mut-3 x Patharkutchi	21.35	-6.90	High x Low	High
	B Mut-3 x Berika	17.21	-12.93	High x High	Low
Days to first flowering	AC *Aft* x Berika	-15.79	-16.67	Low x Medium	Medium
	BCT-115 *dg* x Berika	-18.66	-24.78	Low x Medium	Medium
	B Mut-3 x Berika	-11.68	-13.86	Low x Medium	Medium
Days to 50% flowering	AC *Aft* x Berika	-12.60	-15.27	High x Low	Medium
	BCT-115 *dg* x Berika	-16.49	-22.73	Medium x Low	Medium
	B Mut-3 x Berika	-7.69	-8.40	Low x Low	Medium
Trusses per plant	AC *Aft* x Berika	62.18	38.25	High x High	High
	P Mut-11 x Patharkutchi	36.63	0.81	High x Low	High
	P Mut-11 x Berika	25.80	-4.25	High x High	Low
Flowers per truss	B Mut-3 x Berika	-23.63	-49.82	High x Medium	High
Polar diameter	BCT-115 *dg* x Berika	4.88	4.56	High x High	Medium
	P Mut-11 x Berika	2.71	2.1	High x High	Medium
Equatorial diameter	BCT-115 *dg* x Berika	30.13	29.75	High x High	High
	P Mut-5 x Berika	15.90	12.17	High x High	Medium
	AC *Aft* x Berika	12.29	6.04	Low x High	Low
Pericarp thickness	BCT-115 *dg* x Berika	32.96	19.79	High x High	High
	P Mut-5 x Berika	24.66	5.71	High x High	Low
	P Mut-5 x Patharkutchi	63.78	48.02	High x Low	High
Locule number	P Mut-11 x Berika	17.74	3.13	Low x Medium	Medium
	B Mut-3 x Berika	7.62	-12.59	Low x Medium	Medium
Fruit weight	BCT-115 *dg* x Berika	31.97	28.56	High x High	High
	AC *Aft* x Berika	12.89	-8.14	High x High	Medium
Fruits per plant	B Mut-3 x Berika	39.49	7.0	High x Medium	High
	B Mut-3 x Patharkutchi	-4.44	-17.73	High x Medium	Low
Yield per plant	B Mut-3 x Berika	30.21	20.0	High x High	High
	AC *Aft* x Berika	29.89	25.65	High x High	High
	BCT-115 *dg* x Berika	53.67	26.51	Medium x High	Medium
Yield per hectare	B Mut-3 x Berika	30.28	20.07	High x High	High
	AC *Aft* x Berika	30.22	26.0	High x High	High
	BCT-115 *dg* x Berika	53.61	26.57	Medium x High	High

locules, and fruits per plant, exhibited desirable heterotic expression even from crosses involving poor general combiners. In contrast, the yield-contributing traits observed in crosses involving a wide range of combiners, ranging from good to poor, indicate the involvement of both additive and dominance gene actions in the expression of heterosis for these traits.The significance of both additive and non-additive genetic components in the inheritance of plant height and number of fruits per plant has also been supported by earlier studies (Kumari and Sharma, 2012). Similarly, Rao *et al.* (2008) emphasized the genetic determinants of plant height, while Hannan *et al.* (2007) reported genetic control over traits such as fruits per plant and number of flowers per cluster. Conversely, traits such as polar diameter and fruit weight in the F_1 hybrids appeared to be predominantly influenced by high general combining ability (GCA) and low specific combining ability (SCA), indicating that additive genetic effects played a major role in their expression. This suggests that these traits are amenable to improvement through recombination breeding, followed by effective selection in later generations. Similar findings were reported by Izzo *et al.* (2022), who highlighted the significant role of additive gene action in governing fruit weight and polar diameter. In the present study, a broad spectrum of heterosis was observed across all evaluated traits when compared to both mid-parent and better-parent values. Notably, total yield exhibited heterosis ranging from 53.61% to -9.81% over the mid-parent and from 26.57% to -16.84% over the better parent. These results underscore the potential for enhancing commercially important traits through heterosis breeding. Among the evaluated crosses, *B Mut-*

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3 × *Berika*, *AC Aft* × *Berika*, and *BCT-115 dg* × *Berika* emerged as the most promising combinations. These crosses recorded the highest number of desirable traits, particularly for total yield, with relative heterosis and heterobeltiosis values of 30.28% & 20.07%, 30.22% & 26.00%, and 53.61% & 26.57%, respectively.

The present investigation demonstrated the relative significance of both additive and non-additive gene action in the manifestation of important traits. Although, for polar diameter, equatorial diameter, locules number, and fruit weight, additive gene components were found important. Hence, overdominance was the predominant genetic mechanism observed for most traits, except for trusses per plant, polar diameter, fruit weight, and fruits per plant, where partial dominance played a more significant role. The crosses **B Mut-3 ×** *Berika***, AC** *Aft* **×** *Berika*, and **BCT-115 dg ×** *Berika* exhibited the highest magnitudes for several desirable growth and yield-related traits and were thus identified as superior hybrid combinations.

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