J. Agric. Sci. Technol. (2024) Vol. 26(2): 343-357

Breeding Sweet Pepper for Improvement in Yield Components and Fruit Quality Traits under Low Cost Protected Structure

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ABSTRACT

Exploitation of heterosis is one of the potential means for improvement of sweet pepper (*Capsicum annuum* var. *grossum* L.) that can further be utilized for identification of desirable recombinants. Promising hybrids could be acceptable to growers of tropical and subtropical climates if it is a high yielder with attractive fruit colour and blocky shape. Seven diverse parents were selected through multivariate analysis and were crossed in half diallel mating design to determine the extent of heterosis, mode of gene action, combining ability effects, and dominance estimates for 18 quantitative characters. Expression of fruit colour and shape at physiological maturity stage in the F_1 generation indicated the dominance of red coloured group over other fruit colour groups and dominance of blocky fruit shape over elongate and round fruit shape. Preponderance of non-additive gene action for most of the characters under study suggested the usefulness of exploitation of hybrid vigour. Three genotypes, 8/4, C/4, and Baby Bell were found most promising donors. The hybrids, Arya×Baby Bell, 8/4×Baby Bell and C/4×8/4 were identified as promising based on per se performance, heterosis manifested, and relevance of specific combining ability effects, for possible commercialization under low cost protected structure of tropical and subtropical climates after critical testing. Partial to over dominance response in inheritance of most traits contributed to the genetic basis of heterosis. Isolation of pure lines from the segregating generation of heterotic hybrids emerged as a promising approach to develop line-bred variety having improved fruit yield and quality.

Keywords: *Capsicum annuum* var. *grossum* L., Combining ability, Dominance effect, Heterosis.

INTRODUCTION

Sweet pepper (*Capsicum annuum* var. *grossum* L.), also known as bell pepper or Shimla Mirch, is a popular vegetable for its delicate taste and pleasant flavor coupled with high nutritive value and anti-inflammatory compounds (Marin *et al*., 2004). The colour and shape of fruit decides the market value of the produce. Based on the fruit shape and size, sweet pepper can be grouped into four broad market categories: (i) Fresh market (green, red, multi-colour whole fruits), (ii) Fresh processing (sauce, paste, canning, pickling), (iii) Industrial extracts (paprika/ oleoresin, capsaicinoids and carotenoids), and (iv) Ornamental (plants and/or fruits) (Poulos, 1994). Cultivation of coloured sweet pepper in low cost poly houses has proved to be a very remunerative venture to small and marginal growers to get maximum economic returns. The varieties or hybrids so far released by both public and private sectors are poor yielder and vulnerable to insect-pest and diseases. There is an urgent need to identify suitable hybrids for low cost polyhouse in tropical and sub-tropical

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[DOI: 10.22034/JAST.26.2.343]

climates. There is little breeding targeted toward enriching nutritive values in the tropics and sub-tropics where cultivation of sweet peppers remains limited and sporadically grown under open field conditions.

Heterosis breeding in sweet pepper provides an opportunity to achieve improvement that would otherwise require extensive time, using other breeding methods. This breeding approach continues to be the preferred method of improving yield and economically important traits. Sweet pepper possesses a wide range of genetic variability, although this advantage has not been fully assessed and utilized to develop improved varieties/hybrids for use in tropics and sub-tropics. Heterosis for various characters including early maturity, plant height, and certain yield components in sweet pepper have been reported (Lee and Shin, 1989; Galal *et al*., 2018). Diallel mating design (Griffing, 1956) is an analysis useful for preliminary evaluation of genetic stock for use in hybridization to identify good general, specific-combiners and illustrates the nature and magnitude of gene action involved in the expression of desirable traits. This investigation was undertaken to determine the mode of gene action to choose a breeding strategy; to determine the extent of heterosis and dominance effect, and to estimate combining ability for specific characters in sweet pepper grown under low cost protected structure.

MATERIALS AND METHODS

Plant Materials and Field Growing

Present investigation was carried out under low cost poly house at “C” Block Farm of Bidhan Chandra Krishi Viswavidyalaya (BCKV), Kalyani, Nadia, West Bengal, India. Twenty-one advanced breeding lines of sweet pepper collected from Mission for Integrated Development of Horticulture, BCKV, Mohanpur, West Bengal and Indian Institute of Vegetable Research, Varanasi, constituted the plant materials for this study. On the basis of fruit colour (RHS colour), shape, and other economically important traits, 7 diverse sweet pepper genotypes, namely, C/4 (Red Group 42A, Blocky), 8/4 (Orange Red Group 34A, Elongate shape), Arya (Red Group 45A, Blocky shape), Baby Bell (Red Group 42A, Blocky shape), BC CAP Purple (Purple Group N77A, Blocky shape), Royal Wonder (Green Group N137B, Almost Round shape) and BC CAP White (Green white Group 157 C, Blocky shape), collected from Mission for Integrated Development of Horticulture, BCKV, were selected for hybridization programme through multivariate analysis (Banerjee, 2020). Selfed seeds of 7 sweet pepper genotypes were sown in well-prepared nursery bed to raise the seedlings during the first week of November, 2017. Thirty- day-old seedlings were transplanted in well prepared separate beds measuring 1.0×4.0 m at 50×50 cm spacing under poly house in the afternoon hours. Well rotten FYM at 15 tons/ha along with a fertilizer dose of 150 kg N, 75 kg P_2O_5, and 75 kg K_2O ha^{-1} was applied to the crop. All the cultural practices scheduled for its cultivation were followed in time as per Chattopadhyay *et al*. (2007). During full bloom, crossing was carried out in the morning. Matured fruits were harvested for extraction of seeds, and dried seeds were kept for the next season. Seeds of 21 F_1s and 7 parental lines were again sown in well-prepared nursery bed to raise the seedlings during first week of October, 2018. Thirty-day-old seedlings were transplanted in well prepared separate beds following Randomized Complete Block Design with 3 replications under low cost poly house in the afternoon hours. Spacing and fertilizer management was followed as per previous method. The crop was maintained according to Chattopadhyay *et al*. (2007).

Observations Recorded

Observations were recorded from ten randomly selected plants from each genotype and the average was worked out for statistical computation. Ten fruits per genotype per replication were taken for

[DOI: 10.22034/JAST.26.2.343]

recording different fruit characters. The fruits were cut into two halves to record pericarp thickness (mm) and locules per fruit. The details of all observations taken for the study are described below.

Quantitative and Fruit Quality Traits

Data were taken on plant height (cm), days to first flowering, days to 50% flowering, days to first harvest, number of branches per plant, fruit length (cm), fruit diameter (cm), shape index, pericarp thickness (mm) of fruit, number of locules per fruit, number of seeds per fruit, number of fruits per plant, average fruit weight (g), and fruit yield per plant (kg). The cut fruits were used to make replication-wise composite sample to estimate fruit quality characters i.e., Total Soluble Solids (TSS) content of fruit (^{0}brix) determined by hand Refractometer, vitamin-C content of fruit (mg 100 g^{-1}), lycopene content of fruit (mg 100 g^{-1}) and β-carotene content of fruit (mg 100 g^{-1}) as per Sadasivam and Manickam (1996).

Statistical Analysis

To identify the factor dimension of the data, Principal Component Analysis (PCA) was used to summarize varietal information in a reduced number of factors for selection of the best performing genotypes. Following analysis of variance to test significance for each character, combining ability analyses were carried out according to Singh and Chaudhary (1985). Combining ability analysis was worked out according to Griffing's (1956) fixed-effect model. Magnitude of heterosis for all the hybrids was estimated over Mid-Parent (MP), Better-Parent (BP), and Standard Heterosis (SH) over two commercial hybrids, Orobelle and Asha as per Hayes *et al*. (1965). Significance of heterosis was determined following the "t" test suggested by Wynne *et al*. (1970). The Dominance Estimates (DE) was computed using the formula suggested by Smith (1952). Statistical analyses were done following the software package Windostat (ver. 8.0, Indostat Services, Hyderabad, India).

RESULTS AND DISCUSSION

Genetic Diversity through Multivariate Analysis

Knowledge on genetic divergence among the available germplasm is important to a plant breeder for an efficient choice of parents for hybridization. Selection of parents identified based on diversity analysis would be more effective for a hybridization programme. Divergence analysis of 21 sweet pepper genotypes was investigated through the study of Principle Component Analysis (PCA) in the present investigation (Table 1).

The PCA was performed to obtain a simplified view of the relationship between the characters β-carotene content, number of fruits per plant, lycopene content of fruit and average fruit weight, which explained almost 100 per cent contribution towards divergence, and variable loadings for components PC_1 (β-carotene content of fruit), PC_2 (number of fruits per plant), PC_3 (lycopene content of fruit) and PC_4 (average fruit weight) were estimated (Table 1). These components were chosen because their eigenvalues were more than 1.0 and explained almost 100% of total variance. The first component (PC_1) explained 81.65% of total variance in which an increase of β-carotene content of fruit content leads to increase in lycopene content of fruit and fruit weight, and decrease in number of fruits/plant. The second component (PC_2) explained an additional 18.13% of total variance in which a decrease in number of fruits per plant leads to decrease in β-carotene content of fruit and lycopene content of fruit, and increase in fruit weight. The third component (PC_3) explained an additional 0.16% of total variance in which an increase in lycopene content of fruit leads

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Table 1. Results of Principal Component Analysis (PCA) for characters contributing to divergence in sweet pepper and contribution of diverse traits in the principal components of sweet pepper.

Principal components	Eigen value (%)	Variance (%)	Cumulative variance (%)	
Eigen values and per cent variance accounted for by PCA based on correlation matrix				
PC_1	2090.54865	81.65	81.65	
PC_2	464.19798	18.13	99.79	
PC_3	4.19595	0.16	99.95	
PC_4	1.04796	0.04	99.99	
Variables	PC_1	PC_2	PC_3	PC_4
Factor loadings due to PCs with eigenvalues greater than 1				
β- carotene content of fruit(mg 100 g^{-1})	0.007941	-0.003849	0.032368	0.686042
Number of fruits/Plant	-0.011586	-0.064189	0.991897	-0.028470
Lycopene content of fruits (mg 100 g^{-1})	0.006106	-0.010310	0.008407	0.726529
Average fruit weight (g)	0.523937	0.849507	0.060787	0.001495

to increase in β-carotene content, number of fruits/plant and average fruit weight (Table 1). Genotypes in close proximity are perceived as being similar in PCA; genotypes that are further apart are more diverse. The differences observed in the data, and summarized in the PCA (Figure 1), indicated genotypes C/4, 8/4, Arya, Baby Bell, BC CAP Purple, Royal Wonder, and BC CAP White were quantitatively dissimilar from others. The remainder of genotypes had similar features forming a separate cluster. Based on PCA, fruit colour, shape and average performance for fruit yield, genotypes C/4, 8/4, Arya, Baby Bell, BC CAP Purple, Royal Wonder, and BC CAP White were good candidates for utilization in breeding programs.

Expression of Fruit Colour and Shape in F_1 Generation

In the present investigation, all the sweet pepper hybrids revealed wide variation in fruit colour according to the colour chart of Royal Horticultural Society (RHCC) involving different coloured parents (Table 2). Seventeen out of 21 hybrids showed red color (with distinct shades), which manifested dominance of red coloured group over other colour groups. In other hybrid combinations, purple colour (BC CAP Purple) was dominant over orange red (8/4) and white (BC CAP White), while green color (Royal Wonder) was dominant over purple (BC CAP Purple) and white (BC CAP White). Coloured bell pepper genotypes attain specific fruit colour at physiological maturity. Fruit color at physiological maturity happens due to degradation in chlorophyll and accumulation of anthocyanin and carotenoid pigments (Stommel and Griesbach, 2008). *Phytoene synthase (Psy), Lycopene-β-cyclase (Lcyb), β-Carotene hydroxylase (Crtz),* and *Capsanthin/capsorubin synthase (Ccs)* genes are involved in the carotenoid biosynthesis pathway during pepper fruit colour formation (Guzman *et al*., 2010). β-carotene is the precursor for the predominant orange and red pigments in sweet pepper, and genotypes with high concentrations of β-carotene proved to be the richest in total carotenoid content. Therefore, β-carotene content may be a selection criterion for developing highly coloured sweet pepper. In the case of violet/purple fruited peppers, anthocyanins (flavonoid derivatives) contribute to the violet/purple colour (Lightbourn *et al*., 2008). Violaxanthin, β-carotene, lutein, antheraxanthin, and zeaxanthin are the most important pigments in yellow and yellow-orange fruited peppers

[DOI: 10.22034/JAST.26.2.343]

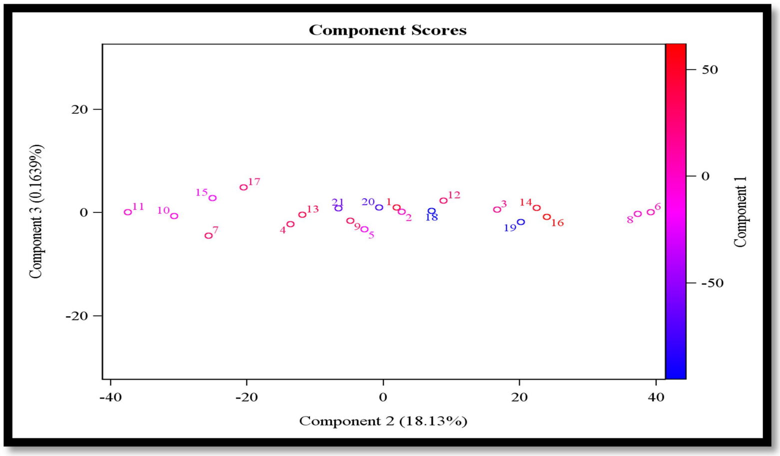

Figure 1. Scatter diagram of regression factor scores for the first, second and third components as determined by principal component analysis. Points in diagram closest to the intersection of 0 on the X- and Y-axes indicate similarity. Outliers on the X-axis, that is, 6= Royal Wonder, 8= 8/4, 3= C/4, 14= Arya, 16= Baby Bell, 19= BC CAP Purple, 11= BC CAP White, indicate diversity.

Table 2. Manifestation of fruit colour and shape at marketable stage of 7 parents and 21 hybrids of sweet pepper genotypes.

	Fruit colour	Fruit shape
Parents		
C/4	Red Group 42A	Blocky
8 /4	Orange Red Group 34A	Elongate
Arya	Red Group 45A	Blocky
Baby Bell	Red Group 42A	Blocky
BC CAP Purple	Purple Group N77A	Blocky
Royal Wonder	Green Group N137B	Almost round
BC CAP White	Green White Group 157C	Blocky
Hybrids		
C/4×8/4	Red Group 44A	Blocky
C/4×Arya	Red Group 45A	Blocky
C/4×Baby Bell	Red Group 46A	Blocky
C/4×BC CAP Purple	Red Group 45A	Blocky
C/4×Royal Wonder	Red Group 42A	Blocky
C/4×BC CAP White	Red Group 46A	Blocky
8/4×Arya	Red Group 45A	Intermediate
8/4×Baby Bell	Orange Red Group N34A	Intermediate
8/4×BC CAP Purple	Purple Group N77A	Blocky
8/4×Royal Wonder	Orange Red Group N34A	Blocky
8/4×BC CAP White	Red Group 45A	Blocky
Arya×Baby Bell	Red Group 45A	Blocky
Arya×BC CAP Purple	Red Group 44B	Blocky
Arya×Royal Wonder	Red Group 45A	Blocky
Arya×BC CAP White	Red Group 44A	Blocky
Baby Bell×BC CAP Purple	Red Group 42A	Blocky
Baby Bell×Royal Wonder	Red Group 46A	Blocky
Baby Bell×BC CAP White	Red Group 45A	Blocky
BC CAP Purple×Royal Wonder	Green Group N137B	Blocky
BC CAP Purple×BC CAP White	Purple Group N79A	Blocky
Royal Wonder×BC CAP White	Yellow Green Group 145A	Blocky

[DOI: 10.22034/JAST.26.2.343]

(Wahyuni *et al*., 2011). The red colour of hybrid fruits with different shades in the hybrids might be due to the effect of modifier genes. Kumar *et al*. (2009) and Banerjee *et al.* (2022) studied the inheritance pattern of fruit colour at seed maturity and physiological maturity stages, respectively, in sweet pepper. They found that red colour was dominant over others at both stages, which also agreed well with the present findings. Sweet pepper produces red fruit when both genes (R and Y) are present in dominant form (R_Y_) and produce yellow fruit when one of the two genes is present in dominant form and the other in recessive form, or both the genes are present in recessive form (R_yy, rrY_, or rryy) (Banerjee *et al*., 2022). Ikeno (1913) obtained a 3 purple:1 non-purple ratio in F_2 generation and postulated a monofactorial difference in purple colour inheritance.

In the present study, 19 out of 21 hybrids showed blocky fruit shape suggested that blocky fruit shape was dominant over other fruit shapes. The hybrids 8/4 (elongate)×Arya (blocky) and 8/4 (elongate)×Baby Bell (blocky) produced intermediate type of fruit shape. Whereas, 8/4 (elongate)×Royal Wonder (almost round) produced blocky shaped fruit. The intermediate fruit shape of hybrids resulted from the crosses involving elongate and blocky fruit shapes, and elongate and almost round might be due to the effect of epistasis gene interaction. Roy *et al*. (2019) also studied the fruit shape of different parents and hybrids and they reported the predominance of blocky fruit shape over other fruit shapes. Blocky fruit shape is dominant over others (McArdle and Bouwkamp, 1983) and found support from the present findings at physiological maturity.

Genetic Control of Quantitative Traits

The analysis of variance revealed that the parents were highly significant for all the characters under study, indicating suitability for developing promising hybrids utilizing these parental lines (Table 3). Presence of sufficient amount of genetic variation suggests the possibility of improvement of economic traits through hybridization followed by selection and heterosis breeding in sweet pepper. Highly significant variances for parents, hybrids, and parents vs. hybrids of dissimilar category for most of the components traits in sweet pepper were also observed by Galal *et al*. (2018) and Kaur *et al*. (2018). The analysis of variance for combining ability based on Griffing's Model 1 and Method 2 revealed significant component of general combining ability (GCA) and specific combining ability (SCA) mean squares for fruit yield per plant, along with all studied traits in F_1 generation (Table 3). This indicated that the inheritance of fruit yield per plant, most of the yield components and fruit quality traits were apparently controlled by both additive and non-additive gene action.

The importance of additive and non-additive genetic effects for the control of characters is also ascertained by the predictability ratio as suggested by Baker (1978). The study reflected the preponderance of non-additive gene effects (Predictability ratio< 0.50) for plant height, days to first flowering, days to 50% flowering, days to first harvest, number of branches per plant, fruit diameter, shape index, pericarp thickness, number of seed per fruit, TSS content of fruit, vitamin-C content of fruit, lycopene content of fruit, β-carotene content of fruit, number of fruit per plant, average fruit weight, and fruit yield per plant (Table 3). Heterosis breeding would be the best possible option for improving these traits in sweet pepper. Fruit length and number of locule per fruit were controlled by both additive and non-additive gene action (Predictability ratio≥ 0.50 and < 0.80). Population improvement approach through diallel selective mating (Jensen, 1970) or mass selection with concurrent random mating (Redden and Jensen, 1974) or restricted recurrent selection by intermating the most desirable segregates followed by selection (Bhutia *et al*., 2015) could be followed

[DOI: 10.22034/JAST.26.2.343]

Table 3. Analysis of variance (mean squares) for 18 characters in 7×7 half diallel cross and combining ability (Griffing's Model 1 and Method 2) of sweet pepper.

Source of Variation	Mean sum of square					
	Replication	Treatments	Parents	Hybrids	Parents *vs*. hybrids	Error
Degree of freedom	2	27	6	20	1	54
Plant height (cm)	48.617	1104.735**	702.487**	1226.236**	1088.215*	199.561
Days to first flowering	2.393	92.830**	25.714**	84.416**	663.813**	7.232
Days to 50% flowering	3.726	167.448**	166.302**	114.163**	1240.004**	7.776
Days to first harvest	42.048	677.339**	751.778**	471.787**	4341.730**	9.270
Number of primary branches/plant	0.125	0.582**	0.770**	0.458**	1.949**	0.109
Fruit length (cm)	10.898	10.198**	8.575**	10.316**	17.564**	1.164
Fruit diameter (cm)	0.065	1.953**	1.863**	2.076**	0.032	0.300
Shape index	0.292	0.385**	0.308**	0.399**	0.563**	0.059
Pericarp thickness (mm)	0.014	3.818**	1.314**	4.589**	3.425**	0.251
Number of locules/Fruit	0.033	0.353**	0.318**	0.369**	0.227**	0.008
Number of seeds/Fruit	11.309	5546.815**	1539.579**	6973.297**	1060.589**	91.772
TSS content of fruit (^{0} brix)	0.072	4.422**	2.278**	5.265**	0.429	0.121
Vitamin-C content of fruit (mg 100 g^{-1})	34.969	5094.886**	2472.240**	4446.231**	33803.874**	35.135
Lycopene content of fruit (mg 100 g^{-1})	0.002	4.381**	2.970**	4.860**	3.260**	0.002
β-carotene content of fruit (mg 100 g^{-1})	0.010	4.536**	4.268**	4.699**	2.891**	0.003
Number of fruits/Plant	0.049	55.200**	7.061**	66.299**	122.056**	1.299
Average fruit weight (g)	0.282	1275.053**	1960.550**	1117.327**	316.602**	9.514
Fruit yield/Plant (kg)	0.002	0.795**	0.164**	0.934**	1.800**	0.019
	Mean sum of square					
	GCA	SCA	Error	α^2a	α^2na	α^2a/(α^2a+α^2na)
Degree of freedom	6	21	54			
Plant height (cm)	531.795**	321.516**	66.520	103.394	254.996	0.289
Days to first flowering	43.144**	27.458**	2.411	9.052	25.047	0.265
Days to 50% flowering	116.362**	38.517**	2.592	25.282	35.925	0.413
Days to first harvest	229.837**	224.620**	3.090	50.388	221.530	0.185
Number of primary branches/ plant	0.199**	0.193**	0.036	0.036	0.156	0.188
Fruit length (cm)	8.560**	1.925**	0.388	1.816	1.537	0.542
Fruit diameter (cm)	1.156**	0.507**	0.100	0.235	0.407	0.366
Shape index	0.263**	0.090**	0.020	0.054	0.070	0.437
Pericarp thickness (mm)	1.808**	1.120**	0.084	0.383	1.036	0.270
Number of locules/Fruit	0.298**	0.066**	0.003	0.066	0.063	0.509
Number of seeds/Fruit	2787.322**	1580.829**	30.591	612.607	1550.238	0.283
TSS content of fruit (^{0} brix)	1.506**	1.465**	0.040	0.326	1.425	0.186
Vitamin-C content of fruit (mg 100 g^{-1})	1645.768**	1713.303**	11.712	363.124	1701.592	0.176
Lycopene content of fruit (mg 100 g^{-1})	2.919**	1.044**	0.001	0.649	1.043	0.383
β-carotene content of fruit (mg 100 g^{-1})	3.180**	1.036**	0.001	0.706	1.035	0.406
Number of fruits/Plant	27.667**	15.752**	0.433	6.052	15.319	0.283
Average fruit weight (g)	845.131**	304.985**	3.171	187.102	301.814	0.383
Fruit yield/Plant (kg)	0.403**	0.225**	0.006	0.088	0.219	0.287

* and **: Significant at 0.05 and 0.01 levels of probability.

[DOI: 10.22034/JAST.26.2.343]

for the exploitation of both additive and non-additive gene action for the traits fruit length and number of locule per fruit. The overwhelming response of non-additive gene action (Aditika *et al*., 2020) and both additive and non-additive gene action (Gendy and Badr, 2018) for the control of concerned traits in the present study was reported irrespective of parents, environments, and biometrical techniques adopted.

Identification of Good and Specific Combiners

No single parent was found to be a good general combiner for all the traits under study (Table 4). The parent 8/4, C/4 and Baby Bell recorded the maximum significant GCA effects in the desired direction for yield, yield contributing and quality traits. By ranking parents according to the GCA effects and *per se* performance, three parents, namely, 8/4, C/4, and Baby Bell were found most promising genitors because they produced the maximum frequency of high yielding hybrids with appreciable fruit quality and earliness when crossed with other genitors. On the other hand, no single cross was judged as good specific combiner for all characters under study (Table 5). The crosses, Arya×Baby Bell, 8/4×Baby Bell, and C/4×8/4 exhibited the maximum significant SCA effects in the desired direction for fruit yield per plant along with earliness and fruit quality traits utilizing crosses of dissimilar parents and environments. Crosses with High×High GCA effects, as 8/4×Baby Bell and C/4×8/4 for the trait fruit yield per plant could produce desirable transgressive segregates in advance generations because additive genetic effect present in the good combiner and complementary epistatic effect in the F_1 may act in the same direction to maximize desirable plant attributes. Crosses exhibiting desirable SCA effects may be used to develop improved genotypes. Based on SCA effects and *per se* performance for earliness, fruit yield per plant and yield attributing traits along with fruit quality parameters, three cross combinations, namely, Arya×Baby Bell, 8/4×Baby Bell and C/4×8/4 could be identified as good specific combiners for future breeding in sweet pepper. Significant GCA and SCA effects in the desired direction for fruit yield per plant and other characters have also been reported by earlier workers (Galal *et al*., 2018; Aditika *et al*., 2020)

Extent of Heterosis and Dominance Estimates

The highest significant heterobeltiosis in the desired direction was found for fruit yield per plant followed by number of fruits per plant, number of seeds per fruit, lycopene content of fruit and vitamin-C content of fruit (Table 5). The negative estimates of heterosis would be desirable for days to first flowering, days to 50% flowering, and days to first harvest. In the present study, the highest significant negative heterobeltiosis was manifested for days to first flowering followed by days to 50% flowering and days to first harvest. The perusal of analyses suggested that three cross combinations, i.e. 8/4×Baby Bell, Arya×Baby Bell, and C/4×8/4, showed the maximum significant heterobeltiosis in the desired direction for fruit yield per plant along with days to first flowering, days to 50% flowering, number of fruits per plant, vitamin-C content of fruit, and lycopene content of fruit. The essence of the superiority of F_1 hybrids over the better parent *vis-a-vis* the standard hybrid can profitably be exploited for commercial production. In the present study, high extent of relative heterosis and heterobeltiosis, as observed for fruit yield and yield components, could be attributed to its facultative cross-pollinated nature of the crop (Bosland and Votova, 2003). Rather than relative heterosis and heterobeltiosis, the standard (useful or economic) heterosis reflects the actual superiority of the newly

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Table 4. Estimates of general combining ability (g_i) effects and *per se* performance in 7 parents of sweet pepper.

	C/4	8/4	Arya	Baby Bell	BC CAP Purple	Royal Wonder	BC CAP White	SE (gi)
Plant height (cm)	-7.66** (103.89)	7.47** (94.56)	3.21 (121.56)	10.39** (128.11)	0.39 (107.67)	-10.54** (92.94)	-3.26 (86.72)	2.52
Days to first flowering	-0.52 (39.67)	-0.48 (39.33)	-1.41** (33.67)	-3.48** (36.00)	1.67** (40.00)	1.00* (39.00)	3.22** (42.67)	0.48
Days to 50% flowering	-3.78** (42.33)	-1.86** (46.00)	-1.52** (46.00)	-3.67** (41.33)	4.96** (62.33)	1.74** (47.33)	4.07** (54.67)	0.5
Days to first harvest	5.59** (126.67)	-8.64** (98.33)	2.18** (129.33)	-5.27** (101.33)	2.77** (136.33)	2.59** (128.33)	0.77 (136.00)	0.54
Number of primary branches/Plant	0.04 (2.00)	-0.09 (2.50)	-0.16** (2.50)	0.02 (2.00)	0.01 (2.33)	0.29** (3.5)	-0.11 (2.33)	0.06
Fruit length (cm)	0.81** (11.41)	1.26** (12.96)	0.53** (10.37)	0.09 (10.45)	-1.50** (8.67)	-0.26 (9.53)	-0.92** (7.92)	0.19
Fruit diameter (cm)	0.48** (7.18)	-0.34** (5.85)	-0.06 (6.32)	0.17 (7.63)	0.16 (7.04)	0.23* (6.68)	-0.58** (5.38)	0.1
Shape index	0.005 (1.59)	0.28** (2.23)	0.10* (1.64)	0.01 (1.37)	-0.27** (1.23)	-0.11* (1.45)	-0.01 (1.47)	0.04
Pericarp thickness (mm)	0.31**(5.58)	-0.71** (5.05)	0.30** (6.03)	0.18* (5.56)	-0.59** (4.94)	0.31** (6.84)	0.21* (6.14)	0.09
Number of locules/Fruit	-0.09** (3.00)	-0.16** (3.34)	0.08** (3.67)	0.06** (3.67)	0.32** (4.00)	-0.23** (3.33)	0.02 (3.34)	0.02
Number of seeds/ fruit	0.301 (109.71)	13.50** (96.90)	-23.14** (70.02)	24.55** (140.83)	11.77** (90.67)	-9.24** (118.54)	-17.73** (93.84)	1.71
TSS content of fruit (^{0} brix)	0.31** (8.67)	-0.01 (7.73)	0.21** (6.97)	0.35** (7.90)	-0.86** (6.70)	-0.02 (6.07)	0.02 (7.77)	0.06
Vitamin-C content of fruit (mg 100 g^{-1})	-2.53* (176.41)	-7.83** (130.81)	17.28** (133.65)	10.25** (184.83)	-23.26** (130.77)	-2.72* (123.11)	8.80** (186.65)	1.06
Lycopene content of fruit (mg 100 g^{-1})	0.05** (1.21)	0.15** (1.69)	0.45** (2.42)	0.88** (2.16)	-0.75** (0.11)	-0.60** (0.29)	-0.17** (0.06)	0.01
β-carotene content of fruit (mg 100 g^{-1})	0.32** (2.60)	0.14** (2.27)	0.51** (2.14)	0.74** (2.46)	-0.72** (0.16)	-0.79** (0.20)	-0.22** (0.10)	0.01
Number of fruits/Plant	1.04** (9.76)	2.66** (10.00)	-0.28 (7.25)	1.23** (9.51)	-0.60** (7.67)	-2.30** (6.03)	-1.75** (7.27)	0.2
Average fruit weight (g)	11.52** (116.4)	-5.53** (82.94)	3.77** (115.03)	8.33** (95.01)	-11.07** (65.32)	5.70** (126.7)	-12.72** (62.89)	0.55
Fruit yield/Plant (kg)	0.21** (1.14)	0.21** (0.83)	0.01 (0.83)	0.20** (0.9)	-0.17** (0.5)	-0.20** (0.76)	-0.27** (0.46)	0.02

* and **: Significant at 0.05 and 0.01 levels of probability.

Table 5. Promising cross combinations in F_1 generation with type of cross combinations based on GCA effects, better parent and standard heterosis of sweet pepper hybrids.

Characters	Crosses with high heterobeltiosis in desired direction along with type of cross combination[a]	Range of Heterobeltiosis (%)	Significant Heterobeltiosis (%)	*Per se* performance with SCA effect of the cross	Significant standard heterosis over Orobelle (%)	Significant standard heterosis over Asha (%)
Plant height (cm)	8/4×BC CAP Purple (H×L)	-30.53 to 40.97	40.97**	151.78 (32.62**)	8/4×BC CAP Purple (54.18 **)	8/4×BC CAP Purple (81.18**)
	8/4×Royal Wonder (H×L)		40.83**	133.17 (24.94**)		
Days to first flowering	C/4×8/4 (L×L)	6.93 to -46.61	-46.61**	21.00 (-11.75**)	C/4×8/4 (-44.74**)	C/4×8/4 (-51.16**)
	Arya×Baby Bell (H×H)		-37.62**	21.00 (-7.86**)		
Days to 50% flowering	C/4×8/4 (H×H)	-36.22 to-21.01	-36.22**	27.00 (-9.32**)	C/4×8/4 (-38.64**)	C/4×8/4 (-45.64**)
	8/4×Royal Wonder (H×L)		-21.01**	36.33 (-5.51 **)		
Days to first harvest	Royal Wonder×BC CAP White (L× L)	-34.03 to 19.66	-34.03**	84.67 (28.57**)	8/4×BC CAP Purple (-20.19**)	8/4×BC CAP Purple (-26.45**)
	Arya×Royal Wonder (L×L)		-28.57**	91.67 (-22.98**)		
Number of primary branches/ plant	C/4×Baby Bell (L×L)	-31.81 to 64.00	64.00**	3.28 (0.51**)	-	Baby Bell×Royal Wonder (42.08**)
	C/4×BC CAP Purple (L×L)		42.86**	3.33 (0.57**)		
Fruit length (cm)	Arya×Baby Bell (H×L)	-28.44 to 27.59	27.59**	13.33 (1.73**)	C/4×8/4 (58.74**)	C/4×8/4 (52.26**)
	Arya×Royal Wonder (H×L)		26.48**	13.12 (1.87**)		
Fruit diameter (cm)	Arya×BC CAP White (L×L)	-30.20 to 22.83	22.83**	7.77 (1.85**)	-	C/4×Royal Wonder (16.99*)
	C/4×Royal Wonder (H×H)		13.09**	8.12 (0.871**)		
Shape index	Arya×Baby Bell (H×L)	-30.99 to 52.54	52.54**	2.51 (0.69**)	Arya×Baby Bell (96.86**)	Arya×Baby Bell (76.53**)
	C/4×BC CAP White (L×L)		49.58**	2.38 (0.68**)		
Pericarp thickness (mm)	C/4 × Arya (H×H)	-31.37 to 54.04	54.04**	9.28 (2.59**)	C/4×Arya (23.67**)	C/4×Arya (17.07**)
	Baby Bell×BC CAP Purple (H×L)		36.09**	7.57 (1.89**)		
Number of locules/Fruit	8/4×Royal Wonder (H×H)	-17.30 to 33.30	-17.30**	2.76 (-0.25**)	8/4×Royal Wonder (-24.75**)	8/4×Royal Wonder (-17.30**)
Number of seeds fruit	8/4×BC CAP White (H×L)	-87.89 to 106.67	106.67**	200.26 (95.40**)	8/4×BC CAP White (92.34**)	8/4×BC CAP White (92.34**)
	8/4×BC CAP Purple (H × H)		83.70**	178.00 (43.66**)		
TSS (^{0}brix)	Baby Bell×Royal Wonder (H×L)	-41.81 to 40.55	40.55**	11.10 (3.24**)	Baby Bell×Royal Wonder (48.04**)	Baby Bell×Royal Wonder (74.67**)
	Arya×Royal Wonder (H×L)		31.34**	9.15 (1.44**)		
Vitamin-C content of fruit (mg 100 g^{-1})	Arya×BC CAP Purple (H×L)	-26.47 to 85.00	85.00**	247.25 (66.17**)	Arya×BC CAP Purple (47.76 **)	Arya×BC CAP Purple (58.67**)
	8/4×Royal Wonder (L×L)		80.73**	236.41 (59.90**)		
Lycopene content of fruit (mg 100 g^{-1})	C/4×8/4 (H×H)	-93.66 to 93.10	93.10**	3.26 (1.60**)	C/4×8/4 (196.67**)	C/4×8/4 (67.92**)
β-carotene content of fruit (mg 100 g^{-1})	C/4×Arya (H×H)	-94.36 to 52.82	52.82**	3.97 (1.40**)	C/4×Arya (175.93**)	C/4×Arya (136.51**)
	Arya×BC CAP White (H×L)		52.26**	3.25 (1.22**)		
Number of fruits/Plant	8/4×Baby Bell (H×H)	-34.43 to 139.77	139.77**	23.39 (9.21**)	8/4×Baby Bell (162.32**)	8/4×Baby Bell (151.42**)
	Arya×Baby Bell (L×H)		128.64**	19.16 (7.907**)		
Average fruit weight (g)	8/4×BC CAP White (L×L)	-59.47 to 30.03	30.03**	107.85 (27.86**)		
	Baby Bell × BC CAP Purple (H×L)		21.40**	115.34 (19.82**)		
Fruit yield/Plant (kg)	8/4×Baby Bell (H×H)	-52.89 to 157.93	157.93**	2.33 (0.89**)	8/4×Baby Bell (89.95**)	8/4×Baby Bell (93.63**)
	Arya×Baby Bell (L×H)		150.18**	2.26 (1.02**)		
	C/4×8/4 (H×H)		89.15**	2.15 (0.70**)		

[a] H= Significant GCA effects, L= Non-significant GCA effects. * and ** Significant at 0.05 and 0.01 levels of probability.

developed F_1 hybrids over the best existing cultivar to be replaced, and appears to be more relevant and practical. With this point of view, the F_1 hybrids identified in the present study were evaluated and selected based on the standard heterosis. Two standard hybrids Orobelle and Asha were chosen for the present study. The extent of standard heterosis observed in most promising hybrid (8/4×Baby Bell) over Orobelle and Asha for fruit yield per plant (89.95 and 93.63%**, respectively) and other desirable horticultural traits appeared to be highly acceptable for commercial exploitation of heterosis. All crosses produced negative or low positive heterobeltiosis for the trait fruit diameter. This shows that high-performing parents having poor GCA may not produce highly heterotic crosses. Therefore, it may be concluded that a superior performance of the hybrids for fruit diameter depends on the GCA of the parents involved. We, therefore, conclude that progress in improving the desired trait will be slow if the parental selection is based on *per se* performance alone. For continued improvement, the selection of parents should be based on *per se* performance as well as the combining ability. Manifestation of heterosis in some of the crosses for number of seeds per fruit and fruit yield per plant was relatively high in the present study. The parents involved in these crosses are genetically more diverse than two other parents that manifested little or no heterosis in their crosses. Sweet pepper hybrid utilizing dissimilar parents showing higher fruit yield along with good horticultural traits was earlier reported (Gomide *et al*., 2003; Galal *et al*., 2018) utilizing dissimilar parents.

The perusal of different heterotic cross combinations based on GCA effects of the parents revealed that the crosses involved four types of combinations namely, H×H, H×L, L×H and L×L, where H stands for significant GCA effect in desired direction and L for non-significant GCA effect of the parent (Table 5). In the H×H type cross combinations additive as well as additive×additive type of interactions were involved. These crosses would be very useful as desirable segregates would be fixed in early advance generation. On the other hand, crosses of H × L type or L × H type involved at least one parent with significant GCA effect which indicated that predominantly additive effect was present in good combiner and possibly complementary epistatic effect in poor combiner and these two gene actions acted in complementary fashion to maximize the expression (Salimath and Bahl, 1985). In crosses involving L×L category SCA effects seemed to have played a very important role for these cross combinations and high performance was due to non-additive gene action (Bhutia *et al*., 2015).

Potence ratio can be used to indicate the dominance of inherited traits, with values greater than ±1 indicating overdominance, values between -1 and +1 revealing partial dominance, values of +1.0 indicating complete dominance and values of 0 indicating no dominance. Values of dominance estimates in 21 F_1 hybrids are presented in Table 6. In the present study different degrees of dominance i.e. complete, partial to overdominance effects, and no dominance were involved in inheritance of traits under study. However, preponderance of overdominance and partial dominance reactions for most of the crosses in the inheritance of these traits was noticed. Overwhelming response of over dominance (Devi and Sood, 2018) and partial to overdominance (Rao and Badiger, 2017) in majority of the hybrids in yield and its contributing traits was reported.

CONCLUSIONS

The present study illustrated that heterosis breeding is the best possible breeding strategy for improving yield, yield component and fruit quality traits in sweet pepper, all of which are mostly governed by non-additive gene effects. Three parents, 8/4, C/4, and Baby Bell emerged as most

[DOI: 10.22034/JAST.26.2.343]

Table 6. Estimates of dominance effects of 18 characters of sweet pepper.[a]

Hybrids	PH	DFF	D50F	DFH	NPBP	FL	FD	SI	PT	NLF	NSF	TSS	VIT-C	LP	β-C	NFP	AFW	FYP
C/4×8/4	2.51	-111.00	-9.36	-1.21	3.44	3.69	0.96	0.61	6.31	-1.01	1.75	1.29	1.32	7.55	2.74	70.50	0.94	7.64
C/4×Arya	-3.20	-1.56	-4.64	-7.75	3.44	4.10	0.88	10.73	15.54	-0.25	0.44	-0.96	4.28	2.30	6.97	1.20	-19.58	0.26
C/4×Baby Bell	-0.72	-5.91	-11.67	0.29	0.00	-1.09	-1.71	0.08	103.61	0.49	1.48	-2.56	-3.96	-1.84	-16.27	-12.35	2.15	0.23
C/4×BC CAP Purple	-3.62	-29.00	-1.57	-4.72	7.00	-0.38	-0.38	0.02	-0.86	1.01	1.46	-0.58	1.19	-1.06	-1.02	8.08	0.13	2.52
C/4×Royal Wonder	-0.43	-7.00	-1.13	-8.20	-0.19	0.03	4.78	-3.11	0.31	-1.00	4.74	-0.04	0.80	1.80	0.23	0.71	0.16	0.96
C/4×BC CAP White	2.42	-4.78	-1.49	-3.29	2.67	2.38	-0.52	14.02	0.92	1.99	-7.11	-0.26	-1.27	0.37	0.18	0.49	0.16	0.18
8/4×Arya	1.70	-0.53	0.00	0.23	0.00	0.31	-1.58	0.55	-2.77	-3.00	-0.44	1.18	55.50	-4.22	-21.38	0.55	-1.68	-40.07
8/4×Baby Bell	2.21	-6.40	-3.43	-5.67	3.22	0.26	-1.09	0.77	2.73	-2.98	2.76	7.06	2.56	2.41	-2.90	55.41	1.76	39.45
8/4×BC CAP Purple	7.73	1.00	-0.80	-1.74	2.33	-0.72	-0.52	-0.38	-16.24	1.00	27.05	-5.25	-1899.8	-0.28	0.32	1.64	1.05	1.42
8/4×Royal Wonder	48.93	-55.00	-15.50	0.29	-1.22	0.76	1.47	-0.02	-1.39	-116.3	-5.28	0.73	28.44	-1.25	-1.05	1.51	-0.58	6.72
8/4×BC CAP White	0.66	-4.20	-2.38	-0.98	-1.67	0.73	1.53	0.58	1.16	-160.2	68.67	-8.50	1.83	2.17	1.85	3.30	3.48	4.21
Arya×Baby Bell	2.97	-11.86	-4.00	0.05	0.11	80.63	-2.54	7.34	-2.14	52.76	-0.80	1.45	1.83	5.56	3.96	9.55	1.27	41.87
Arya×BC CAP Purple	-0.61	-0.26	-1.57	-9.76	-3.00	1.07	-1.55	1.34	0.74	-2.01	4.96	9.51	79.85	-0.58	0.60	9.24	-0.41	0.47
Arya×Royal Wonder	-1.38	-2.00	-8.50	-74.33	-0.89	7.54	3.86	3.02	2.42	-1.50	-0.18	5.85	20.45	-0.62	0.46	1.20	-3.41	-1.46
Arya×BC CAP White	1.38	-0.70	-3.08	-10.20	3.00	0.63	4.05	-3.19	20.48	1.50	-2.71	1.46	2.92	1.49	2.09	299.56	1.07	2.84
Baby Bell×BC CAP Purple	-1.32	-5.50	-1.51	-1.17	5.33	-0.26	1.19	-1.23	7.46	-2.03	1.34	-2.16	1.28	2.01	1.67	1.81	2.37	2.39
Baby Bell×Royal Wonder	-1.03	-5.00	-1.89	-0.56	1.07	3.55	-1.13	8.74	1.84	-2.98	1.11	4.49	2.57	1.66	1.19	0.13	-0.37	0.12
Baby Bell×BC CAP White	1.61	-1.40	-1.35	-1.17	3.00	1.48	-0.66	9.47	1.94	-0.01	-0.08	-17.72	11.52	1.89	1.81	-2.58	1.60	-0.48
BC CAP Purple×Royal Wonder	0.24	-15.00	-1.67	-2.17	0.49	2.55	0.25	1.28	-0.62	-0.79	1.26	-1.81	2.63	-0.18	2.80	0.19	0.52	1.17
BC CAP Purple×BC CAP White	1.32	-4.75	-1.87	-111.0	0.00	-0.22	-0.49	0.52	0.27	-0.20	6.17	0.56	0.48	1.56	2.43	-1.35	5.70	1.49
Royal Wonder×BC CAP White	2.77	0.09	1.36	-12.39	0.24	-0.39	-1.08	8.92	0.19	-66.29	-7.58	0.11	1.79	2.41	-0.40	0.58	-1.36	-1.64

[a] PH= Plant Height (cm); DFF= Days to First Flowering; D50F = Days to 50% Flowering; DFH = Days to First Harvest; NPBP= Number of Primary Branches/Plant; FL= Fruit Length (cm); FD= Fruit Diameter (cm); SI= Shape Index; PT = Pericarp Thickness (mm); NLF= Number of Locule/Fruit; NSF= Number of Seeds/Fruit; TSS= TSS content of fruit (^{0}brix); VIT-C= Vitamin-C content of fruit (mg 100 g^{-1}); LP= Lycopene content of fruit (mg 100 g^{-1}); β-C= β-Carotene content of fruit (mg 100 g^{-1}); NFP = Number of Fruits/Plant; AFW= Average Fruit Weight (g), FYP= Fruit Yield/Plant (kg).

promising genitors which could be utilized in future breeding. Three promising hybrids, 8/4×Baby Bell (Orange Red fruit colour with intermediate shape), Arya×Baby Bell (Red fruit colour with blocky shape) and C/4×8/4 (Red fruit colour with blocky shape) in this investigation could either be commercialized after critical evaluations or advanced further in segregating generations for isolation of desirable recombinants. Preponderance of partial to overdominance effects were involved in the inheritance of fruit yield and other horticultural traits. The outcome of the study for improved fruit quality and productivity of sweet pepper grown under low cost poly house will enable and encourage small and marginal growers of tropical and sub-tropical countries to meet consumers demand and fetch high economic return.

ACKNOWLEDGEMENTS

We are grateful to the Principal Investigator, Mission for Integrated Development of Horticulture, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India for providing genotypes of coloured sweet pepper.

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[DOI: 10.22034/JAST.26.2.343]

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بهنژادی فلفل شیرین برای بهبود اجزای عملکرد و صفات کیفی میوه در یک سازه حفاظت شده کم هزینه

چکیده

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[DOI: 10.22034/JAST.26.2.343]

استفاده از از هتروزیس یکی از ابزارهای مناسب برای بهبود فلفل شیرین (Capsicum annuum var. grossum L.) است که می تواند بیشتر برای شناسایی نوترکیب های (recombinants) مطلوب مورد استفاده قرار گیرد. برای تولید کنندگان مناطق گرمسیری و نیمه گرمسیر، چنانچه عملکرد محصول زیاد و رنگ میوه جذاب و شکل مکعبی (blocky) باشد هیبریدهای امیدبخش(Promising) می تواند قابل قبول باشد. برای تعیین میزان هتروزیس، نحوه عملکرد ژن، اثرات توانایی ترکیب، و تخمین غالبیت(dominance) برای ۱۸ صفت کمّی هفت والد متنوع از طریق تجزیه و تحلیل چند متغیره انتخاب شدند و در طرح جفت گیری نیمه دی آلل (half diallel mating) تلاقی داده شدند. بیان رنگ و شکل میوه در مرحله بلوغ فیزیولوژیکی در نسل F1 نشان دهنده غلبه گروه رنگ قرمز بر سایر گروه های رنگ میوه و غلبه شکل میوه مکعبی بر شکل میوه دراز و گرد بود. غلبه(Preponderance) عملکرد ژن غیرافزایشی(non-additive) برای اکثر صفت‌های مورد بررسی، به سودمندی بهره‌برداری از نیروی هیبریدی (hybrid vigour) اشاره داشت. سه ژنوتیپ 8/4، C/4 و Baby Bell امیدبخش‌ترین دهندگان(donors) بودند. پس از آزمایش‌های دقیق، هیبریدها Arya × Baby Bell، 8/4 × Baby Bell و C/4 × 8/4 بر اساس عملکرد(per se performance) ، هتروزیس آشکار شده، و ارتباط اثرات توانایی ترکیبی خاص، برای تجاری سازی احتمالی در یک سازه حفاظت شده کم هزینه مناطق گرمسیری و نیمه گرمسیری به عنوان امیدبخش شناسایی شدند. در وراثت بیشتر صفات، پاسخ جزیی تا بیش از حد به غالبیت، به پایه‌های ژنتیکی هتروزیس کمک کرد. جداسازی لاین‌های خالص از نسل تفریقی(segregating generation) هیبریدهای هتروتیک به عنوان رویکردی امیدوارکننده برای توسعه واریته‌های اصلاح‌شده لاینی(line-bred) با بهبود عملکرد و کیفیت میوه شناسایی شد.