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Research Article

Combining ability and gene action analysis of some bacterial wilt resistant intraspecific hybrids of bell pepper (*Capsicum annuum* var. *grossum*)

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Abstract
Genetically diverse bell pepper cultivars and their 30 F_1 hybrids were developed by means of diallel mating system including reciprocals. Variance analysis illustrated considerable disparity among newly developed bacterial wilt resistant hybrid lines for all the studied traits. General Combining ability (*gca*) effects were more pronounced than specific combining ability effects (*sca*). The *gca* effects were high with parents DPBWRC-6-1, EC-464107, EC-464115 and DPBWRC-39 for fruit yield and yield-enhancing traits. Further, reciprocal effects influenced all parameters except fruit width, TSS and lobes per fruit. Among the additive and non-additive genetic variance, the latter had a more significant influence on the inheritance of all studied characters except for fruit width and pericarp thickness. Based on *sca* analysis, three cross-combinations viz., DPBWRC-29×EC-464107, DPBWRC-39× DPBWRC-1 and EC-464115 × DPBWRC-29 were found to be good specific combiners for the majority of traits and can further be utilized to isolate superior segregates or released as hybrids.

Key words: Gene action, General combining ability, Non-additive effect, Reciprocal effects, Specific combining ability.

INTRODUCTION

Bell pepper (*Capsicum annuum* L. var. *grossum*) belongs to the family Solanaceae. It is popular worldwide for its delightful taste, gratifying flavour, aroma, and color. It is grown all over the world on an area of 3.8 million hectares with a production of 36 million tones including hot pepper (FAOSTAT, 2017). In past decades, bell pepper cultivation has gained attention in India due to suitable growth conditions, with acreage and production figures of 34,000 hectares and 4,87,000 metric tonnes, respectively (NHB, 2019). However, the total production and productivity of bell pepper are still low on an account of poor yielding varieties. Hence, it is imperative to develop a high yielding variety. The accomplishment of crop breeding programs depends primarily on the correct selection of parents for hybridization, knowledge of genetic makeup of the breeding material as well as nature of gene action entailed in the manifestation of the traits to be enhanced. However, it is difficult to fix superior parents that will give superior progenies. The common approach of choosing the parents on the basis of performance, adaptation and genetic variability do not give useful results. In such a situation, combining ability study assists in selection of well combining parents and hybrids for further exploitation. Thus, the investigation on the general and specific combining ability is very useful in the selection of parents and also in the formulation of a crossing plan. The most appropriate approach in preliminary screening of the material for combining ability is to employ diallel analysis (Griffing's Method I, Model I). The same approach has been used in the present study to evaluate six parental lines and their 30 F_1 crosses to identify superior parents and hybrids based on gene actions engrossed in the expression and inheritance of yield and quality traits. Griffing's analyses have been extensively used by vegetable breeders in cowpea (Umaharan 1997), pepper (Zewdie and Bosland, 2001; Nascimento *et al.*, 2014), watermelon (Varga *et al.,* 2011).

MATERIALS AND METHODS

Six bacterial wilt resistant inbred lines namely DPBWRC-1, DPBWRC-6-1, DPBWRC-29, DPBWRC-39, EC-464107, and EC-464115 (**Table 1**) were selected based on their performance in preliminary trials (self pollinated for 7 generations under screen house conditions to confirm the purity of the parental lines) and were crossed diallel fashion to identify best-uniting parents as well as superior combinations. Thirty F_1 crosses were evaluated along with their parents in open fields at Vegetable Research Farm of Himachal Pradesh Krishi Vishvidalaya, Palampur, India during summer season of 2019. The trial was laid out in Randomized Complete Block Design with three replications. Each simulation comprised of seven plots of 3.6 m length and 3.6 m width and each plot comprised of six rows. Data was recorded for 12 quantitative and 6 qualitative traits *viz*., duration for 50 percent flowering, days to first picking, plant height, number of primary branches, harvest duration, fruit length, fruit width, pericarp thickness, lobes/fruit, average fruit weight, marketable fruits per plant, marketable fruit yield per plant, fruit colour, fruit shape, fruit shape at blossom end, fruit shape at pedicel attachment, fruit position and TSS. Quality characters like fruit shape was recorded visually and colour was recorded in accordance to royal horticultural chart.

Average values for each genotype in each replication for the traits studied were used for further statistical analysis. The analysis of variance was worked out for individual trials as per the method given by Panse and Sukhatme (1984).Combining ability analysis was carried out in accordance with Griffing's (1956) Method I, Model I (including parents, F_1's and reciprocals). The data were analyzed *via* Indostat software.

RESULTS AND DISCUSSION

The data obtained from an assessment of variance (**Table 2**) illustrated clearly, that the genotypes differed significantly for all the studied characters except bacterial wilt incidence. This indicated that the genotypes differed genetically and hence their further analysis was appropriate. Earlier researchers *viz*., Sood and Kumar (2011), Ahmed *et al.* (2012), Pandey *et al.* (2013), Naik *et al.* (2014), Rana *et al.* (2015), Sharma *et al.* (2017) also accounted analogous results.

Hybrids are quite common in bell pepper on account of their superiority in fruit yield and components traits over the open pollinated varieties. The choice of parents to be involved in an effective breeding programme depends on the average performance of the parents under selection for the desirable traits. It is therefore necessary to identify the parents which can be exploited for genetic improvement through hybrid progenies (Eswaran *et al.,* 2012). The results of *per se* performance revealed that the diallel hybrids DPBWRC-29 × EC-464107, DPBWRC-1 × EC-464107, EC-464107 × DPBWRC-29, DPBWRC-6-1× EC-464115 and DPBWRC-6-1 × EC-464107 (**Table 3**) were among the earliest flowering and fruiting genotypes. However, the hybrids DPBWRC-1 × DPBWRC-29 and DPBWRC-1 × DPBWRC-39 took more days for first picking in comparison to time taken for 50 per cent of the plants to blossom. This implies that the diverse origin of parental lines might have resulted in the genotypic differences with respect to plant physiological and biochemical processes starting from flowering to fruit maturity. Similar differences

Table 1. Description of parental lines used

Parents	Growth habit	Fruit shape	Fruit shape at pedicel attachment	Fruit shape at blossom end	Fruit position	Fruit colour	Bacterial wilt resistance	Source
DPBWRC-1	Semideterminate	Blocky	Cordate	Sunken	Pendent	Medium light green	Highly resistant	School of Vegetable Science & Floriculture, CSK HPKV, Palampur (H.P.)
DPBWRC-6-1	Semideterminate	Blocky	Cordate	Sunken	Pendent	Light green	Highly resistant	
DPBWRC-29	Semideterminate	Blocky	Cordate	Sunken	Pendent	Medium dark green	Highly resistant	
DPBWRC-39	Semideterminate	Blocky	Cordate	Sunken	Intermediate	Dark Green	Highly resistant	
EC-464107	Indeterminate	Blocky	Cordate	Sunken	Upright	Yellow-green	Highly resistant	AVRDC Taiwan
EC-464115	Indeterminate	Blocky	Cordate	Sunken	Pendent	Light Green	Highly resistant	AVRDC Taiwan

Table 2. Analysis variance for phenological, fruit yield and quality traits

S. No.	Traits	Mean squares		
		Replication	Genotype	Error
			d.f.	
		2	35	70
Quantitative traits				
a.)	Phenological and structural traits			
	Days to 50 % flowering	1.29	38.58*	7.48
	Days to first picking	2.01	56.30*	7.34
	Plant height	16.98	176.83*	5.86
	Primary branches per plant	0.39	0.16*	0.06
	Harvest duration	3.82	57.62*	6.92
b.)	Fruit yield traits			
	Fruit length	0.08	3.21*	0.09
	Fruit width	0.43	0.21*	0.06
	Pericarp thickness	0.16	0.28*	0.05
	Lobes per fruit	0.14	0.20*	0.06
	Average fruit weight	16.64	19.75*	4.62
	Marketable fruits per plant	4.89	25.67*	3.84
	Marketable fruit yield per plant	1106.48	24466.26*	1952.81
Quality traits				
	Total soluble solids (^{0}Brix)	0.12	0.22*	0.09
Bacterial wilt incidence				
	Plant Survival	0.02	0.05	0.02

Significant at *P $\leq$0.05

with regard to days to 50% flowering and first harvest have also been reported earlier by Sharma *et al.* (2013) and Aditika *et al.* (2018). The hybrid DPBWRC-29 × EC-464107 exhibited high *per se* performance for pericarp thickness. Fruit shape index and fruit length were maximum in the hybrid EC-464115 × EC-464107 (7.92 cm), while fruit width was maximum in hybrid DPBWRC-39 × DPBWRC-1 (4.3 cm). The hybrids DPBWRC-1 × DPBWRC-39, DPBWRC-6-1 × DPBWRC-39, DPBWRC-29 × DPBWRC-1, DPBWRC-29 × DPBWRC-39, DPBWRC-39 × DPBWRC-6-1, DPBWRC-39 × DPBWRC-1, DPBWRC-39 × DPBWRC-29 reflected fruit shape index ratio of 1 (approximately). The results depicted that the genotypes DPBWRC-1 × DPBWRC-6-1 (3.40) and DPBWRC-1 × DPBWRC-39 (35.36 g) outperformed the remaining 28 hybrids for lobes per fruit and average fruit weight. Indeterminate plants are desirable in rainy areas to prevent rotting of the fruits. Among the evaluated 30 hybrids, DPBWRC-29 × EC-464115 (74.28 cm) (**Table 3**) recorded the maximum plant height, whereas DPBWRC-6-1 × DPBWRC-29 (46.52 cm) showed the minimum average plant height. Primary branches are directly correlated to yield. Higher number of primary branches significantly increases the yield by increasing the number of fruits per plant. The data pertaining to primary branches revealed that the hybrid DPBWRC-39 × DPBWRC-6-1 recorded the highest number of primary branches i.e. 3 (**Table 3**). The hybrid DPBWRC-39 × EC-464115 (2.13) recorded minimum primary branches. Thus from the above findings, it is concluded that plant height is inversely related to number of primary branches. It is relevant to state that plant height is not the sole element influencing the yield as the hybrids DPBWRC-6-1× EC-464115 and DPBWRC-6-1× EC-464107 showing highest yield and number of marketable fruits per plant displayed significantly low plant height (48.43 cm and 51.68 cm). All the hybrids and parents produced blocky fruits. All the hybrids yielded fruits of green colour except the accessions DPBWRC-6-1 × EC-464115, DPBWRC-1 × EC-464107, DPBWRC-1 × EC-464115, DPBWRC-6-1, EC-464107 × EC-464115, EC-464115, EC-464107 × DPBWRC-1, EC-464115 × EC-464107 and EC- 464107, which produced yellowish green fruits. Earlier researchers Nkansah *et al.* (2011), Sood and Kumar (2011), Sharma *et al.* (2017) and Sood and Thakur (2017) also reported similar results with different study material.

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Table 3. Mean performance of parental lines and hybrids for quantitative and quality traits

Parental lines / Cross combinations	Quantitative traits												Quality traits	Disease reaction
	Phenological and structural traits					Fruit yield traits								
	DFF (days)	DFP (days)	PH (cm)	PBP	HD (days)	FL (cm)	FW (cm)	PT (mm)	LPF	AFW(g)	MFPP	MFYPP (g)	TSS (°Brix)	BWI (PS %)
Parents														
1. DPBWRC-1	45.33	61.00	53.30	2.45	39.67	4.31	3.90	3.40	3.66	26.41	11.46	302.00	4.46	91.75
2. DPBWRC-6-1	46.33	50.67	41.10	2.80	50.33	4.83	3.82	3.99	3.13	28.06	12.13	337.60	4.68	100.00
3. DPBWRC-29	40.00	56.00	53.61	2.27	45.00	4.79	4.07	3.50	3.26	31.27	10.67	330	4.56	90.00
4. DPBWRC-39	39.00	56.00	47.66	2.82	45.00	4.60	4.09	3.80	3.33	34.71	13.27	433.53	4.91	93.75
5. EC-464107	41.67	52.67	56.76	2.47	48.33	6.40	3.42	3.08	3.00	28.12	10. 53	279.00	4.78	100.00
6. EC-464115	44.33	66.33	66.45	2.37	34.67	6.07	3.49	3.05	3.26	27.74	11.60	315.47	4.65	100.00
Hybrids														
1. DPBWRC-1 × DPBWRC-6-1	35.67	58.67	51.66	2.78	42.33	5.26	4.00	3.55	3.40	29.96	14.87	436.40	4.27	100.00
2. DPBWRC-6-1 × DPBWRC-1	37.33	59.33	48.92	2.58	41.67	5.21	3.95	3.88	3.13	31.93	16.27	522.13	4.05	95.83
3. DPBWRC-1 × DPBWRC-29	34.33	63.33	53.31	2.80	37.67	5.02	4.03	3.56	3.07	34.00	12.00	406.47	4.07	87.57
4. DPBWRC-29 × DPBWRC-1	42.00	59.00	48.99	2.60	42.00	4.79	3.98	3.23	3.33	30.43	10.53	319.33	4.54	91.67
5. DPBWRC-1 × DPBWRC-39	33.67	67.67	55.76	2.93	33.00	4.57	4.13	4.06	3.07	35.36	13.53	476. 73	4.47	100.00
6. DPBWRC-39 × DPBWRC-1	37.00	50.67	50.92	2.53	47.33	4.29	4.30	3.56	3.20	31.23	10.27	334.00	4.95	91.06
7. DPBWRC-1 × EC-464107	34.00	52.00	59.59	2.73	49.00	6.89	3.91	3.50	2.87	24.02	15.93	429.00	4.41	87.50
8. EC-464107 × DPBWRC-1	40.67	57.67	55.47	2.88	43.33	5.34	3.66	3.21	3.07	27.60	15.03	424.53	4.72	100.00
9. DPBWRC-1 × EC-464115	39.33	57.67	65.69	2.47	49.67	6.21	3.76	3.19	3.07	28.82	19.33	557.33	4.93	91.66
10. EC-464115 × DPBWRC-1	42.67	57.67	62.95	2.95	43.33	5.87	3.88	3.08	3.13	25.89	15.36	409.13	4.95	100.00
11. DPBWRC-6-1 × DPBWRC-29	35.00	54.00	46.52	2.53	47.00	5.04	3.93	3.97	3.27	32.80	16.80	550.93	4.52	95.83
12. DPBWRC-29 × DPBWRC-6-1	38.00	55.00	47.43	2.53	46.00	5.02	3.90	3.85	3.13	30.21	17.93	527.47	4.25	100.00
13. DPBWRC-6-1 × DPBWRC-39	36.67	59.67	50.43	2.47	41.33	4.91	4.01	3.76	3.00	29.86	15.67	488.93	4.21	86.30
14. DPBWRC-39 × DPBWRC-6-1	36.67	54.67	49.53	3.00	46.33	4.84	4.16	3.82	3.13	29.76	19.17	556.53	4.23	100.00
15. DPBWRC-6-1 × EC-464107	35.33	53.33	51.68	2.53	47.67	6.63	3.55	3.48	2.93	28.21	20.47	596.33	4.57	95.83
16. EC-464107 × DPBWRC-6-1	42.67	54.67	46.77	2.52	47.33	6.49	3.74	3.16	2.87	29.41	19.47	564.33	4.81	95.23
17. DPBWRC-6-1 × EC-464115	35.00	54.00	48.43	2.93	47.00	7.48	3.68	3.56	2.33	29.83	20.07	602.33	4.42	95.83
18. EC-464115 × DPBWRC-6-1	40.67	55.67	49.00	2.77	45.33	6.99	3.60	3.28	2.67	27.48	13.87	382.00	4.51	85.70
19. DPBWRC-29 × DPBWRC-39	43.00	59.00	54.51	2.43	42.00	4.75	4.20	3.61	3.20	33.25	13.27	440.20	4.78	85.00
20. DPBWRC-39 × DPBWRC-29	42.00	62.00	50.53	2.60	39.00	4.63	4.27	3.45	3.07	29.97	12.60	371.87	4.43	82.00
21. DPCBWR-29 × EC-464107	34.00	52.00	61.03	2.40	49.00	7.53	3.38	3.63	2.67	31.92	17.53	562.93	4.29	100.00
22. EC-464107 × DPBWRC-29	34.67	53.33	57.65	2.28	47.67	6.98	3.70	3.41	3.13	33.33	15.40	512.00	4.40	95.83
23. DPCBWR-29 × EC-464115	37.67	49.67	74.28	2.20	51.33	6.21	3.90	3.46	2.80	31.79	15.47	492.27	4.41	100.00
24. EC-464115 × DPBWRC-29	44.33	55.33	65.53	2.47	45.67	7.11	3.63	2.82	2.80	31.89	15.13	480.73	5.01	100.00
25. DPBWRC-39 × EC-464107	38.67	55.67	52.73	2.87	45.33	5.91	3.52	3.13	2.87	28.43	17.33	488.13	4.92	86.90
26. EC-464107 × DPBWRC-39	37.67	55.67	52.47	2.54	45.33	6.51	3.53	3.60	2.60	27.20	18.87	515.47	4.86	100.00
27. DPBWRC-39 × EC-464115	41.33	55.33	72.70	2.13	45.67	5.44	3.70	3.18	3.07	29.14	16.20	467.80	4.89	100.00
28. EC-464115 × DPBWRC-39	37.67	55.67	60.69	2.53	45.33	5.23	3.87	3.25	3.12	29.78	13.40	388.60	4.91	91.66
29. EC-464107 × EC-464115	42.33	53.33	66.51	2.33	47.67	6.95	3.33	3.08	3.07	26.89	14.13	378.67	4.29	100.00
30. EC-464115 × EC-464107	42.00	65.00	56.00	2.87	36.00	7.92	3.36	3.21	2.65	28.94	13.13	380.67	4.47	90.46
SE(d)±	2.19	2.19	2.02	0.19	2.10	0.24	0.197	0.19	0.20	1.72	1.54	34.91	0.24	1.57
Range	33.67-46.33	49.67-67.67	41.10-74.28	2.13-3.23	19.50-51.33	4.03-7.92	3.33-4.88	2.82-4.06	2.33-3.66	21.92-50.93	4.66-20.47	169.67-602.33	3.93-5.01	7.00-100.00

DFF = Days to 50 per cent flowering, DFP = Days to first picking, PH = Plant height, PBP = Primary branches per plant, HD = Harvest duration, FL = Fruit length, FW = Fruit width, PT = Pericarp thickness, LPF = Lobes per fruit, AFW = Average fruit weight, MFPP = Marketable fruits per plant, MFYP = Marketable fruit yield per plant, TSS = Total soluble solids, BWI = Bacterial wilt incidence, PS% = Plant survival percentage

Mean sum of squares for GCA and SCA (**Table 4**) were significant for all traits except for fruit width, which shows the presence of both additive and non-additive gene action. Alternatively, this suggests the presence of genetic variability among the parents and crosses (hybrids) for marketable fruit yield and component traits. No single parent exhibited significant positive *gca* effects for all the traits. DPBWRC-6-1 was good general combiner for days to first picking, primary branches per plant, harvest duration, pericarp thickness, marketable fruits per plant and marketable fruit yield per plant (**Table 5**). EC-464107 was good general combiner for days to first picking, plant height, harvest duration, fruit length and marketable fruits per plant. DPBWRC-39 was good general combiner for fruit width, pericarp thickness, average fruit weight and TSS . EC-464115 exhibited high *gca* effects for plant height, fruit length and TSS (**Table 5**). Thus the parental lines DPBWRC-6-1, DPBWRC-39, EC-464107 and EC-464115 shall prove fruitful in recombination breeding aimed at getting desirable transgressive segregants. Different parents expressing high *gca* effects for yield and component traits have also been reported by Khalil and Hatem (2014) and Galal *et al.* (2018).

The data analysis revealed significant specific combining ability effects among F1's and their reciprocals suggesting the prospect of utilizing the hybrid potency for all the phenological characters studied. No single cross could reveal significant *sca* for all the traits. For days to 50% flowering, three crosses expressed high specific combining ability effects, with DPBWRC-29 × EC-464107 (Average × Average) being the best for earliness (**Table 6 and 7**). For days to first picking, seven crosses exhibited positive SCA effects and EC-464115 × EC-464107 (Poor × Good), DPBWRC-29 × EC-464115 (Average × Poor) and DPBWRC-39 × EC-464115 (Poor × Poor) were the three best specific combiners (**Table 7**). Fourteen hybrids exhibited significant positive *sca* effects for plant height, four hybrids exhibited significant *sca* effects for primary branches per plant and eight crosses exhibited significant positive *sca* for harvest duration. Seven crosses exhibited significant positive *sca* effects for fruit length (**Table 6**) whereas, no hybrid revealed significant positive *sca* effects for fruit width. For pericarp thickness, EC-464115 × DPBWRC-29 (Poor × Average), DPBWRC-39 × DPBWRC-1 (Good × Average) and DPBWRC-1 × DPBWRC-39 (Average × Good) showed highest *sca* effect. Only one hybrid viz., EC-464115 × EC-464107 (0.21) exhibited significant *sca* effect for lobes per fruit (**Table 6**). Six and nine hybrids exhibited significant *sca* effects for average fruit weight and marketable fruits per plant (**Table 6**), respectively. Twelve hybrids exhibited significant *sca* effects for marketable fruit yield per plant and EC-464115 × DPBWRC-6-1 (Poor× Good), DPBWRC-29 × EC-464107 (Poor × Average) and DPBWRC-1 × EC-464115 (Poor × Poor) were the three best specific combiners (**Table 7**). For total soluble solids only two hybrids *viz.,* DPBWRC-1 × EC-464115 (0.31) (Poor × Good) and DPBWRC-6-1 × EC-464107 (0.22) (Poor × Average) (**Table 6 and 7**) were good specific combiners. RCA effects were significant for all studied traits except fruit width, lobes per fruit and TSS.

Table 4. Estimates of analysis of variance and components of variance for combining ability

Components / Traits	GCA	SCA	RCA	Error	σ^2gca	σ^2sca	σ^2rca	σ^2A	σ^2D	GCA/ SCA
Degree of freedom	5	15	15	70	-	-	-	-	-	-
Days to 50% flowering	10.00 *	17.22 *	9.45 *	2.49	0.63	14.73	3.48	1.25	14.73	0.04
Days to first picking	29.43*	15.65 *	18.33*	2.45	2.25	13.20	7.94	4.49	13.20	0.17
Plant height	283.64*	27.70*	15.28*	1.95	23.47	25.75	6.66	46.95	25.75	0.91
Primary branches per plant	0.11*	0.04*	0.05*	0.02	0.01	0.02	0.02	0.01	0.02	0.36
Harvest duration	27.95 *	18.67 *	16.83 *	2.31	2.14	16.36	7.26	4.27	16.36	0.13
Fruit length	5.40*	0.51*	0.18*	0.03	0.45	0.48	0.07	0.90	0.48	0.93
Fruit width	0.40 *	0.02	0.01	0.02	0.03	-0.01	-0.00	0.06	-0.00	20.29
Pericarp thickness	0.41 *	0.03 *	0.05 *	0.02	0.03	0.02	0.02	0.07	0.02	2.23
Lobes per fruit	0.17 *	0.07 *	0.03	0.02	0.01	0.05	0.01	0.02	0.05	0.24
Average fruit weight	20.92*	5.47*	2.99*	1.54	1.62	3.93	0.69	3.23	3.93	0.41
Marketable fruits per plant	12.87*	12.32*	3.36 *	1.28	0.97	11.04	1.04	1.93	11.04	0.09
Marketable fruit yield per plant	8825.88*	11873.70*	4213.65*	650.94	681.25	11222.77	1781.36	1362.49	11222.77	0.06
Total soluble solids	0.14*	0.09*	0.04	0.03	0.01	0.06	0.01	0.02	0.06	0.17

Significant at *P $\leq$0.05, GCA = General combining ability**,** SCA = Specific combining ability, RCA = Reciprocal combining ability, σ^2gca = variance due to general combining ability, σ^2sca = variance due to specific combining ability, σ^2A = Additive variance, σ^2D = Dominance variance

Table 5. Estimates of general combining ability (*gca*) effects of the parents for various traits

Parents	DFF	DFP	PH	PBP	HD	FL	FW	PT	LPF	AFW	MFYPP	MFPP	TSS
DPBWRC-1	-0.19	2.16*	-0.19	0.05	-2.07 *	-0.58*	0.14*	0.01	0.18*	-0.54	-36.21 *	-1.12 *	-0.08*
DPBWRC-6-1	-0.32	-1.62*	-7.47*	0.09*	1.60*	-0.12*	0.03	0.24 *	-0.03	-0.25	45.75 *	1.61 *	-0.14*
DPBWRC-29	-0.38	-0.43	0.40	-0.15*	0.32	-0.20*	0.11 *	0.05	0.05	1.97 *	-2.45	-0.96 *	-0.09
DPBWRC-39	-0.60	0.69	-1.38*	0.05	-1.07*	-0.73*	0.17 *	0.13 *	0.04	1.24 *	3.48	-0.23	0.13*
EC-464107	-0.35	-1.82*	0.94 *	-0.02	1.80*	0.91*	-0.27 *	-0.16 *	-0.15 *	-1.36 *	4.70	0.73*	0.04
EC-464115	1.84*	1.02 *	7.71*	-0.06	-0.59	0.71*	-0.17 *	-0.27 *	-0.10 *	-1.05 *	-15.26*	-0.02	0.10*
SE (g_i) ±	0.42	0.41	0.37	0.04	0.40	0.05	0.04	0.03	0.04	0.33	6.72	0.30	0.05
SE (g_i - g_j) ±	0.65	0.64	0.57	0.06	0.62	0.07	0.06	0.05	0.06	0.51	10.42	0.46	0.07

Significant at *P ≤0.05

DFF = Days to 50 per cent flowering, DFP = Days to first picking, PH = Plant height, PBP = Primary branches per plant, HD = Harvest duration, FL = Fruit length, FW = Fruit width, PT = Pericarp thickness, LPF = Lobes per fruit, AFW = Average fruit weight, MFPP = Marketable fruits per plant, MFYP = Marketable fruit yield per plant, TSS = Total soluble solids

Table 6. Estimates of specific combining ability (*sca*) effects of cross combinations

Hybrids	DFF	DFP	PH	PBP	HD	FL	FW	PT	LPF	AFW	MFPP	MFYPP	TSS
DPBWRC-1 × DPBWRC-6-1	-2.12*	1.82	2.77*	-0. 09	-1.99*	0.19	-0.01	0.01	0.07	1.85*	0.12	23.60	-0.23*
DPBWRC-6-1 × DPBWRC-1	-0.83	-0.33	1.37	0.10	0.33	0.02	0.03	-0.17*	0.13	-0.99	-0.70	-42.87*	0.11
DPBWRC-1 × DPBWRC-29	-0.40	2.79*	-4.24*	0.17*	-2.88*	-0.07	-0.05	-0.12	-0.07	0.91	-1.61*	-44.57*	-0.13
DPBWRC-29 × DPBWRC-1	-3.83*	2.17*	2.16*	0.10	-2.17*	0.11	0.02	0.17*	-0.13	1.79*	0.73	43.57*	-0.23*
DPBWRC-1 × DPBWRC-39	-3.01*	-0.32	-0.27	0.01	-1.16	-0.02	0.09	0.21*	-0.13	2.72*	-1.71*	-8.03	0.05
DPBWRC-39 × DPBWRC-1	-1.67	8.50*	2.42*	0.20*	-7.17*	0.14	-0.08	0.25*	-0.07	2.06*	1.63*	71.37*	-0.24*
DPBWRC-1 × EC-464107	-1.26	-2.16*	1.61	0.14	1.98*	0.03	0.11	0.04	-0.11	-2.17*	0.91	12.14	0.01
EC-464107 × DPBWRC-1	-3.33	-2.83*	2.06*	-0.07	2.83*	0.77*	0.12	0.15	-0.10	-1.79*	0.45	2.23	-0.15
DPBWRC-1 × EC-464115	0.21	-2.16*	1.63	0.09	4.70*	0.16	0.04	-0.06	-0.02	-0.93	3.53*	88.57*	0.31*
EC-464115 × DPBWRC-1	-1.67	0.00	1.37	-0.24*	3.17*	0.17	-0.06	0.06	-0.03	1.46	1.99*	74.10*	-0.01
DPBWRC-6-1 × DPBWRC-29	-1.93*	-0.10	-1.14	-0.01	0.12	-0.40*	-0.04	0.17*	0.14	-0.09	1.76*	49.77*	0.04
DPBWRC-29 × DPBWRC-6-1	-1.50	-0.50	-0.45	0.00	0.50	0.01	0.01	0.06	0.07	1.30	-0.57	11.73	0.13
DPBWRC-6-1 × DPBWRC-39	-1.54	1.45	3.65*	0.00	-1.16	-0.03	0.06	-0.03	0.01	-1.06	1.07	27.37	-0.35*
DPBWRC-39 × DPBWRC-6-1	0.00	2.50*	0.45	-0.27*	-2.50*	0.03	-0.07	-0.03	-0.07	0.05	-1.75*	-33.80*	-0.01
DPBWRC-6-1 × EC-464107	0.55	0.79	0.58	-0.14	-0.35	0.02	0.07	-0.22*	0.03	0.54	2.66*	83.75*	0.22*
EC-464107 × DPBWRC-6-1	-3.67*	-0.67	2.45*	0.01	0.17	0.07	-0.10	0.16 *	0.03	-0.60	0.50	16.00	-0.12
DPBWRC-6-1 × EC-464115	-2.82*	-1.21	-6.71*	0.22*	0.70	0.90*	-0.03	-0.00	-0.41*	0.07	0.42	15.55	-0.07
EC-464115 × DPBWRC-6-1	-2.83*	-0.83	-0.28	0.08	0.83	0.24*	0.04	0.14	-0.17*	1.18	3.10*	110.17*	-0.04*
DPBWRC-29 × DPBWRC-39	4.35*	3.59*	-1.68*	0.02	-3.21*	-0.14	0.14	-0.01	0.01	-1.47*	-0.84	-41.13*	-0.01
DPBWRC-39 × DPBWRC-29	0.50	-1.50	1.99*	-0.08	1.50	0.06	-0.03	0.08	0.07	1.64*	0.33	34.17*	0.17
DPBWRC-29 × EC-464107	-4.07*	-1.74	2.82*	-0.09	1.76	0.79*	-0.11	0.18*	-0.03	2.14*	1.73*	89.08*	-0.18
EC-464107 × DPBWRC-29	-0.33	-0.67	1.69*	0.06	0.67	0.27*	-0.16	0.11	-0.23*	-0.71	1.07	25.47	-0.05
DPBWRC-29 × EC-464115	0.41	-4.74*	6.61*	-0.05	4.32*	0.39*	0.02	-0.09	-0.18*	1.05	1.32	58.08*	0.12
EC-464115 × DPBWRC-29	-3.33*	-2.83*	4.37*	-0.13	2.83*	-0.45*	0.14	0.32*	0.00	-0.05	0.17	5.77	-0.30
DPBWRC-39 × EC-464107	-0.01	0.15	-2.14*	0.09	0.15	0.28*	-0.20*	-0.07	-0.20*	-1.94*	2.63*	47.49*	0.15
EC-464107 × DPBWRC-39	0.50	0.00	0.13	0.16*	0.00	-0.30*	-0.01	-0.24*	0.13	0.62	-0.77	-13.67	0.03
DPBWRC-39 × EC-464115	-0.87	-2.85*	5.19*	-0.25*	2.70*	-0.40*	-0.03	-0.10	0.11	-0.61	0.09	-6.15	0.09
EC-464115 × DPBWRC-39	1.83	-0.17	6.00*	-0.20*	0.17	0.11	-0.08	-0.04	-0.03	-0.32	1.40*	39.60*	-0.01
EC-464107 × EC-464115	1.55	3.31*	-2.57*	0.09	-3.82*	0.06	-0.03	0.11	0.07	0.45	-2.04*	-55.91*	-0.33*
EC-464115 × EC-464107	0.17	-5.83*	5.25*	-0.27*	5.83*	-0.49*	-0.01	-0.07	0.21*	-1.02	0.50	-1.00	-0.09
SE(S_{ij})±	0.95	0.94	0.84	0.08	0.91	0.11	0.09	0.08	0.08	0.75	0.68	0.75	0.12
SE(S_{ij}-S_{ik}) ±	1.44	1.43	1.28	0.12	1.39	0.16	0.13	0.12	0.12	1.13	1.03	23.29	0.16
SE(S_{ij}- S_{kl}) ±	1.29	1.28	1.14	0.11	1.24	0.15	0.12	0.11	0.11	1.01	0.92	20.83	0.14

Significant at *P ≤0.05

DFF = Days to 50 per cent flowering, DFP = Days to first picking, PH = Plant height, PBP = Primary branches per plant, HD = Harvest duration, FL = Fruit length, FW = Fruit width, PT = Pericarp thickness, LPF = Lobes per fruit, AFW = Average fruit weight, MFPP = Marketable fruits per plant, MFYP = Marketable fruit yield per plant, TSS = Total soluble solids

Table 7. Cross combinations depicting significant and desirable *sca* effects along with *gca* effect of their parents

Traits	Best specific combiner	*sca* effect	*gca* (Female)	*gca* (Male)	Combination
Days to 50 percent flowering	DPBWRC-29 × EC-464107	-4.07*	-0.38	-0.35	Average × Average
	DPBWRC-29 × DPBWRC-1	-3.83*	-0.38	-0.19	Average × Average
	EC-464107 × DPBWRC-6-1	-3.67*	-0.35	-0.32	Average × Average
Days to first picking	EC-464115 × EC-464107	-5.83*	1.02*	-1.82*	Poor × Good
	DPBWRC-29 × EC-464115	-4.74*	-0.43	1.02 *	Average × Poor
	DPBWRC-39 × EC-464115	-2.85*	0.69	1.02 *	Poor × Poor
Plant height	DPBWRC-29 × EC-464115	6.61*	0.40	7.71*	Average × Good
	EC-464115 × DPBWRC-39	6.00*	7.71*	-1.38*	Good × Poor
	EC-464115 × EC-464107	5.25*	7.71*	0.94*	Good × Good
Primary branches per plant	DPBWRC-6-1 × EC-464115	0.22*	0.09*	-0.06	Good × Poor
	DPBWRC-39 × DPBWRC-1	0.20*	0.05	0.05	Average × Average
	DPBWRC-1 × DPBWRC-29	0.17*	0.05	-0.15*	Average × Poor
Harvest duration	EC-464115 × EC-464107	5.83*	-0.59	1.80*	Poor × Good
	DPBWRC-1 × EC-464115	4.70*	-2.07*	-0.59	Poor × Poor
	DPBWRC-29 × EC-464115	4.32*	0.32	-0.59	Average × Poor
Fruit length	DPBWRC-6-1 × EC-464115	0.90*	-0.12*	0.71*	Poor × Good
	DPBWRC-29 × EC-464107	0.79*	-0.20*	0.91*	Poor × Good
	EC-464107 × DPBWRC-1	0.77*	0.91*	-0.58*	Good × Poor
Fruit width	-	-	-	-	-
Pericarp thickness	EC-464115 × DPBWRC-29	0.32*	-0.27*	0.05	Poor × Average
	DPBWRC-39 × DPBWRC-1	0.25*	0.13*	0.01	Good × Average
	DPBWRC-1 × DPBWRC-39	0.21*	0.01	0.13*	Average × Good
Lobes per fruit	EC-464115 × EC-464107	0.21*	-0.10*	-0.15*	Poor × Poor
Average fruit weight	DPBWRC-1 × DPBWRC-39	2.72*	-0.54	1.24*	Poor × Good
	DPBWRC-29 × EC-464107	2.14*	1.97*	-1.36*	Good × Poor
	DPBWRC-39 × DPBWRC-1	2.06*	1.24*	-0.54	Good × Poor
Marketable fruits per plant	DPBWRC-1 × EC-464115	3.53*	-1.12*	-0.02	Poor × Poor
	EC-464115 × DPBWRC-6-1	3.10*	-0.02	1.61*	Poor × Good
	DPBWRC-6-1 × EC-464107	2.66*	1.61*	0.73*	Good × Good
Marketable fruit yield per plant	EC-464115 × DPBWRC-6-1	110.17*	-15.26*	45.75*	Poor× Good
	DPBWRC-29 × EC-464107	89.08*	-2.45	4.70	Poor × Average
	DPBWRC-1 × EC-464115	88.57*	-36.21*	-15.26*	Poor × Poor
TSS	DPBWRC-1 × EC-464115	0.31*	-0.08	0.10 *	Poor × Good
	DPBWRC-6-1 × EC-464107	0.22*	-0.14*	0.04	Poor × Average

Significant at *P $\leq$0.05

The results of *sca* effects clearly revealed that the high specific combiners involved good × good, poor × poor and good × poor general combiners as parents (**Table 7**), clearly reflecting that superior cross combinations are not only obtained from the combination of good × good general combiners but also from the combination of good × poor and poor × poor general combiners. Thus, high *gca* effects of the parents are not a reliable criterion for the prediction of high *sca* effects. High performance of these crosses may be attributed to additive × additive (good × good), additive × dominance (good × poor), or dominance × dominance (poor × poor) epistatic interactions. The superiority of the crosses involving good × poor, or poor × poor general combiners as parents may be attributed to the genetic diversity in the form of several heterozygous loci of the parents involved in the cross combinations (Kumar *et al.,* 2006). Cross pairings of parents with good and poor *gca* effects demonstrated the importance of both additive and non-additive gene activity. In such cases, selection would be successful in later generations. Combinations including both parents that have low *gca* effects highlight the importance of non-additive gene activity. These crosses can be progressed by using recurrent selection in the early generations, followed by single plant selection. A careful perusal of σ²gca, σ²sca, and σ²rca (**Table 4**) markedly designated that the non-additive gene effects were more eloquent than additive gene effects in the inheritance of estimated traits. Only two traits viz., fruit width, and pericarp thickness exhibited high GCA/SCA ratio. This reflected the opulence of additive genetic variance in the improvement of these traits. The accessible additive variance can be well exploited

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by resorting to population improvement methods, like recurrent selection, mass selection, pedigree method, bulk method etc. whereas non-additive genetic variance can be exploited by resorting to heterosis breeding or by delaying selection to later generations in order to maximize the desirable frequency of these traits, for instance, yield, TSS, early yield, fruit shape etc. Roy *et al.* (2018) and Nascimento *et al.* (2014) revealed that non-additive gene action was more prominent in the inheritance of the studied traits *viz.,* pericarp thickness, fruit yield, days to fruiting and TSS with exception to some characters such as fruit length, fruit diameter and fruit weight which were controlled by additive gene effects. Janaki *et al.* (2017) reported a significant role of non-additive gene action in the inheritance of traits like fruit yield per plant, plant spread, days to 50% flowering, number of fruits per plant etc. Meanwhile, Adday *et al.* (2016) reported that additive gene effects played a more important role than non-additive effects in the inheritance of all traits except the number of branches per plant. Significant maternal effects were observed for all characters except fruit width, lobes per fruit and TSS.

Based on the overall results of *sca* analysis three cross-combinations viz., DPBWRC-29 × EC-464107, DPBWRC-39 × DPBWRC-1 and EC-464115 × DPBWRC-29 were found to be good specific combiners for the majority of traits and can further be utilized to isolate superior segregants. Four cross combinations *viz.,* DPBWRC-6-1 × EC-464107, DPBWRC-1 × EC-464115, DPBWRC-29 × EC-464107 and DPBWRC-6-1 × DPBWRC-29 showed high mean performance, high heterosis and high *sca* for fruit yield and related traits. These cross-combinations with blocky fruit shape, yellow green to green fruit colour, pendent fruit position, cordate fruit shape at pedicel attachment and sunken fruit shape at blossom end along with resistance to the bacterial wilt disease offer high scope for further exploitation. These cross-combinations can be released as hybrids after field testing and can also be utilized in future breeding programmes.

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