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COMBINING ABILITY AND HETEROTIC EFFECTS OF CHILI PEPPER (*Capsicum annuum* L.) GENOTYPES FOR YIELD COMPONENTS AND CAPSAICIN CONTENT

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SUMMARY

The productivity of chili pepper (*Capsicum annuum* L.) can be increased by the use of hybrid cultivars. Promising hybrid cultivars can be obtained by maximizing the combining ability value between two parents. The objective of this study was to estimate the general combining ability and specific combining ability (SCA) of the yield components and capsaicin content of chili plants obtained via diallel crossing. This study was conducted at the Leuwikopo Experimental Field, Department of Agronomy and Horticulture, Bogor Agriculture University. The experimental design was a single-factor randomized complete block design with three replications. On the basis of the results, the C5 × F074 hybrid was identified as the recommended hybrid for improving productivity potential. The Bara × F9160291 cross showed positive heterosis and the highest mean performance and SCA effects for capsaicin content. The C5 × F6074 hybrid showed high mean performance and the highest SCA effect for fruit weight per plant. The results of this study can be exploited further in chili breeding for the development of hybrids with high capsaicin content and productivity or hybridization programs.

Keywords: Diallel, general combining ability, hybrid, productivity, specific combining ability

Key findings: This study recommended chili hybrids and parents for future use on the basis of yield components and capsaicin content.

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INTRODUCTION

Chili peppers are important horticultural crops worldwide. They are harvested for their spicy taste and burn sensation. They are also used in food and medicines. Hybrid cultivars have been introduced and used by farmers to increase pepper productivity. However, the number of hybrid chili pepper cultivars remains low. Plant breeding activities aim to develop new cultivars that have advantages over previous cultivars (Crossa *et al*., 2017). One of the most commonly known breeding techniques is hybridization (Vishnuprabha *et al*., 2020). Hybridization aims to combine the genetics of two parents to produce new superior cultivars by utilizing heterosis (Ali *et al*., 2019). Next, a diallel method can be used to analyze the mechanism of genes that are involved at the beginning of a generation (Hasanuzzaman and Golam, 2011). A full dialell method can provide a random mating population that is balanced in accordance with the Hardy–Weinberg principle (Yunianti *et al*., 2011). In addition, it can discover information about the general combining ability (GCA) and specific combining ability (SCA) of crossing results (Singh and Chaudry, 1979).

GCA and SCA variants indicate the dominant action of nonadditive genes for the inheritance of all traits and the possibility of exploiting heterosis (Darshan *et al*., 2017; Herath *et al*., 2017). Rao *et al*. (2017) also reported the high heterotic response of hybrids supported by the predominant role of nonadditive gene action in the inheritance of the studied characters. The analysis of mid- and over-high parent heterosis indicates the existence of sufficient heterosis for fresh and dry fruit yield (Abrham *et al*., 2017). The value of GCA and SCA can also be obtained from the results of dialell crosses under various environmental conditions (Jaiswal and Patel, 2018; Sharma *et al*., 2019) and in male sterility populations (Dixit *et al*., 2019; Gramaje *et al*., 2020). In plant breeding programs, GCA and SCA research is performed to increase productivity (Aisyah *et al*., 2016; Askander and Osman, 2018; Dharva *et al*., 2018)

Information about GCA and SCA is crucial to chili breeding activities (Rodrigues *et al*., 2012; Navhale *et al*., 2014). GCA can be applied to recommend parents for use in assembling cultivars with the targeted character (Sitaresmi *et al*., 2010). Meanwhile, SCA can be used to recommend hybrids to be planted for the next generation (Sharma *et al*., 2016). Ganefianti and Fahrurrozi (2018) reported the combining ability and heterosis of seven parental lines and identified the parents C(KG 3), F(KG6), B(KG2), D(KD4), and G(KD7) as good general combiners for different yield-contributing traits and the hybrids G(KG7) × C(KG3) and F(KG6) × C(KG3) as the most promising chili pepper hybrids for ultisol areas. Rohini *et al*. (2017) also reported greater variance for SCA than for GCA for all the studied traits and identified LCA625, K1, and PKM1 as the best general combiners and the hybrid K1 × Arka Lohit as the best reciprocal combiner for quality parameters.

The problem encountered in chili breeding is that information regarding GCA and SCA for capsaicin content remains limited. Therefore, this study is expected to generate information on the GCA and SCA of the capsaicin content and yield components of chili plants resulting from diallel crossing.

MATERIALS AND METHODS

Study area and genetic material

This research was conducted at the IPB University Experimental Field, Dramaga Subdistrict, Bogor, West Java, Indonesia. Capsaicin was analyzed in the laboratory of the Indonesian Center for Agricultural Postharvest Research and Development, Bogor, West Java. The genetic material used in this study consisted of 36 genotypes, including six parental lines of chili and 30 hybrid F1 genotypes resulting from a full diallel cross. The six chili parent genotypes were C5, F6074, F9160291, Yuni, Bara, and Giant. These genetic materials were from a collection of the Genetics and Plant Breeding Laboratory, IPB University. The design used was a randomized complete block design with three replications. Each replication consisted of 20 plants per genotype.

Morphological characterization

Harvesting age, fruit length, fruit weight, total amount of fruit plant^{-1}, fruit weight plant^{-1}, and capsaicin content were observed in reference to the Descriptor of Capsicum International Plant Genetic Resources Institute (IPGRI, 1995). Yield component characters, including harvesting age, fruit length, fruit weight, fruit weight per plant, total amount of fruit per plant, and capsaicin content, were observed.

Experimental activity began with seeding activities. Fertilization was performed when the seedlings were 2 weeks old by using NPK 15:15:15 fertilizer (10 g L^{-1} water). Planting was conducted when the chili seeds were 30 days old or had attained a plant height of approximately 15 cm and leaf number of 8. Beds measured 1 m × 5 m with an interval of 50 cm between beds. The beds were covered with silver black plastic mulch, and planting holes were made at intervals at 50 cm × 50 cm. Maintenance activities were carried out as follows: watering in the morning and evening; fertilization once a week by using NPK fertilizer (15:15:15, 10 g L^{-1} water) at the rate of as high as 250 mL plant^{-1}; and pesticide application once every 2 weeks by using a fungicide with the active ingredient Mankozeb (2 g L^{-1}) and insecticide with the active ingredient Prefonofos (2 mL L^{-1}). Harvesting was done when the chili plants had reached a level of maturity of 75% or at the age of 70 days after planting, which was carried out every week for 8 weeks.

Capsaicin analysis

Sample preparation

In this research, capsaicin analysis was performed by using a modified HPLC method (Tilahun *et al*., 2013). The initial step in the analysis of capsaicin was to dry the chili sample by using an oven at 50 °C for 2 × 24 h. The next step was to measure the water content at 59 °C then to crush the chilies until smooth. A total of 0.5 g of chili powder was placed in a 50 mL volume test tube containing 5 mL of acetone p.a. The tube was then shaken by hand and subjected to ultrasonic treatment for 5 min at room temperature. The test tube was closed by using alufo and heated in a water bath for 8 h at 80 °C. Then, the sample was cooled in a refrigerator overnight at 4 °C. Subsequently, the sample was filtered with Whatman 41 filter paper into a test tube scale. A 30 mL sample was taken and then ultrasonicated for 20 min. Subsequently, a part of the solution was collected by using a 0.45 µm syringe filter and placed in a 1.5 mL vial bottle for HPLC. In this study, two samples were used per genotype.

HPLC conditions

A HPLC Detector DAD UV–VIS with C18 column (4.6 mm × 150 mm, 4 µm) was used. The C18 column was used for the effective partitioning and quantification of capsaicinoids (Othman *et al*., 2011). The column temperature was 30 °C, and the sample temperature was 4 °C. The analysis was performed at 250 mm and 276–280 nm wv. Other conditions were as follows: fluorescence 1.5 mL min^{-1} and injection volume of 20 µm. The mobile phase was acetonitrile:phosphate acid 0.1% (40:60).

Capsaicinoid quantitation

The major capsaicinoids in peppers, capsaicin, and dihydrocapsaicin were determined through comparison with external reference standards injected under the same conditions (Schmidt *et al*., 2017). Their identification was based on the retention times measured under identical HPLC conditions, and their quantitative determination in different pepper samples was carried out by using the peak areas. The ratio between these capsaicinoids was calculated by dividing capsaicin and dihydrocapsaicin content by the total capsaicinoid content. The capsaicinoid concentrations in the samples are expressed as µg g^{-1} pepper.

Scoville head unit conversions

Capsaicin contents were converted into Scoville heat units (SHU) by multiplying the pepper dry weight capsaicin content in g of capsaicin per g of pepper by the coefficient of the heat value for capsaicin, which is 1.6×10^7 in the literature (Todd *et al*., 1977).

Data analysis

Data analysis was performed by using ANOVA and combining ability analysis. ANOVA was performed in accordance with a general linear model by using SAS software package version 9.0. Combining ability for yield components and capsaicin content was analyzed by Griffing's methods I and II, respectively. Capsaicin was analyzed on the basis of HPLC extraction results of chili fruit to obtain quantitative data on capsaicin content.

RESULTS AND DISCUSSION

The mean square value of the GCA of the yield components (Table 1) and chili capsaicin content (Table 2) had a very significant effect on all observational variables. The mean square value of the SCA of the yield components and capsaicin content also exerted a significant effect on all observed variables. Abishek *et al*. (2017) stated that significant variance between the GCA and SCA for yield component and capsaicin content indicates the presence of genetic variability for parents and their hybrids. The reciprocal values of the

Table 1. ANOVA of the yield components of chili genotypes.

Source of variation	d.f.	Mean squares				
		Harvesting age	Fruit length	Fruit weight	Total amount of fruit plant^{-1}	Fruit weight plant^{-1}
Replications	2	2.81	1.04	0.46	14.3	4198.42
Genotypes	35	36.92**	27.67**	35.5**	5633.74**	52320.58**
GCA	5	39.22**	51.58**	65.64**	11896.89**	84129.02**
SCA	15	12.56**	1.79**	4.94**	396.66**	9565.64**
Reciprocals	15	3.08**	2.54**	0.78**	19.51**	3085.13**
Error	70	0.5	0.37	0.19	2.1	960.51
CV%		1.84	13.23	15.31	2.79	16.38

**: Significant at $P \leq 0.01$

Table 2. ANOVA of the capsaicin content of chili genotypes.

Sources	d.f.	Mean squares
Replications	1	281565.67
Genotypes	20	563268008.51**
GCA	5	877700682**
SCA	15	82945112**
Error	20	193365.8
CV %	1.57	

**: Significant at $P \leq 0.01$

yield components have a significant effect on all observed variables. The significant influence of reciprocals indicated a significant difference between the F1 and F1 reciprocals tested in this study. Capsaicin content did not show a reciprocal effect because a half-diallel population was used in capsaicin analysis. El Badawy (2013) also used a dialell population of maize (*Zea mays* L.).

The results of GCA can be used to identify the parents that can be recommended for future research. One of the important indicators in producing superior genotypes is the estimated value of GCA (Bharati *et al*., 2019). Abdalla *et al*. (2017) reported that genotypes that have a high GCA value can be used as parents for generating synthetic cultivars. The highest GCA value for the six parents in this study is spread evenly between each character observed. This result showed that each parent has an advantage in a particular desired character. GCA and SCA were significant (α = 1%) for all traits (Tables 3 and 4). The significant GCA and SCA implied that additive and dominance effects contributed to the genetic control of all the traits of the lines used in this study. Similar results have been observed for the vitamin C and soluble solid contents of pepper (Geleta and Labuschagne, 2006).

Bara and F9160291 had the highest mean performance and also showed significant (α = 1%) positive GCA effects for the total amount of fruit per plant and capsaicin content (Table 3). These parental lines were good combiners for the total amount of fruit per plant and capsaicin content and could be the best candidates for

Table 3. Means and general combining ability (GCA) effects of chili parental cultivars for yield components and capsaicin content.

Genotypes	Harvesting Age		Fruit length		Fruit weight		Total amount of fruit plant^{-1}		Fruit weight plant^{-1}		Capsaicin content	
	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA
C5	33^{d}	−0.69	7.76^{bc}	0.49*	8.30^{ab}	2.38**	62.34^{e}	−19.19**	517.12^{a}	115.85**	19784.10^{e}	−10834.8**
BARA	29.67^{e}	−1.99	2.65^{de}	−2.27**	0.93^{e}	−2.56**	178.03^{b}	35.45**	165.84^{e}	−78.66**	58130.80^{e}	12323.97**
F6074	32^{e}	−1.99**	8.81^{b}	0.77**	5.38^{c}	0.85**	81.86^{d}	−8.57**	440.29^{ab}	92.87**	25868.60^{d}	−5139.27**
GIANT	38.67^{a}	2.2**	6.31^{bc}	0.42*	3.94^{a}	2.71**	16.00^{f}	−40.73**	144.80^{c}	−27.23*	122298.30^{f}	−11505.3**
YUNI	35.67^{b}	1.4	13.20^{a}	3.05**	2.83^{d}	−0.86**	84.11^{c}	−6.44**	237.04^{cd}	−31.53**	39787.50^{c}	5895.41**
F9160291	31.33^{bc}	1.07**	3.55^{e}	−2.45**	0.93^{e}	−2.52**	181.44^{a}	39.48**	169.14^{e}	−71.31**	45453^{b}	9260.051**

**,*: Significant at $P \leq 0.01$ and $P \leq 0.01$, respectively, Numbers followed by the same letter in the same column were not significantly different by DMRT 5% level

improving the total amount of fruit per plant and capsaicin content. The parents C5 and F6074 were good combiners for fruit weight and fruit weight per plant as demonstrated by their significant positive GCA effects and highest mean performance (Table 3).

The SCA effects for yield components were estimated for all the 30 hybrids, whereas those for capsaicin content were estimated for 15 hybrids. The estimates of the SCA effects of hybrids for all traits are presented in Table 4. Out of the 15 hybrids, 11 had significant (α = 1%) positive SCA effects, whereas four hybrids had significant (α = 1%) negative SCA effects for capsaicin content. For the total amount of fruit per plant, most hybrids had significant negative SCA effects, whereas significant positive SCA effects were found in two hybrids (Bara × F9160291 and F9160291 × Bara).

The hybrid Bara × F9160291 showed the highest mean performance, and significant SCA effect was observed for crosses between parents with high GCA effects for capsaicin content. In addition, the C5 × F6074 hybrids produced by crossing parents with high GCA effects showed high mean performance (703.06 g plant^{-1}) and significant positive SCA effect (171.53) for fruit weight per plant. Thus, GCA effects should be considered in the selection of parental lines for capsaicin content, and this cross could be used as a source population for pedigree selection for fruit weight per plant and capsaicin content because it had more additive genetic effects than other hybrids (Iriany *et al*., 2011). By contrast, parents with low GCA effects produced hybrids with high SCA effects (Bara × Yuni) for fruit weight per plant. Kumari *et al*. (2015) stated that gene action plays a complementary role.

Table 4. Means, specific combining ability (SCA) and reciprocal (Rec.) effects in F1 hybrids of chili pepper.

Genotypes	Harvesting age		Fruit length		Fruit weight		Total amount of fruit plant^{-1}		Fruit weight plant^{-1}		Capsaicin content	
	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA	Mean	SCA
BARA × C5	29.67 $^{a-e}$	1.50**	5.84 ^{hij}	0.06	2.81 $^{j-m}$	0.47**	98.74 ^{g}	−6.76**	274.83 $^{f-j}$	22.97**	–	–
BARA × F6074	30.33 $^{a-d}$	−0.23**	6.75 $^{g-j}$	−0.05	3.15 $^{j-m}$	−0.09**	110.77 ^{e}	−9.00**	349.11 $^{c-f}$	−11.66**	51541.60 ^{c}	4795.60**
BARA × GIANT	26.33 $^{d-k}$	−3.76**	6.13 $^{g-j}$	−0.35	3.09 $^{i-m}$	−2.22**	81.89 ^{ij}	−2.81**	253.21 $^{f-i}$	5.38**	41935.90 ^{g}	1555.97**
BARA × YUNI	27.33 $^{c-i}$	−2.95**	7.76 $^{f-i}$	1.26**	2.20 $^{k-o}$	1.31**	101.30 ^{fg}	−18.60**	222.84 $^{g-j}$	60.20	55075.10 ^{b}	-2705.58**
BARA × F9160291	23.00 $^{j-n}$	−0.12**	3.25 ^{l}	0.14	1.07 ^{no}	1.23**	197.29 ^{a}	27.39**	210.48 ^{hij}	17.90	78992.60 ^{a}	17847.27**
C5 × BARA	32.00 ^{ab}	0.63**	5.96 ^{hij}	−0.26	3.75 $^{h-k}$	−1.41**	85.22 ^{i}	−14.19**	320.77 $^{d-h}$	−67.19**	31714 ^{j}	-9336.45**
C5 × F6074	32.33 ^{ab}	−0.87	9.58 ^{def}	0.74	8.94 ^{cd}	0.92	78.74 ^{jk}	16.51**	703.06 ^{a}	171.53**	16933.60 ^{k}	-6653.60**
C5 × GIANT	27.00 $^{c-j}$	−2.23**	9.56 ^{def}	0.83	13.07 ^{b}	4.11**	32.60 ^{p}	2.22**	424.71 ^{bcd}	35.61	17833.20 ^{k}	612.04**
C5 × YUNI	20.67 ^{n}	−0.43**	12.12 ^{bc}	0.11	6.49 ^{ef}	−0.91**	73.06 ^{lm}	7.71**	476.54 ^{b}	−16.34	40216.90 ^{h}	5595.03**
C5 × F9160291	23.33 $^{i-n}$	0.41	5.71 ^{ij}	−0.25**	3.25 $^{i-m}$	−1.38**	92.69 ^{h}	−23.07**	301.03 $^{e-i}$	−81.25**	43984.50 ^{f}	5997.99**
F6074 × C5	33.00 ^{a}	−0.67	10.31 ^{dc}	−0.37	9.08 ^{c}	−0.07	78.57 ^{jk}	0.09**	713.03 ^{a}	−4.98	–	–
F6074 × BARA	29.33 $^{a-e}$	1.00**	6.03 ^{hij}	0.36	2.97 $^{i-m}$	0.09**	104.80 ^{f}	2.98**	311.59 $^{e-i}$	18.76**	–	–
F6074 × GIANT	31.00 ^{abc}	−0.59**	9.88 ^{def}	0.94	9.76 ^{c}	0.88	40.71 ^{o}	0.88**	399.36 $^{b-e}$	7.34**	16627.50 ^{k}	-6289.21**
F6074 × YUNI	27.00 $^{c-j}$	−1.79	6.97 $^{g-j}$	−1.43**	3.45 $^{i-l}$	−0.23**	69.65 ^{m}	−2.02	239.94 $^{f-j}$	−49.97	–	–
F6074 × F9160291	22.67 $^{k-n}$	0.38**	6.63 $^{g-j}$	0.48**	2.85 $^{j-m}$	−0.29	105.83 ^{f}	−15.47**	301.97 $^{e-i}$	−43.98**	47067.30 ^{d}	3385.23**
F9160291 × C5	22.67 $^{k-n}$	0.00	5.76 ^{hij}	−0.02**	3.45 $^{i-l}$	−0.10**	81.55 ^{ij}	5.57**	281.16 $^{f-j}$	9.93**	–	–
F9160291 × BARA	22.00 ^{lmn}	−1.17**	3.48 ^{kl}	−0.12	0.97 ^{o}	0.05**	187.16 ^{b}	5.07**	180.98 ^{j}	14.75	–	–
F9160291 × F6074	21.67 ^{mn}	−1.33**	6.85 $^{g-j}$	−0.11**	2.95 $^{i-m}$	−0.05	104.84 ^{f}	0.50**	308.79 $^{e-i}$	−3.41**	–	–
F9160291 × GIANT	25.00 $^{g-m}$	−1.17**	5.69 ^{ij}	−0.16	3.83 ^{hij}	0.05	79.83 ^{jk}	1.28**	304.32 $^{e-i}$	9.84**	–	–
F9160291 × YUNI	27.33 $^{c-i}$	0.67**	7.89 $^{e-h}$	0.14**	2.16 $^{l-o}$	−0.15	126.71 ^{d}	2.35	273.19 $^{f-j}$	−9.75	–	–
GIANT × C5	24.00 $^{i-n}$	−0.50**	9.80 ^{def}	−0.12	15.06 ^{a}	−0.99**	31.83 ^{p}	0.38**	479.35 ^{b}	−27.32	–	–
GIANT × BARA	26.33 $^{d-k}$	−1.67**	5.35 ^{jk}	0.39	2.48 $^{j-n}$	0.31**	81.76 ^{ij}	0.07**	201.37 ^{ij}	25.92**	–	–
GIANT × F6074	31.00 ^{abc}	−0.17**	10.26 ^{cd}	−0.19	8.85 ^{cd}	0.46	42.27 ^{no}	−0.78**	402.20 $^{b-e}$	−1.42**	–	–
GIANT × YUNI	24.00 $^{i-n}$	1.19	11.41 ^{cd}	1.41	5.06 ^{gh}	−0.38**	46.23 ^{n}	−0.30**	234.26 $^{f-j}$	−4.68**	45575.90 ^{e}	11624.55**
GIANT × F9160291	28.33 $^{b-h}$	−1.31**	5.38 ^{jk}	−0.37	3.93 ^{hij}	−1.17	82.40 ^{ij}	−7.54**	324.00 $^{d-h}$	84.90**	38317.50 ^{i}	1001.45**
YUNI × C5	22.33 $^{k-n}$	0.50**	11.08 ^{cd}	0.52	4.44 ^{ghi}	1.03**	70.92 ^{m}	1.07**	315.02 $^{e-i}$	80.76	–	–
YUNI × BARA	29.00 $^{a-g}$	−2.67**	12.21 ^{bc}	−2.23**	3.31 $^{i-m}$	−0.56**	99.33 ^{g}	0.99**	332.78 $^{c-g}$	−54.97	–	–
YUNI × F6074	25.33 $^{f-m}$	1.50	13.69 ^{ab}	−3.36**	5.79 ^{fg}	−1.17**	76.09 ^{kl}	−3.22	438.39 ^{bc}	−99.22	51907.70 ^{c}	11590.29**
YUNI × GIANT	24.67 $^{h-n}$	−1.33	14.24 ^{a}	−1.42	7.59 ^{de}	−1.26**	38.64 ^{o}	3.79**	294.45 $^{e-i}$	−30.10**	–	–
YUNI × F9160291	26.00 $^{e-l}$	0.32**	8.16 ^{efg}	−0.51**	1.85 ^{mno}	0.52	131.42 ^{c}	6.12	253.68 $^{f-j}$	38.48	51741.70 ^{c}	9260.05**

**: Significant at $P \leq 0.01$, Numbers followed by the same letter in the same column were not significantly different by DMRT 5% level

Table 5. Heterosis and heterobeltiosis in F_1 hybrids of chili for yield components and capsaicin content.

Genotypes	Harvesting age		Fruit length		Fruit weight		Total amount of Fruit $plant^{-1}$		Fruit weight $plant^{-1}$		Capsaicin content	
	H_{MP}	H_{HP}	H_{MP}	H_{HP}	H_{MP}	H_{HP}	H_{MP}	H_{HP}	H_{MP}	H_{HP}	H_{MP}	H_{HP}
BARA × C5	−3.40	−4.33	14.57	−23.15	−18.76	−54.82	−29.09	−52.13	−6.07	−37.97	–	–
BARA × YUNI	−7.48	−10.00	54.07	−7.50	76.31	17.25	−24.21	−44.20	65.20	40.39	12.49	−5.26
BARA × F6074	−8.87	−11.06	5.24	−31.56	−5.81	−44.75	−19.35	−41.13	2.81	−29.23	22.72	−11.34
BARA × F9160291	−3.37	−3.37	12.32	−1.88	3.72	3.68	4.13	3.15	8.05	7.00	52.52	35.89
BARA × GIANT	−11.76	−16.67	19.37	−15.24	−50.28	−72.58	−15.73	−54.08	29.64	21.42	19.09	−27.86
C5 × BARA	−7.77	−8.65	12.26	−24.70	−39.09	−66.12	−17.84	−44.53	−19.52	−46.85	−18.59	−45.44
C5 × YUNI	−5.66	−9.09	5.69	−16.09	−20.11	−46.46	−3.15	−15.69	−16.46	−39.08	35.02	1.08
C5 × F6074	−4.48	−5.88	24.48	17.06	32.79	9.43	8.97	−4.02	48.95	37.88	−25.82	−34.54
C5 × F9160291	−1.46	−2.40	1.89	−25.77	−25.25	−58.43	−33.09	−55.05	−18.06	−45.63	34.85	−3.23
C5 × GIANT	−8.68	−14.53	39.27	26.25	73.54	66.27	−18.73	−48.94	44.84	−7.30	11.17	−9.86
F6074 × BARA	−5.91	−8.17	17.80	−23.38	−0.11	−41.40	−14.76	−37.78	15.19	−20.71	–	–
F6074 × C5	−6.47	−7.84	15.59	8.70	30.82	7.80	9.22	−3.80	46.87	35.96	–	–
F6074 × YUNI	−9.57	−14.09	24.37	3.69	41.20	7.66	−8.30	−9.53	29.45	−0.43	–	–
F6074 × F9160291	0.00	−2.40	10.82	−22.29	−6.45	−45.11	−20.36	−42.22	1.33	−29.87	31.99	3.55
F6074 × GIANT	−7.41	−14.53	35.69	16.42	22.59	−2.31	−13.61	−48.36	37.48	−8.65	−12.87	−35.72
F9160291 × C5	−1.46	−2.40	1.00	−26.42	−29.66	−60.88	−23.96	−48.91	−12.27	−41.79	–	–
F9160291 × BARA	−6.73	−6.73	4.79	−8.46	14.34	14.30	9.77	8.74	25.66	24.44	–	–
F9160291 × YUNI	−1.40	−4.09	−2.51	−38.16	−1.64	−34.58	−1.02	−27.57	24.91	7.02	–	–
F9160291 × F6074	−3.94	−6.25	7.31	−24.74	−9.55	−46.93	−19.61	−41.67	−0.90	−31.42	–	–
F9160291 × GIANT	−8.14	−13.25	9.18	−14.72	−21.23	−56.56	−16.53	−54.58	106.41	91.55	–	–
GIANT × F6074	−7.87	−14.96	30.75	12.18	35.29	7.81	−16.80	−50.27	36.51	−9.30	–	–
GIANT × C5	−10.05	−15.81	35.96	23.24	50.69	44.38	−16.78	−47.71	28.33	−17.87	–	–
GIANT × YUNI	−3.52	−6.41	45.99	7.88	27.75	−16.21	−22.80	−54.06	54.23	24.22	75.00	14.55
GIANT × BARA	−16.29	−20.94	36.93	−2.77	−38.07	−65.85	−15.59	−54.00	63.02	52.68	–	–
GIANT × F9160291	−4.98	−10.26	15.47	−9.80	−23.40	−57.76	−19.13	−56.00	93.87	79.92	32.70	−15.70
YUNI × F6074	−5.26	−10.00	−36.63	−47.17	−15.77	−35.78	−16.07	−17.20	−29.15	−45.50	58.12	30.46
YUNI × BARA	−14.95	−17.27	−2.08	−41.21	17.14	−22.09	−22.71	−43.10	10.62	−5.99	–	–
YUNI × C5	−4.25	−7.73	15.65	−8.18	16.82	−21.72	−0.23	−13.14	26.38	−7.85	–	–
YUNI × F9160291	−3.27	−5.91	−5.73	−40.20	14.83	−23.62	−4.57	−30.16	34.52	15.25	21.40	13.84
YUNI × GIANT	−7.05	−9.83	16.94	−13.59	−14.73	−44.07	−7.64	−45.03	22.70	−1.18	–	–

Heterosis and heterobeltiosis for selection should also be considered in the assembly of hybrid cultivars through breeding activities. If hybrid cultivars have the best heterosis and heterobeltiosis values but poor performance, they cannot be easily utilized as hybrid cultivars (Hei *et al*., 2016). The heterosis value is a form of the superior appearance of a hybrid compared with the mean of the two parents, whereas the heterobeltiosis value is the form of the superior appearance of a hybrid compared with the appearance of the best parent (Meena *et al*., 2017). Heterosis compares the mean values of the two parents, whereas heterobeltiosis compares the best performance value of the parents (Rohini and Lakshmanan, 2017).

The ranges of heterosis over the mid parent (HMP) and high parent (HHP) for fruit weight per plant (Table 5) were −29.15%–106.41% and −46.85%–91.55%, respectively, and the numbers of hybrids that had positive heterosis over the HMP and HHP were 23 and 12, respectively. The highest positive heterosis for fruit weight per plant was shown by F9160291 × Giant and Giant × F9160291 hybrids. The mean performance for the yield components of F9160291 × Giant and Giant × F9160291 hybrids was higher than that of the parents (Table 4). Several studies have shown that the character of fruit weight per plant has high heterosis that ranges from −39.19% to 211.00% (Sekhar *et al*., 2010; Ahmad *et al*., 2011; Farzane *et al*., 2012; Souza *et al*., 2013)

Similarly, the ranges of heterosis over the HMP and HHP for capsaicin contents were −25.82%–75.00% and −45.44%–35.89%, respectively, and the numbers of hybrids that had positive heterosis over the HMP and HHP were 13 and 7, respectively (Table 5). The hybrids Giant × Yuni had the highest positive heterosis for capsaicin content and had further potential to become the hottest hybrid cultivar because it also had the highest SCA value. The Bara × F9160291 hybrid also had further potential to become a hybrid cultivar considering its SCA value, heterobeltiosis, and mean value. Sahid *et al*. (2020) also reported that the Bara × F9160291 hybrid has high capsaicin content.

CONCLUSION

The significance of GCA and SCA implied that additive and dominance effects contributed to the genetic control of the total amount of fruit per plant and capsaicin contents. Bara and F9160291 showed significant GCA effects for both traits and could be exploited in hybridization programs. The crossing results of Bara × F9160291 showed positive heterosis, as well as the highest mean performance coupled with the highest SCA effects for capsaicin content. The C5 × F6074 hybrid showed high mean performance and the highest SCA effect for fruit weight per plant. The results of this study can be exploited further in chili breeding and hybridization programs for the development of hybrids with high capsaicin content and productivity.

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