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RESEARCH ARTICLE

Combining Ability and Heterosis for Yield and Related Traits in Chili (*Capsicum annuum* L.)

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Abstract:

Introduction:

An experiment was conducted to study combining ability and heterosis for yield and related traits in chili during November 2015 to September 2017.

Materials and Methods:

The experimental material consisted of six parents and their fifteen F_1's developed by half diallel mating design. Analysis of variance for combining ability exhibited significant General and Specific Combining Ability (GCA and SCA) effects for all the characters studied.

Results:

The SCA variance was higher than GCA variance for all the traits except ten fresh fruit weight, fruit length and fruit width indicating the predominance of non-additive type of gene action. The parents P_1 and P_6 were identified as the best general combiners and the hybrids $P_1 \times P_6$, $P_1 \times P_4$ and $P_2 \times P_5$ were identified as the best specific combinations for fresh fruit yield per plant and related traits. The hybrids $P_1 \times P_6$, $P_1 \times P_4$ and $P_3 \times P_6$ showed significant average heterosis and heterobeltiosis for fresh fruit yield per plant and its related traits. $(H_1/D)^{0.5}$ ratio indicated partial dominance effect of genes for all the traits.

Conclusion:

Therefore, it may be possible to take advantages of better heterotic effects to be fixed in the later generations to facilitate further selection and best specific combinations for development of the hybrid variety of chili which can help to increase the total production in Bangladesh.

Keywords: Half diallel, Heterobeltiosis, Partial dominance, Hybrid, SCA, GCA.

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1. INTRODUCTION

Chili (*Capsicum annuum* L.) is an important commercial vegetable and condiment species that is grown all over the world. It is a dicotyledonous flowering plant and pertaining to the genus Capsicum of Solanaceae family, Solanoideae sub-family and Capsiceae tribe with different names such as hot pepper, chili pepper, bell pepper, pod pepper, red pepper, cayenne pepper, paprika, pimento and capsicum in the different parts of the world which have superfluous nutritional and medicinal value [1, 2]. The place of origin of chili is Latin American regions of New Mexico, Guatemala and Bulgaria [3]. The center of diversity of chili is deemed to be south to central South America [4]. Chili is a diploid (2n = 24), self-pollinated and chasmogamous crop species whose flowers open only after pollination [5]. Though it is a self-pollinated crop, 2 to 96% out crossing was noticed under open pollination [6].

Capsicum has been known as part of the human diet as spice, condiments and vegetables since the commencing of civilization [7]. Green fruits of chili are used as vegetable. On the other hand, ripe dried fruits as spice because of its pungency and imposing flavor [8]. Green chili is a great source of vitamin C and red chilies contain large amounts of Capsaicin. Capsaicin is deliberated a secure and operative topical anodyne in the relief of natural pain, headaches and lowers risk of type 2 diabetes and obesity, it stops spreading

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prostate cancer , prevents sinusitis and relieves congestion, prevents stomach ulcers, improves heart health and protects against strokes [9, 10]. Chili is inseparably involved with almost every kitchenette in Bangladesh and its demand is increasing day by day due to its pungency, appealing color and flavor [11].

According to FAOSTAT [12] in 2014, the yield of dry chili in Bangladesh was 1.22 ton/ha which is very low compared to China (6.75 tons/ha) and India (1.93 tons/ha). In 2013, Bangladesh exported 312 tons of chili and imported 28863 tons dry chili which shows that a large amount of chili had been imported to fulfill the domestic demand and also exported 1162 tons of green chili which was much lower than Mexico (605484 tons) and imported 602 tons of green chili. The main cause of lower chili production in Bangladesh is the lack of available and suitable chili hybrids for higher yield in different climatic zones. Only four hybrids chili varieties namely BARI Morich-1, BARI Morich-2, BARI Morich-3 and BARI Mistimorich-1 were released by Bangladesh Agricultural Research Institute [13, 14] which are not enough to fulfill the requirements of the country. But a wide range of genetic variability exists among the cultivated land races of chili in Bangladesh that can be exploited for its improvement. The variability among indigenous and exotic genotypes are genetic attributes which can be combined through hybridization to develop varieties with higher yield and nutritional qualities. There is a great scope of a breeder to develop high yielding varieties through selection, either from existing genotypes or from the segregating population. Hence, information on gene action, its nature and magnitude in respects of yield and quality traits need to be properly assessed for its improvement.

For planning efficient breeding programs, the study of genetic information such as combining ability, heterosis and nature of gene action are more essential. Sprague & Tatum [15], first proposed the concepts of General Combining Ability (GCA) and Specific Combining Ability (SCA). According to them, GCA variance is due to additive variance and SCA variance is due to non-additive variance. Shull [16] proposed the term heterosis and Whaley [17] was of the opinion that it would be more appropriate to term the developed superiority of the hybrids as hybrid vigor and to refer the mechanism by which the superiority is developed as heterosis. Jinks and Griffing [18, 19] delineated analysis of diallel crosses which provides rapid overall evaluation of certain genetic relationship, such as combining ability among the parents and their crosses entering diallel crosses. Diallel cross approach being quick and efficient to estimate the combining ability, mode of reproduction and components of variance was adopted to investigate yield and quality characters. According to Johnson (1963) [20], diallel analysis is experimentally a systematic approach, and analytically a comprehensive genetic evaluation approach which enables the breeder to provide the behavior of a cross in further generations by making use of F_1 itself. Hayman method was used to study the action of genes, allied genetic components and heritability [21]. Both the Griffing and Hayman data analysis methods are usually used together for complementary data interpretation. These methods (either one or both) have been previously used in different crops, such as in chili pepper [22 - 31], wheat [32, 33], bottlegourd [34], barley [35], peanut [36], papaya [37], and peas [38]. For developing hybrids, heterosis was also studied by many researchers on chili [39 - 47].

In chili, Ganefianti and Fahrurrozi [31] studied the combining ability and heterosis for seven parental lines and identified the parent C(KG 3), F(KG6), B(KG2), D(KD4) and G(KD7) as good general combiner 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 area. Darshan *et al.* and Herath *et al.* [28, 29] reported GCA/SCA variance which indicated the preponderance of non-additive gene action for the inheritance of all the traits and possibility of exploiting heterosis. Rohini *et al.* [30] found greater SCA variance than GCA for all the traits studied and identified LCA625, K1 and PKM1 which were the best general combiners and the hybrid K1×Arka Lohit was the best reciprocal combiner for quality parameters. Analysis of mid and better parent heterosis indicates the existence of sufficient heterosis on fresh and dry fruit yield and oleoresin content [45]. Rao *et al.* [46] noticed the high heterotic response of the hybrids supported by the predominant role of non-additive gene action in the inheritance of the characters that they were studied.

These genetic analysis act as important diagnostic tools in the selection of suitable parents and cross combination. Keeping these points in view, the present investigation was carried out to achieve the following objectives - (i) to study the combining ability of selected parents and their hybrids for fruit yield and related traits; and (ii) to estimate heterosis for fruit yield and related traits to identify superior hybrids.

2. MATERIALS AND METHODS

2.1. Materials and Field Experiment

The investigation was conducted at the experimental field and laboratory of the Department of Genetics and Plant breeding, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur, Bangladesh. Twenty divergent genotypes of chili were studied for their genetic variability [48] and six of them were selected which have desired characteristics. The six parents were crossed by follo-wing half diallel mating design from November 2015 to April 2016 for generating their F_1's. These six parental genotypes along with their 15 hybrids were evaluated from November 2016 to May 2017 for yield and related horticultural traits to study combining ability, gene action and heterosis. The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications.

2.2. Climate and Soil Type of Experimental Site

The experimental site is situated in the sub-tropical climate zone, characterized by heavy rainfall during the months from May to September and scanty in water with a gradual fall of temperature from the month of September. The soil type of experimental field is Shallow Red Brown Terrace type soil belongs to the Salna Series in Madhupur Tract (Agro Ecological Zone 28), which is nearly equivalent to Ochrept sub order of USDA soil taxonomy. The soil is a silt loam in texture and having a pH = 6.7 [49].

2.3. Data Collection

Five plants were selected randomly from each replication and selected plants were marked by labeling for recording data. The data were recorded for the following horticultural

Table 1. Simple Analysis of Variance (ANOVA) for eleven horticultural traits in a 6×6 half diallel population of chili.

Source of Variation	df	Mean Sum of Square										
		DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
Replication	2	47.25	40.06	5.95*	4.52	33.34	1.75*	0.01	0.00	135.75	0.01	87.51
Genotype	20	76.20**	124.92**	23.33**	613.89**	2091.80**	12.32**	0.12**	7.52**	1256.28**	0.04**	8525.34**
Parents	5	116.67**	235.03**	20.40**	911.93**	1880.44**	13.64**	0.23**	7.23**	1376.89**	0.09**	5195.01**
F_1	14	65.09**	55.45*	23.79**	551.12**	2310.35**	11.68**	0.09**	7.96**	1194.20**	0.02**	10195.19**
Parents *vs.* F_1	1	29.36	546.93**	31.48**	2.39	88.84	14.70**	0.02**	2.65**	1522.36**	0.02	1799.02
Error	40	21.75	21.96	1.52	12.17	216.27	0.54	0.01	0.01	86.57	0.00	983.48

* and ** indicate significance at 5% and 1% levels respectively, df – Degrees of freedom
DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

Table 2. Analysis of Variance (ANOVA) of combining ability for eleven horticultural traits in 6×6 half diallel population of chili.

Source of Variation	df	Mean Sum of Square										
		DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
GCA	5	36.06**	77.13**	8.89**	733.23**	1438.17**	13.18**	0.14**	6.51**	805.46**	0.02**	4840.63**
SCA	15	21.84**	29.81**	7.41**	28.43**	450.30**	1.08**	0.01**	1.17**	289.86**	0.01**	2175.50**
Error	40	7.25	7.32	0.51	4.06	72.09	0.18	0.00	0.00	28.86	0.00	327.83
Components												
σ^2g		1.78	5.92	0.18	88.10	123.48	1.51	0.02	0.67	64.45	0.00	333.14
σ^2s		14.59	22.49	6.91	24.37	378.21	0.90	0.01	1.17	261.00	0.01	1847.67
σ^2g/σ^2s		0.12	0.26	0.03	3.61	0.33	1.68	2.98	0.57	0.25	0.24	0.18

* and ** indicate significance at 5% and 1% levels respectively, df – Degrees of freedom
σ^2g – General combining ability variance, σ^2s – Specific combining ability variance
DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

characters - days to first flowering, days to first fruit setting, plant height at first fruiting (cm, number of fruits per plant, fruit length (cm), fruit width (cm), ten fruits weight (g), ten dry fruits weight (g), number of seeds per fruit, hundred seed weight (g), fruit yield per plant (g).

2.4. Statistical Analysis

2.4.1. Simple ANOVA, Mean and LSD Test

Simple Analysis of Variance (ANOVA), mean, Standard Error (SE), Coefficient of Variation (CV) were done from the replicated data of different characters by using computer software STAR (Statistical Tools for Agricultural Research).

LSD (Least Significant Difference) test was done by using the following equation:

LSD = t_α × SE Where,

t_α = Tabulated 't' value at error degrees of freedom at 5% level of significance

SE = Standard error

2.4.2. Combining Ability (Griffing's Approach)

Method II of Griffing [21] was followed for combining ability analysis. The analytical methods and procedures were often quoted with worked out examples, which could be found in reference literature [50 - 53]. The combining ability analysis of the present study was mainly done by following Sharma [51].

2.4.3. Estimation of Heterosis

Heterosis expressed as percentage increase or decrease in the performance of F_1 hybrid over mid parent (average or relative heterosis) and better parent (heterobeltiosis). Mid parent heterosis, heterobeltiosis and their significant tests were done for each character by following the equation described at Chaudhary *et al.* and Abrham *et al.* [45, 54]

2.4.4. Gene Action by Hayman's Analysis

The analysis of variance for the half diallel analysis done by Hayman [21] and genetic variance components along with allied genetic parameters was delivered by Hayman [55]

3. RESULTS

3.1. Combining Ability Analysis (Griffing's Approach)

Simple analysis of variance (Table **1**) was carried out for eleven horticultural characters of chili. The differences among the parents *vs.* F_1's were observed to be significant for all the characters except days to first flowering, ten fresh fruit weight,

Table 3. General Combining Ability (GCA) effects for eleven horticultural traits in 6×6 half diallel population of chili.

Parents	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
P_1	0.26	-0.94	0.90*	6.29**	-7.84*	1.40**	0.07**	0.98**	5.58*	0.00	23.65**
P_2	-0.99	0.72	0.79*	-4.93**	21.90**	-0.02	-0.08**	-0.24**	4.17	-0.08**	9.75
P_3	1.22	3.64**	0.31	-4.75**	-0.27	-0.79**	-0.03	-0.58**	-4.62*	0.04*	-13.37
P_4	0.81	-0.24	-1.77**	-6.56**	-7.98*	-1.21**	-0.08**	-0.81**	-13.28**	0.08**	-28.13**
P_5	2.39*	2.18**	0.54	-6.84**	8.87*	-1.10**	-0.11**	-0.63**	-6.50*	-0.03	-22.10*
P_6	-3.69**	-5.36	-0.76*	16.79**	-14.68**	1.73**	0.23**	1.29**	14.66**	-0.02	30.21**
SE(gi)	0.87	0.87	0.23	0.65	2.74	0.14	0.02	0.02	1.73	0.01	5.84

* and ** indicate significance at 5% and 1% levels respectively

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

the number of fruits per plant and hundred seed weight, indicating the existence of wider genetic variations among the parents and crosses. The analysis of variance for combining ability (Griffing's Approach) for eleven horticultural traits under this study is presented in Table **2**. The mean squares of GCA and SCA were found to be highly significant in all the characters. Specific combining ability variance (σ^2s) was higher than the general combining ability variance (σ^2g) for all the traits other than ten fresh fruit weight, fruit length and fruit width. The low magnitude of σ^2g/σ^2s ratio was reported for all the traits other than ten fresh fruit weight, fruit length and fruit width.

3.2. General Combining Ability (GCA) Effect of Parents

The estimates of GCA effects of six parents (Table **3**) revealed that the parents P_1 (23.65**) and P_6 (30.21**) had positive and highly significant GCA effect for fresh fruit yield per plant (23.65** and 30.21** respectively). Parent P_1 also had a significant positive GCA effect for other yield contributing traits like plant height at first fruiting (0.90*), ten fresh fruit weight (6.29**), fruit length (1.40**), fruit width (0.07**), ten dry fruit weight (0.98**) and the number of seeds per fruit (5.58*). Another parent P_6 had also significant and positive GCA effect for other yield contributing traits like ten fresh fruit weight (16.79**), fruit length (1.73**), fruit width (0.23**), ten dry fruit weight (1.29**) and number of seeds per fruit (14.66**).

3.3. Specific Combining Ability (SCA) Effect of F_1 Hybrids

Estimation of SCA effects on the crosses in F_1 generation revealed that there are a good number of crosses having significant positive and negative SCA effects on different traits of chili. The promising F_1 hybrids based on SCA effect for yield and related traits studied are presented in Table **4**. The highest positive and significant SCA effects for fresh fruit yield per plant in F_1 generation was noted in the cross $P_1{\times}P_6$ (117.43**) followed by cross $P_1{\times}P_4$ (51.81**) and $P_2{\times}P_5$ (49.85**). The cross $P_1{\times}$ P_6 and $P_1{\times}P_4$ also showed significant positive SCA effects for other component traits in F_1 generation, such as plant height at first fruiting (1.96** and 2.89** respectively), ten fresh fruit weight (12.88** and 4.07* respectively), number of fruits per plant (21.18* and 21.99* respectively), fruit length (1.66** and 1.77** respectively) and ten dry fruit weight (1.40** and 0.11* respectively) and the cross $P_1{\times}P_4$ showed significant negative SCA effects for days to first flowering (-7.15**), days to first fruiting (-6.33*) and hundred seed weight (-0.21**). Besides positive and highly significant SCA effect for fresh fruit yield per plant, the combination $P_2{\times}P_5$ also had significant positive SCA effects for days to first flowering (5.52*), number of fruits per plant (49.35**), ten dry fruit weight (0.79**) and hundred seed weight (0.09*) and had significant negative SCA effect for the number of seeds per fruit (-17.38**).

3.4. Heterosis (Mid Parent Heterosis and Heterobeltiosis)

The mean performance of the parents and hybrids for different horticultural traits revealed the presence of sufficient variability among the parents and hybrids (Table **5**). The heterotic responses of hybrids over mid parent (average) and better parent (heterobeltiosis) for the eleven horticultural traits are presented in Tables **6** and **7**, respectively. It was noticed that a significant positive and negative heterosis in the traits was studied. None of the hybrids in this study had shown maximum heterosis for all the characters, however, a significant and desirable level of heterosis over mid parent and better parent was obtained in several hybrids. The maximum positive and significant mid parent heterosis and heterobeltiosis for fresh fruit yield per plant were found in hybrid $P_1{\times}P_6$ (121.68%** and 120.97%** respectively). It had also significant positive mid parent heterosis and heterobeltiosis for other related traits, such as plant height at first fruiting (22.08%** and 14.96%** respectively), ten fresh fruit weight (37.02%** and 9.45%** respectively), number of fruits per plant (59.40%** and 29.33%** respectively), fruit length (44.76%** and 25.65%** respectively) and ten dry fruit weight (28.08%** and 25.36%** respectively) The hybrid $P_1{\times}P_4$ had also positive and significant mid parent heterosis as $P_1{\times}P_6$. Besides, significant positive mid parent heterosis for fresh fruit yield per plant (55.39%*), the hybrid $P_3{\times}P_6$ had significant positive mid parent heterosis for number of fruits per plant (32.37%*), fruit length (8.16%**), fruit width (1.03%**) and number of seeds per fruit (34.67%**).

3.5. Gene Action by Hayman's Analysis

Analysis of variance after Hayman [21] revealed a highly significant values of additive effect (a) and non-additive effect (b) for all the traits (Table **8**). The item 'b_1' was highly significant for the traits like days to first fruiting (212.70**), plant height at first fruiting (12.24**), fruit length (5.72**), ten dry fruit weight (1.03**) and number of seeds per fruit (592.03**); item 'b_2' was highly significant for all the characters except the number of fruits per plant, fruit width and fresh fruit yield per plant and the 'b_3' values were highly significant for all the characters studied.

The genetic components of variation [55] were estimated in pursuance of Hayman's approach of diallel analysis as shown in Table **9**. The estimates of additive variance (D) and dominant variances (H_1 and h^2) were highly significant and additive component (D) was much higher than the dominant component (H_1) for all the characters. The expected environmental component of variance (E) was positive and significant for all the traits except plant height at first fruiting (0.58 cm) and ten dry fruit weight (0.002g). The overall dominance effects of heterozygous loci in Hayman's model (h^2) were highly significant and controlled all the studied traits except ten fresh fruit weight (-0.75). The components H_1 and H_2 were significant for all the characters and had differences between them. The ratio of $H_2/4H_1$ was not equal to 0.25 for all characters. The $[(4DH_1)^{0.5}+F]/[(4DH_1)^{0.5}–F]$ ratio which was greater than the unity for all the traits except days to first flowering (-3.70), days to first fruiting (-0.23) and plant height at first fruiting (-158.57 cm). The $(H_1/D)^{0.5}$ ratio was found to be greater than zero but less than one for all the eleven characters and the h^2/H_2 ratio was less than 1.0 for all the traits except fruit length (1.25 cm). The heritability in narrow sense (h^2_n) was high for days to first flowering (1.05), days to first fruiting (1.68), plant height at first fruiting (1.20), fruit width (1.07) and hundred seed weight (2.40).

Table 4. Specific Combining Ability (SCA) effects for eleven horticultural traits in 6×6 half diallel population of chili.

Crosses	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
$P_1×P_2$	0.31	-2.95	-1.92**	-2.69	-42.22**	0.87*	0.14**	0.58**	-9.41	-0.02	-83.59**
$P_1×P_3$	5.43*	-1.54	-3.84**	-1.01	-1.10	0.82*	-0.13**	-2.02**	-27.07**	0.06	-14.76
$P_1×P_4$	-7.15**	-6.33*	2.89**	4.07*	21.99*	1.77**	0.00	0.11*	25.70**	-0.21**	51.81**
$P_1×P_5$	-1.73	-2.08**	4.56**	-7.43**	-8.20	-0.48	-0.12*	-0.59**	21.26**	-0.08*	-35.32*
$P_1×P_6$	5.02	5.46	1.96**	12.88**	21.18*	1.66**	-0.02	1.40**	8.39	-0.06	117.43**
$P_2×P_3$	-1.98	-9.87	5.00**	-0.27	19.21*	-0.12	-0.11*	-0.37**	14.46**	-0.01	19.35
$P_2×P_4$	-0.57	-4.66	1.91**	2.46	-2.08	-0.86*	-0.07	-0.27**	25.45**	-0.08*	5.17
$P_2×P_5$	5.52*	-0.08	-0.17	-0.22	49.35**	0.05	0.09	0.79**	-17.38**	0.09*	49.85**
$P_2×P_6$	5.60*	1.46	-1.07	-1.87	-15.67	0.64	0.00	0.62**	-2.86	0.06	-7.15
$P_3×P_4$	5.23*	-0.58	1.70*	-0.22	-0.50	0.53	0.07	-0.77**	-4.64	-0.01	-7.54
$P_3×P_5$	1.31	-3.33	-1.05	1.84	-7.02	0.24	0.06	-0.39**	-1.87	0.06	6.76
$P_3×P_6$	1.06	2.88	-1.78*	-1.25	7.33	-0.23	0.04	-0.09	20.43**	-0.03	22.91
$P_4×P_5$	-2.61	1.88	-2.70**	0.08	-8.61	0.17	-0.02	-0.24**	-0.28	0.06	-4.38
$P_4×P_6$	-3.52	-2.24	1.35*	-10.45**	1.30	-0.22	-0.13**	-1.48**	-12.72*	-0.01	-34.35*
$P_5×P_6$	-5.44*	-5.99*	-0.14	5.94	-23.69**	-0.25	0.05	0.77	7.18**	0.02	-35.51**
SE(sij)	2.39	2.40	0.63	1.79	7.53	0.38	0.04	0.04	4.76	0.04	16.05

* and ** indicate significance at 5% and 1% levels respectively

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

Table 5. Mean performance of eleven horticultural traits of six parents and fifteen F_1's in 6×6 half diallel population of chili.

Genotypes	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
P_1	103.67	116.00	14.21	31.60	34.67	6.10	1.01	5.74	71.73	0.58	117.21
P_2	97.67	123.67	13.94	13.36	85.67	5.30	0.63	2.38	73.20	0.24	115.39
P_3	101.00	127.67	14.83	12.89	36.67	3.43	0.79	4.19	60.10	0.46	47.59
P_4	110.00	119.67	8.11	10.83	24.15	2.51	0.73	3.24	26.68	0.70	26.10
P_5	110.33	123.33	15.06	8.15	63.00	3.56	0.57	2.09	52.53	0.29	52.79
P_6	95.33	102.67	12.55	52.89	21.59	8.29	1.31	5.50	89.10	0.39	116.45
$P_1× P_2$	103.67	111.00	14.00	20.59	18.00	7.87	0.93	4.85	70.33	0.32	37.51
$P_1× P_3$	111.00	115.33	11.60	22.47	36.96	7.06	0.72	1.91	43.88	0.52	83.22
$P_1× P_4$	98.00	106.67	16.25	25.73	52.33	7.58	0.80	3.81	88.00	0.29	135.03
$P_1× P_5$	105.00	113.33	20.23	13.95	39.00	5.44	0.66	3.28	90.33	0.31	53.93
$P_1× P_6$	105.67	113.33	16.33	57.89	44.83	10.42	1.10	7.20	98.63	0.34	258.99
$P_2× P_3$	102.33	108.67	20.33	11.97	87.00	4.69	0.59	2.34	84.00	0.37	103.43
$P_2× P_4$	103.33	110.00	15.17	12.89	58.00	3.54	0.58	2.21	86.33	0.34	74.49

(Table 5) contd.....

Genotypes	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
$P_2 \times P_5$	111.00	117.00	15.40	9.93	126.28	4.55	0.71	3.45	50.28	0.40	125.20
$P_2 \times P_6$	105.00	111.00	13.19	31.91	37.72	7.97	0.96	5.20	85.97	0.39	120.52
$P_3 \times P_4$	111.33	117.00	14.47	10.39	37.42	4.16	0.77	1.37	47.46	0.52	38.66
$P_3 \times P_5$	109.00	116.67	14.03	12.18	47.75	3.98	0.74	1.93	57.00	0.48	58.99
$P_3 \times P_6$	102.67	115.33	12.00	32.72	38.55	6.34	1.06	4.15	100.47	0.41	127.45
$P_4 \times P_5$	104.67	118.00	10.30	8.60	38.44	3.48	0.61	1.85	49.93	0.53	33.09
$P_4 \times P_6$	97.67	106.33	13.05	21.70	24.80	5.93	0.85	2.53	58.65	0.47	55.44
$P_5 \times P_6$	97.33	105.00	13.87	37.82	16.67	6.00	1.00	4.96	85.33	0.39	60.30
CV (%)	4.48	4.10	8.65	15.91	31.85	13.04	9.98	2.38	13.29	16.65	35.76
SE	3.81	3.83	1.01	2.85	12.01	0.60	0.07	0.07	7.60	0.06	25.61
LSD (0.05)	7.70	7.74	2.04	5.76	24.27	1.21	0.13	0.14	15.36	0.11	51.76

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

Table 6. Mid parent heterosis for eleven horticultural traits of fifteen F1's in 6×6 half diallel population of chili.

Crosses	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
$P_1 \times P_2$	2.98	-7.37	-0.53	-8.39**	-70.08**	38.05**	13.96**	19.49**	-2.94	-22.03**	-67.75*
$P_1 \times P_3$	8.47*	-5.34	-20.11**	1.00	3.62	48.09**	-19.58**	-61.61**	-33.43**	-0.91**	0.99
$P_1 \times P_4$	-8.27*	-9.48*	45.62**	21.27**	77.96**	76.05**	-8.02**	-15.18**	78.83**	-54.69**	88.46**
$P_1 \times P_5$	-1.87	-5.29	38.25**	-29.81**	-20.14	12.61**	-16.86**	-16.17**	45.39**	-28.22**	-36.55
$P_1 \times P_6$	6.20	3.66	22.08**	37.02**	59.40**	44.76**	-5.46**	28.08**	22.64**	-30.20**	121.68**
$P_2 \times P_3$	3.02	-13.53**	41.33**	-8.75**	42.23**	7.54**	-16.06**	-28.67**	26.03**	5.26**	26.93
$P_2 \times P_4$	-0.48	-9.59*	37.57**	6.60*	5.63	-9.33**	-14.38**	-21.35**	72.87**	-27.63**	5.30
$P_2 \times P_5$	6.73	-5.26	6.19**	-7.61*	69.89**	2.84**	18.56**	54.36**	-20.02*	52.50**	48.89
$P_2 \times P_6$	8.81*	-1.91	-0.39	-3.66	-29.66*	17.34**	-0.52**	31.98**	5.94	21.32**	3.97
$P_3 \times P_4$	5.53	-5.39	26.11**	-12.38**	23.05	39.91**	1.34**	-63.12**	9.37	-10.02**	4.95
$P_3 \times P_5$	3.15	-7.04	-6.17**	15.84**	-4.18	13.92**	8.66**	-38.54**	1.21	29.30**	17.53
$P_3 \times P_6$	4.58	0.14	-12.36**	-0.51	32.37*	8.16**	1.03**	-14.34**	34.67**	-4.32**	55.39*
$P_4 \times P_5$	-4.99	-2.88	-11.08**	-9.35**	-11.77	14.71**	-6.36**	-30.58**	26.07**	7.05**	-16.11
$P_4 \times P_6$	-4.87	-4.35	26.36**	-31.89**	8.47	9.78**	-17.35**	-42.11**	1.31	-14.42**	-22.22
$P_5 \times P_6$	-5.35	-7.08	0.48	23.92**	-60.59**	1.32*	6.05**	30.61**	20.50**	15.62**	-28.75

* and ** indicate significance at 5% and 1% levels respectively

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

Table 7. Heterobeltiosis for eleven horticultural traits of fifteen F_1's in 6×6 half diallel population of chili.

Crosses	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
$P_1 \times P_2$	0.00	-10.24**	-1.47	-34.84**	-78.99**	28.93**	-7.59**	-15.50**	-3.92	-44.85**	-68.00**
$P_1 \times P_3$	7.07*	-9.66**	-21.80**	-28.91**	0.79	15.71**	-28.51**	-66.80**	-38.82**	-11.50**	-29.00
$P_1 \times P_4$	-10.91**	-10.86**	14.37**	-18.59**	50.96**	24.28**	-20.56**	-33.66**	22.68**	-58.34**	15.21
$P_1 \times P_5$	-4.83	-8.11*	34.32**	-55.86**	-38.10**	-10.84**	-34.98**	-42.83**	25.93**	-46.44**	-53.99*
$P_1 \times P_6$	1.93	-2.30	14.96**	9.45**	29.33**	25.65**	-16.28**	25.36**	10.69	-41.66**	120.97**
$P_2 \times P_3$	1.32	-14.88**	37.08**	-10.35**	1.56	-11.36**	-24.48**	-44.07**	14.75*	-19.61**	-10.36
$P_2 \times P_4$	-6.06	-11.05**	8.80**	-3.48	-32.30**	-33.14**	-20.60**	-31.79**	17.94**	-51.23**	-35.44
$P_2 \times P_5$	0.60	-5.39	2.24*	-25.63**	47.41**	-14.01**	13.06**	44.96**	-31.31**	40.47**	8.50
$P_2 \times P_6$	7.51*	-10.24**	-5.36**	-39.66**	-55.97**	-3.86**	-26.41**	-5.45**	-3.52	-1.89**	3.49
$P_3 \times P_4$	1.21	-8.36*	-2.47**	-19.37**	2.05	21.17**	-1.95**	-67.30**	-21.04**	-25.34**	-18.75
$P_3 \times P_5$	-1.21	-8.62*	-6.88**	-5.47*	-24.21*	11.89**	-6.28**	-53.94**	-5.16	5.14**	11.74
$P_3 \times P_6$	1.65	-9.66**	-19.10**	-38.13**	5.15	-23.52**	-19.19**	-24.55**	12.76	-11.29**	9.45

(Table 7) contd.....

Crosses	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
P_4×P_5	-5.14	-4.32	-31.60**	-20.58**	-38.98**	-2.15**	-16.88**	-42.90**	-4.95	-24.37**	-37.32
P_4×P_6	-11.21**	-11.14**	4.01**	-58.97**	2.72	-28.47**	-35.50**	-54.00**	-34.18**	-33.11**	-52.40*
P_5×P_6	-11.78**	-14.86**	-7.90**	-28.49**	-73.54**	-27.58**	-23.92**	-9.88**	-4.23	0.20**	-48.22*

* and ** indicate significance at 5% and 1% levels respectively

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

Table 8. Hayman's Analysis of Variance (ANOVA) for eleven horticultural traits in 6×6 half diallel population of chili.

Source of Variation	df	Mean Sum of Square										
		DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
a	5	51.03**	88.23**	12.56**	1168.03**	2290.93**	22.75**	0.20**	12.03**	1194.11**	0.03**	8283.41**
b	15	149.66**	215.24**	32.57**	462.29**	2608.89**	10.90**	0.11**	6.10**	1565.41**	0.06**	11286.90**
b_1	1	11.42	212.70**	12.24**	0.93	34.55	5.72**	0.01	1.03**	592.03**	0.01*	699.62
b_2	5	35.58**	24.62*	3.25**	11.09*	82.80	1.86**	0.01	2.86**	84.28*	0.02**	667.65
b_3	9	228.39**	321.43**	51.12**	764.23**	4298.31**	16.49**	0.18**	8.46**	2496.41**	0.09**	18362.84**
Error	40	7.25	7.32	0.51	4.06	72.09	0.18	0.00	0.00	28.86	0.00	327.83

* and ** indicate significance at 5% and 1% levels respectively, df – Degrees of freedom, a – Additive effect, b – Non-additive effect

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

Table 9. Genetic components of variation for eleven horticultural traits in a 6×6 half diallel population of chili.

Components	DFFl	DFFr	PHFF	TFFW	NFPP	FL	FW	TDFW	NSPF	HSW	FFYPP
D	31.23**	70.74**	6.22**	300.04**	557.63**	4.35**	0.07**	2.41**	429.32**	0.03**	1418.07**
F	35.39**	55.20**	4.01**	-83.22**	-173.88**	-2.07**	0.01**	0.30**	77.59**	0.03**	-1002.50**
H_1	3.31**	-3.88**	0.63**	-3.10**	-129.30**	0.71**	-0.01**	1.90**	-22.84**	0.01**	-391.18**
H_2	59.11**	75.56**	26.24**	102.06**	1631.92**	2.76**	0.02**	3.63**	1015.68**	0.02**	7785.59**
h^2	0.78**	-25.97**	4.90**	-0.75	-29.67**	3.45**	-0.12**	-1.52**	19.81**	-0.13**	-134.79**
E	7.66**	7.61**	0.58	3.94**	69.19**	0.20**	0.002**	0.002	29.64**	0.002**	313.60**
Allied components											
$(H_1/D)^{0.5}$	0.33	0.23	0.32	0.10	0.48	0.41	0.19	0.89	0.23	0.61	0.53
$H_2/4H_1$	4.47	-4.87	10.42	-8.23	-3.16	0.98	-2.28	0.48	-11.12	0.55	-4.98
$[(4DH_1)^{0.5}+F]/[(4DH_1)^{0.5}–F]$	-3.70	-0.23	-158.57	6.49	1.96	0.26	0.67	1.15	0.44	96.92	5.12
h^2/H_2	0.01	-0.34	0.19	-0.01	-0.02	1.25	-4.88	-0.42	0.02	-5.52	-0.02
h^2_n	1.05	1.68	1.20	0.76	0.63	0.56	1.07	0.60	0.96	2.40	0.43

* and ** indicate significance at 5% and 1% levels respectively

D – Variance due to additive effects of genes, F – Mean of the covariance of additive and dominance effects across all arrays, H_1 – Variance component due to dominance deviation, h^2 – Algebraic sum of dominance effects across all loci in heterozygous phase in all crosses, E – Expected environmental component of variance, h^2_n – Heritability in narrow sense

DFFl – Days to first flowering, DFFr – Days to first fruiting, PHFF – Plant height at first fruiting (cm), TFFW – Ten fresh fruit weight (g), NFPP – Number of fruits per plant, FL – Fruit length (cm), FW – Fruit width (cm), TDFW – Ten dry fruit weight (g), NSPF – Number of seeds per fruit, HSW – Hundred seed weight (g), FFYPP – Fresh fruit yield per plant (g)

4. DISCUSSION

Simple analysis of variance revealed wide spectrum of variation among 21 genotypes which includes six parents and their fifteen F_1's that were developed by 6×6 half diallel crosses, indicating the presence of highly significant genetic variability. This variability can be exploited through selection by studying heterosis, General Combining Ability (GCA) and Specific Combining Ability (SCA). The analysis of variance for combining ability (Griffing's Approach) revealed the importance of both additive and non-additive gene action as the cause of observed variation for all the traits Table **2** which are in congruence with the findings of Darshan *et al.* [28] in chili. The low magnitude of $\sigma^2 g/\sigma^2 s$ ratio for all the traits other than ten fresh fruit weight, fruit length and fruit width confirmed the non-additive gene effects which appeared to be predominant with a possibility of exploiting heterosis for yield enhancement. On the other hand, the high magnitude $\sigma^2 g/\sigma^2 s$ ratio for ten fresh fruit weight, fruit length and fruit width confirmed the additive gene effects which appeared to be predominant (Table **2**) and the result supported by the findings of Do Nascimento *et al.* [26].

The estimation of GCA of parents in the diallel design is an important indicator of its potential for generating superior breeding populations. A high GCA estimate indicates that the parental mean is superior or inferior to the general mean and it represents a strong evidence of favorable gene flow from parents to offspring at high frequency and gives information about the concentration of the predominantly additive genes [56]. In addition, crosses involving genotypes with greater estimates of GCA should be potentially superior for the selection of lines in the advanced generations [57]. The estimates of GCA effects of six parents for eleven horticultural traits are presented in Table **3**. The estimates of GCA effects of six parents suggested that the parents P_1 and P_6 could be selected as the best general combiner for fresh fruit yield per plant (g) and other yield contributing traits. These results are in accordance with the findings of Geleta and Labuschagne [23]. Besides fresh fruit yield per plant (g) the parent P_6 could also be selected as a good combiner for early flowering and lower number of seeds per fruit (Table **3**). The parents P_4 and P_5 could not be selected for the enhancement of fruit yield due to their negative and significant GCA effect for fresh fruit yield per plant (g).

Specific Combining Ability (SCA) effects are indicative of heterosis and both dominant and epistatic components of genetic variation which are non-fixable and associated with hybrid vigor [58]. It represents the performance of specific cross combination. High SCA effects may arise not only in crosses involving high general combiners but also in those involving low combiners. In this experiment the results revealed that the hybrid $P_1 \times P_6$ could be selected for increasing fresh fruit yield per plant followed by the hybrid $P_1 \times P_4$ and $P_2 \times P_5$. Besides higher fresh fruit yield per plant, the hybrid $P_1 \times P_6$ and $P_1 \times P_4$ could be selected for increasing plant height at first fruiting, ten fresh fruit weight, fruit length and ten dry fruit weight (Table **4**) which supported the findings of Navhale *et al.* [59] and the hybrid $P_2 \times P_5$ could be selected for increasing ten dry fruit weight and hundred seed weight. The hybrid $P_1 \times P_4$ could also be selected as good specific combiner for early flowering and fruiting and reduction of hundred seed weight and the hybrid $P_2 \times P_5$ gives evidence of late flowering, lowering number seeds per fruit (Table **4**). The combinations having no or negatively significant SCA effect could not be selected for increasing fresh fruit yield per plant. Therefore, the combinations with positive and significant SCA effects could only be selected for increasing fresh fruit yield per plant.

Heterosis is the basis for improvement of crop yield and heterozygosity which is due to superior gene content possible in a hybrid contributed by both the parents [60]. Advancement in the exploitation of heterosis has served in many ways to develop hybrids with increased yield as well as good quality traits. The nature and magnitude of better parent heterosis helps in identifying the superior hybrids and their exploitation to get better transgressive segregants [45]. Therefore, it appeared from the results that better parent heterosis or heterobeltiosis for fresh fruit yield per plant in hybrid $P_1 \times P_6$ could ascribe mainly due to its component traits such as plant height at first fruiting, ten fresh fruit weight, number of fruits per plant, fruit length and ten dry fruit weight and this hybrid could be cultivated for higher fruit yield. This result supported the findings of previous report by Chaudhary *et al.*, Rao *et al.* and Abrham *et al.* [45, 46, 54].

Highly significant values of – additive effect (a) suggested that additive components were involved in the regulation of all the traits and non-additive effect (b) indicated that this component was important in genetic control of the characters studied (Table **8**). Highly significant values of 'b_1' for the traits like days to first fruiting, plant height at first fruiting, fruit length, ten dry fruit weight and number of seeds per fruit detected unidirectional dominance and significant difference between parental and hybrid grand mean for these traits. An asymmetrical distribution of dominant genes was suggested by the highly significant 'b_2' value for the characters days to first flowering, days to first fruiting, plant height at first fruiting, ten fresh fruit weight, fruit length, ten dry fruit weight, number of seeds per fruit and hundred seed weight. The 'b_3' values were also highly significant for all the characters studied which indicated the dominance deviations which are not attributed to 'b_1' and 'b_2' and showed important contribution to the non-additive gene action (Table **8**).

Highly significant values of additive variance (D) and dominant variances (H_1 and h^2) expressed the importance of both additive and dominance variance for the inheritance of all the characters studied (Table **9**). The highly significant values for D and H corroborated the findings of Syukur *et al*. [24]. However, additive component (D) was much higher than the dominant component (H_1) for all the traits suggesting that additive variance played a major role in the inheritance of the traits and selection would be efficient for improvement of the traits. Positive and significant expected environmental component of variance (E) for all the traits except plant height at first fruiting and ten dry fruit weight indicated sufficient variation due to environment in the expression of characters. The presence of considerable amount of dominant genes in the parental genotypes could be due to highly significant value of the overall dominance effects of heterozygous loci in Hayman's model (h^2). Differences between two components H_1 and H_2 for all the characters indicated asymmetry in distribution of positive and negative alleles in the parents for these characters. The component H_1 which measures the dominance variation was significant for all the characters, indicating the importance of dominance gene effect in controlling the characters. The component H_2 was also significant for all the traits, indicating dominance with asymmetry of positive and negative effects and the value of $H_1 < H_2$ indicated the presence of more negative genes [24]. The ratio of dominant genes with negative and positive effects ($H_2/4H_1$) in parents revealed that the $H_2/4H_1$ ratio was not equal to 0.25 for all the characters which indicated that the dominant gene have an increasing and decreasing effect on all the characters and are also responsible for irregular distribution of genes in the parents (Table **9**).

Asymmetrical distribution of dominant and recessive alleles in parents was supported by the direction of F. This was also confirmed by the $[(4DH_1)^{0.5}+F]/[(4DH_1)^{0.5}-F]$ ratio which was greater than the unity for all the traits except days to first flowering, days to first fruiting and plant height at the first fruiting, indicating excess of dominant alleles and minority of recessive alleles. The $(H_1/D)^{0.5}$ ratio which measured the average degrees of dominance over all loci was found to be greater than zero but less than one for all the eleven characters indicating partial dominance for these characters which was in conformity with the result of Syukur *et al.* (2010) for fruit length, fruit width and fruit yield per plant. The h^2/H_2 ratio suggested that, at least one gene group was operating the inheritance of all the traits except fruit length. The inheritance of fruit length was operated by many group of genes because its h^2/H_2 ratio was greater than one. The heritability in narrow sense (h^2_n) was high for days to first flowering, days to first fruiting, plant height at first fruiting, fruit width and hundred seed weight which indicated major part of additive gene action in phenotypic variability in nature and selection should be effective for improvement of these characters in chili.

CONCLUSION

In conclusion, it was revealed that sufficient genetic diversity was present among the parents and hybrids in the present investigation which helps to select the best parents and promising hybrid combinations for fresh fruit yield per plant and yield contributing characters. The estimation of combining ability revealed that the parents P_1 and P_6 were identified as the best general combiners and the hybrid $P_1 \times P_6$, $P_1 \times P_4$ and $P_2 \times P_5$ were the best specific combinations for fresh fruit yield per plant and related traits. Results of heterosis revealed that the hybrid $P_1 \times P_6$ exceeded the performance of its mid parents and better parent and the hybrid $P_1 \times P_4$ and $P_3 \times P_6$ showed significant mid-parent heterosis for fresh fruit yield per plant and related traits. By further selection based on better specific combining ability and heterotic effect in the following generation, we can develop a better hybrid chili which will contribute towards the total chili production in Bangladesh.

LIST OF ABBREVIATIONS

GCA	=	General Combining Ability
RCBD	=	Randomized Complete Block Design
SCA	=	Specific Combining Ability
STAR	=	Statistical Tools for Agricultural Research

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No animals/humans were used for studies that are the basis of this research.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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