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Crossing to improve fruit yield and shape characteristics in Chili pepper

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Abstract

Chili pepper (*Capsicum annum* L.) is a self-pollinating plant from Solanaceae family and one of the most important vegetables for food and medicinal consumption. Iran is one of the regions with the highest production level of this product. Estimates of combining ability are useful in determining breeding value of chili pepper lines by proposing the correct breeding method to produce new hybrids with high yield and quality. This study was conducted to evaluate general and specific combining ability in 7 inbred lines recommended for chili pepper breeding, based on a previous research. Analysis of variance revealed significant differences among genotypes for the studied traits. The highest number of fruit per plant (145) was observed in ‘2×5’ hybrid. For fruit per plant, the highest specific and general combining abilities were observed in ‘1×5’ hybrid and line ‘2’, respectively. The highest mid- and max-heterosis for the number of fruit per plant was observed in ‘2×3’ and ‘1×4’ hybrids. The highest heterosis for fruit length and diameter was observed in ‘2×6’ hybrid. Yield heterosis is the primary target for increasing productivity but the biological complexity of yield as a trait frequently makes it difficult to draw meaningful conclusions in order to track individual causal elements involved in heterosis. Therefore, chili breeders might develop F1 cultivars based on high specific combining ability for yield-related characteristics such as fruit number per plant and fruit length. Crossing lines ‘2’ and ‘6’ are suggested for hybrid production due to high values of this hybrid for many characters related to chili pepper yield and quality.

***Key words*:** Additive effects, Diallel analysis, Dominant effects, General combining ability, Specific combining ability.

INTRODUCTION

Chili pepper (*Capsicum annuum* L.) is a self-pollinating plant from Solanaceae family and one of the most important vegetables for food and medicinal consumption. Iran is one of the regions with the highest production level of this product. The area under greenhouse cultivation in Iran is 12,157 hectares (FAO, 2013), and the ministry of agriculture strategies is to increase the country’s greenhouse area to more than 48,000 hectares and transfer all vegetable farms to greenhouses within 10 years to meet the needs of the local breeding program for vegetables.

Chili peppers (Capsicum) are diploid and mostly perform self-pollination (Allard, 1960). At present, there are many selection methods in plant breeding (including chili peppers) and choosing the method is influenced mainly by the intended objective and plants used as parents (Singh *et al.,* 2014).

Mass selection, pedigree selection, single seed descent -SSD selection, backcross method, recurrent selection are those more utilized (Coon *et al.,* 2008;

Kulkarni and Phalke, 2009; Nsabiyera *et al.,* 2013; Manzur *et al.,* 2014). The selection of the best method or a combination of them depends mainly on the type of inheritance (monogenic, oligogenic, or polygenic) of characters to be improved (Lee *et al.,* 2013). Evaluations of combining ability are beneficial in determining the breeding worth of chili pepper lines by suggesting the correct use of lines in breeding programs. In studying combining ability, the most usually used experimental method is diallel design. The GCA is a measure of the additive genetic action; SCA is expected to be a deviation from additivity. Crossing a line by other lines provides mean performance of the line in all its crosses. This mean performance, when articulated as a deviation from the mean of all crosses, is called the general combining ability of the line. Any particular cross, then, has an expected value which is the sum of the general combining abilities of its 2 parental lines. In the case of chili pepper breeders follow the selection breeding method. The cross may, however, deviate from this estimated value to a greater or lesser extent. This deviation is called the specific combining ability of the 2 lines in combination. In these cases, breeders monitor cross breeding methods to generate new hybrid cultivars of chili pepper. In statistical terms, the general combining abilities are main effects and the specific combining ability is an interaction (Olfati *et al*., 2012; Dianati *et al*., 2018).

Heterosis has been used to exploit dominance variance through production of hybrids (Olfati *et al*. 2011; Dianati *et al*. 2018). There are reports on positive and negative heterosis in chili pepper (Gvozdenovic *et al.,* 1995; Lankesh Kumar *et al.,* 2014).

Based on what was mentioned above, general and specific combining ability habe to be estimated in any hybridization program. This investigation was conducted to estimate general and specific combining ability, heterosis as well as additive and dominant effects in chili pepper inbred lines and hybrids, for a breeding program according to our previous research (Akbarnia *et al.,* 2019), using MANOVA analysis like PCA and cluster analysis in order to produce hybrids with high number of fruits per plant and fruit yield.

MATERIALS AND METHODS

Chili pepper genotypes collected from different production regions of Iran and selected elite plants were selfed in each population. In the next generation, the progeny of each plant was evaluated and selfed again when the purity of each progeny was ensured.

Chili pepper inbred lines were selected for crossing in a 7×7 half-diallel design to produce 21 F1 hybrids during spring and summer 2018.

The experiment was conducted in a greenhouse in 2018. The lines were crossed with a partial diallel test in which reciprocal crosses were not used, since a previous study indicated that direct (Parent A as a female and parent B as a male) and reciprocal crosses (Parent B as a female and parent A as a male) do not affect many characters in chili pepper (Geleta and Labuschagne, 2006).

In spring 2018, 21 F1 families and 7 parental lines were planted in the greenhouse. Three replications were arranged in a randomized complete block design. Seeds were sown on the 4th Apr 2018 in single plastic pots (12×11 cm) filled with cocopeat and perlite (1:1). Transplantation took place on the 23rd Apr. 2018 with a plant density of 3.1 plants.m^{-2}. Data were collected from plants per plot of each hybrid and inbreed. The number of fruit per plant, yield as well as dry matter contents were determined.

Analyses of variance (ANOVA) of data were performed. Means were separated with honesty significant differences (HSD). For the GCA, measurements within plots were averaged and examined in the computer program Diallel (Burrow and Coors, 1994). The parental effects were considered fixed, because they were specifically selected with a limited number. The model used was based on Griffing (1956) which assumes epistasis is not significant (Kupper and Staub, 1988).

RESULTS

Analysis of variance showed that responses for all measured traits differed, except for yield, peduncle diameter and immature fruit dry weight (Table 1-2). The highest number of fruit and marketable fruit per plant was related to 2×5 hybrid with 145 and 144 fruit per plant (Table 3). The highest harvesting period was related to 3×4 hybrid while the highest earliness was related to 5×7 and 6×7 hybrids. First flower appeared at 5×7 and 6×7 hybrids earlier than others and the first harvesting took place at them one month earlier than line 3 (Table 3). The longest fruits with the highest width were related to 2×6 hybrid (Table 3) while the highest fruit length to width ratio was related to 5×7 and 6×7 hybrids. The highest thickness of pericarp was related to line 6 and 1×6 and 2×6 hybrids (Table 4).

Table 1. ANOVA for yield and its components in the studied chili pepper diallel population.

Source	df	Mean of squares								
		Yield	Number of fruit per plant	Number of marketable fruit per plant	Days to flowering	Days to harvest	Fruiting period	Fruit length	Fruit diameter	Fruit length to diameter ratio
Replication (R)	2	4360957.6**	2696.39**	1814.89**	110.04**	172.11*	570.14*	29.43**	11.48*	97.91**
Genotype (G)	27	3887777.1^{ns}	10638.62**	10579.28**	777.44**	1693.73**	836.32**	18.92**	204.92**	140.41**
R×G	54	4013078.4	568.17	604.08	9.67	25.74	159.51	1.19	5.57	8.10
E_S	168	49806	155.54	146.53	13.80	37.53	244.58	3.48	3.01	2.80
Coefficient of variation (%)		14.49	13.33	13.37	12.95	12.93	12.39	12.53	13.12	13.21

ns, *, **: non-significant or significant at P≤0.05 and P≤0.01, respectively.

Table 2. ANOVA for vegetative characteristics, fruit dry matter and ash in the studied chili pepper diallel population.

Source	df	Mean of squares										
		Plant length to first flower	Plant height	Number of branches	Leaf length	Leaf width	Pericarp thickness	Peduncle length	Peduncle diameter	Immature fruit dry weight	Mature fruit dry weight	Mature fruit ash
Replication (R)	2	22.11^{ns}	2236.32**	10.43**	0.92^{ns}	0.36^{ns}	0.07^{ns}	0.01^{ns}	36.17^{ns}	2094.99**	5.97^{ns}	4.53**
Genotype (G)	27	156.46**	2780.60**	18.25**	3.55**	2.59**	1.53**	1.14**	41.65^{ns}	1144.75^{ns}	82.05**	48.88**
R×G	54	32.09	336.10	2.76	1.29	0.14	0.05	0.13	37.41	1014.55	4.53	0.58
E_S	168	10.75	141.45	0.57	0.77	0.15	0.02	0.18	0.47	8.65	4.58	3.57
Coefficient of variation (%)		12.62	12.49	12.95	12.42	12.52	13.21	12.45	18.60	20.04	12.54	12.48

ns, **: non-significant or significant at P≤0.01.

Table 3. Mean comparison of the effect of chili pepper lines and hybrids on yield and its components.

Lines and hybrids	Yield (g/plant)	Number of fruit per plant	Number of marketable fruit per plant	Days to flowering	Days to harvest	Fruiting period (days)	Fruit length (days)	Fruit diameter (cm)	Fruit length to diameter ratio
1	1291.4^{a}	112.67^{abc}	105.33^{a-e}	22.33^{i}	34.00^{ij}	106.67^{d}	13.17^{hi}	7.91^{e}	16.70^{ab}
2	1595.3^{a}	142.00^{ab}	142.00^{ab}	23.00^{hi}	54.67^{c-f}	134.67^{abc}	13.50^{f-i}	9.29^{e}	15.62^{abc}
3	1339.0^{a}	43.00^{g}	40.33^{h}	48.00^{a}	69.00^{a}	113.33^{a-d}	13.37^{ghi}	16.37^{bc}	8.19^{gh}
4	1388.5^{a}	47.00^{efg}	44.00^{gh}	41.33^{bcd}	51.00^{d-g}	137.67^{ab}	13.50^{f-i}	16.82^{b}	8.02^{gh}
5	976.6^{a}	124.33^{abc}	120.33^{abc}	23.33hi	39.00^{hij}	126.67^{a-d}	13.00^{i}	8.48^{e}	15.39^{a-d}
6	1135.9^{a}	57.33^{d-g}	54.00^{e-h}	39.33^{cde}	64.33^{abc}	131.00^{a-d}	13.00^{i}	17.36^{b}	7.48^{h}
7	1308.5^{a}	107.33^{a-d}	100.67^{a-e}	23.00^{hi}	35.33^{ij}	126.67^{a-d}	13.25^{hi}	7.00^{e}	19.13^{a}
1*2	1383.8^{a}	128.33^{abc}	126.33^{abc}	22.33^{i}	49.33^{e-h}	123.33^{a-d}	15.87^{a-e}	9.63^{e}	16.51^{ab}
1*3	1423.6^{a}	48.00^{efg}	43.33^{gh}	46.67^{ab}	68.00^{ab}	115.00^{a-d}	16.00^{a-e}	17.47^{b}	9.20^{e-h}
1*4	1363.9^{a}	118.33^{abc}	113.33^{abc}	24.33^{ghi}	35.00^{ij}	108.33^{cd}	14.83^{b-i}	8.80^{e}	16.95^{ab}
1*5	1706.0^{a}	114.00^{abc}	109.67^{a-d}	24.33^{ghi}	38.00^{ij}	126.33^{a-d}	16.77^{abc}	9.60^{e}	17.56^{ab}
1*6	1420.8^{a}	61.33^{d-g}	61.00^{d-h}	37.33^{de}	61.00^{a-d}	129.67^{a-d}	13.37^{ghi}	15.40^{bcd}	8.70^{gh}
1*7	1337.5^{a}	107.00^{a-d}	105.00^{a-e}	21.33^{i}	32.67^{j}	111.33^{bcd}	15.20^{b-i}	11.70^{cde}	14.76^{a-f}
2*3	1682.6^{a}	136.33^{abc}	132.67^{abc}	21.67^{i}	54.00^{c-f}	136.00^{ab}	17.13^{ab}	10.77^{de}	15.98^{ab}
2*4	1611.9^{a}	129.33^{abc}	131.33^{abc}	22.00^{i}	56.33^{cde}	138.33^{a}	14.25^{d-i}	11.53^{cde}	12.39^{b-h}
2*5	1551.6^{a}	145.00^{a}	144.00^{a}	21.67^{i}	38.67^{hij}	128.67^{a-d}	15.67^{b-g}	9.73^{e}	16.15^{ab}
2*6	2262.7^{a}	43.67^{fg}	41.67^{gh}	29.33^{fgh}	58.00^{b-e}	131.33^{a-d}	18.03^{a}	26.90^{a}	6.70^{h}
2*7	1317.3^{a}	123.67^{abc}	114.67^{abc}	21.33^{i}	32.00^{j}	131.00^{a-d}	15.73^{a-f}	10.17^{e}	15.53^{abc}
3*4	1424.0^{a}	50.67^{efg}	48.00f^{gh}	45.00^{abc}	69.33^{a}	139.33^{a}	16.73^{abc}	17.33^{b}	9.72^{c-h}
3*5	1397.1^{a}	117.00^{abc}	114.00^{abc}	21.33^{i}	34.67^{ij}	131.00^{a-d}	13.17^{hi}	8.73^{e}	15.07^{a-e}
3*6	1276.0^{a}	60.00^{d-g}	59.67^{d-h}	45.00^{abc}	71.67^{a}	105.33d	14.17^{e-i}	19.37^{b}	7.34^{h}
3*7	1377.5^{a}	93.67^{b-f}	90.33^{b-h}	23.33^{hi}	34.67^{ij}	131.33^{a-d}	14.42^{d-i}	10.47^{de}	13.98^{a-g}
4*5	1442.0^{a}	94.33^{b-f}	92.33^{a-g}	30.67^{fg}	44.00^{f-i}	131.67^{a-d}	15.33^{b-h}	17.50^{b}	8.81^{fgh}
4*6	1586.4^{a}	61.33^{d-g}	58.00^{d-h}	34.67^{ef}	61.00^{a-d}	130.33^{a-d}	16.03^{a-e}	16.89^{b}	9.51^{e-h}
4*7	1454.0^{a}	46.33^{efg}	44.00^{gh}	24.67^{ghi}	33.33^{ij}	129.33^{a-d}	16.53^{a-d}	17.40^{b}	9.50^{e-h}
5*6	1359.5^{a}	91.33^{c-f}	87.67^{c-h}	25.00^{ghi}	40.33^{g-i}	131.67^{a-d}	14.40^{d-i}	18.13^{b}	7.94^{h}
5*7	1312.2^{a}	115.67^{abc}	113.00^{abc}	20.67^{i}	30.33^{j}	125.67^{a-d}	16.05^{a-e}	9.97^{e}	16.51^{ab}
6*7	1390.6^{a}	101.67^{a-d}	98.33^{a-f}	20.00^{i}	36.67^{ij}	123.67^{a-d}	14.57^{c-i}	9.27^{e}	15.10^{a-e}

values in columns followed by the same letter are not significantly different, $p<0.05$, Tukey.

The highest peduncle length was recorded in 2×6 hybrid (Table 4). The first flower appeared at the lowest distance in line 1. The highest plant height was related to 3×6 hybrid. Line 1 and hybrid 2×6 had the highest number of branches per plant. The highest leaf width and length were recorded in line 4 and 2×6 hybrid (Table 4). These characteristics are related with high yield in pepper (Lankesh Kumar *et al.,* 2014). Fruit dry matter and ash had the best values in 2×4 hybrid (Table 4).

In Griffing's method 2, variances due to GCA and SCA effects were significant for all traits related to yield, except for the number of flowers per plant and harvesting period (Table 5). Variances due to GCA effects were also significant for the traits related to fruit, except for fruit length, pericarp thickness, and peduncle length (Table 6). In Griffing's method 2, variances due to SCA effects were significant for all traits related to fruit, except for peduncle length (Table 5). Variances due to GCA effects were not significant for all vegetative characteristics, while SCA effect were significant for all vegetative characteristics, except for length to the first flower, number of branches and leaf length (Table 6). Variances due to GCA effects were also significant for ash percentage in fruit and SCA were significant for mature fruit dry matter and ash percentage (Table 6). Combining ability analysis is used in selection of parents in formulations of a crossing plan (Moradipour *et al.,* 2016).

Lines 5 and 2 had the highest GCA for the number of marketable fruit per plant. The lowest days to flowering GCA was observed in lines 7 and 2. The lowest days to harvest GCA were observed in lines 7 and 5 (Table 7). The highest fruit diameter GCA was observed in lines 6 and 4. The highest fruit length to diameter ratio was observed in lines 7 and 1. The highest peduncle length was in 5 and 1 lines (Table 7). There were no differences between lines GCA for vegetative characteristics (Table 8) and finally the highest ash content GCA was observed in lines 2 and 5 (Table 8).

Table 4. Effect of chili pepper genotypes on vegetative characteristics, fruit dry matter and ash.

Lines and hybrids	Plant length to first flower (cm)	Plant Height (cm)	Number of branches	Leaf Length (cm)	Leaf width (cm)	Pericarp thickness (cm)	Peduncle length (cm)	Peduncle diameter (cm)	Immature fruit dry weight (g)	Mature fruit dry weight (g)	Mature fruit Ash (% in DM)
1	15.67^{c}	73.67^{def}	8.33^{a}	7.87^{ab}	3.19^{c-j}	0.73^{de}	3.13^{de}	2.91^{a}	13.24^{a}	19.79^{abc}	17.16^{ab}
2	27.67^{ab}	72.00^{ef}	5.67^{abc}	5.96^{b}	2.42j	0.86^{cde}	3.38^{b-e}	2.89^{a}	12.49^{a}	20.39^{abc}	17.27^{a}
3	24.33^{abc}	84.33^{b-f}	3.67^{c}	6.97^{ab}	3.57^{b-e}	1.49^{ab}	3.83^{a-d}	3.46^{a}	8.72^{a}	13.24^{fgh}	12.09^{g}
4	28.00^{ab}	89.33^{b-f}	4.67^{bc}	8.93^{a}	4.35^{a}	1.57^{ab}	3.13^{de}	3.51^{a}	9.14^{a}	13.18^{fgh}	11.76^{g}
5	27.67^{ab}	81.67^{b-f}	7.00^{abc}	6.20^{b}	2.53^{hij}	0.83^{cde}	3.45^{b-e}	3.13^{a}	12.16^{a}	16.72^{b-h}	17.80^{a}
6	26.33^{abc}	64.67^{f}	3.67^{c}	7.23^{ab}	3.51^{b-f}	1.78^{a}	3.35^{cde}	3.62^{a}	10.24^{a}	13.20^{fgh}	12.79^{fg}
7	28.67^{ab}	79.33^{b-f}	6.00^{abc}	6.80^{ab}	2.89^{d-j}	0.78^{de}	3.10^{de}	3.33^{a}	12.64^{a}	18.04^{a-e}	15.64^{bcd}
1*2	22.17^{abc}	104.67^{b-e}	7.00^{abc}	7.00^{ab}	2.80^{e-j}	1.20^{bcd}	3.20^{de}	2.93^{a}	11.63^{a}	21.13^{ab}	16.81^{abc}
1*3	25.17^{abc}	109.00^{b-e}	4.00^{c}	7.40^{ab}	3.60^{a-d}	1.64^{ab}	3.50^{b-e}	3.5^{a}	8.53^{a}	13.90^{e-h}	11.83^{g}
1*4	17.17^{bc}	98.00^{b-f}	7.67^{ab}	7.27^{ab}	3.30^{c-h}	0.78^{de}	3.17^{de}	2.63^{a}	13.20^{a}	20.97^{ab}	16.64^{abc}
1*5	28.50^{ab}	106.67^{b-e}	6.67^{abc}	6.67^{ab}	2.60^{hij}	0.73^{de}	3.47^{b-e}	3.03^{a}	12.10^{a}	16.90^{b-h}	17.43^{a}
1*6	28.83^{ab}	93.00^{b-f}	4.00^{c}	7.57^{ab}	3.70^{abc}	1.73^{a}	3.57^{a-e}	3.73^{a}	11.23^{a}	14.70^{d-h}	13.10^{efg}
1*7	17.17^{bc}	101.00^{b-f}	7.67^{ab}	6.97^{ab}	2.97^{c-j}	0.76^{de}	2.93^{e}	2.33^{a}	12.87^{a}	19.90^{abc}	17.05^{ab}
2*3	28.50^{ab}	102.33^{b-f}	6.00^{abc}	6.17^{b}	2.50^{ij}	0.85^{cde}	3.50^{b-e}	2.94^{a}	11.97^{a}	20.80^{ab}	17.20^{ab}
2*4	27.00^{abc}	101.67^{b-f}	6.67^{abc}	6.20^{b}	2.47^{ij}	0.92^{cde}	3.17^{de}	2.80^{a}	13.63^{a}	22.37^{a}	17.40^{a}
2*5	27.00^{abc}	115.00^{ab}	6.67^{abc}	7.07^{ab}	2.53^{hij}	0.79^{de}	3.50^{b-e}	3.20^{a}	11.83^{a}	17.23^{b-g}	17.80^{a}
2*6	33.33^{a}	113.00^{abc}	8.33^{a}	8.13^{ab}	4.20^{ab}	1.77^{a}	4.30^{a}	3.83^{a}	16.73^{a}	19.13^{a-d}	17.87^{a}
2*7	26.33^{abc}	86.00^{b-f}	6.33^{abc}	6.90^{ab}	2.73^{f-j}	0.84^{cde}	3.00^{e}	3.14^{a}	12.28^{a}	17.47^{b-f}	14.61^{de}
3*4	24.33^{abc}	111.83^{a-d}	4.33^{bc}	6.27^{b}	3.60^{a-d}	1.47^{ab}	4.10^{ab}	3.83^{a}	9.87^{a}	12.70^{h}	12.33^{g}
3*5	25.67^{abc}	75.67^{c-f}	6.67^{abc}	6.73^{ab}	2.60^{hij}	0.73^{de}	3.23^{de}	3.13^{a}	12.53^{a}	16.08^{c-h}	18.13^{a}
3*6	26.00^{abc}	148.33^{a}	5.00^{abc}	7.33^{ab}	3.57^{b-e}	1.67^{ab}	3.57^{a-e}	4.04^{a}	8.27^{a}	12.43^{h}	12.60^{g}
3*7	23.67^{abc}	96.67^{b-f}	6.00^{abc}	7.17^{ab}	2.73^{f-j}	0.70^{e}	3.13^{de}	3.10^{a}	12.30^{a}	17.77^{b-e}	16.78^{abc}
4*5	25.33^{abc}	100.67^{b-f}	5.33^{abc}	7.43^{ab}	3.23^{c-i}	1.20^{bcd}	3.23^{de}	3.44^{a}	11.93^{a}	14.43^{e-h}	14.24^{def}
4*6	26.33^{abc}	80.00^{b-f}	4.67^{bc}	7.17^{ab}	3.43^{b-g}	1.64^{ab}	3.53^{b-e}	3.73^{a}	11.63^{a}	12.80^{gh}	12.17^{g}
4*7	30.00^{a}	89.33^{b-f}	5.33^{abc}	7.37^{ab}	2.67^{g-j}	1.31^{abc}	3.20^{de}	3.33^{a}	12.13^{a}	16.87^{b-h}	15.20^{cd}
5*6	30.17^{a}	116.33^{ab}	7.00^{abc}	7.17^{ab}	3.73^{abc}	1.60^{ab}	3.50^{b-e}	3.53^{a}	12.40^{a}	17.33^{b-f}	12.43^{g}
5*7	32.83^{a}	91.33^{b-f}	4.67^{bc}	6.90^{ab}	3.23^{c-i}	0.77^{de}	4.10^{ab}	3.40^{a}	12.07^{a}	18.30^{a-e}	15.40^{cd}
6*7	23.50^{abc}	79.67^{b-f}	3.67^{c}	7.20^{ab}	3.23^{c-i}	0.65^{e}	4.07^{abc}	14.47^{a}	13^{a}	20.41^{abc}	12.27^{g}

values in columns followed by the same letter are not significantly different, $p<0.05$, Tukey.

Table 5. Mean squares from diallel analysis for yield and its components in chili pepper (Griffing's model I Method 4).

Source	df	Number fruit per plant	Number marketable fruit per plant	Days to flowering	Days to harvest	Fruiting period (Days)	Fruit length	Fruit diameter	Fruit length to diameter ratio
GCA	6	334.30^{ns}	330.61^{ns}	24.77**	65.47**	18.45^{ns}	0.21^{ns}	4.69**	5.08**
SCA	21	450.35*	447.14^{ns}	35.77**	57.59**	38.42^{ns}	2.39**	13.98**	5.93**
Error	28	189.39	201.36	3.22	10.24	36.06	0.40	0.53	1.29

ns, *, **: non-significant or significant at P≤0.05 and P≤0.01, respectively.

Table 6. Mean squares obtained from diallel analysis for vegetative characteristics, fruit dry matter and ash in chili pepper (Griffing's model I Method 4).

Source	df	Plant length to first flower	Plant height	Number of branches	Leaf length	Leaf width	Pericarp thickness	Peduncle length	Mature fruit dry weight	Mature fruit ash
GCA	6	2.94^{ns}	28.01^{ns}	0.27^{ns}	0.04^{ns}	0.06^{ns}	0.04^{ns}	0.19^{ns}	2.06^{ns}	1.21**
SCA	21	7.94^{ns}	327.64**	1.19^{ns}	0.17^{ns}	0.16**	0.08**	0.49^{ns}	4.49**	2.94**
Error	28	7.90	112.03	0.92	0.13	0.05	0.02	0.39	1.51	0.19

ns, **: non-significant or significant at *P*≤0.01, respectively.

Table 7. General combining ability of lines for yield and its components according to Griffing's method 2.

Parent	Number fruit per plant	Number marketable fruit per plant	Days to flowering	Days to harvest	Fruiting period (Days)	Fruit length	Fruit diameter	Fruit length to diameter ratio
1	5.95	5.01	-0.94	-2.88	-9.21	-0.09	-2.18	2.02
2	26.84	27.82	-5.01	2.20	5.31	0.5	-0.83	1.36
3	-17.46	-17.29	7.73	10.27	-2.84	-0.09	1.35	-1.62
4	-17.16	-16.59	3.84	2.57	4.76	0.17	2.04	-2.14
5	19.69	19.67	-4.34	-8.21	2.02	-0.2	-1.57	1.18
6	-23.86	-23.33	4.51	8.23	0.42	-0.29	3.99	-3.55
7	5.99	4.71	-5.79	-12.77	-0.47	-0.02	-2.79	2.75
Standard Error	3.75	3.86	0.49	0.87	1.98	0.17	0.20	0.31

The highest number of fruit per plant SCA was observed in the 1×4 hybrid. Cross 1×3 had the highest SCA for days to flowering and harvest (Table 9). Cross 2×6 had the highest fruit length and diameter SCA (Table 9). Cross 1×4 and 1×3 had the highest SCA for fruit length to diameter ratio and pericarp thickness, respectively (Table 9). Cross 3×6 and 2×6 had the highest SCA for plant height and leaf width, respectively (Table 10). Finally, Cross 1×4 and 3×5 had the highest SCA for dry matter and ash, respectively (Table 10).

The highest heterosis, in relation to the mean and maximum parental value, was obtained in the crosses 2×3 and 4×6, for the number of fruit per plant, respectively. The highest heterosis, in relation to the mean and maximum parental value, was obtained in the crosses 2×3 and 1×4 for the number of marketable fruit per plant, respectively. The highest negative heterosis, in relation to the mean and maximum parental values

Table 8. General combining ability of lines for vegetative characteristics, fruit dry matter and ash according to Griffing's method 2.

Parent	Plant length to first flower	Plant height	Number branches	Leaf length	Leaf width	Pericarp thickness	Peduncle length	Mature fruit dry weight	Mature fruit ash
1	-4.16	-0.22	0.8	0.23	0.03	-0.09	0.63	1.16	0.68
2	1.32	0.56	0.65	-0.35	-0.34	-0.11	-0.33	2.48	1.68
3	-0.65	5.65	-0.79	-0.18	0.07	0.1	-0.19	-1.83	-0.89
4	-0.18	-0.11	-0.35	0.33	0.25	0.15	-0.41	-1.13	-1.06
5	1.89	0.82	0.5	-0.25	-0.23	-0.18	0.84	-0.32	1.11
6	1.45	-0.22	-0.72	0.27	0.42	0.39	-0.13	-1.49	-1.67
7	0.34	-6.49	-0.09	-0.05	-0.2	-0.28	-0.42	1.13	0.17
Standard Error	0.89	2.89	0.26	0.18	0.06	0.04	0.89	0.33	0.12

Table 9. Specific combining ability of hybrids for yield and its components according to Griffing's method 2.

Hybrid	Number fruit per plant	Number marketable fruit per plant	Days to flowering	Days to harvest	Fruiting period (Days)	Fruit length	Fruit diameter	Fruit length to diameter ratio
1*2	1.94	2.97	-0.4	2.78	0.95	0.56	-0.45	0.34
1*3	-34.09	-34.92	11.19	13.37	0.77	1.28	5.21	-3.98
1*4	35.94	34.38	-7.25	-11.93	-13.49	-0.15	-4.15	4.30
1*5	-5.24	-5.55	0.94	1.85	7.25	2.16	0.26	1.58
1*6	-14.35	-11.21	5.08	7.81	12.18	-1.15	0.5	-2.55
1*7	1.46	4.75	-0.62	1.07	-5.27	0.41	0.25	0.54
2*3	33.35	31.60	-9.73	-5.7	7.25	1.82	-2.85	3.45
2*4	26.06	29.56	-5.51	4.33	1.99	-1.32	-2.77	0.39
2*5	4.87	5.97	2.34	-2.56	-4.94	0.47	-0.96	0.83
2*6	-52.91	-53.36	1.16	-0.26	-0.68	2.92	10.64	-3.89
2*7	-2.76	-8.40	3.45	-4.67	-0.12	0.35	0.69	-1.36
3*4	-8.31	-8.66	4.75	9.26	11.14	-1.44	0.86	0.7
3*5	21.17	21.08	-10.73	-14.63	5.55	-0.35	-4.14	2.73
3*6	7.72	9.75	4.08	5.33	-18.35	-0.37	0.94	-0.27
3*7	11.54	12.38	-7.29	-10.07	8.36	0.46	-1.18	0.07
4*5	-1.80	-1.28	2.49	2.41	-1.38	1.25	3.94	-3.00
4*6	8.76	7.38	-2.36	2.37	-1.12	1.48	-2.23	2.43
4*7	-36.09	-34.66	-2.06	-3.7	-0.9	-1.5	5.06	-3.88
5*6	1.91	0.79	-3.84	-7.52	2.95	-0.01	2.62	-2.46
5*7	-3.61	-1.92	2.12	4.07	-2.16	1.37	1.23	-0.2
6*7	25.94	26.42	-7.40	-6.63	-2.56	-0.02	-5.03	3.12
SE[a] (ij-ik)	10.59	10.92	1.38	2.46	5.61	0.49	0.56	0.87
SE (ij-kl)	9.91	10.22	1.29	2.31	5.25	0.45	0.53	0.82

[a]SE: Standard Error.

Table 10. Specific combining ability of hybrids for vegetative characteristics, fruit dry matter and ash according to Griffing's method 2.

Hybrid	Plant length to first flower	Plant height	Number of branches	Leaf length	Leaf width	Pericarp thickness	Peduncle length	Mature fruit dry weight	Mature fruit ash
1*2	-0.96	9.12	-0.26	0.06	-0.03	0.26	-0.91	0.42	-0.68
1*3	4.00	8.36	-1.81	0.28	0.37	0.48	-0.75	-2.51	-3.09
1*4	-4.46	3.12	1.41	-0.36	-0.12	-0.42	-0.85	3.85	1.89
1*5	4.80	10.86	-0.44	-0.39	-0.33	-0.12	8.19	-1.02	0.51
1*6	5.57	-1.77	-1.89	-0.002	0.12	0.28	-0.74	-2.05	-1.04
1*7	-4.98	12.51	1.15	-0.28	-0.001	-0.01	-1.08	0.53	1.07
2*3	1.85	0.92	0.33	-0.38	-0.37	-0.28	0.21	3.08	1.27
2*4	-0.11	6.00	0.56	-0.85	-0.59	-0.26	0.11	3.94	1.65
2*5	-2.19	18.42	-0.3	0.59	-0.03	-0.06	-0.81	-2.00	-0.12
2*6	4.59	17.45	2.59	1.14	0.98	0.35	0.96	1.07	2.72
2*7	-1.30	-3.27	-0.04	0.24	0.13	0.1	-0.05	-3.22	-2.38
3*4	-0.81	11.08	-0.33	-0.96	0.14	0.07	0.9	-1.42	-0.85
3*5	-1.56	-26.00	1.15	0.08	-0.37	-0.33	-1.22	1.16	2.78
3*6	-0.78	47.69	0.7	0.17	-0.06	0.03	0.08	-1.32	0.03
3*7	-2.00	2.31	1.07	0.32	-0.28	-0.26	-0.06	1.39	2.37
4*5	-2.35	4.75	0.63	0.27	0.08	0.09	-0.99	-1.20	-0.93
4*6	-0.91	-14.88	-0.07	-0.51	-0.38	-0.04	0.28	-1.66	-0.23
4*7	3.87	1.23	-0.04	0.02	-0.53	0.3	0.23	-0.21	0.96
5*6	0.85	20.53	1.41	0.07	0.41	0.25	-1.01	2.07	-2.13
5*7	4.63	1.81	-1.56	0.13	0.53	0.08	-0.12	0.41	-1.01
6*7	-4.26	-8.82	-1.33	-0.09	-0.13	-0.6	0.81	3.69	-1.36
SE[a] (ij-ik)	2.52	112.87	0.74	0.51	0.16	0.1	2.53	0.95	0.34
SE (ij-kl)	2.36	21.56	0.69	0.47	0.15	0.1	2.37	0.88	0.32

[a]SE: Standard Error.

were obtained from the cross 3×5 for days to flowering and harvesting. The highest heterosis, in relation to the mean and maximum parental value, was observed in the crosses 3×4 and 3×7 for harvesting period, respectively (Table 11).

The highest heterosis, in relation to the mean and maximum parental values were obtained in the cross 2×6 for fruit length and diameter. The highest heterosis, in relation to the mean and maximum parental value was obtained in the crosses 1×4 and 3×4 for fruit length to diameter ratio. The highest heterosis, in relation to the mean and maximum parental value was obtained in the crosses 1×3 and 1×2 for pericarp thickness, respectively. The highest heterosis, in relation to the mean and maximum parental value was obtained in the cross 1×5 for peduncle length (Table 11).

The highest heterosis, in relation to the mean and maximum parental value was observed in the cross 2×6 for the number of branches and leaf width. The highest heterosis, in relation to the mean and maximum parental value was obtained in the crosses 1×6 and 2×6 for plant length to the first flower. The highest heterosis, in relation to the mean and maximum parent value was obtained in the cross 3×6 for plant height. The highest heterosis, in relation to the mean and maximum parental value was observed in the crosses 2×6 and 5×7 for leaves length (Table 12).

The highest heterosis, in relation to the mean and maximum parental value was obtained in the crosses 2×4 and 6×7 for fruit dry matter and the highest heterosis, in relation to the mean and maximum parental value was obtained in the crosses 3×5 and 3×7 for fruit ash (Table 12).

Although heterosis is the primary target for increasing productivity, the biological complexity of yield as a trait frequently makes it difficult to draw meaningful conclusions in order to track individual causal elements involved in heterosis. Cucumber breeders might develop high-yielding cultivars based on high GCA for certain traits (Olfati *et al*., 2011).

DISCUSSION

Estimates of combining ability are important in determining the breeding value of chili pepper lines by proposing the appropriate use of lines in breeding.

Table 11. Heterosis for yield and its components compared to mid- and max-parent.

Hybrid	Number of fruit per plant		Number of marketable fruit per plant		Days to flowering		Days to harvest		Fruiting period (Days)		Fruit length		Fruit diameter		Fruit length to diameter ratio	
	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Mid parent	Mid parent	Max parent	Mid parent	Max parent	Max parent	Max parent	Mid parent	Max parent	Mid parent	Max parent
1*2	1	-13.67	2.67	-15.67	-0.33	2.53	1.03	0.34	0.34	-0.2	2.37	-0.67	5	-5.33	2.67	-11.33
1*3	-29.83	-64.67	-29.5	-62	11.5	2.73	5.33	1.1	-3.24	-0.75	2.63	-1.33	16.5	-1	5	1.67
1*4	38.5	5.67	38.67	8	-7.5	1.5	-3.56	-8.02	4.59	0.25	1.33	-17	-7.5	-16	-13.83	-29.33
1*5	-4.5	-10.33	-3.17	-10.67	1.5	3.68	1.40	1.12	1.5	0.85	3.60	1	1.5	-1	9.67	-0.33
1*6	-23.67	-51.33	-18.67	-44.33	6.5	0.28	2.76	-1.96	-3.39	-8	0.2	-2	11.83	-3.33	10.83	-1.33
1*7	-3	-5.67	2	-0.33	-1.33	1.99	0.91	0.45	0.18	-1.04	1.95	-1.67	-0.17	-1.33	-5.33	-15.33
2*3	43.83	-5.67	41.5	-9.33	-13.83	3.7	-2.06	-5.6	4.08	0.36	3.63	-26.33	-7.83	-15	12	1.33
2*4	34.83	-12.67	38.33	-10.67	-10.17	0.75	-1.52	-5.28	0.57	-3.23	0.75	-19.33	3.5	1.67	2.17	0.67
2*5	11.83	3	12.83	2	-1.5	2.42	0.85	0.44	0.65	0.53	2.17	-1.67	-8.17	-16	-2	-6
2*6	-56	-98.33	-56.33	-99.33	-1.83	4.78	13.58	9.54	-4.85	-8.92	4.53	-10	-1.5	-6.33	-1.5	-3.33
2*7	-1	-18.33	-6.67	-27.33	-1.67	2.36	2.02	0.88	-1.84	-3.60	2.23	-1.67	-11.17	-22.67	0.33	-3.67
3*4	5.67	3.67	5.83	4	0.33	3.30	0.74	0.52	1.61	1.53	3.23	-3	9.33	0.33	13.83	1.67
3*5	33.33	-7.33	33.67	-6.33	-14.33	-0.02	-3.69	-7.63	3.27	-0.33	-0.2	-26.67	-19.33	-34.33	11	4.33
3*6	9.83	2.67	12.5	5.67	1.33	0.98	2.50	2.01	-0.49	-0.85	0.8	-3	5	2.67	-16.83	-25.67
3*7	18.50	-13.67	19.83	-10.33	-12.17	1.10	-1.22	-5.90	0.32	-5.15	1.05	-24.67	-15.67	-34.33	11.33	4.67
4*5	8.67	-30	10.17	-28	-1.67	2.08	4.85	0.68	-2.90	-6.59	1.83	-10.67	-1	-7	-0.5	-6
4*6	9.17	4	9	4	-5.67	2.78	-0.2	-0.47	1.76	1.49	2.53	-6.67	3.33	-3.33	-4	-7.33
4*7	-30.83	-61	-28.33	-56.67	-7.5	3.16	5.49	0.58	-4.07	-9.63	3.03	-16.67	-8	-17.67	-2.5	-8
5*6	0.5	-33	0.5	-32.67	-6.33	1.5	5.21	0.78	-3.5	-7.45	1.40	-14.33	-11.33	-24	2.83	0.67
5*7	-0.17	-8.67	2.5	-7.33	-2.5	2.92	2.22	1.49	-0.75	-2.62	2.80	-2.67	-5	-8.67	-1	-1
6*7	19.33	-5.67	21	-2.33	-11.7	1.44	-2.91	-8.09	1.79	-4.03	1.32	-19.33	-11.33	-27.67	-5.17	-7.33

Table 12. Heterosis for vegetative characteristics, fruit dry matter and ash compared to mid- and max-parent.

Hybrid	Plant length to first flower		Plant height		Number of branches		Leaf length		Leaf width		Pericarp thickness		Peduncle length		Mature fruit dry weight		Mature fruit ash	
	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent	Mid parent	Max parent
1*2	0.5	-5.5	31.83	31	0.00	-1.33	0.08	-0.87	-0.002	-0.39	0.4	0.34	-0.06	-0.18	1.04	0.75	-0.4	-0.46
1*3	5.17	0.83	30	24.67	-2.00	-4.33	-0.02	-0.47	0.22	0.03	0.53	0.15	0.02	-0.32	-2.61	-5.89	-2.79	-5.33
1*4	-4.67	-10.83	16.5	8.67	1.17	-0.67	-1.13	-1.67	-0.47	-1.05	-0.37	-0.79	0.03	0.03	4.48	1.18	2.18	-0.52
1*5	6.83	0.83	29	25	-1	-1.67	-0.37	-1.20	-0.26	-0.59	-0.02	-0.08	10.17	10.02	-1.35	-2.89	-0.05	-0.37
1*6	7.83	2.5	23.83	19.33	-2	-4.33	0.02	-0.3	0.35	0.19	0.47	-0.06	0.32	0.22	-1.79	-5.09	-1.87	-4.06
1*7	-5	-11.5	24.5	21.67	0.5	-0.67	-0.37	-0.9	-0.07	-0.22	0.01	-0.02	-0.18	-0.2	0.98	0.11	0.65	-0.11
2*3	2.5	0.83	24.17	18	1.33	0.33	-0.3	-0.8	-0.49	-1.07	-0.32	-0.63	-0.11	-0.33	3.99	0.41	2.52	-0.07
2*4	-0.83	-1	21	12.33	1.5	1	-1.25	-2.73	-0.91	-1.88	-0.29	-0.65	-0.09	-0.22	5.59	1.98	2.89	0.13
2*5	-0.67	-0.67	38.17	33.33	0.33	-0.33	0.99	0.87	0.06	-4.44	-0.05	-0.07	0.08	0.05	-1.32	-3.15	0.27	0.00
2*6	6.33	5.67	44.67	41	3.67	2.67	1.54	0.91	1.24	0.69	0.45	-0.02	0.93	0.92	2.34	-1.25	2.84	0.6
2*7	-1.83	-2.33	10.33	6.67	0.5	0.33	0.52	0.1	0.08	-0.15	0.03	-0.01	-0.24	-0.38	-1.75	-2.92	-1.85	-2.66
3*4	-1.83	-3.67	25	22.5	0.17	-0.33	-1.68	-2.67	-0.36	-0.75	-0.06	-0.1	0.62	0.27	-0.51	-0.54	0.41	0.24
3*5	-0.33	-2	-7.33	-8.67	1.33	-0.33	0.15	-0.23	-0.45	-0.97	-0.43	-0.76	-0.41	-0.6	1.10	-0.64	3.19	0.33
3*6	0.67	-0.33	73.83	64	1.33	1.33	0.24	0.11	0.03	-4.44	0.03	-0.12	-0.02	-0.27	-0.78	-0.8	0.16	-0.19
3*7	-2.83	-5	14.83	12.33	1.17	0.00	0.28	0.2	-0.49	-0.83	-0.43	-0.79	-0.33	-0.7	2.13	-0.27	2.92	1.14
4*5	-2.5	-2.67	15.17	11.33	-0.5	-1.67	-0.13	-1.5	-0.21	-1.11	-0.002	-0.37	-0.06	-0.22	-0.51	-2.29	-0.54	-3.56
4*6	-0.83	-1.67	3	-9.33	0.5	0.00	-0.91	-1.77	-0.49	-0.91	-0.04	-0.15	0.29	0.18	-0.39	-0.4	-0.1	-0.62
4*7	1.67	1.33	5.5	0.5	0.88	-0.67	-0.5	-1.57	-0.95	-1.68	0.14	-0.26	0.08	0.07	1.26	-1.17	1.5	-0.44
5*6	3.17	2.5	43.17	34.67	1.67	0.00	0.45	-0.06	0.71	0.22	0.29	-0.18	0.1	0.05	2.37	0.61	-2.86	-5.37
5*7	4.67	4.17	10.83	9.67	-1.83	-2.33	0.4	1	0.52	0.35	-0.04	-0.07	0.82	0.65	0.92	0.26	-1.32	-2.4
6*7	-4	-5.17	7.67	0.33	-1.17	-2.33	0.19	-0.03	0.03	-0.28	-0.63	-1.13	0.84	0.72	4.79	2.37	-1.95	-3.37

Parents of hybrids with high SCA values are selected to be used in cross breeding methods in chili pepper (Legesse, 2000).

Combining ability analysis is used in selection of parents for designing a crossing plan. The diallel study provides evidence for existence of significant additive variation of some traits through large GCA values. The GCA of a parental clone provides an assessment of its breeding value, as judged by mean performance of its progenies obtained from crosses with other clones (Olfati *et al*. 2011). As suggested by Baker (1978), the relative importance of GCA and SCA in determining progeny performance should be assessed by estimating the ratio of mean squares. Dominant variance is important for almost trait of chili pepper in this research, and breeders are able to produce suitable materials via crossing. Progeny of lines with the highest GCA for each trait can be released for selection as new elite breeding lines (Lankesh Kumar *et al.,* 2014).

Although yield heterosis is the primary target for increasing productivity, the biological complexity of yield as a trait frequently makes it difficult to draw meaningful conclusions in order to track individual causal elements involved in heterosis. Chili breeders might develop F1 cultivars based on high SCA for their traits. Crossing lines 2 and 6 are suggested for hybrid production due to high value of this hybrid for many characters related to chili pepper yield and quality. Cross breeding is suggested for chili pepper improvement. Breeders are able to produce suitable hybrids via choosing parental lines with high SCA for fruit length (hybrid 2×6 in this research).

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