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RESEARCH ARTICLE

Genetic components of characters related to yield in pepper guajillo: Method II of Griffing

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ABSTRACT

The *Capsium* genus comprises one of the most economically important and gastronomic plant groups in the world. In Mexico, *C. annuum* one of the five species was domesticated. Guajillo chili belongs to this species; whose main use is dry. In this type of chili, little is known about its genetic parameters. The objective was to identify populations with better plant characteristics and high yield in order to obtain information on his heterotic patterns. For this study, nine populations of Guajillo chili from different entities of Mexico were used, which by means of a partial dialectic design, originated 36 crosses. The analysis of variance showed highly significant effects ($P \leq 0.001$) in the general combining ability (GCA) in the parents, as well as for the specific combining ability (SCA) in their crosses mainly in the performance variables. In the variable number of fruit per plant (NFP), a higher GCA was observed, as well as in the cross P1 x P9 that showed higher value of heterosis and heterobeltiosis. The fresh fruit yield, the positive heterotic value, was observed in the crosses P2 x P5, P3 x P4, P3 x P5, P4 x P9 and P7 x P9. While the yield of dried fruit showed the positive and highly significant heterotic and heterobeltiosis value, at the P1 x P9 and P2 x P6 crosses. While the cross P3 x P9 only shows a significant positive value of heterosis.

Keywords: Genetic; Yield; Guajillo; General combining ability; Specific combining ability

INTRODUCTION

Chili (*Capsicum annuum* L.) is one of the five domesticated and most cultivated species for its economic, medicinal and nutritional importance. Currently China (18.2 t), Mexico (3.4 t), Turkey and Indonesia (2.5 t) are top four fresh chili producers while India (1.8 t), China (.321 t), Ethiopia (.294 t) and Thailand (.247 t) are the dried chili producers (Bravo et al., 2006; FAO, 2018). The production of dried peppers has great importance in Mexico, and the Guajillo chili is one of them, used mainly in the preparation of marinades, barbecue and providing a red color in different regional dishes.

According to Gutiérrez et al. (2004) and De la Cruz-Lázaro et al. (2010) mention that to obtain new varieties of plants in plant breeding programs, the most important decision is the selection of parental germplasm and the combinatorial aptitude of the parents. The evaluation of GCA and SCA by dialelic crossing is efficient in the classification of progenitors, as well as the identification of germplasm in plant breeding (Castañón-Nájera et al., 2005). The GCA is translated as the average yield of a line through its hybrid combination, meanwhile, the SCA correspond to certain cases of specific hybrid combinations of good performance in relation to what is observed in their parents (Sprague and Tatum, 1942; Martínez-Vázquez et al., 2017). Therefore, the estimation of these genetic parameters is obtained through the analysis of diallelic designs (four designs) proposed by Griffing (1956).

The value of a genotype depends on its potential per se and its ability to combine. Germplasm evaluation is a decisive aspect in breeding programs (De la Cruz-Lázaro et al., 2010). Particular aspects such as productivity, resistance, tolerance to biotic and abiotic stress, architecture, fruit quality and precocity are fundamental objectives of study in the breeding of the *Capsicum* genus (Do Rêgo et al.,

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2011). Likewise, the study of the genetic diversity of the genus *Capsicum* provides parameters for the identification of parents that produce greater heterotic effects and the probability of obtaining superior genotypes in the following generations (Sudré et al., 2005; Costa et al., 2016).

Capsicum is native to the tropical and subtropical Americas, and the majority of the genetic diversity is concentrated in Bolivia, Peru, Brazil, and Mexico (García-Gaytán et al., 2017). *Capsicum annuum* was domesticated in Mexico thousands of years ago and includes both sweet and spicy fruits, with a myriad of shapes, colors, and sizes (Perry and Flannery, 2007; Wang and Bosland, 2006; García-Gaytán et al., 2017). In *Capsicum*, it have been realized experiment have examined general combining ability (GCA) and specific combining ability (SCA) (Geleta and Labuschagne, 2006; Hasanuzzaman et al., 2012; Do Nascimiento et al., 2014).

In Mexico, the exploration of the genetic potential of local materials by estimating GCA and SCA has been limited in the case of *Capsicum*. Pech et al., (2010) estimated the combinatorial aptitude and heterosis of seven Creole populations of "Dulce" chili and the resulting crosses between them, the variables measured were: fruit yield, fruit weight, number of fruits per plant, start harvest, plant height, length and diameter of fruit. They found that the additive effects estimated by the GCA were larger than the dominance effects estimated by the SCA. For their part, Hernández-Pérez et al., (2011) evaluated the GCA and SCA in chili genotypes and their direct crosses. Six types of chili were used: three jalapeño type, yellow Hungarian type and a wide type. The variables evaluated were: days to flowering and cutting, fruit yield per plants, diameter, length and average weight of the fruit and yield per hectare. For both cases in the GCA and SCA they found genotypes and crosses with high yield. Previous studies demonstrate research on the genetic diversity of *Capsicum* materials in different states of Mexico. However, it is necessary to continue to elucidate its potential for improvement, to achieve progress in obtaining new plants. Therefore, the objectives of the following research were: 1) to evaluate the GCA and SCA of 9 parents and their 36 crosses from Guajillo in a dialelic mating scheme and the evaluation of the parents and the F1 set in one direction on the agronomic basis of yield. 2) Identify the best crosses with high yield potential and good heterosis.

MATERIALS AND METHODS

Experimental design

The experiment was conducted in 2015 in a metal greenhouse with plastic cover at the Postgraduate College, Campus Montecillo, Mexico, located at 19° 20' N, 53' W, at an altitude of 2250 masl. The seedlings were transplanted 60 days after germination in white polyethylene bags with dimensions of 40 x 40 cm with capacity for 12 L. Red tezontle was used as substrate with granulometry 7 mm. The irrigation system was drip, Steiner nutrient solution was applied (Steiner, 1966), with the following concentrations in $mol_c\ m^{-3}$ 12.0 NO_3^-, 1.0 $H_2PO_4^{-1}$, 7.0 SO_4^{2-}, 7.0 K^+, 9 Ca^{2+}, y 4.0 Mg^{2+}. The concentrations were modified according to the phenological stage. Vegetables absorb and translocate the nutrients from the roots to the demand and development organs such as leaves, flowers and fruits (Jesus et al., 2020). Once flowering begins, the crosses and self-fertilization were carried out to obtain the F_1 generation. Of the nine populations a partial dialectic was formed with self-fertilization and simple crosses: 1x1, 2x3, 3x4…..9x9, with a total of 36 crosses and the nine parents.

Vegetal material

The populations used as the parents were formed, based on the characteristics of size, shape and color of fruit from the states of Durango, Zacatecas, San Luis Potosi and Guanajuato, Mexico (Table 1 and Fig. 1). A partial dialectic was formed with nine parents (populations) with a total of 36 crosses.

For the germination of the seed, of the nine populations of Guajillo chili, 100 seeds from each population were used, which were placed in polystyrene trays with 200 cavities, and as a substrate land of mount, subsequently the trays were stowed and covered with black plastic until germination.

Evaluation of parents and F1 crosses

Subsequently the evaluation of hybrids and their parents, it was carried out in 2017, in the La Huasteca Experimental Field-National Institute of Forestry, Agriculture and Livestock Research (INIFAP), located south of Tamaulipas, Mexico. The experiment was established in a randomized complete block design with four repetitions, the experimental unit was represented by

Table 1: Fruit form and origin of the accessions of the nine populations of Guajillo chili in Mexico

Population	Description	Origin
P1	Guajon Red Guajillo	Dgo. Zac. y Villa de Reyes SLP
P2	Intermediate Red Guajillo	Dgo. Zac. y Villa de Reyes SLP
P3	Small Red Guajillo	Dgo. Zac. y Villa de Reyes SLP
P4	Guajon Red Guajillo	San Luis Potosí
P5	Intermediate Red Guajillo	San Luis Potosí
P6	Small Red Guajillo	San Luis Potosí
P7	Guajon Red Guajillo	Guanajuato
P8	Intermediate Red Guajillo	Guanajuato
P9	Small Red Guajillo	Guanajuato

a plot of 1.84 m2 useful (two rows of 2 m long by 0.92 cm wide). The experimental unit was represented by a plot of 1.84 m2 useful (two rows of 2 m long by 0.92 cm wide).

The characters evaluated, according to the descriptor manual for *Capsicum* (IPGRI, 1995) were: plant height (AP), canopy cover (CD) (cm), height of the first fork (APB) (cm); fresh fruit weight (PFF) (g), dry fruit weight (PFS) (g), for these two characters the average weight of 12 fruits was taken, fruit length (LF) (cm), fruit width (AF) (cm), peduncle length (LP) (cm), and number of fruits per plant (NFP); yield of dry fruit (RFS, t h^{-1}) and yield of fresh fruit (RFF, t h^{-1}). The evaluation of the plant variables was carried out in four plants in each experimental unit and that of the fruits in three fruits per plant. The evaluation of the green and dry yield variables was carried out considering all the plants of the experimental unit according to the following Equation 1:

$$t\ ha^{-1}=[[10{,}000\ m^2/\text{useful plot}\ (1.84\ m^2)]*\text{yiel of the plot}]] \quad (1)$$

Fig 1. Fruit form of the accessions of the nine populations of Guajillo chili in Mexico (a) Guajon Red Guajillo, (b) Intermediate Red Guajillo and (c) Small Red Guajillo.

Data analysis

An analysis of variance (ANOVA) was performed on the experimental data and the means were compared by the Tukey test ($P \leq 0.05$), with the SAS statistical package ver. 9.3. Percentage heterosis (Hm) was estimated with respect to the average of each of the agronomic and yield variables. The herterobeltiosis (Hs) was estimated percentaje of deviation of the F_1 hybrid from better parental value. By means of the "t" test described by Wynne et al. (1970) the significance of heterosis and heterobeltiosis was evaluated with respect to the average of the parents. The general combining ability (GCA) and specific (SCA) were calculated following method 2 of Griffing's dialelic (Griffing, 1956). The DIALLEL-SAS program estimated the effects of GCA and SCA (Zhang and Kang, 2003).

RESULTS AND DISCUSSION

Analysis of variance of parents and their F1 crosses

The analysis of variance showed highly significant differences in parents and F1 crosses in most of the variables, except in CD, APB and AF (Table 2). Highly significant effects ($P \leq 0.001$) of the GCA were observed in seven of the 11 variables, while SCA had highly significant differences in RFF, RFS, PFS and significant AP, LF and NFP. The lowest coefficient of variation between the variables was observed in the length of fruits (LF) (6.92%), pedicel length (LP) (7.39%) and plant height (AP) (9.23%). While in the NFP, RFF and RFS variables it was greater than 20% (Table 2). Shows the F1 fruits of the crosses developed in the greenhouse

Table 2: Mean squares of the analysis of variance for agronomic characteristics and yield in populations of Guajillo chili

Variables evaluated	Variance analysis					
	Repetition	Parents and F1 crosses	GCA	SCA	Error	CV (%)
df	3	44	8	36	132	
Plant height (cm)	438.22**	111.10*	75.98	118.91*	73.22	9.23
Docel coverage (cm)	950.06**	58.89	52.66	60.28	48.32	10.25
Height of the first bifurcation (cm)	5.90	2.55	4.85	2.05	2.53	27.82
Number of fruits per plant	60.61**	24.89***	52.24***	18.81*	11.81	25.07
Fruit length (cm)	1.22	1.87***	4.90***	1.20*	0.81	6.92
Fruit width (cm)	0.28	0.30	0.61	0.23	0.37	14.79
Peduncle length (cm)	0.37	0.34***	0.85***	0.23	0.17	7.39
Fresh fruit weight (g)	16.81	29.05***	80.93***	17.52	14.30	10.74
Dry fruit weight (g)	0.51	1.00***	225.43**	125.06**	0.48	12.74
Fresh fruit yield (t ha-1)	23.22*	19.54***	28.45***	17.56***	7.96	22.50
Dry fruit yield (t ha-1)	2.70**	1.84***	3.74***	1.42***	0.63	26.38

*, **, ***: [a]Significant at 0.05, 0.01, and 0.001 respectively. GCA = general combining ability; SCA = specific combining ability; CV = coefficient of variation; df = degrees of freedom.

Fig 2. Generation of F1 seeds developed in a greenhouse. Flowering and crosses (a), immature fruit obtained from the cross (b), and development of the fruit obtained from the cross (c). Fruit ripening, Intermediate Red Guajillo (a), Small Red Guajillo, (b) Guajon Red Guajillo.

(Fig. 2). Fruits of the F1 crosses developed in the field to obtain F2 seeds (Fig. 3).

The results show the existing variation in the populations and their crosses, which is because these populations come from a broad genetic base. Similar results have been reported in RF, NFP, AP and LF in sweet pepper (May et al., 2010). The GCA of the populations and their crosses differed significantly ($P \leq 0.001$) in NFP, LF, LP, PFF, PFS, as well as the RFF and RFS in t ha^{-1}. In the case of the GCA, significant differences were observed in the variables NFP, LF, LP, PFF, PFS, RFF Y RFS and for ACE in the variables AP, NFP, PFS, RFF and RFS. As seen in Table 2, the GCA are greater in magnitude than the SCA in most of the variables except in AP (75.98) and CD (52.6). Therefore, the evaluated germplasm characters were associated more with additive effects than with non-additive ones, indicating that satisfactory gains can be achieved with the selection of these characters (Medeiros et al., 2014). Similar results were observed by Medeiros et al. (2014) and Sitaresmi et al. (2016) who report that the NFP, PF LF, DF of *C. annuum*, and *C. baccatum* var. *Pendulum*, were more associated with additive effects.

For SCA, significant effects ($P \leq 0.05$) were found on AP, NFP, LF and highly significant ($P \leq 0.001$) PFS, RFF and RFS, indicating the presence of non-additive genetic action (dominance) in these characters (Table 2). Similarly,

Fig 3. Fruits of the F1 crosses ((a), (b), (c), (d)) developed in the field to obtain F2 seeds.

Esquivel-Esquivel et al. (2011) observed significant effects for ACE in NFP, DF and PPF; while Pech et al. (2010) reported that in sweet pepper they did not observe significance in PFF, AP and LF.

Comparison of means of crosses and populations of the evaluated variables of Guajillo chili

In the case of the comparison of means, only 11 of the 36 crosses with the highest yield and the nine parents

involved were taken (Table 3). In addition, it is observed that of the eight variables analyzed there were differences greater than 20% in the average of RFS, RFF, and NFP of the crosses with respect to the average of populations. While in the rest of the variables analyzed the differences were less than 10%. The increase in the yield of the RFS variable, it is considered very important because this type of chili is consumed dry, and it is also related to the increase in NFP.

In this case, only the populations P5 and P8 present statistical differences in the RFS, although all the populations present higher yields of 2 to 4 t ha-1, values above the national mean of 1.46 t ha^{-1}, except for population 8. The results of the highest yield are explained by the origin of the populations, because they come from collections that were selected for presenting higher yields.

Although there were only statistical differences between the P5 and P8, the P5 stands out along with the P4 and P7 for presenting higher yields in RFS, RFF and in the NFP. Such populations could be selected to be used as varieties *per se*.

Regarding the LF variable of the populations, they ranged from 11.16 for P6 to 13.54 for P4. The difference of these last three populations, with the rest, it may be because they come from the selection of fruits that were called Guajillo small fruit; while for the variables AP and LP they did not present statistical differences between the different populations.

For plant height (AP) it is observed that the crosses P1 x P9, P3 x P7 and P4 x P9 have a height greater than one meter and the rest ranges from 0.77 to 0.98 m. These results suggest that, for this type of chili, a higher plant height does not necessarily imply a higher fruit yield. In genetic improvement, plant height becomes relevant when considering the type of management to which it will be subjected; thus, compact and medium-sized plants are ideal for field cultivation, while tall plants or plants with undetermined growth habits will be optimal for greenhouse cultivation (Greenleaf, 1986; May et al., 2010).

With the cross P5 x P6 it was higher and the highest NFP (18.6) was obtained with respect to the populations and crosses, in the cross P2 x P5 I present the highest LF. Obtaining the highest PFF was possible with the crosses P2 x P5 (38.75 g) and P7 x P9 (38.54 g), regarding populations (Table 3).

The highest RFF is observed in the cross P4 x P9, which may be because it is one of the crosses with the highest NFP, LF and AP. However, despite the high RFF, a greater number of green fruits (CONV = 4.28) is required to obtain a ton of dried fruit; while P3 x P9 obtained the lowest RFF (11.13), an average of 15 fruits per plant

Table 3: Comparison of means of the populations and crosses of the Guajillo pepper of the evaluated variables

Population and crosses	RFS	CONV	RFF	PFF	PFS	NFP	LF	AP	LP
P1	2.74 a-d	4.44	12.17 a-d	37.29 ab	5.62 a	13.00 a-c	12.85 ab	93.75 ab	5.81 a-c
P2	2.64 a-d	4.92	12.99 a-d	33.96 ab	5.33 a	13.44 a-c	12.88 ab	93.94 ab	5.53 a-c
P3	3.02 a-d	3.41	10.31 a-d	30.84 ab	4.71 a	14.53 a-c	11.58 ab	89.69 ab	5.15 a-c
P4	3.85 a-d	3.74	14.40 a-d	32.71 ab	4.86 a	16.43 ab	13.54 ab	92.31 ab	5.94 a-c
P5	4.15 a	3.29	13.67 a-d	32.30 ab	4.92 a	15.75 a-c	11.22 b	85.75 ab	5.42 a-c
P6	2.99 a-d	3.75	11.23 a-d	30.63 ab	4.85 a	13.86 a-c	11.16 b	96.19 ab	4.98 c
P7	3.39 a-d	3.93	13.34 a-d	36.04 ab	5.15 a	13.45 a-c	13.16 ab	97.84 ab	5.96 a-c
P8	1.50 cd	4.68	7.02 cd	32.92 ab	4.56 a	8.50 bc	12.99 ab	83.50 ab	5.66 a-c
P9	2.31 a-d	4.54	10.51 a-d	34.79 ab	5.26 a	12.35 a-c	12.36 ab	94.56 ab	5.51 a-c
Mean	**2.95**	**4.08**	**11.74**	**33.50**	**5.02**	**13.48**	**12.42**	**91.95**	**5.55**
P1×P9	3.90 ab	3.7	14.44 a-d	36.04 ab	5.76 a	17.32 ab	13.19 ab	101.75 a	5.55 a-c
P3×P4	3.90 ab	4	15.62 ab	36.25 ab	6.01 a	17.00 ab	13.27 ab	97.00 ab	5.86 a-c
P4×P6	3.89 ab	3.2	12.48 a-d	35.00 ab	5.62 a	15.20 a-c	13.93 a	98.50 ab	6.00 a-c
P2×P6	3.82 ab	3.97	15.17 ab	34.58 ab	5.63 a	17.05 ab	12.87 ab	92.63 ab	5.28 a-c
P3×P5	3.79 ab	3.3	12.53 a-d	34.58 ab	5.46 a	15.28 a-c	13.45 ab	94.94 ab	5.04 bc
P4×P9	3.76 a-c	4.28	16.10 a	37.71 ab	6.02 a	16.83 ab	13.46 ab	101.00 ab	5.83 a-c
P5×P6	3.68 a-c	4.16	15.32 ab	28.54 b	4.59 a	18.60 a	12.65 ab	96.00 ab	5.52 a-c
P3×P9	3.60 a-c	3.09	11.13 a-d	32.30 ab	5.35 a	14.58 a-c	12.51 ab	88.06 ab	5.60 a-c
P3×P7	3.57 a-d	3.51	12.54 a-d	34.38 ab	5.43 a	14.10 a-c	12.77 ab	101.19ab	5.74 a-c
P2×P5	3.45 a-d	4.23	14.62 a-c	38.75 ab	5.86 a	15.70 a-c	13.86 a	98.25 ab	5.79 a-c
P7×P9	3.44 a-d	4.03	13.88 a-d	38.54 ab	6.06 a	15.70 a-c	13.20 ab	81.87 ab	5.50 a-c
Mean	**3.71**	**3.77**	**13.98**	**35.15**	**5.61**	**16.12**	**13.20**	**91.56**	**5.61**

[a]Means with different letters in a column are statistically different (Tukey P ≤ 0.05). RFS: Yield of dried fruit (t ha^{-1}); RFF: Yield of fresh fruit (t ha^{-1}); CONV: RFF to RFS conversion (t ha^{-1}); PFF: Average weight of fresh fruit (g); PFS: Average weight of dried fruit (g); NFP: Number of fruits per plant; LF: Fruit length (cm); AP: Plant height (cm); LP: length of pedicel (cm)

and less in LF and AP. The advantage of this cross over the others is that it requires fewer units of green fruit (CONV = 3.09) to provide a ton of dried fruit. Both P3 and P9 are small fruit Guajillo's and come from distant places, that is, Zacatecas and Guanajuato, respectively. In addition, it can be seen that in the crosses where P9 intervenes as a male, two of those crosses (P1 x P9, P4 x P9) have the highest PA and in the crosses (P3 x P9 and P7 x P9) they have the smallest plants height.

These results highlight that there is great variability between crosses and populations for the yield variables. Similarly, Do Nascimiento et al. (2014) in *C. annuum* and Patel et al. (2010) also reported coincident results regarding fruit length. According to Sitaresmi et al. (2016), showed that in the crosses they made, observed a higher weight of fruit per plant, as well as a greater number of fruits per plant, which shows the great advantages of obtaining genetic traits by crossing between populations of *Capsicum* spp.

Combinatorial capacity of the Guajillo pepper populations

The Table 4 shows that general combining ability is important for the selection of appropriate parents in hybridization, since it gives an idea if a particular population combines well in a cross (Nagaraju and Sreelathakumary, 2017). P5 showed a positive and significant value (P≤0.05) in GCA in the NFP variable (1.08 *), followed by P6 (0.97 *), while P8 (-1.94 ***) showed the lowest value, highly significant but negative, for the same variable. However, P5 in the PFF variable showed a negative effect on the GCA (-0.22), indicating that P5 produced a higher NFP but low weight. In contrast, P1 showed a highly significant positive value (P≤0.001) of GCA for the PFF variable, but a highly significant and negative effect on the NFP variable (-1.53 **), which indicates that said behavior is inverse since few fruits per plant were produced, but with greater weight.

The GCA values for the RFS variable (t ha-1), P5 was the best, followed by P4; while the one with the lowest GCA value was P8. These populations show positive and significant values of GCA in the variables RFF, LF and LP in P4, while P5 only in NFP (Table 4). P5 showed a significant difference in NFP, indicating that the plant had a good number of fruits and a PFF not very heavy, but that is reflected in the higher RFS t ha^{-1}. For P4, although it did not show significant differences in NFP, its PFF was also high, which was reflected in both RFF and RFS t ha^{-1}. For P4, although it did not show significant differences in NFP, its PFF was also high, which was reflected in both RFF and RFS t ha^{-1}.

Specific combining ability, heterosis and heterobeltiosis in Guajillo chili crosses

Specific combining ability (ACE) measures the specific behavior of each hybrid in relation to its corresponding parents and estimates the dominant genetic effects (Sprague and Tatum, 1942). Both heterosis and heterobeltiosis are biological phenomena that have aroused interest due to their importance in plant genetic improvement. The results of these phenomena are shown in Table 5, 6 and 7.

The significant SCA effects for RFF were presented in the 1x9 and 3x4 crosses, with 3.61, 2.55 (t ha^{-1}), in RFS, the crosses P1 x P9 (1.43) and P2 x P6 (0.83 t ha^{-1}) stood out (Table 5). The cross P1 x P9 (6.94%) presented the highest value, for the NFP variable (Table 6). Do Nascimiento et al. (2014) observed that in four of their parents they obtained the highest values for GCA, and their crosses had a higher ACE value, thus indicating that they can be selected with the objective of increasing the yield per plant and obtaining fruits with a greater amount of pulp, high content of dry and fresh biomass. For their part, Rohini and Lakshmanan, (2017), they selected six out of 30 crosses as the best hybrids, since they showed a high Heterobeltiosis, these crosses could be used for subsequent breeding programs.

The variables RFS and NFP showed the highest heterosis effects (54.46 and 36.65% respectively) and heterobeltiosis (42.34 and 33.2), at the cross P1 x P9 (Table 5 and 6).

Table 4: General combining ability (GCA) of nine populations of Guajillo chili

Pob.	RFS	RFF	PFF	PFS	NFP	LF	AF	AP	LP
P1	-0.31**	-0.80*	1.94***	0.30**	-1.53**	0.29*	-0.04	-0.54	0.20***
P2	-0.24*	0.22	0.73	0.12	-0.04	0.26*	0.17*	-0.35	-0.05
P3	0.12	-0.67	-1.34**	-0.15	0.49	-0.39**	0.12	0.03	-0.14*
P4	0.23*	1.19**	0.86	0.15	0.78	0.40**	0.11	0.8	0.14*
P5	0.33**	0.68	-0.22	-0.01	1.08*	-0.17	-0.19*	-0.49	-0.06
P6	0.21	0.07	-2.70***	-0.33***	0.97*	-0.52***	-0.11	2.29	-0.18**
P7	0.08	0.36	0.57	0.09	-0.04	0.17	-0.06	0.06	0.15**
P8	-0.53***	-1.38***	0.4	-0.13	-1.94***	0.2	0.04	-2.59*	0.05
P9	0.12	0.33	-0.24	-0.03	0.55	-0.24	-0.04	0.77	-0.12*

*, **, *** [a]Different from zero to a probability of 0.05, 0.01 and 0.001, respectively. Pop: Population; RFS: Yield of dried fruit (t ha^{-1}); RFF: Yield of fresh fruit (t ha^{-1}); PFF: Average weight of fresh fruit (g); PFS: Average weight of dried fruit (g); NFP: Number of fruits per plant; LF: Fruit length (cm); AF: Fruit width; AP: Plant height (cm); LP: length of pedicel (cm)

Table 5: Specific combining ability (SCA), percentage of heterosis (Hm) and heterobeltiosis (Hs) in the Guajillo chili crosses

CROSS	RFS			RFF			PFF			PFS		
	SCA	Hm %	Hs %	SCA	Hm %	Hs%	SCA	Hm %	Hs %	SCA	Hm %	Hs%
P1×P9	1.43***	54.46***	42.34**	3.61*	27.34*	18.65	-2.68	0	-3.35	-0.39	5.88	2.49
P2×P5	0.34	1.62	-16.87	1.18	9.68	6.95	3.02	16.96**	14.10*	0.30	14.34*	9.94
P2×P6	0.83*	35.70*	27.76*	2.34	25.27*	16.78	1.34	7.08	1.83	0.39	10.61	5.63
P3×P4	0.54	13.54	1.3	2.55*	26.43*	8.47	1.51	14.08*	10.82	0.56	25.60*	23.66**
P3×P5	0.32	5.72	-8.67	-0.03	4.5	-8.34	0.92	9.53	7.06	0.16	13.4	10.98
P3×P7	0.35	11.39	5.31	0.31	6.05	-6	-0.08	2.81	-4.61	0.04	10.14	5.44
P3×P9	0.12	35.08*	19.21	-1.97	6.92	5.9	-3.06	-1.57	-7.16	-0.37	7.32	1.71
P4×P6	0.43	13.74	1.04	-1.32	-2.61	-13.33	1.62	10.51	7.00	0.35	15.76*	15.64*
P4×P9	0.78	22.08	-2.34	1.51	29.27*	11.81	-2.36	11.73*	8.39	-0.46	18.97*	14.45*
P5×P6	0.12	3.08	-11.33	2.03	23.05*	12.07	-3.76*	-9.3	-11.64	-0.52	-6.04	-6.71
P7×P9	0.43	20.7	1.47	0.76	16.39	4.05	2.66	8.82	6.94	0.04	16.43*	15.21*

*, **, *** [a]Different from zero at a probability of 0.05, 0.01 and 0.001, resp. RFS: Yield of dried fruit (t ha^{-1}); RFF: Fresh fruit yield (t ha^{-1}); PFF: Average weight of fresh fruit (g); PFS: Average weight of dried fruit (g)

Table 6: Specific combining ability (SCA), percentage of heterosis (Hm) and heterobeltiosis (Hs) in the Guajillo chili crosses

CROSS	NFP			LF		
	SCA	Hm %	Hs %	SCA	Hm %	Hs %
P1×P9	6.94***	36.65*	33.2*	-0.64	4.67	2.67
P2×P5	1.27	7.57	-0.32	0.74	15.03***	7.66*
P2×P6	2.73	24.91	23.02	0.1	7.08	-0.06
P3×P4	2.02	9.82	3.47	0.24	5.67	-1.97
P3×P5	0	0.92	-2.98	0.98*	17.93***	16.12***
P3×P7	-0.05	0.79	-2.96	-0.03	3.22	-2.99
P3×P9	-0.32	8.48	0.34	-0.54	4.54	1.26
P4×P6	-0.26	0.36	-7.49	1.03*	12.78***	2.86
P4×P9	2.94	16.96	2.43	-0.01	3.93	-0.62
P5×P6	2.84	25.63*	18.1	0.32	13.07***	12.73**
P7×P9	1.31	21.71	16.73	0.05	3.48	0.3

*, **, *** [a]Different from zero at a probability of 0.05, 0.01 and 0.001, resp. NFP: Number of fruits per plant; LF: Length of fruits (cm)

Table 7: Specific combining ability (SCA), percentage of heterosis (Hm) and heterobeltiosis (Hs) in the Guajillo chili crosses

CROSS	AP			LP		
	SCA	Hm %	Hs %	SCA	Hm %	Hs %
P1×P9	10.96*	8.07	7.60	-0.34	-2.04	-4.62
P2×P5	6.4	9.36	4.59	0.30	5.88	4.83
P2×P6	-2.01	-2.56	-3.7	-0.09	0.57	-4.37
P3×P4	3.48	6.59	5.08	0.25	5.64	-1.44
P3×P5	2.71	8.23	5.85	-0.38*	-4.66	-7.04
P3×P7	8.40*	7.92	3.42	0.12	3.36	-3.7
P3×P9	-8.5	-4.41	-6.87	0.05	5.08	1.63
P4×P6	2.72	4.51	2.4	0.43*	9.84*	0.98
P4×P9	4.76	8.09	6.81	0.26	1.78	-1.93
P5×P6	1.51	5.53	-0.2	0.14	6.13	1.88
P7×P9	-6.62	-14.89**	-16.32***	-0.08	-4.01	-7.65*

*, **, *** [a]Different from zero at a probability of 0.05, 0.01 and 0.001, resp. AP: Plant height (cm); LP: Pedicel length (cm)

Therefore, these traits could be improved more efficiently by genetic improvement methods that exploit the effects of non-additive gene action, such as hybridization (May et al., 2010). Similar results were reported by Nagaraju and Sreelathakumary, (2017), in the Capsicum genus where the highest effect of ACE for NFP was registered in the CA-6xCA-23 cross, showing significant ACE effects for other characters such as plant height, fruit weight, green fruit yield per plant, fruit length, fruit diameter. For their part, Hernández-Pérez et al. (2011) also found similar results, where the best crosses were P6 x P16 and P4 x P6, the P1 x P118 cross showed high yields. For their part, Sitaresmi et al. (2020) report high heterosis for the IPB C8xIPB C19 cross for the weight of fruit per plant and the IPB C8xIPB C15 cross for the highest number of fruits per plant, in IPB C19 the best GCA was found for the weight of fruit per plant. Studies carried out by Medereiros et al. (2014) recorded higher values for SCA and in heterosis in the number of fruits per plant in the hybrids UENF 1616Xuenf1629 and UENF1616Xuenf1732.

The heterosis and heterobeltiosis with the highest value, for PFF is presented at the P2 x P5 cross and for the PFS variable at P3 x P4 (Table 5).

The effects of the ACE for the highest plant height were presented in the crosses P1 x P9 and P3 x P7, with values of 10.96 and 8.40 cm, respectively, the cross P2 x P5 (9.36) presented the highest value of Hm, also, with the cross P1 x P9 the highest value for heterobeltiosis was presented (7.60) (Table 7).

Regarding the effects of SCA for LF, the crosses that showed significant positive values were P3 x P5 (0.98) and P4 x P6 (1.03) (Table 6). For the LP, the crosses with the greatest significant and positive SCA effect correspond to the P4 x P6 cross (Table 7). Similar results were reported by Medereiros et al. (2014) in crosses of *Capsicum baccatum* var. *pendulum*, where they obtained the highest ACE values for the LF variable with the crosses UENF 1616 x UENF 1629 and UENF 1629 x UENF 1639, these authors also reported positive heterosis for most crosses for LF.

In the expression of heterosis the crosses that presented the highest and most positive values for the LF variable were P2 x P5, P3 x P5, P4 x P6 and P5 x P6 and in P5, while the crosses with the highest Hs for the same variable were P2 x P5, P3 x P5 and P5 x P6 with values of 7.66, 16.12 and 12.73% respectively (Table 6). These results are similar with those of Rao and Reddy, (2016), for the variables AP, LF, PF and fruit yield. Other similar results were observed by Nagaraju and Sreelathakumary, (2017), for the variables AP, LF, PF, NFP and. For the LP variable, the highest value of heterosis was in the cross P4 x P6 (9.84) and for heterobeltiosis, it was observed in the cross P2 x P5 (4.83). Similar results were reported by Patel et al. (2010), with a heterobeltiosis of 24.24% when crossing AVNPC-131 x acs-03-14. The estimate of heterosis showed that the number of crosses with heterosis was higher compared to heterobeltiosis for all variables. These results are similar with those of Bhutia et al. (2015), for AP, LF, RFP and NFP; Singh et al. (2012), for AP; and NFP; Patel et al. (2010), for LF.

In Mexico, several species of plants were domesticated, including that of chili, which has been one of the main crops of economic and cultural importance. Due to its importance, there is a need to generate new materials to supply the national and international market.

Heterosis can be extrapolated as the sum total of many physiological and phenotypic traits including vegetative growth rate Baranwal et al. (2012). Most parental inbred lines have a small number of upper alleles, high-yielding hybrid varieties have several; therefore, the accumulation of numerous rare superior alleles with positive dominance is an important contributor to heterotic phenomena (Huang et al., 2015). Heterosis as a genetic tool has an important role in crop yields and in many cases of commercial importance, such as tomato, watermelon, cabbage, cauliflower and cucumber (Vaishnav et al., 2009).

The populations used for the Guajillo pepper show significant differences for the yield variables, indicating their high divergence and ability to combine with each other, obtaining in this way a high SCA which can present a positive but significant impact on the fresh and dry fruit yield. Thus, it is possible to take advantage of such heterotic effects that will be fixed in subsequent generations, in addition, select the parents with good agronomic behavior of their hybrids (Méndez-Natera et al. (1997) in our study, the crosses P5 X P6 and P1 x P9 presented a greater number of fruits, giving high values for both heterosis in the first cross and heterosis and herobeltiosis in the second. Desired characteristics in the improvement of *Capsicum* is the length of the fruit and our results highlight a good behavior of the crosses for this character, which included the crosses: P3 x P5, P4 x P6, P5 x P6. The commercialization of this species of chili is dry, therefore, some of the crosses with high heterosis and heterobeltiosis values that stood out were; P1 x P9, P2 x P6 and P3 x P4.

The positive combination capacity of the populations to generate hybrids with favorable performance characteristics, indicates the predominance of the action of the additive gene in the inheritance for said variable. The action of an additive gene in inheritance has been observed in capsaicinoids in *C. pubescens* (Zewdie et al., 2001). Studies have suggested that hybridization is the most suitable breeding method for obtaining high yields and a greater number of fruits per plant in *C. annuum*, based on GCA and heterosis studies (May et al., 2010). Hybrids with good yield potential and fruit characteristics in Capsicum can be developed from the parents (Geleta and Labuschagne, 2004). Crossbreeding involving related distant relatives provides a broad spectrum of variability that ensures greater selection efficiency for better genotypes (Banerjee et al., 2007). Isolation of pure lines from heterotic F1 progenies is one possible way to improve fruit yield and chili quality (Khalil and Hatem, 2014). Studies carried out by Do Rêgo et al. (2011) also found positive values in the GCA and SCA related to the quality of the fruit of chili peppers (fruit weight, fruit width, fruit length and pericarp thickness). However, plant breeders require a more detailed scientific understanding of heredity or heritability potential for the expression of these traits of interest, to more effectively exploit parent lines and produce superior hybrids (Butcher et al., 2013). It has been observed in many cases that the best parent of the developed hybrid is inferior to the commercial varieties; therefore, a good selection of parents with better heterotic response should be carried out (Shrestha et al., 2011). The systemic approach to developing F1 hybrids in any crop depends mainly on the magnitude of the desirable heterosis (Sharma et al., 2013). New studies for the genetic improvement of the Capsicum genus suggest weighted correlation networks, to discover correlation structures and link patterns in morpho-agronomic characteristics Silva et al., (2016), which would help to increase the effectiveness in the selection of the genotype. In chili peppers for being a rich source of nutrients of utmost importance in the human diet and for preventing diseases such as cancer and cardiovascular diseases, it is necessary to increase the yield potential (Sood and Kumar, 2010).

Finally, hybrid development programs must be continuous so that the seeds are available to producers at an affordable cost (Chaudhary et al., 2013). Also, efforts should focus on the development of male sterility-based hybrids using cytoplasmic male sterile lines to minimize the cost of F1 seeds (Tembhurne and Rao, 2012). Also, the molecular

markers developed for mapping and assisted selection in the improvement of chili peppers should be used (Minamiyama et al., 2006; Ince et al., 2010), but also, *C. annuum* populations in Mexico are a valuable resource that must be conserved (Pacheco-Olvera et al., 2012). Future investigations of the Guajillo pepper of interest should include aspects such as the physiology of the seed, vigor, germination, volumetric weight of roots and resistance to biotic and abiotic stress.

CONCLUSIONS

The populations that presented the highest GCA for dry yield were P5 and P4 with 0.33 and 0.23 respectively, which makes them of great potential to be used as populations in Chili breeding programs. Populations were identified whose crosses originated plants with desirable characteristics mainly for RFS, RFF and NFP for both GCA, heterosis and heterobeltiosis (P1 x P9 and P2 x P6).

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Author´s contributions

Fanny Hernández-Mendoza conducted the greenhouse and field experiments, collected the data, performed the statistical analyses, and wrote her PhD dissertation based on this project. Tarsicio Corona-Torres directed the project, and review of the manuscript. Víctor García-Gaytán support in greenhouse experiment, editing and formatting of the manuscript. Irma Sanchez-Cabrera support in greenhouse experiment and laboratory. Víctor Heber Aguilar-Rincón collaborated in the project. Fernando Carlos Gómez-Merino collaborated in the project and review of the manuscript.

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