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IDENTIFICATION OF OUTSTANDING SALADETTE TOMATO LINES WITH A WIDENED GENETIC BASE

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ABSTRACT

The "bell pepper" or "chino criollo" tomato is a native Mexican variety with similar characteristics to the "Saladette" tomato and the potential to be used as a source of germplasm to generate commercial hybrids of this type. The aim of this investigation was to identify and select advanced lines with a wide genetic base, derived from crosses between Saladette tomatoes and native populations to generate free pollination varieties and potential parents of Saladette tomato hybrids. The hypothesis was that crosses between native populations and Saladette commercial hybrids generate outstanding offspring. The 103 genotypes evaluated included 10 native parents, three parents derived from commercial hybrids, one commercial hybrid control ("El Cid") and 89 S4 advanced lines. The evaluation was carried out in a greenhouse and hydroponics during the 2020 spring-summer cycle, using a randomized complete block experimental design with three replications and four plants per replication. The total weight and number of fruits were recorded based on the sum of the two cuts performed. The days to flowering of the first cluster, average fruit weight, and total soluble solids were also determined. Analyses of variance were carried out for each variable, as well as orthogonal contrasts and correlations between different combinations of the materials of interest. The comparison of means was carried out using Tukey's test ($p \leq 0.05$). Nine advanced lines with similar or greater characteristics to the control were identified and are recommended to be recombined genetically in a diallelic cross scheme to identify new outstanding offspring. The advanced line 2051 (LOR85 X C) was identified, with a similar yield to that reported for the control, which can be used as an open pollination variety since it has similar characteristics to the control "El Cid", but with native tomato genes.

Keywords: *Solanum lycopersicum*, horticulture breeding, wild tomato.

INTRODUCTION

Cultivated tomato has only 4.48 % of the variation found in its wild parents (Parra-Gómez *et al*., 2016; Miller and Tanksley, 1990). To obtain improved genetic material in the short term, intervarietal crosses between elite materials and native collections or

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local varieties can be used in order to take advantage of the wide genetic variability present in the native germplasm (Shah *et al*., 2015).

In Mexico, given the high price of commercial hybrid tomato seeds produced by foreign companies and scarcity of public research on this species, it is worth supporting national genetic breeding programs and using the potential of wild parents and native varieties. Examples of this include the potential use of rootstocks (Velasco-Alvarado *et al*., 2017) and the resistance to abiotic factors, pests, and diseases (Salas-Gómez *et al*., 2022), which require the collection, conservation, characterization, and evaluation of the germplasm (Bonilla-Barrientos *et al*., 2014; Flores-Hernández *et al*., 2017). These actions would contribute to the generation of varieties and hybrids with a larger number of clusters, fruits per cluster, and fruit size, as well as improved quality, accessibility for small- and medium-scale farmers, and competitiveness with those offered by the private sector.

The "bell pepper type" or "chino criollo" tomato is a native Mexican variety with similar characteristics to the "Saladette" tomato (Hernández-Bautista *et al*., 2014) and has the potential to be used as a source of germplasm to generate commercial hybrids (Bonilla-Barrientos *et al*., 2014). Vázquez-Martínez *et al*. (2016) observed that some crosses between lines derived from native "chino criollo" germplasm (referred to as "widened genetic base lines" in this study) and lines derived from commercial "Saladette" hybrids presented a high yield potential, equal to that of commercial hybrid controls, such as the cross LOR111 x R, which yielded 3624 g per plant, in contrast to the commercial control, which yielded 3452 g per plant. These authors found that heterosis values were high and positive in most variables, with the exception of days to flowering, which correlated negatively with yield. The greatest heterosis was obtained in the total weight of fruits and days to flowering.

According to Vázquez-Martínez *et al*. (2016), a nine-line derivation program began in segregating populations of the outstanding lines, which had 89 S4 lines. Based on the hypothesis that crosses between native populations and commercial Saladette hybrids generate outstanding offspring, the aim of this investigation was to identify and select advanced lines with a wide genetic base, derived from crosses between Saladette tomato and native "bell pepper" or "chino criollo" populations, to generate open pollination varieties and potential parents of Saladette tomato hybrids.

MATERIALS AND METHODS

Genetic material

A total of 103 genotypes were evaluated, including 10 native parents, three parents derived from commercial hybrids, one commercial control hybrid ("El Cid"), and 89 advanced S4 lines. The native parents were S9 lines derived from native "bell pepper" tomato (LOR-79, LOR-81, LOR-82, LOR-84, LOR-85, LOR-91, LOR-95, LOR-97, LOR-103, LOR-111). The parents derived from commercial hybrids were S9 "Saladette" lines derived from the commercial hybrids "Cuauhtémoc" (C), "Loreto" (L), and

“Reserva” (R). The 89 advanced S4 advanced lines came from crosses between both types of parents: 40 from LORs x C, 35 from LORs x L, and 14 LORs x R.

The native lines were generated by self-fertilization and individual selection (Bonilla-Barrientos *et al.*, 2014), whereas the “Saladette” lines were developed using the pedigree methodology (Hernández-Leal *et al.*, 2013). The native lines used in the crosses had a higher number of fruits, higher number of clusters, higher individual weight, and the highest fruit quality, whereas the “Saladette” lines provided characteristics of firmness, shape, and the characteristic color of the “Saladette” fruit. The combined outstanding characteristics of both germplasm groups were expected in the offspring. The evaluation was carried out in a greenhouse and hydroponics, during the 2020 spring-summer cycle in Montecillo, Texcoco, Mexico.

Experimental design and agronomic management

The genotypes were evaluated in a randomized complete block design, with three replications and four plants per replication. The plants were handled in a single stem and guided with raffia thread. The plants were established on May 23, 2020 and transplanted 30 days later in polyethylene bags (40 x 40 cm) filled with red *tezontle* volcanic rock as a substrate. The nutrient solution proposed by Steiner (1984) was used throughout the entire crop cycle. The concentration was 50 % in the vegetative state and increased to 100% during the flowering and fructification stages (Pérez-Díaz *et al.*, 2020).

The pH of the solution was kept between 5.5 and 6.0. The following fungicides and pesticides were applied in the doses recommended by the manufacturer: Captan® and Cupravit® to prevent gray leaf spot (*Stemphylium solani*), early blight (*Alternaria solani*), late blight (*Phytophora infestans*); Confidor® and Ampligo® to control whitefly (*Bemisia tabaci gennadius, Hemiptera aleyrodidae*) and potato psyllid (*Bactericera cockerelli*) populations. During the flowering period, the guide threads were shaken to promote self-fertilization. Fruits were harvested by hand, plant by plant, in two cuts on days 143 and 170 after transplanting.

Variables

The total weight of fruits (TWF in kg) and total number of fruits per plant (TNF), based on the sum of two cuts performed, were recorded, as well as the days to flowering of the first cluster (DFC1) of the two earliest plants. Additionally, the average weight of fruits (AWF, g) and total soluble solids (TSS, °Bx) were measured in two fruits per plant of the first cut.

Statistical analysis

For each variable, analyses of variance, orthogonal contrasts and correlations were carried out among diverse combinations of the materials of interests. The comparison of means was carried out using Tukey’s test ($p \leq 0.05$) and the statistical analyses, using the Statistical Analysis System program, v.9.0 (SAS Institute, 2002).

RESULTS AND DISCUSSION

Analysis of variance

All variables and sources of variation were significant, except for soluble solids among genotypes and soluble solids among advanced lines plus the control (Table 1). These results show that there is a wide genetic variability in yield and its components among genotypes, which was mostly attributed to the genetic diversity among them due to their diverse sources of germplasm. In similar papers, several authors observed similar results that coincide with those obtained in this investigation (Maldonado-Peralta *et al.*, 2016; Marín-Montes *et al.*, 2016).

Table 1. Mean squares of fruit yield and quality variables in Saladette tomato genotypes with a widened genetic base and a commercial control.

SV	DF	TWF	TNF	DFC1	AWF	TSS
Repetition	2	15.83[þ]	355.30[þ]	1.64 *n.s.*	632.25[§]	15.58[þ]
Genotypes	102	0.88[þ]	184.35[þ]	74.19[þ]	1458.57[þ]	1.11 *n.s.*
Parents[†]	13	1.39[þ]	328.10[þ]	114.05[þ]	3171.89[þ]	0.80[þ]
Lines[¶]	89	0.83[þ]	163.49[þ]	68.13[þ]	1040.86[þ]	1.16 *n.s.*
Error	204	0.17	31.01	4.75	157.01	1.25
C.V. (%)		12	12	4	10	20

[†]Parents plus control; [¶]advanced lines plus control; SV: source of variation; DF: degrees of freedom; TWF: total weight of fruits per plant; TNF: total number of fruits per plant; DFC1: days to flowering of first cluster; AWF: average weight of fruits; TSS: total soluble solids; C.V.: coefficient of variation; [§]$p \leq 0.05$ and [þ]$p \leq 0.01$; *n.s.*: not significant.

When comparing the effects of the source of variation of the advanced lines depending on the male parent involved in the initial cross (L, R, or C), differences were found for most of the variables among the three groups of offspring (Table 2).

Table 2. Means squares of fruit yield and quality variables for advanced lines from crosses LOR × C, LOR x L, and LOR x R.

SV	DF	TWF	TNF	DFC1	AWF	TSS
Repetition	2	15.83[§]	355.30[§]	1.64 *n.s.*	632.25[¶]	15.58[§]
Lines[†]	89	0.83[§]	163.49[§]	68.13[§]	1040.86[§]	1.16 *n.s.*
LOR x C	40	1.02[§]	182.00[§]	59.50[§]	1070.94[§]	1.01 *n.s.*
LOR x L	35	0.62[§]	123.76[§]	73.35[§]	1051.05[§]	1.03[§]
LOR x R	14	1.22[§]	139.49[§]	36.28[§]	756.20[§]	1.41 *n.s.*
Error		0.18	26.95	4.03	165.67	1.18
C.V. (%)		12	11	3	11	20

[†]Advanced lines plus control; SV: source of variation; DF: degrees of freedom; TWF: total weight of fruits per plant; TNF: total number of fruits per plant; DFC1: days to flowering of first cluster; AWF: average weight of fruits; TSS: total soluble solids; C.V: coefficient of variation; [¶]$p \leq 0.05$ and [§]$p \leq 0.01$; *n.s.*: not significant.

Orthogonal contrasts

The contrasts LOR × C vs. LOR × L and LOR × L vs. LOR × R (Table 3) were found to be significant for DFC1, with measurements of 58, 62, and 59 days for groups LOR × C, LOR × L, and LOR × R (Table 4). These results are similar to those of Ríos-Osorio *et al*. (2014), who observed an average of 57.45 days to the start of flowering after planting in 57 collections of ruderal or semidomesticated tomato evaluated during the spring in Oaxaca, Mexico. The DFC1 variable helps the farmer visualize the approximate time to harvest the first fruits and to classify tomato genotypes as early, intermediate, and late. Some authors report that, the greater the earliness, the lower the individual and total weight of fruits will be. Bonilla-Barrientos *et al.* (2014) observed that "squared" materials displayed an average individual weight of 81.25 g and a late flowering of 109.75 days to flowering in the third cluster, in contrast with kidney-shaped genotypes,

Table 3. Means squares of the orthogonal contrasts in the fruit yield and quality variables in three groups of advanced lines and control.

Contrasts	DF	TWF	TNF	DFC1	AWF	TSS
LOR x C vs. LOR x L	1	0.05 *n.s.*	374.41†	734.90¶	151.41 *n.s.*	4.28 *n.s.*
LOR x C vs. LOR x R	1	0.01 *n.s.*	1281.91¶	45.07 *n.s.*	2624.55 *n.s.*	8.30¶
LOR x L vs. LOR x R	1	0.06 *n.s.*	440.83¶	175.55¶	1705.76†	1.73 *n.s.*
LOR x C vs. Control	1	3.03¶	330.93†	24.47 *n.s.*	217.60 *n.s.*	2.74 *n.s.*
LOR x L vs. Control	1	2.83¶	188.90 *n.s.*	123.77†	142.02 *n.s.*	1.39 *n.s.*
LOR x R vs. Control	1	2.97†	49.73 *n.s.*	46.96 *n.s.*	0.88 *n.s.*	0.57 *n.s.*

C: Cuauhtémoc; L: Loreto; R: Reserva; DF: degrees of freedom; TWF: total weight of fruits per plant; TNF: total number of fruits per plant; DFC1: days to flowering of first cluster; AWF: average weight of fruits; TSS: total soluble solids; †$p \leq 0.05$ and ¶$p \leq 0.01$; *n.s.*: not significant.

Table 4. Comparison of means of the parent groups and the control for fruit yield and agronomic quality variables.

Genotype	TWF (kg)	TFN	DFC1 (days)	AWF (g)	TSS (°Bx)
LOR x C	3.453 b	47 b	58 ab	122.89 a	5.53 a
LOR x L	3.485 b	49 ab	62 a	121.24 a	5.25 a
LOR x R	3.440 b	53 ab	59 ab	113.70 a	5.01 a
El Cid	4.470 a	57 a	55 b	114.26 a	4.56 a
HSD	0.70	9.19	5.33	23.80	1.20

Genotypes with different letters in each column indicate a significant statistical variation (Tukey, $p \leq 0.05$). C: Cuauhtémoc; L: Loreto; R: Reserva; TWF: total weight of fruits per plant; TNF: total number of fruits per plant; DFC1: days to flowering of first cluster; AWF: average weight of fruits; TSS: total soluble solids; HSD: honest significant difference. DFC1 average of the two earliest plants, AWF and TSS represent the average of two fruits in first cut.

which presented a mean of 94.32 days to flowering in the third cluster and an average individual weight of 33.32 g.

Contrasts between LOR x C vs. LOR x L, LOR x C vs. LOR x R, and LOR x L vs. LOR x R were significant in the total number of fruits per plant (Table 3), with means of 47, 49, and 53, respectively (Table 4). In the contrasts between LOR x C, LOR x L, LOR x R vs. control, differences were observed for the total weight of fruits. The populations of advanced lines averaged 3.453, 3.485, and 3.440 kg per plant, in comparison to the 4.470 kg per plant of the control. This superiority of "El Cid" is attributed to the rigorous breeding process, in which commercial varieties are hybrids that capitalize on the favorable heterotic characteristics, including yield. However, Maldonado-Peralta *et al*. (2016) noted attributes of some native varieties, such as the recovery of vegetation after a hailstorm in open fields, a higher average weight of fruits, and a higher content of soluble solids, which indicates a higher quality due to the greater quantity of antioxidants present in the fruit, in comparison with commercial hybrids.

Means comparison of advanced lines

At least nine advanced lines matched the commercial hybrid "El Cid" in terms of fruit yield, flowering characteristics, and fruit quality (Table 5). Genotype 2051 produced the highest yield, surpassing the commercial hybrid despite having a lower number of total fruits. These results confirm the potential for high yield of the new advanced lines, particularly those from initial crosses with the commercial hybrid Cuauhtémoc. Vázquez-Martínez *et al*. (2016) found that the best initial crosses for the total weight of fruits involved native parents LOR111, LOR81, LOR79, LOR84, and LOR103 with commercial parents R and C. This study shows that the yields of the outstanding

Table 5. Means of the agronomic characteristics of ten high-yielding Saladette tomato genotypes.

Genotype	Origin	TWF (kg)	TNF	DFC1 (days)	AWF (g)	TSS (°Bx)
2051	LOR85**x**C	4.525 a	47 b-o	55 j	132.15 b-r	5.25 a
20103	EL CID	4.470 ab	57 a-l	55 j	114.26 d-u	4.56 a
2019	LOR85xL	4.280 ac	52 a-o	56 h-j	118.68 b-u	4.69 a
2054	LOR91**x**C	4.269 a-d	56 a-m	55 j	117.57 b-u	4.60 a
2069	LOR81xC	4.243 a-d	55 a-m	55 j	121.63 b-t	5.57 a
2096	LOR103xR	4.187 a-e	56 a-m	56 hj	135.10 b-q	5.40 a
2061	LOR95xC	4.185 a-e	60 a-i	55 j	108.01 l-u	5.16 a
2015	LOR85xL	4.160 a-f	42 i-p	68 a	152.27 b-l	5.11 a
2080	LOR82xC	4.106 a-g	52 a-o	55 ij	124.64 b-s	5.29 a
2071	LOR81xC	4.093 a-g	61 a-g	56 hj	128.95 b-r	5.34 a
HSD		1.48	19.98	7.8	44.97	3.7

Genotypes with the same letter in each column are statistically equal (Tukey, $p \leq 0.05$). C: Cuauhtémoc; L: Loreto; R: Reserva; TWF: total weight of fruits per plant; TNF: total number of fruits per plant; DFC1: days to flowering of first cluster; AWF: average weight of fruits; TSS: total soluble solids; HSD: honest significant difference. DFC1 average of the two earliest plants, AWF and TSS represent the average of two fruits in first cut.

advanced lines involved the same commercial parents. However, three of those nine lines are from LOR85, indicating that it is a native parent that combines favorably with the parents from commercial hybrids. It is therefore recommended to recombine these nine advanced lines in a diallel cross scheme to identify new outstanding offspring. Although the aims of this study did not include the evaluation of the general combining ability of the lines, it was evident that the parent Cuauhtémoc (Table 5) displayed a positive interaction with native genotypes. Therefore, the use of the advanced lines derived from the hybrid Cuauhtémoc as a parent in new crosses and backcrosses is proposed.

Regarding the ten genotypes with the lowest yields (1.610 and 2.683 kg per plant), 40 % came from parent LOR97 and its crosses with lines derived from Loreto and Cuauhtémoc (Table 6). However, its total amount of fruits and total solids in most cases are found in the same statistical group as "El Cid", indicating a positive result in the selection of advanced lines.

In relation to DFR1, the 89 advanced lines behaved similarly to the commercial control, with flowering times ranging from 55 to 68 days from planting. This indicates that the first flower emergence was recorded on day 26 after transplanting, which is apparently earlier than what was observed by Vázquez-Martínez *et al*. (2016), who recorded the beginning of flowering on day 76 after planting, i.e., 34 days after transplanting, in the F_2 that generated the current advanced lines. This is mainly attributed to the differences in planting dates and locations (Carrillo-Rodríguez *et al*., 2013) between studies, as both cases included the hybrid "El Cid" as a control, with the genotypes

Table 6. Means of the agronomic characteristics of ten low-yield advanced Saladette tomato lines and of the commercial control.

Genotype	Origin	TWF (kg)	TNF	DFC¤ (days)	AWF (g)	TSS (°Bx)
20103	EL CID	4.470 ab	57 a-l	55 j	114.26 d-u	4.56 a
2088	LOR97 x C	2.683 f-m	38 l-p	66 ac	103.96 n-v	5.24 a
2076	LOR79 x C	2.683 f-m	41 h-p	66 a-d	123.46 b-s	6.42 a
2006	LOR95	2.650 g-m	50 b-o	66 ac	142.69 b-o	6.07 a
2064	LOR103 x C	2.560 h-m	38 k-p	55 j	126.77 b-s	5.32 a
2068	LOR103 x C	2.567 i-m	36 m-p	56 hj	112.56 h-u	6.02 a
2047	LOR97 x L	2.524 i-m	44 d-p	68 a	115.65 b-u	6.85 a
2050	LOR85 x C	2.404 j-m	44 d-p	55 j	99.63 o-w	5.19 a
2087	LOR97 x C	1940 k-m	64 a-c	57 e-j	58.48 w	6.86 a
2090	LOR91 x R	1.754 l-m	38 k-p	66 a-d	78.00 t-w	6.52 a
2013	LOR97	1.610 m	71 a	55 j	63.01 v-w	6.01 a
HSD		1.49	19.99	7.82	44.97	3.78

Genotypes with different letter in each column indicate significant statistical variation (Tukey, $p \leq 0.05$). C: Cuauhtémoc; L: Loreto; R: Reserva; PTF: total weight of fruits per plant; TNF: total number of fruits per plant; DFC1: days to flowering of first cluster; AWF: average weight of fruits; TSS: total soluble solids; HSD: honest significant difference. DFC1 average of the two earliest plants, AWF and TSS represent the average of two fruits in first cut.

flowering similarly to the control. This means that during the selection and formation process of the materials, the earliness was not modified.

Correlations

The correlations between total yield (TWF) and its components varied by offspring group. In the advanced lines derived from the crosses LOR Cuauhtémoc, LOR x Loreto, and LOR x Reserva, the correlation between PTF and NTF was r = 0.46, 0.27, and 0.68 ($p \leq 0.01$). The correlation between TWF and AWF existed in the group of lines from LOR x Loreto (r = 0.31; $p \leq 0.05$) and LOR x Reserva (r = 0.33; $p \leq 0.05$); these results are similar to those obtained by Parra-Gómez *et al*. (2016) for the variable of fruit yield per plant in relation to the average weight of fruits (r = 0.57), and by Monge-Pérez and Loía-Coto (2021), who reported a positive correlation for yield in regard to the average weight of fruits (r = 0.59; $p \leq 0.01$).

As expected, the average weight of fruits displayed a correlation with the total number of fruits in the groups LOR x Cuauhtémoc (r = -0.48; $p \leq 0.01$) and LOR x Loreto (r = -0.59; $p \leq 0.01$). Monge-Pérez and Loía-Coto (2019) associated the total number of fruits and fruit weight and noticed that as the number of fruits rises, the average weight of fruits decreased as a consequence of a greater partition of photoassimilates per cluster. León-Burgos *et al*. (2021) recommend thinning fruits in order to obtain a higher-quality fruit, since it is the organ that imports between 50 and 90 % of the production of photoassimilates from source organs. The correlations are consistent with the means of the highest-yielding genotypes. The nine advanced lines derived from crosses of LOR x Cuauhtémoc, LOR x Loreto, and LOR x Reserva were observed to be outstanding, at the same rate as the commercial control "El Cid", since they resulted statistically equal in all variables, with the exception of DFR1, a variable in which eight of the nine advanced lines were clustered, along with "El Cid".

The correlation results suggest that in the LOR x Cuauhtémoc offspring group, the germplasm selection must focus on materials with early flowerings, similar to the control, with a higher total number of fruits to increase total weight, and a fruit weight ranging between 114–132 g (Table 5). The selection of lines with the highest number of fruits will not imply a reduction in the total content of soluble solids, given the low correlation values found between the number of fruits and the content of soluble solids in the LOR x Cuauhtémoc group. Therefore, the advancement or consideration of such lines within a block of crosses is a valuable opportunity to obtain hybrids with a higher nutraceutical value than those found in the market nowadays.

As for the correlation (r = -0.35; $p \leq 0.01$) of total soluble solids and average weight of fruits, Monge-Pérez and Loía-Coto (2019) also found a negative correlation (r = -0.72) in 63 genotypes. As the fruit weight is reduced, the percentage of soluble solids increases. Parra-Gómez *et al*. (2016) observed that the variables positively related with yield (TWF) influence the concentration of total soluble solids (r = -0.38). Gabriel *et al*. (2016) reported a high and negative correlation between total soluble solids and weight in the Corleone pear variety, with lower weights indicating a higher content of total soluble solids.

Concerning the offspring derived from the LOR x Loreto crosses, we propose that selection focus on later plants with values closer to the control, while maintaining the average weight of fruits. On the other hand, the advancement of plants with a higher number of total fruits implies an increase in total weight but a moderate reduction in the average weight of fruit. To solve this situation, identifying recombinant individuals between both variables will aid in the selection of plants with higher numbers of fruits and a higher average weight of fruits.

Regarding the offspring generated from crosses LOR x Reserva, the plants that displayed early flowering in the first cluster increased their total amounts of fruits, average weight of fruits, and total weight of fruits. These results are similar to the correlations reported by Hernández-Bautista *et al*. (2016), who found a positive effect in early flowering in regard to the average weight of fruits and final yield.

CONCLUSIONS

Genotypes 2051, 2019, 2054, 2069, 2096, 2061, 2015, 2080, and 2071 were identified as advanced lines with similar characteristics to the control, out of which the advanced lines with origins LOR85 x C, LOR85 x L, LOR91 x C stood out. Genotype 2051 ($LOR85_xC$) is a potential open pollination tomato variety, since it displays similar characteristics to the control "El Cid", but with native tomato genes.

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