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Agronomic performance of native Mexican tomato (*Solanum lycopersicum* L.) populations, grown under two growing systems.

Comportamiento agronómico de poblaciones mexicanas de tomate (*Solanum lycopersicum L.*) nativo bajo dos sistemas de producción.

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ABSTRACT

The environmental diversity of Mexico has allowed the development of different native and cultivated forms of tomato. This work was carried out with the objective of evaluating the agronomic quality of 23 Mexican native tomato populations and two commercial hybrids as control, established under greenhouse and open field conditions. This research was established at the Colegio de Postgraduados, Campus Montecillo, Texcoco, State of Mexico, from February to June 2018. The native tomato populations were obtained from central and southern Mexico; agronomic variables and fruit quality were evaluated. The results show that the tomato populations were more affected by the population factor, in the variables: number of fruits, polar and equatorial diameter, and number of locules; the environment produced the greatest effect on plant height, number of leaves, fruit weight, yield and pericarp thickness. It should be noted that under protected and open field conditions the native G3 genotype generated the highest fruit yield, with 4.4 kg/plant in the greenhouse and 2.8 kg/plant in the field. The average fruit yield in the greenhouse was 131 % higher compared to that in the open field. In conclusion, it was possible to observe that the genotype Guerrero 3 evaluated in protected conditions presented a higher fruit yield with respect to the control. In the greenhouse, its weight and fruit yield increased by 200 and 130 %, respectively, compared to the field. These results show that some native materials could be exploited in a better way under a greenhouse and others in the open field.

KEY WORDS: Native tomato, environment, greenhouse, open field, yield.

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RESUMEN

La diversidad ambiental de México ha permitido el desarrollo de diferentes formas nativas y cultivadas de tomate. Este trabajo se realizó con el objetivo de evaluar la calidad agronómica de 23 poblaciones mexicanas de tomate nativo y dos híbridos comerciales como testigo, establecida en condiciones de invernadero y campo abierto. Esta investigación se estableció en el Colegio de Postgraduados, Campus Montecillo, Texcoco, Estado de México, de febrero a junio de 2018. Las poblaciones nativas de tomate fueron obtenidas del centro y sur de México; se evaluaron variables agronómicas y calidad de fruta. Los resultados muestran que las poblaciones de tomate fueron más afectadas por el factor población, en las variables: número de frutos, diámetro polar y ecuatorial, y número de lóculos; el ambiente produjo el mayor efecto en altura de planta, número de hojas, peso de fruto, rendimiento y grosor de pericarpio. Cabe destacar que bajo condiciones protegidas y de campo abierto el genotipo nativo G3 generó el mayor rendimiento de frutos, con 4.4 kg/planta en invernadero y 2.8 kg/planta en campo. El rendimiento promedio de fruto en invernadero fue mayor en un 131 % comparado con el de campo abierto. En conclusión, se pudo observar que el genotipo Guerrero 3 evaluado en condiciones protegidas presentó un rendimiento mayor de fruta con respecto al testigo. En invernadero se incrementó su peso y rendimiento de fruto en 200 y 130 %, respectivamente con respecto a campo. Estos resultados demuestran que algunos materiales nativos pudieran ser explotados de mejor forma bajo invernadero y otros en campo abierto.

PALABRAS CLAVE: Tomate nativo, ambiente, invernadero, campo abierto, rendimiento.

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the three most important vegetables grown in the world (Hernández *et al*., 2014; Calero *et al*., 2019), with China being the main producer with 34% of the total production (FOASTAT, 2021). The United States is the main importer of tomatoes and Mexico is the main exporter of this vegetable, allocating 99.7 % of its exports to that market. (SIAP, 2020). Per capita consumption in the world in 2021 was 22 kg/year/inhabitant, and these quantities have been increasing in 2020, consumption in Mexico was 13 kg/year/inhabitant (SADER, 2022).

Tomato is the most important vegetable at the national level due to its wide consumption, the harvested area, and the economic value of production (Abera *et al*., 2020). Cultivation in the open field has decreased, while cultivation under cover has increased, largely due to the fact that tomato production under the latter system (shade net or greenhouse) has brought an increase in yield per unit area; in fact, tomato cultivation in the open field is becoming increasingly difficult due to adverse environmental conditions such as frost, rain, hail, dew and

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the incidence of pests and diseases (Gatahi, 2020; Juárez-López *et al*., 2012a). On the other hand, high levels of quality, food safety, and product certification are achieved under protected conditions (Bojacá *et al*., 2009).

Native species have developed tolerance to adverse conditions, which has allowed them to gain different traits to face biotic and abiotic threats, with the environment being one of the factors that most influence biological variability (Álvarez-Hernández *et al*., 2009; Sanjuan-Lara *et al*., 2014). A decrease in genetic variation in modern tomato cultivars has limited crop improvement (Fridman *et al*., 2000; Bai & Lindhout, 2007). The diversity available in wild relatives can be used to improve traits of interest; for example, the sensory traits of cherry tomatoes could be used to generate hybrids (Lecomte *et al*., 2004; Salgado-Meraz *et al*., 2018).

It is worth mentioning that there are fundamental studies evaluating native tomato species in different states of the country (Estrada-Castellanos *et al*., 2011; Ríos-Osorio *et al*., 2014; Sanjuan-Lara *et al*., 2014; Maldonado-Peralta *et al*., 2016); however, there are not reports comparing the adaptability of native tomato to a production system under cover for marketing purposes, since this genetic resource continues to maintain a wide use being found in local markets in different regions of Mexico (Bonilla-Barrientos *et al*., 2014; Magdaleno-Hernández *et al*., 2016). The hypothesis of this research was that there are tomato landraces that could be adapted to an intensive production system under cover while maintaining their fruit quality features. Hence, the present research was carried out with the aim of evaluating the agronomic performance of 23 Mexican populations of native tomatoes and two commercial hybrids as a control, established under greenhouse and open field conditions.

Material and Methods

Location of the study area

The experiment was conducted at the Colegio de Postgraduados Campus Montecillo, Texcoco, Estado de Mexico, located at 19° 29’ N, 98° 53’ W, and at an altitude of 2,240 masl. The average annual temperature is 15.2 °C, and the climate is temperate subhumid, with rainfall in summer and an average annual rainfall of 636.5 mm (García, 2004).

Genetic material

The native tomato (*Solanum lycopersicon* L.) came from the states of Campeche (C1, C2, C3, and C4), Estado de México (M1 and M2), Guerrero (G1, G2, and G3), Oaxaca (O1, O2, O3, O4, and O5), Puebla (P1, P2, P3, P4, P5, and P6), Yucatán (Y1 and Y2) and Veracruz (V1), all collected by Dr. Porfirio Ramírez Vallejo†; as a result of the Integral Evaluation Project of the Diversity of Native Populations of Mexican Tomato (CONACYT), in the Postgraduate Program in Genetic Resources and Productivity, Colegio de Postgraduados. It is worth mentioning that these tomatoes were preserved by the producers since they are sold in local and regional markets in Mexico (Figure 1).

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The crop was established from February to June 2018 under greenhouse and open field conditions, where 23 populations of native tomatoes with indeterminate growth habits were evaluated and the commercial hybrids El Cid and Reserva (Harris Moran® and Nunhems®, Saladette type), referred to as H1 and H2 in this study, were used as controls.

Figure 1. Different shapes and sizes of Mexican populations of native tomatoes represent the place of collection.

Conduct of the experiment

Sowing was carried out in germination trays with 200 cavities using peat-moss® as a substrate and under a controlled environment. 40 days after germination, the transplanting was carried out in the greenhouse and field.

In the greenhouse, transplanting was made in black polyethylene bags with a capacity of 10 liters, with red tezontle seal type, as a substrate (diameter ≤ 12 mm), at a density of

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6 plants/m^2. Plants were fertilized with Steiner nutrient solution at 100 % (Steiner, 1984), with a pH of 5.5 and Electrical Conductivity of 1.0 to 2.5 dsm^{-1}, throughout the development and production cycle. Irrigation was determined based on information from Flores *et al*. (2007), who report that this crop in the initial stage consumes 0.2 L d^{-1} of water per plant, and in the adult stage 1.5 L d^{-1}, as maximum water demand. During the development of the crop, the following activities were carried out: tutoring, pruning of shoots, leaves, and fruits, a stem was handled, and insecticides and fungicides were applied.

In the open field, the transplant was carried out in previously prepared soil, in lines 1.2 m apart, and using a density of 3 plants/m^2. In each furrow, reed stakes were placed at 2 m intervals; the plants were supported on both sides during their growth with polypropylene raffia yarn. All stems per plant were left and the lower leaves were removed. Agronomic management practices such as irrigation, fertilization, and agrochemical application were performed according to the recommendations of León & Arozamena (1980).

Response variables

The agronomic variables taken in the greenhouse and in the field were evaluated from 150 days after transplanting, during the crop cycle, in all treatments; they were: 1) plant height, was determined with a flexometer and measured from the base of the plant to the apex; 2) the number of leaves, the number of leaves per plant was counted; 3) the number of fruits per plant, counted in each sampling; 4) weight per fruit (g), with the total weight of fruits between the total number of fruits; 5) were calculated, while the fruit yield (kg), was taken in the fruits collected per cutting, whose weights were added to obtain the total sum.

Harvesting in the field and in the greenhouse started after 100 days. To obtain the quality variables, four fruits were randomly selected and measured for 1) polar and 2) equatorial diameter (mm), using a digital vernier (Truper® brand) to measure from pole to pole and at the equator of the fruit, respectively; 3) the number of locules, for counting fruits were transversely cut 4) total soluble solids (TSS) content, measured in three drops of fruit juice placed on the cell of a digital refractometer ATAGO PR-100® (Japan), expressed in percentage (AOAC, 2012) and 5) pericarp thickness (mm), measured with a Vernier on the same slice fruit

Statistical Analysis

For the analysis of the data of the agronomic and fruit variables, a statistical analysis was used according to the experimental design in complete random blocks with a factorial arrangement 25 X 2 (25 genotypes*2 environments); An analysis of variance was performed using the following statistical model:

$$y_{ijk} = \beta_k(S_j) + P_i + S_j + P * S_{ij} + E_{ijk}$$

where: Y_{ijk} value of the response variable corresponding to population $_i$ in production system j into block k; μ = overall mean, β_k=effect of block k nested in production system j;

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P_i = effect of population i; S_j =effect of production system j; PS_{ij} = population by production system interaction; E_{ij} k= experimental error.

Finally, a comparison of means using Tukey´s test ($p \leq 0.05$) was employed for the factors and interaction, computed in the statistical package SAS® 9.0 (SAS Institute 2009).

Results

With the exception of the variable locule number, the results in Tables 1 and 2 showed that most of the variables were significantly different ($p \leq 0.05$) for the factors: population (Pob), production system (Sis), and the Pob x Sis interaction, demonstrating the presence of a significant genetic variation within the total population, a different agronomic behavior of the populations between the two production systems evaluated and a different efficiency of the production systems among the variables. However, the proportion of genetic effect or environmental effect differed between variables. Among the agronomic variables (Table 1), the number of fruits per plant varied mainly due to the effect of the Pob factor, with a proportion of 55 % with respect to the total variation of the treatments. In contrast, the Sis factor accumulated a greater proportion of the variation in the agronomic variables, plant height (61 %), number of leaves (81 %), weight per fruit (64 %), and yield (57 %). For these variables, the Pob x Sis interaction showed significant effects, with proportions of variation ranging from 9 to 38 %, which shows that not all populations respond to the same production system. This suggests that the behavior of the populations is highly dependent on the conditions they receive, as shown by the variable number of fruits and yield.

The fruit quality variables (Table 2) mainly influenced by the Pob factor were: polar diameter (42 %), equatorial diameter (43 %), and locule number (93%). Whereas, pericarp thickness (49 %), equatorial diameter (49 %), and TSS (43 %) showed a greater effect caused by the Sis factor. The interaction Pob x Sis was also significant for all variables, but with small magnitudes, ranging from 7 to 30 %.

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Table 1. Mean squares of the agronomic variables measured in native tomato plants grown in greenhouses and in the field.

SV	DF	Plant height (m)	Number of Leaves	Number fruit	Fruit weight (g)	Yield (kg/plant)
Treatments	53	16.3**	1077468**	17034**	344030**	206.8**
Pob(Block)	4	0.1NS(0)	44NS(0)	20NS(0)	39NS(0)	0.1*(0)
Pob	24	4.0**(25)	107401**(10)	9307**(55)	79365**(23)	50.9**(25)
Sis	1	9.9**(61)	873024**(81)	1206** (7)	218989**(64)	111.9**(54)
PobXSis	24	2.3**(14)	96999**(9)	6501**(38)	45637**(13)	43.9**(21)
Error	96	0.7	762	175	462	0.4
Total	149	17.0	1078230	17209	344492	207.2

**: Statistical significance ($p \leq 0.05$); NS: not significant; SV: sources of variation; DF: degrees of freedom; Pob: Population, Sis: System, PobXSis: PopulationXSystem. The proportion of the mean squares of each factor (Pob, Sis, and PobXSis) in the total sum of the mean squares for each variable is indicated within brackets.

Table 2. Mean squares of the fruit quality variables of native tomato plants grown in greenhouses and in the field.

SV	DF	Polar diameter (cm)	Equatorial diameter (cm)	Locule number	TSS (%)	Pericarp thickness (mm)
Treatment	53	23033**	23000**	1156**	64**	809**
Pob(Block)	4	8NS(0)	10NS(0)	2NS(0)	0NS(0)	0*(0)
Pob	24	9602**(42)	9968**(43)	1071**(93)	23**(36)	272**(34)
System	1	6519**(28)	11134**(49)	0NS(0)	28**(44)	400**(49)
PobXSis	24	6904**(30)	1888** (8)	83** (7)	13** (20)	137**(17)
Error	96	160	266	20	0	1
Total	149	23193	23266	1176	64	810

**: Statistical significance ($p \leq 0.05$); NS: not significant; SV: sources of variation; DF: degrees of freedom; Pob: TSS: Total soluble solids, Population, Sis: System, PobXSis: PopulationXSystem. The proportion of the mean squares of each factor (Pob, Sis, and PobXSis) with respect to the total sum of the mean squares for each variable is given within brackets.

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Table 3. ANOVA and Tukey's test between the agronomic variables of native tomato plants grown in two production systems: the five best and the five worst genotypes.

No.	Plant height (m)		Number of Leaves		Number fruit		Weight per fruit (g)		Yield (kg/plant)	
1	**H1i**	2.2^{a}	**V1c**	329^{a}	**O3c**	57^{a}	**G3i**	179^{a}	**G3i**	4.4^{a}
2	**G3i**	2.1^{a}	**O4c**	294^{b}	**V1i**	55^{a}	**G1i**	176^{a}	**P5i**	4.2^{ab}
3	**H2i**	2.1^{ab}	**O1c**	264^{c}	**P5c**	53^{ab}	**O3i**	164^{b}	**P3i**	4.2^{abc}
4	**2Pi**	2.0^{abc}	**Y1c**	250^{d}	**C2c**	49^{bc}	**P6i**	161^{b}	**P1i**	4.1^{bcd}
5	**P1i**	1.9^{abcd}	**P6c**	230^{e}	**P6c**	46^{cd}	**H1i**	146^{c}	**H1i**	4.1^{bcd}
46	**G2i**	1.1^{pqrs}	**Y2i**	33^{pqr}	**Y1i**	18^{tu}	**P1c**	22^{xy}	**G1c**	0.5^{w}
47	**H2c**	1.0^{qrs}	**O2i**	33^{pqr}	**G3i**	18^{tu}	**P5c**	21^{xy}	**O2c**	0.5^{w}
48	**P4c**	0.9^{rs}	**M2i**	32^{pqr}	**G1c**	14^{uv}	**P4c**	18^{xyz}	**P4c**	0.4^{w}
49	**O2c**	0.9^{s}	**M1i**	29^{qr}	**Y1c**	13^{v}	**C4c**	15^{yz}	**C3c**	0.4^{w}
50	**G2c**	0.9^{s}	**G2i**	27^{r}	**O2c**	12^{v}	**C3c**	12^{z}	**Y1c**	0.4^{w}

Populations (bold): Means with different letters within columns are statistically different (Tukey, 0.05).

Comparing the means of the Pob x Sis combinations (Tables 3 and 4), plants grown in the greenhouse (i=greenhouse) were taller than those grown in the field (c=field), with the control (H1) having the tallest plants in both growing environments and G2c having the smallest size. The number of leaves was higher in the native genotype V1c with 329 leaves; in the protected conditions a range of 27 to 40 leaves was obtained (G2i and Y1i).

Table 4. ANOVA and Tukey test between the quality variables of native tomato fruits grown in two production systems: the five best and worst genotypes.

No.	Pollard diameter (cm)		Equatorial diameter (cm)		Number of locules		Total soluble solids (%)		Pericarp thickness (mm)	
1	**H2i**	7.3^{a}	**O4i**	8.3^{a}	**O3i**	11.5^{a}	**P1i**	5.5^{a}	**P3i**	10.6^{a}
2	**P1i**	6.9^{ab}	**O2i**	8.2^{ab}	**O1i**	11.1^{ab}	**M1i**	5.5^{a}	**G3i**	10.3^{b}
3	**P4i**	6.9^{b}	**O5i**	7.8^{abc}	**O2i**	11.0^{abc}	**M2i**	5.5^{a}	**P5i**	9.8^{c}
4	**P3i**	6.8^{bc}	**G3i**	7.7^{bc}	**C1i**	10.5^{abc}	**C1i**	5.5^{abc}	**H2i**	9.7^{cd}
5	**G2i**	6.7^{bc}	**O3i**	7.6^{bcd}	**O4i**	10.3^{abcd}	**C1c**	5.4^{abc}	**P4i**	9.3^{de}
46	**V1c**	3.3^{vw}	**C1c**	4.0^{tuv}	**G2c**	2.1^{tu}	**O5c**	3.5^{uv}	**P5c**	2.7^{vw}
47	**C1c**	3.1^{w}	**H1c**	3.9^{uv}	**H1i**	2.1^{tu}	**O1c**	3.4^{v}	**P1c**	2.5^{w}
48	**G1c**	3.1^{w}	**P2c**	3.6^{v}	**H1c**	2.0^{u}	**V1c**	3.3^{vw}	**G1c**	2.1x
49	**P1c**	3.1^{w}	**M2c**	3.5^{v}	**H2c**	2.0^{u}	**P1c**	3.2^{w}	**M1c**	1.7y
50	**P3c**	3.0^{w}	**M1c**	3.4^{v}	**H2i**	2.0^{u}	**O4c**	2.9^{x}	**C1c**	1.5^{y}

Populations (bold): Means with different letters within columns are statistically different (Tukey, 0.05).

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The number of fruits ranged from 12 to 55 fruits per plant, with the O3c population having the highest number in the study with a value of 57 fruits per plant. The fruit weight under protected conditions was the highest of the G3i genotype with 179 g, while the lowest fruit weight under field conditions was obtained in the C3c genotype with 12 g. In this situation, the native genotype G3i produced the highest yield under protected conditions with 4.4 kg/plant. The yields obtained in the open field were very variable, the average production ranged from 0.4 to 2 kg/plant; the lowest yield corresponded to the genotype P4c and the highest to the genotype G3i.

Obtained values of the variables polar and equatorial diameter, locule number, TSS, and pericarp thickness from the fruits produced under protected conditions were higher than those obtained under field conditions. The largest polar diameter was presented by the control (H2i), with 7.3 cm, and the equatorial diameter by the O4i population, with 8.3 cm; it is worth mentioning that H2i presented elongated fruits, while those of O4i were wider, a variable that determines the packaging to be used for shelf-life. Similarly, the locule number was higher in the native genotype O3i, with 11.5 locules, and in the field, it was the control H2c, with only 2 locules. The highest TSS value was 5.5 % in genotype P1i and the lowest was 2.9 % in the native population O4c; and the greatest pericarp thickness was obtained by the native genotype P3i, with 10.6 mm, tomato produced in the greenhouse, while in field conditions the fruits showed the lowest thickness, with 1.5 mm (C1c).

Table 5. ANOVA and Tukey test were applied for the average features between protected and open fields of Mexican populations of native tomato plants.

Variable	Production system		Difference	%
	Greenhouse	Field		
Plant height (m)	1.7a	1.2b	0.5	41
Number of Leaves	35b	187a	152	434
Number fruit	29b	35a	6	21
Weight per fruit (g)	115a	39b	76	200
Yield (kg/plant)	3.1a	1.3b	1.7	131
Polar diameter (mm)	54a	41b	13	32
Equatorial diameter (mm)	64a	47b	17	36
Locules number	5.9a	5.8a	0.1	2
Total soluble solids (%)	4.9a	4.0b	0.9	23
Pericarp thickness (cm)	6.9a	3.6b	3.3	92

Means with different letters within columns are statistically different (Tukey, 0.05)

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In the averages of the agronomic and fruit quality variables in the protected and open field conditions, statistical differences (Tukey, 0.05) were found in most of the evaluated variables (Table 5). In the greenhouse, eight variables stood out, the most important being fruit weight with a difference of 200 % with respect to that observed in the open field, yield with 131%, and pericarp thickness with 92 %; in the open field, only two variables were superior to those obtained in the greenhouse: leaves number (434 %) and fruits number (21 %).

Discussion

The native tomato populations were significantly affected ($p \leq 0.05$) by the production environment in which they were cultivated (Tables 1 and 2), as evidenced by the observation of significant differences in the factors system, genotype, and system-genotype interaction for most of the variables. These results indicated that some populations improved or decreased their yield and fruit quality attributes under certain production system conditions. In this sense, Zanne *et al*. (2014) suggested that changes in the morphology and physiology of certain populations could be a consequence of evolutionary adaptations to environment in which plants grow.

The production system factor explained to a greater extent the variation in the effects on the variables plant height, number of leaves, weight per fruit, fruit yield, equatorial diameter, pericarp thickness, and TSS, while the population-production system interaction influenced to a greater extent the number of fruits. According to Bhandari *et al*. (2021), this is explained by the climatic condition which is a factor affecting quality and yield in tomato production. However, such a situation could be better managed in the greenhouse by partially controlling climatic variables to favor conditions for plant growth (Holcman *et al*., 2017).

In the mean comparison analysis, genotypes superior to the control were identified in several variables measured in the greenhouse and in the field. Plant heights in genotypes H1i, G3i, H2i, P2i, and P1i were the highest, with values ranging from 2.2 to 1.9 m at 150 days, indicating that some native materials had similar growth vigor compared with the control, an important feature in a canopy production system. Similar results were reported by Núñez *et al*. (2012), who evaluated the tomato cultivar Beatrice and reported that plants reached an average height of 2.3 m at 150 days. In contrast, Carrillo & Chávez (2010), who evaluated native tomato populations in the greenhouse, reported a plant height of 1.3 to 1.8 m. Besides, in the present study it was observed that most of the materials evaluated in the open field showed low height values. According to Juárez-López *et al*. (2012b), these differences between the behavior of materials in greenhouse and open field could be an opportunity for growers who prefer medium-sized genotypes, which allows them to reduce labor in cultural tasks of the crop.

The highest number of leaves at 150 days of development was recorded in most of the genotypes grown in the open field, with V1c having the highest value with 329 leaves. According to Keller *et al*. (2021), mature leaves are important for an open field production system as they produce up to 80% of the photosynthetic carbon. On the other hand, in the greenhouse, the number of leaves was less than 38 after 150 days, and genotype P2i had the highest number of leaves. These values were lower than those reported by Núñez *et al*. (2012), who counted 53 mature leaves under a canopy system.

Fruit weight is closely related to several parameters, such as the number of ovary carpels, the position of the fruit in the cluster, and the prevailing environmental conditions during the fruit growth phase (Delgado-Vargas *et al*., 2018); in addition to the supply of photoassimilates and water, which determine its growth and development (Quinet *et al*., 2019). The fruits with the highest weight were obtained under protected conditions, being genotypes G3i and G1i, which showed the highest values, 179 and 176 g, respectively. These genotypes are within the ranges of high-quality caliber, as indicated by PHG (2012) in its classification of tomato fruits, which considers them as large-sized when they weigh between 121 and 180 g.

According to Diouf *et al*. (2018), the ability of plant material to have a high yield is given by the ability to accumulate biomass in the organs to be harvested. In this study, the best yield was achieved by the native genotype G3i with a yield of 4.4 kg/plant, followed by genotypes P5i and P3i. However, under field conditions, the yield of G3i was 2.8 kg/plant. This result suggests that this genotype had a better capacity for biomass accumulation under greenhouse conditions; while, exhibiting poor yield under field conditions. On the other hand, in previous work by Maldonado-Peralta *et al*. (2016) with the same genotypes, the G3 population reported a lower yield (0.39 kg/plant) than the obtained yield in this research. In general, the differences in the agronomic performance of the populations studied in the two production systems are due to the fact that open-field populations grow under uncontrolled conditions, whereas growing in favorable environments allows their traits to be better expressed (Kissoudis *et al*., 2015).

Tomato populations native to Mexico show a wide morphological diversification, fruit quality, and a high degree of adaptation (Table 4), which allows for finding well-defined morphological features in local and regional cultivars. In this study, the native populations fruits were wider than long (globosa), compared to the controls (H1 and H2), which presented elongated fruits. The populations from Oaxaca (O4i) had a kidney shape and those from Guerrero (G3i) had a ball with ribs. According to Van der Knaap *et al*. (2002), samples of the genus *Lycopersicum* vary in color intensity, fruit shape, and size, as well as growth habit and leaves morphology. In the production systems, the native genotypes had fruits with the highest number of locules, the O3i population presented 11.5 and kidney shape. Vázquez-Ortiz *et al*. (2010), found that fruits with this shape have an average of 11 locules, a variation that induces the particular shape they take. However, shape transformation has pleiotropic effects on fruit architecture, such as those related to increasing the number of carpels and locules (Lippman & Tanskley, 2001).

Diez (2001) mentions that tomato fruit for industry should have an average total soluble solids (TSS) between 4.5 and 5.5 %. Foolad (2007) mentions that tomatoes for fresh consumption require a value of 4.6 %. The TSS of the five best genotypes presented values higher than 5.3 % of (TSS) in protected conditions (Table 4), acceptable values for industry and fresh consumption. According to Ruiz *et al*. (2005), TSS is composed of 65% reducing sugars, such as fructose, glucose, and traces of sucrose, while the rest is represented by citric and

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malic acids, minerals, vitamin C, and other compounds in low concentrations. Besides a direct relationship between TSS levels and flavor was reported (Quinet *et al*., 2019); the higher the TSS, the better the flavor intensity (Cheng *et al*., 2020). Therefore, given the TSS levels in the present study, the evaluated materials are a potential source of germplasm to increase flavor in breeding programs.

Quinet *et al*. (2019) mention that a higher flesh thickness (mesocarp) increases the weight and the edible part, thus improving the fruit quality, which was consistent with the P3i, G3, and P5 populations, where materials with high flesh thickness showed high fruit weight. This situation could be advantageous, as greater pericarp thickness allows the fruit to have a longer post-harvest life, an essential factor for marketing (Gan *et al*., 2022).

Overall, the traits measured were higher in the protected conditions, showing that these protected conditions, compared to those obtained in the field, improved fruit quality in terms of fruit size, pulp thickness, and total soluble solids. This agronomic native populations performance within the under-canopy system could be explained by the fact that the materials have been selected by farmers for years in an open field production system, which exerts a high natural selection pressure. Thus, subjective selection by farmers over generations has been responsible for indirectly selecting for traits associated with better fruit size and quality (Ríos-Osorio *et al*., 2014); at the same time, these traits make consumers identify native populations as attractive and are willing to pay a higher price for them (Casals *et al*., 2012). This was clearly observed in the variable of yield, where tomato populations increased their yield by 130 % more compared to open field conditions, in agreement with Kanwar (2011), who reported a yield increase of 136.12 % more compared to open field cultivation. Such a result is due to the protected conditions that create a more favorable environment for production (Tao *et al*., 2016).

Conclusions

Mexican native tomato populations responded differently to the two production systems and there were genotypes that presented better quality and fruit yield under a specific system. Under protected environmental conditions, the Guerrero 3, Puebla 5 and 3 populations that presented a higher fruit yield than the control. In the greenhouse, its weight and average fruit yield increased by 200 and 130 %, respectively. For the pericarp thickness and TSS variables of the fruit, the protected environment also promoted higher quality values than those in the open field. These results show that some native materials could be exploited in a better way under greenhouses and others in the open field.

Contribution of the authors

The author MPMA and author SVD: development of the methodology and experimental validation; author RGAR and author VRJ: results analysis and data management; author MPR and author HBA: writing and preparing the manuscript, writing, reviewing and editing.

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Interest conflict

The authors declare no conflict of interest.

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