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Selection parameters for improvement of yield and quality in tomatillo

Parametros de seleção para aumento na produtividade e qualidade de tomatillo

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ABSTRACT

The extended use of the same variety by farmers over successive generations and reuse of the "seeds" caused natural variability that can be a magnificent opportunity for genetic improvement of tomatillo. Two successive seasons were accomplished to select genotypes with good performance from a heterogeneous population of the local tomatillo "Balady". The results revealed significant differences in early yield as fruit number and average fruit weight over the original population. Additionally, the results revealed a highly significant correlation between fruit set percentage and total soluble solids (TSS) at 60 days and the marketable yield with fruit length and TSS at 60 days. In conclusion, the path analysis along with heritability and selection genetic gain showed that early yield and fruit set are the two most critical component traits for fruit yield in tomatillo. In addition, the average fruit weight showed a low indirect effect on fruit yield per plant. Twenty promising genotypes were selected as a kernel for pure line development through further breeding programs.

Index terms: *Physalis ixocarpa*; phenotypic selection; fruit quality; path analysis; indirect selection.

RESUMO

O uso prolongado de uma mesma variedade pelos agricultores ao longo de sucessivas gerações e a reutilização das "sementes" causaram variabilidade natural sendo uma oportunidade para o melhoramento genético do tomatillo. Duas safras sucessivas foram realizadas para selecionar genótipos com bom desempenho em uma população heterogênea do tomatillo local "Balady". Os resultados revelaram diferenças significativas na produção precoce quanto ao número de frutos e peso médio dos frutos em relação à população original. Além disso, os resultados revelaram correlação altamente significativa entre porcentagem de pegamento de frutos e sólidos solúveis totais (SST) aos 60 dias de idade, e a produtividade comercial com comprimento de frutos e SST aos 60 dias de idade. Em conclusão, a análise de trilha juntamente com a herdabilidade e o ganho genético de seleção mostraram que a produção precoce e a frutificação são as duas características mais críticas para a produção de frutos no tomatillo. Além disso, o peso médio dos frutos apresentou baixo efeito indireto na produção de frutos por planta. Vinte genótipos promissores foram selecionados como sementes para o desenvolvimento de linhagens puras através de programas de melhoramento.

Termos para indexação: *Physalis ixocarpa*; seleção fenotípica; qualidade de frutos; análise de trilha; seleção indireta.

INTRODUCTION

The tomatillo (*Physalis ixocarpa* Brot. 2n = 2x = 24) is a species that is native to Mexico and Central America, and it is currently one of Mexico's most significant vegetable crops. In 2020, this crop was the sixth vegetable with the largest planted area in Mexico, with 40,117 ha and 766,515 tons of production (Sistema de Información Agroalimentaria y Pesquera - SIAP, 2021). It is a fruit vegetable that belongs to the family Solanaceae and bears round or spherical and green or green–purple fruit. The tomatillo fruit is surrounded by an inedible, paper-like husk formed from the calyx (Waterfall, 1967). Tomatillos make a great addition to a high-antioxidant eating plan focused on cancer prevention (Dolson, 2020) due to their high nutritional value, containing 8.24 °Brix, 0.75–1.06% protein, 1.12–2.10% fat and 0.77–1.42% ash (Shenstone et al., 2020). Tomatillo fruits are mainly rich in potassium, and they are also a rich source of Mg, Ca, Na, P, and bioactive compounds (González-Pérez; Guerrero-Beltrán, 2021).

The phenotypic value of an individual, P, measured as a deviation from the population mean, is the sum of two parts: the deviation of its family mean from the population mean, $P_{f.}$ and the deviation of the individual from the family mean, P_{w}. The procedure of selection varies according to the attention given or the weight given to these two parts. If we select based on individual values only, we give equal weight to the two components $P_{f\ and}\ P_w$ of the individual's value P. This is known as individual selection, where individuals are selected solely by their phenotypic values. This method is usually the simplest to operate and, in many circumstances, yields the most rapid response. The genetic principles of individual selection appear to be similar to the pure line selection strategy that has been used in many breeding programs, such as in coffee (Carvalho et al., 1952), beans (Yokoyama et al., 1999; Santos; Abreu; Ramalho, 2002), and rice (Rangel; Zimmermann; Neves, 1998). It is expected that during selection process, a high selection differential could be obtained, to provide greater progress in selection. Genetic gain is closely associated with the heritability of the trait of interest (Araújo et al., 2021). The higher heritability suggests that much of the total genetic variability associated with the selected trait is due to the additive action of genes, indicating that selection for this trait should be effective in the first segregating generations (Cruz; Regazzi; Carneiro 2012).

Correlation and path coefficient analyses are prerequisites for the improvement of any cultivar, including tomatillo, for the selection of superior genotypes (Elsayed, 2017). The information obtained from the correlation coefficients can be enhanced by partitioning into direct and indirect effects for a set of pairwise cause-effect interrelationships (Kang; Miller; Tai, 1983). It is standardized partial regression analysis and deals with a closed system of variables that are linearly related. Hence, this approach would facilitate selection based on more than one trait, which can produce balanced outcomes with selection (Araújo et al., 2021).

In tomatillo, few studies on correlation without investigating the effect of indirect selection, such as path coefficient analysis as a tool for enhancement selection gain, have been reported to estimate the associations between yield and other traits (Peña-Lomelí et al., 2008; Santos et al., 2021). In this respect, multiple traits should be taken into consideration simultaneously in selection to meet farmers, manufacturers and consumer requirements (Carvalho et al., 2021).

Few tomatillo genetic studies have been conducted in Egypt with modest efforts in improvement programs. Hence, the local variety "Balady" suffered from different levels of deterioration with many diseases and pests, resulting in a significant reduction in yield and fruit quality characteristics and asymmetry.

Therefore, the goal of this investigation was to identify and select superior genotypes that possess good performance in traits of interest from a heterogeneous population of the local tomatillo "Balady *cv*". Additionally, to purify a mixed population with differing phenotypes to develop new lines, thereby improving the average performance of the population.

MATERIAL AND METHODS

This study was conducted during two successive seasons, 2019 and 2020, at Elbaramoon Research Farm, Mansoura city, 31°2′25″N 31°22′58″E, 15 m altitude, Horticulture Research Institute, Egypt. The Köppen-Geiger climate classification system classifies its climate as hot desert (BWh). The experimental site is characterized by its silt clay loam soil with pH 8.13 and organic matter 1.7%.

Seeds of the basic population were sown on 20 February 2019 in 209-seedling trays. By the first week of April at 40 days of age, the seedlings were transplanted to the field. During the first season, transplanting of the tomatillo "Balady *cv*" seedlings was conducted with approximately 500 plants of tomatillo grown in bulk in an open field under clay soil conditions with a surface irrigation system. At the flowering stage, visual identification, labeling and selfing of plants with diverse phenotypic characterizations were performed. However, tomatillo plants are non-self-pollinated species, and to guarantee and ensure no cross-pollination by insects that could happen, the flowers were bagged at the bud stage. At the end of the maturity stage, seeds of individuals with superior agricultural and yield traits were collected and picked from each individual separately for seed extraction.

In the following season, seeds of every selected plant at an independent line in 209-seedling trays were sown. tomatillo seedlings were transplanted into the field on the 7th of April 2020. The experimental design used was a randomized complete block design (RCBD) with three replicates. Each entry (plot) contained 20 plants for each genotype. The plot area was 8.4 m$^{2\ and}$ included three rows, each row 0.7 cm apart and 4 m in length. The plants were distributed to complete the number of plants for each genotype, labeling the final plant of each genotype in the third row. The transplants were sown in hills on one side of the ridge as one plant at 0.5 m. All agricultural practices were applied whenever they were needed. Chemical fertilizers, such as phosphorus and potassium fertilizers, were added during soil preparation according to the recommendations of Ministry of Agriculture. Nitrogen fertilizer was divided into three equal portions and added to the soil at 30, 55 and 80 days after transplanting.

Growth characteristics: plant height (cm), number of main branches per plant and number of leaves per plant were recorded. Yield components were estimated: number of flowers per plant, early fruit number (the sum of first five pickings of maturity fruits), early yield (the first five pickings were weighed for plant and recorded as grams plant^{-1}), total number of fruits (estimated by summing number of all picked fruits), total plant yield (determined by summing weight of all picked fruits (g plant^{-1}), total yield per feddan, (0.42 hectare) that was estimated by multiplication the average yield of each plot in kg by the number of plants per feddan, average fruit weight [determined by dividing the weight of 10 fruits by their numbers (gram)], fruit set percentage was estimated by the following Equation 1:

$$\frac{\text{number of fruit set in the first five flower clusters}}{\text{total of flowers anthesis in these clusters}} x100 \quad (1)$$

Marketable yield [determined by summing the weight of all picked fruits without damage (kg)]; fruit length (cm), measured during the harvest stage as the average length of ten randomly selected fruits per replicate using a digital slide caliper; fruit diameter (cm), measured during the harvest stage as the average diameter of ten randomly selected fruits per replicate using a digital slide caliper; shape index, estimated by dividing the value of fruit length by the value of fruit diameter and total soluble solids percentage, estimated two times at 45 and 60 days using a hand refractometer.

Statistical analysis

The statistical model was applied to obtain the analyses of variance of all traits according to (Steel; Torrie, 1960) using a random model as follows: $Y_{ij} = \mu + G_i + R_j + E_{ij,}$ where Y_{ij}: the *i-th* genotype value in the *j-th* replication; μ: population means; G_i: the *i-th* genotype effect; *Rj*: the *j-th* replicate effect;: E_{ij} the experimental error effect.

Combined analysis

In the combined analysis of several assays, the Z_{ijk} and Y_{ijk} values are admitted, which refer to the same variable but are used to represent the values of the controls and the genotypes (families), being more enlightening, since the effects considered in the determination of each observation are differentiated (Bailey, 2008). In this analysis, it considers two sources of variance regarding the genotypes; the first concerns the families in which each group occurs in a given trial, and it is not possible to quantify their interaction with the environments; the second refers to the controls, which are evaluated in a factorial system, quantifying the variation between them and the variation in the interaction with the environment. Contrasts between controls and families were included along with the sources of variation inherent to the environments, characterized by blocks, assay and residual effects. Equation 2, where:

$$Z_{ijk} = \mu + Te_i + B_{j(K)} + E_k + Te_{Eik} + R_{ijk} \quad (2)$$

Since:
Z_{ijk}: value evaluated in the i-*th* common treatment, and j-*th* repetitions of the k trial; μ: general mean of trial; Te_i: effect of i-*th* control (common treatment); $Bj_{(K)}$: effect of the j-*th* block within the k-*th* trial; E_k: effect of k-*th* trail; Te_{Eik}: effect of interaction between the common treatment and the trial (season) and R_{ijk}: random error and Equation 3:

$$Y_{ij(k)} = \mu + F_i + B_j + R_{ij(k)} \text{ for each trial k} \quad (3)$$

where:
$Y_{ij(k)}$: value evaluated in i-*th* treatment (family) in j-*th* replication, for a particular trial k; μ: general mean of the experiment; F_i: effect of i-*th* family in a k trial; B_j: effect of j-*th* block in a k trial and $R_{ij(k)}$: random error in a k trial.

The following parameters were estimated: broad-sense heritability (h^2), experimental coefficient of variation (CV), coefficient of genotypic variation (CV_G) and experimental variation (CV_E). Thereafter, the selection gains (GS) were estimated, adopting a selection intensity of 8% according to Vencovsky (1987) as Equation 4:

$$GS = DS\ p\ h^2 = DS\ p \frac{\hat{\sigma}_g^2}{\hat{\sigma}_f^2} \quad (4)$$

where:
DS: selection differential ($DS = \bar{X}_s - \bar{X}_o$)
P: parental control, this value is equal to one when the relationship between progeny and offspring is obtained by self-pollination or vegetative propagation. $\hat{\sigma}_g^2$: genotypic variation and $\hat{\sigma}_f^2$ phenotypic variation.

Phenotypic correlations between the different vegetative, earliness, and fruit characters were estimated by Pearson's coefficient, and their significance was evaluated by t tests. All statistical analyses procedures were performed with the aid of Genes software program v. 2015.5.0 (Cruz, 2013).

RESULTS AND DISCUSSION

Mean performance of selected individuals

Desirable individuals with superior values are identified, selected and selfed to generate the following generation to develop inbred lines at the end. Twenty individuals for each studied trait, representing approximately 8% of the selection intensity, were selected from the original population that showed the best values for each evaluated trait. Plant number and its mean performance for each trait are presented in Table 1.

Regarding plant height, the mean performance of two selected individuals (G. 13 and 11) were more than 150 cm in height and more than the original population mean (P_0 = 133 cm). However, no significant differences were observed for the number of branches between the selected individuals and the original population, and only two individuals (G. 8 and 20) gave slightly more branches than the original mean (P_0 = 22.7) (Table 1).

Table 1: Mean performance of 20 genotypes with a selection intensity of 8% (from 250 plants) among the S_1 population for vegetative and early yield traits in tomatillo resulting from phenotypic selection.

Plant height (cm)		Number of leaves (unit)		Number of branches (unit)		Number of flowers (unit)		Early Yield (Fruit number)		Early yield/P (g plant^{-1})	
G.	Value	G.	Value	G.	Value	G.	Value	G.	Value	G.	Value
13	156.7$^{n.s}$	15	294.3**	8	23.3*	11	34.3**	16	36.0**	16	159.7**
11	154.7$^{n.s}$	5	259.7**	20	23.3*	15	33.0*	6	30.0**	6	150.3**
2	145.0$^{n.s}$	14	251.7**	7	22.7$^{n.s}$	8	27.7$^{n.s}$	15	30.0**	15	137.7**
1	139.7$^{n.s}$	4	246.7**	2	22.3$^{n.s}$	16	27.3$^{n.s}$	14	28.3*	14	130.3**
10	138.0$^{n.s}$	6	243.7**	12	22.3$^{n.s}$	12	27.3$^{n.s}$	13	26.7$^{n.s}$	5	130.0**
5	137.0$^{n.s}$	3	242.0**	5	21.3$^{n.s}$	10	27.0$^{n.s}$	12	23.3$^{n.s}$	4	124.3**
15	136.7$^{n.s}$	13	241.3**	18	21.3$^{n.s}$	2	26.0$^{n.s}$	5	21.7$^{n.s}$	13	122.3**
12	135.3$^{n.s}$	16	237.0**	10	21.0$^{n.s}$	7	26.0$^{n.s}$	4	20.0$^{n.s}$	8	121.7**
14	135.3$^{n.s}$	12	227.0**	15	21.0$^{n.s}$	3	25.7$^{n.s}$	7	17.7$^{n.s}$	10	121.0**
16	134.3$^{n.s}$	8	222.3**	19	21.0$^{n.s}$	19	25.7$^{n.s}$	8	17.0$^{n.s}$	3	112.7*
6	134.0$^{n.s}$	2	221.7**	14	20.7$^{n.s}$	9	25.3$^{n.s}$	11	17.0$^{n.s}$	12	112.0*
20	133.0$^{n.s}$	20	220.3**	4	20.3$^{n.s}$	13	25.3$^{n.s}$	3	16.7$^{n.s}$	9	110.7*
9	132.0$^{n.s}$	10	217.7**	9	20.0$^{n.s}$	18	25.3$^{n.s}$	10	16.7$^{n.s}$	7	110.3*
3	131.7$^{n.s}$	18	217.3**	17	20.0$^{n.s}$	17	25.0$^{n.s}$	19	16.7$^{n.s}$	11	106.3$^{n.s}$
4	129.7$^{n.s}$	9	214.0*	6	19.7$^{n.s}$	1	24.3$^{n.s}$	20	16.3$^{n.s}$	18	106.0$^{n.s}$
7	129.0$^{n.s}$	7	207.3*	11	19.7$^{n.s}$	14	24.3$^{n.s}$	17	16.0$^{n.s}$	2	103.0$^{n.s}$
8	127.7$^{n.s}$	17	207.0*	1	19.3$^{n.s}$	4	23.7$^{n.s}$	9	15.7$^{n.s}$	19	101.3$^{n.s}$
17	127.3$^{n.s}$	19	200.7$^{n.s}$	16	19.3$^{n.s}$	20	23.7$^{n.s}$	2	14.7$^{n.s}$	20	99.33$^{n.s}$
18	121.3$^{n.s}$	11	187.7$^{n.s}$	13	18.0$^{n.s}$	6	22.3$^{n.s}$	18	14.7$^{n.s}$	17	91.67$^{n.s}$
19	111.3$^{n.s}$	1	185.0$^{n.s}$	3	17.7$^{n.s}$	5	20.0$^{n.s}$	1	12.3$^{n.s}$	1	86.67$^{n.s}$
P_0	133.0	P_0	173.3	P_0	22.7	P_0	21.7	P_0	23.3	P_0	91.47
S_1	134.41	S_1	224.65	S_1	20.80	S_1	25.76	S_1	20.51	S_1	115.65
LSD 5%	25.54	---	31.24	---	4.888	---	8.957	---	4.178	----	18.88
LSD 1%	34.18	---	41.80	---	6.54	---	11.98	---	5.591	---	25.27

P_0 and S_1 refer to the means of the original and selected populations, respectively. LSD: Least significant difference, Fisher's test. $^{n.s}$, *, ** and *** significance of the F test at not significance, 0.05, 0.01 and 0.01% probability, respectively.

For the number of leaves per plant, approximately 17 of the selected plants had significant differences compared to the original population mean (P_0=173.3). On the other hand, the majority of selected plants gave superior values regarding the number of flowers per plant, whereas genotypes 11 and 15 gave the highest number of flowers. Regarding early yield as fruit number, four genotypes (16, 6, 15 and 14) gave significant differences in early yield as fruit number over the original population (P_0 =23.3 fruit number). The same genotypes maintained their arrangement to the early yield per plant (g plant^{-1}). These values of early yield simultaneously with the total number of fruits were obtained over similar individual plants (Elsayed; Elsaid; Habiba, 2015).

For average fruit weight (Table 2), only a selected individual had significant differences compared to the original population mean (no 13 with 9.567 g). The increase in fruit weight ranged between one and two grams over the original mean. For fruit set percentage, 14 plants of 20 gave an increase in fruit set % compared to the original population mean, where genotype 18 gave the highest fruit set, followed by genotypes 16, 12, 10 and 15. On the other hand, nine genotypes had significant differences from the original population mean. Regarding the marketable yield per feddan (0.42 hectare), the majority of the selected plants recorded a significant increase at 5% over the original population means (Table 2).

Table 2: Mean performance of 20 genotypes with a selection intensity of 8% (from 250 plants) among the S_1 population for yield traits in tomatillo resulting from phenotypic selection.

Total Number of fruits (unit)		Average fruit weight (g)		Fruit set (%)		Yield per plant (g)		Yield (kg /0.42 ha)		Marketable yield (kg/0.42 ha)	
G.	Value	G.	Value	G.	Value	G.	Value	G.	Value	G.	Value
16	88.67**	13	9.567**	18	90.13**	6	595.0**	20	3687.3**	16	3439.0**
6	74.33**	5	8.600*	16	89.67**	4	542.0**	9	3654.7**	3	3334.3**
15	71.33**	12	8.540$^{n.s}$	12	89.27**	19	464.0*	15	3603.3**	4	3312.0**
5	62.33**	2	8.500$^{n.s}$	10	89.07**	15	454.3*	19	3601.7**	10	3288.3**
14	61.33**	6	8.500$^{n.s}$	15	88.77**	18	451.0*	16	3578.0**	20	3257.3**
4	58.33**	7	8.150$^{n.s}$	8	88.73**	13	447.3*	4	3420.7**	15	3253.3**
13	56.67**	20	8.150$^{n.s}$	9	88.70**	16	447.0*	10	3386.7**	19	3222.3**
8	56.00**	4	8.017$^{n.s}$	4	88.63**	10	445.7*	5	3384.3**	8	3196.7**
10	56.00**	14	7.983$^{n.s}$	6	88.27**	8	443.3*	14	3358.7**	5	3195.0**
12	55.00**	1	7.967$^{n.s}$	14	88.17**	14	427.3*	3	3350.3**	18	3136.3**
9	53.67**	10	7.850$^{n.s}$	13	87.83**	9	420.7$^{n.s}$	6	3339.7**	13	3081.3**
19	53.33**	16	7.833$^{n.s}$	20	85.67*	3	418.7$^{n.s}$	8	3336.7**	6	3077.3**
18	52.00*	8	7.750$^{n.s}$	7	85.20*	7	406.3$^{n.s}$	13	3232.7**	9	3008.3**
3	51.67*	11	7.750$^{n.s}$	19	84.93*	20	403.3$^{n.s}$	7	3122.7**	14	2992.0**
7	49.67*	15	7.750$^{n.s}$	5	82.70$^{n.s}$	17	374.7$^{n.s}$	18	3091.3**	7	2922.3**
11	47.33$^{n.s}$	9	7.567$^{n.s}$	2	82.00$^{n.s}$	2	367.7$^{n.s}$	17	3068.7**	11	2920.0**
2	46.67$^{n.s}$	19	7.567$^{n.s}$	17	80.33$^{n.s}$	12	357.9$^{n.s}$	2	3013.3**	12	2734.3**
20	46.67$^{n.s}$	3	7.400$^{n.s}$	1	79.23$^{n.s}$	11	339.7$^{n.s}$	12	2864.0**	2	2684.3*
17	46.00$^{n.s}$	17	6.833$^{n.s}$	11	78.53$^{n.s}$	5	333.7$^{n.s}$	11	2725.3**	17	2502.0$^{n.s}$
1	35.33$^{n.s}$	18	6.767$^{n.s}$	3	78.27$^{n.s}$	1	291.7$^{n.s}$	1	2370.7$^{n.s}$	1	2250.0$^{n.s}$
P_0	38.33	P_0	7.600	P_0	75.00	P_0	316.7	P_0	2066.0	P_0	2167.0
S_1	56.12	S_1	7.952	S_1	85.71	S_1	421.57	S_1	3259.54	S_1	3040.32
LSD 5%	11.04	----	1.344	----	9.301	----	110.7	----	419.7	----	458.2
LSD 1%	14.78		1.789		12.44		148.2		561.6		613.2

P_0 and S_1 refer to the means of the original and selected populations, respectively. LSD: Least significant difference, Fisher's test. $^{n.s}$, *, ** and *** significance of the F test at not significance, 0.05, 0.01 and 0.01% probability, respectively.

Regarding fruit shape, fruit diameter and length (Table 3) gave the lowest values for selection, where the round type for tomatillo fruits is considered the preferable shape for the consumer. The regular and uniform round shape is controlled by many other traits, such as the maturity stage, harvest date, fruit set, climatic conditions and other factors that complicate genetic improvement, such as this type of character. When the values of the shape index are approximately zero, this is a preferable value that reflects the regular round shape of tomatillo fruits. Hence, genotypes 11, 5, 18, 4, 19 and 3 could be used for further breeding programs for fruit uniformity improvement.

Path coefficient analysis

Before conducting path analysis, the multicollinearity test was applied as the previous step to avoid collinearity among the traits of interest. According to multicollinearity analysis, the variance inflation factors, VIF, were more than 10, indicating the existence of multicollinearity (Table 4). Moreover, the condition number, the ratio between maximum and minimum eigenvalues, was more than 1000, which indicates severe collinearity before exclusion of the traits with a coefficient of correlation of more than 0.900. Hence, this ratio was adjusted to 941.4, revealing the presence of moderate collinearity.

Table 3: Mean performance of 20 genotypes with a selection intensity of 8% (from 250 plants) among the S_1 population for fruit shape and TSS in tomatillo resulting from phenotypic selection.

Fruit length (cm)		Fruit diameter (cm)		Shape index (unit)		TSS at 45 days (%)		TSS at 55 days (%)	
G.	Value	G.	Value	G.	Value	G.	Value	G.	Value
15	2.767**	14	2.533$^{n.s}$	10	1.263*	12	4.167*	16	5.967**
10	2.633*	6	2.500$^{n.s}$	17	1.140$^{n.s}$	11	4.133*	10	5.933**
11	2.467$^{n.s}$	16	2.500$^{n.s}$	15	1.127$^{n.s}$	2	3.933$^{n.s}$	13	5.900**
20	2.467$^{n.s}$	11	2.467$^{n.s}$	20	1.125$^{n.s}$	8	3.867$^{n.s}$	14	5.900**
6	2.433$^{n.s}$	15	2.467$^{n.s}$	3	1.086$^{n.s}$	16	3.833$^{n.s}$	18	5.900**
2	2.367$^{n.s}$	2	2.433$^{n.s}$	19	1.040$^{n.s}$	6	3.733$^{n.s}$	6	5.833**
12	2.367$^{n.s}$	12	2.400$^{n.s}$	4	1.035$^{n.s}$	10	3.733$^{n.s}$	3	5.733**
16	2.367$^{n.s}$	8	2.367$^{n.s}$	18	1.025$^{n.s}$	3	3.633$^{n.s}$	4	5.733**
3	2.333$^{n.s}$	9	2.333$^{n.s}$	5	1.016$^{n.s}$	18	3.600$^{n.s}$	20	5.700**
19	2.333$^{n.s}$	19	2.300$^{n.s}$	11	1.001$^{n.s}$	1	3.567$^{n.s}$	9	5.633**
5	2.300$^{n.s}$	5	2.267$^{n.s}$	7	0.992$^{n.s}$	17	3.567$^{n.s}$	17	5.567**
9	2.300$^{n.s}$	13	2.267$^{n.s}$	1	0.991$^{n.s}$	15	3.533$^{n.s}$	19	5.500*
14	2.300$^{n.s}$	7	2.233$^{n.s}$	12	0.987$^{n.s}$	5	3.500$^{n.s}$	15	5.467*
17	2.267$^{n.s}$	20	2.233$^{n.s}$	9	0.978$^{n.s}$	20	3.500$^{n.s}$	5	5.400$^{n.s}$
18	2.233$^{n.s}$	18	2.200$^{n.s}$	2	0.977$^{n.s}$	19	3.433$^{n.s}$	2	5.267$^{n.s}$
4	2.200$^{n.s}$	3	2.167$^{n.s}$	6	0.973$^{n.s}$	7	3.400$^{n.s}$	8	5.267$^{n.s}$
7	2.200$^{n.s}$	4	2.167$^{n.s}$	16	0.950$^{n.s}$	4	3.367$^{n.s}$	1	5.200$^{n.s}$
8	2.100$^{n.s}$	10	2.133$^{n.s}$	13	0.926$^{n.s}$	14	3.367$^{n.s}$	12	5.167$^{n.s}$
13	2.100$^{n.s}$	17	2.033$^{n.s}$	14	0.909$^{n.s}$	9	3.333$^{n.s}$	7	5.133$^{n.s}$
1	1.900$^{n.s}$	1	1.933$^{n.s}$	8	0.892$^{n.s}$	13	3.333$^{n.s}$	11	5.067$^{n.s}$
P_0	2.067	P_0	2.203	P_0	0.942	P_0	3.400	P_0	4.867
S_1	2.322	S_1	2.297	S_1	1.086	S_1	3.627	S_1	5.563
LSD 5%	0.463	----	0.428	----	0.272	----	0.636	----	0.458
LSD 1%	0.620	----	0.572	----	0.364	----	0.851	----	0.613

P_0 and S_1 refer to the means of the original and selected populations, respectively. LSD: Least significant difference, Fisher's test. $^{n.s}$, *, ** and *** significance of the F test at not significance, 0.05, 0.01 and 0.01% probability, respectively.

Table 4: Multicollinearity diagnosis of the correlation matrix including some vegetable traits, yield components and fruit characters in tomatillo under individual phenotypic selection.

Order	Eigenvalues	Singular value	Condition index	VIFk
1	3.085	1.756	1.000	3.648
2	1.994	1.412	1.244	1.845
3	1.544	1.243	1.413	3.956
4	1.356	1.164	1.509	3.284
5	0.842	0.917	1.914	1.988
6	0.500	0.707	2.484	3.741
7	0.376	0.613	2.863	107.9
8	0.179	0.424	4.146	90.42
9	0.121	0.347	5.060	108.6
10	0.003	0.057	30.68	1.619

*Small single value indicates collinearity, while high condition index indicates collinearity. Condition number (Max/Min): 941.4 indicates moderate to strong collinearity.

Under these new circumstances, the outcomes of the direct and indirect effects of the vegetative and fruit characteristics and different yield component parameters on total yield can reliably be drawn by adopting path coefficient analysis.

For quantification of the magnitude of phenotypic selection and direction of the interrelationship among studied traits, simple correlation coefficients were estimated among some vegetative, yield components and fruit characters. The correlation analysis was obtained by applying the mean genotypes over all the estimated traits. A negative and significant correlation at 5% probability was obtained between the number of branches per plant and total soluble solids at 45 days (-0.461) with a coefficient of coincidence (C %) of 41.94%. Early fruit number was associated with early yield per plant, the total number of fruits, total yield per plant (TY) and fruit diameter, with significant positive correlations estimated by 0.812, 0.814, 0.438, and 0.627, respectively.

Significant and positive correlation coefficients were observed between early yield per plant and the total number of fruits (0.964), fruit set % (0.608), total yield per plant (0.672), marketable yield (0.551), fruit diameter (0.638), and TSS at 60 days old (0.524). Similar associations were found for the total number of fruits with other yield components in addition to fruit length and diameter. Regarding the correlation between fruit set % and other estimated traits, in addition to its strong positive association with other yield components, a highly significant correlation between fruit set % and TSS at 60 days old was observed (0.600, C % 54.84). Additionally, the marketable yield had a significant positive correlation with fruit length and TSS at 60 days old (Table 5).

Vegetative traits such as plant height and number of branches had a negative correlation but no significant association with yield components, which indicates that short plants with moderate shoots have a higher yield than tall plants. A significant positive association with high coefficient coincidence was estimated between early yield and other yield components, indicating the possibility of practicing early selection for yield using this parameter as a form of indirect selection.

As explained, the correlation of total fruit yield with most of the studied traits except plant height, number of branches, average fruit weight, shape index and TSS at 45 days indicated that indirect selection of yield through early yield per plant is possible because of the high and significant indirect effects.

As outlined previously, nonetheless, the highest direct effect of fruit set percentage on total fruit yield and earliness traits at the beginning of the stage were found to be the most important selection index of tomatillo under our field conditions (Table 5).

In contrast, Shushay, Derbew and Abay (2014) revealed that average fruit weight had the highest direct effect on total fruit yield in cultivars similar to tomato (0.644). The selection indexes aggregate information to multiple characters, and with this, they are able to carry out the selection of a set of variables simultaneously (Carneiro et al., 2021). Hence, direct selection based on earliness can reliably be used for yield improvement in tomatillo.

The residual effects estimated by 0.649 revealed that the causal factors explained approximately 35.10% of the variability in the dependent factor, total fruit yield per plant. The coefficient of determination was 0.578 between early yield and total fruit yield per plant, meaning that 57.80% of the variance in total yield can be explained by early yield%. In a similar study, high additive genetic correlations between the first bifurcation height (FBH), fruit set number (FSN), yield per plant in the first cut (YP) and fruit number per plant (FP) with final yield (FY) were reported by Peña-Lomelí et al. (2008). The same authors reported the possibility of obtaining high gains by indirect selection according to heritability values in the first four characters (secondary variables) than in the main character (FY) based on higher FSN, YP, FP and lower FBH (Hallauer; Miranda, 1981; Falconer, 1986).

Table 5: The direct and indirect effects of nine secondary components on the total fruit yield per plant as the primary component in tomatillo plants resulted from individual phenotypic selection (value of k: 0.218)

Effects	Secondary variables*										
	PH	NOB	EYP	AFW	F set	FL	FD	SI	TSS45d	TSS60d	R**
Direct effect on Y/P	-0.2847	-0.1210	0.3572	0.2769	0.1402	0.1113	0.0929	0.1318	-0.1753	0.1580	
Indirect effect via:											
PH	---	0.0893	-0.0324	-0.1735	0.0506	-0.0187	-0.0562	0.0429	-0.0805	0.024	-0.168
NOB	0.0379	----	0.0288	0.0052	-0.0122	-0.0060	-0.0127	0.0032	-0.0143	0.027	-0.150
EYP	0.0407	-0.0852	---	0.1117	0.2171	0.1455	0.2280	-0.0557	0.0329	0.161	0.672
AFW	0.1687	-0.0118	0.0866	---	0.0490	-0.0155	0.0772	-0.0911	0.0075	-0.001	0.277
Fruit set%	-0.0249	0.0142	0.0852	0.0248	---	0.0435	0.0546	-0.0022	-0.0022	0.052	0.547
FL	0.0073	0.0055	0.0453	-0.0062	0.0345	---	0.0520	0.0664	0.0319	0.030	0.356
FD	0.0183	0.0097	0.0593	0.0259	0.0362	0.0435	---	-0.0394	0.0328	0.007	0.339
ShI	-0.0198	-0.0035	-0.0205	-0.0434	-0.0020	0.0786	-0.0558	---	-0.0024	0.022	0.088
TSS 45d	-0.0495	-0.0208	-0.0162	-0.0047	0.0027	-0.0502	-0.0619	0.0031	---	0.038	-0.208
TSS 60d	-0.0155	-0.0729	0.082	-0.001	0.094	0.043	0.012	0.038	-0.042	---	0.563
Total	-0.1682	-0.1498	0.6715	0.2774	0.5468	0.3562	0.3385	0.0877	-0.2079	0.563	
Coefficient of determination		0.578									
Residual Effects		0.649									

*PH: plant height; NOB: number of branches per plant; EYP: early yield per plant; AFW: average fruit weight; FL: fruit length; FD: fruit diameter; ShI: shape index; TSS 45 d and 60 d: total soluble solids at 45 and 60 days, respectively.
**Correlations between the explanatory variables and the basic variable (Y/P).

Both simple and combined ANOVA revealed a significant genotype effect ($P < 0.01$) for 50% of the evaluated traits, including the number of leaves, earliness parameters, fruit set%, yield and TSS at 60 days old, indicating the existence of genetic variability among the population for these traits (data not shown). On the other hand, statistically, no significant differences among the population individuals could be detected for plant height, number of branches, number of flowers, average fruit weight, fruit morphology characteristics and TSS at 45 days old (data not shown).

The knowledge of population genetic parameters is of great interest for a better understanding of the population structure regarding its genetic variability, expected genetic gains and consequently possible success in the breeding program (Elsayed; Elsaid; Habiba; 2015). The high heritability value estimates for earliness parameters (94.72%, 87.73%) and number of leaves (84.48%) demonstrate high selection gain. On the other hand, direct selection based on these traits could achieve great progress attributed to the insignificant impact of these traits by the environment (Falconer; Mackay, 1996). Moderate estimates for average fruit weight, fruit set%, and marketable yield, and particularly the low heritability estimates for plant height, number of flowers, and TSS at 45 days old, revealed a favorable influence of the environment rather than genotype, and hence, selection gain for these traits would not be rewarding in early generations.

Few of the evaluated traits showed highly significant variation as genetic causes, as revealed by the high values of the coefficients of genetic variation. The possibility of improving the mean performance during the next phases of the selection cycles is high for these traits. In this regard, high values of the coefficient of genotypic variation (CV_G) reveal proper conditions for selection. Except for plant height, number of branches, number of flowers, average fruit weight, fruit set, fruit morphology characteristics and TSS at 45 days, the other traits had high estimates of CV_G, especially the traits related to earliness, which had the highest estimates ranging from 15.27% to 30.20% (Table 6).

Table 6: Estimates of genetic and phenotypic parameters for vegetative, yield components and fruit characters in tomatillo obtained by phenotypic of individual selection for two successive seasons.

Traits	Description					
	σ^2_{Ph}	σ^2_E	σ^2_G	h^2%	CV_G	CV_G/CV_E
Plant height	97.01	79.86	17.14	17.67	3.081	0.267
Number of leaves	770.2	119.5	650.7	84.48	11.35	1.347
Number of branches	2.561	2.925	0.001	0.001	0.001	0.005
Number of flowers	10.59	9.820	0.769	7.269	3.405	0.161
Early Fruit Number	40.51	2.137	38.37	94.72	30.20	2.441
Early Yield/plant	355.9	43.64	312.3	87.73	15.27	1.544
Total Number of Fruits	143.9	14.94	128.9	89.61	20.54	1.696
Average fruit weight	0.379	0.221	0.157	41.64	5.001	0.467
Fruit Set (%)	21.41	10.59	10.54	49.89	3.812	0.576
Yield/Plant	51119	1501.5	3610.4	70.62	14.42	0.895
Yield/Fed*.	174867	2.567	153299	87.67	12.22	1.539
Marketable Y/Fed.	122982	25702	97283	79.10	10.40	1.123
Fruit length	0.036	0.026	0.011	28.56	4.438	0.365
Fruit Diameter	0.026	0.022	0.003	13.97	2.633	0.233
Shape Index	0.008	0.009	0.000	0.000	0.001	0.001
TSS at 45d	0.063	0.049	0.013	21.29	3.198	0.299
TSS at 60d	0.109	0.025	0.083	76.56	5.239	1.044

Feddan equal 4200 m^2 = 0.42 ha.

In a similar study on the same species, Lomelí et al. (2004, 2008) found similar values to those in the present study for CV_G of 28.7% and 14.9% for fruit yield and number of fruits per plant, respectively. In similar study on tomato, Prema, Indiresh andSanthosha (2011) indicated the prevalence of sufficient genetic variation from all the characters studied except plant height at 60 and 90 days after transplanting. Also the same authors recorded high phenotypic and genotypic coefficient for average fruit weight, fruit yield per plant (kg), lycopene content (µg/100g), fruit length (cm), total soluble solids of fruit (°Brix) and fruit width (cm) among cherry tomato genotypes. Kumar et al. (2004) observed moderate heritability and low genetic advance for the number of branches.

According to our findings, the selection gain obtained by the highest values of both CV_G and heritability for the early fruit number trait did not show great gain by selection. While the marketable yield per feddan gave the highest gain by the selection, (32.33%) based on fewer values of both CV_G and h^2. In contrast, high values of CV_G (coefficient of genetic variation) and h^2 have been reported in similar studies on tomato (Asati; Rai; Singh, 2008; Pradeepkumar et al., 2001). From the estimates of phenotypic and genotypic variance and heritability, Vieira et al. (2021) found that with the use of 130 progenies, these estimates tend to stabilize, implying that a high number of progenies does not interfere decisively in the quality of most parameters, except for the limits of maximum and minimum variation.

The CV_G/CV_E ratio (coefficients of genotypic variation and experimental variation) is another parameter for indicating selection feasibility. Values close to or greater than unity for a trait mean that selection is promising because the major portion of the observed variability is attributed to genetic causes (Cruz; Regazzi; Carneiro, 2012). Seven traits, including leaf number, earliness, total yield per plant and per feddan, marketable yield and TSS at 45 days old, presented estimates of CV_G /CV higher than 1 (Table 6). High lighting early fruit number by presenting higher CV_G, h^2, and CV_G/CV_E values. Despite the relatively high values of heritability regarding certain traits such as early fruit number, this is not a guarantee that the selection gain will be large. Hence, higher genetic variability in the original population is necessary to allow the formation of a proportion of individuals whose mean is higher than the original population mean so that when multiplied by heritability, the result will be optimal (Grajales et al., 2000).

Among the objectives of the current investigation was to identify genotypes with higher fruit yield and fruit flavor quality. TSS is considered one of the most important traits related to the organoleptic quality of fruits. TSS is a fast and easy test that can give a general impression of the fruit's sweetness (Mitchell; Uchanski; Elliott, 2019). The means of the individuals selected for the evaluated traits are listed in Tables 1, 2 and 3. In this respect, Pérez-Herrera et al. (2021) reported a high variation in TSS content among genotypes of wild *Physalis spp* ranging from 4.2 to 7.0 °Brix. On the other hand, the direct selection for yield per plant based on plant height, number of branches per plant and TSS at 45 days was not successful, resulting in undesirable gains for these traits.

Relatively high CV_G and h^2 estimates associated with higher gains for the traits of interest indicate the importance of additive gene action (Narayan et al., 1996), enhancing the selection procedure. Grajales et al. (2000) reported lower heritability values through an improved material of *P. ixocarpa* compared to our finding, ranging from 0.26 to 0.23 for fruit yield and number of fruits per plant, respectively. Additionally, Ara et al. (2009) and Saeed et al. (2007) showed high heritability followed by high genetic gain for the total number of fruits per plant.

The species *P. ixocarpa* is known to be self-compatible (Pandey, 1957), so mass selection, half-sibling and blended families of half-siblings are the most appropriate selection methods for their improvement (Peña-Lomelí et al., 2013). However, the formation of hybrids using dihaploid lines obtained by another culture has great potential for use in the species (Ortuño-Olea; Manzo-González; Peña-Lomelí, 1998).

The results obtained here by direct selection on early yield traits emphasize the fact that the high gains for these traits are associated with satisfactory gains for TSS at 60 days old. On the other hand, indirect selection on early yield per plant and fruit set appears to be promising to obtain indirect gains for fruit yield and soluble solids content at 60 days old. According to our findings, individual selection of tomatillo genotypes for early yield and soluble solids content was sufficient for the breeding process 60 days after transplanting, while earlier selection for TSS resulted in undesirable gains.

Early maturing cultivars are preferred for both producers and markets, where they could guarantee high prices due to the lack of this item in the market during this period of the year. In addition, earliness in yield is an important selection criterion by alleviating unfavorable climatic conditions such as drought, heat stress and diseases by escaping. In certain cases, such as a lack of water, the short cycle of varieties with concentrated yield in the first pickings could be a good option under these circumstances.

On the other hand, taste and flavor are the main components of the marketability of tomatillos and other fruits. Total soluble solids are significantly related to fruit flavor and the plant's accumulation of sugars (Jiménez-Santana et al., 2012). Therefore, greater efforts are being made to improve these traits by increasing the total soluble solid content. Through this study, the total soluble solids were affected by the age of the plant when estimating this trait, according to the previous data. The data showed that the increase in the TSS content increased with the age of the plants, *i.e.*, at 60 days compared to 45 days. The nature of the association between TSS content and the yield also changed, as it showed an increase in its value in conjunction with the increase in the total and early yield.

CONCLUSIONS

Path analysis along with heritability and selection gain showed that early yield and fruit set are the two most critical component traits for fruit yield in phenotypic selection in tomatillo. In addition, the average fruit weight revealed a low indirect effect on fruit yield per plant. Among the evaluated materials, ten promising genotypes, 18, 16, 6, 20, 9, 15, 10, 14, 5, and 13, were identified and selected that possess better performance under the current conditions of our investigation.

AUTHOR CONTRIBUTION

Conceptual Idea: Ismal, H.E.M.; Hassanin, A.A.; Methodology design: Zyada, H. G.; Ismal, H.E.M.; Data collection: Ameen, B., Data analysis and interpretation: Elsayed, A. Y; and Writing and editing: Aguilera, J.G.; Elsayed, A.Y.

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