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Tomato (*Solanum lycopersicum* L.) yield and quality depending on the osmotic potential and the number of stems

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ABSTRACT
Objective: To evaluate the biochemical components, physical characteristics (number of stems and fruit), and yield of Saladette tomato (*Solanum lycopersicum* L.), Var. Cid F1, grown under greenhouse conditions and its response to a constant increase (from 1 to 2.5 dS m^{-1}) of the osmotic potential of a nutrient solution, during three phenological stages (transplantation, 2nd cluster fruiting, and 6th cluster fruiting) of plants subjected to a single- and two-stem training system.
Design/Methodology/Approach: A sampling was carried out in the 5th cluster to determine the physical characteristics (firmness, size, number, color) and biochemical components (total soluble solids, titratable acidity, vitamin C, lycopene, pH, electrical conductivity, and ripening index) of the fruits. The experiment was established in 2018, under a greenhouse hydroponic system at Colegio de Postgraduados. The experiment was set as randomized complete block design with four replicates.
Results: The increase of osmotic potential and pruning had a positive effect on yield and number of fruits without affecting the biochemical components. Regarding the physical characteristics, T1 had 76% large fruits, 19% medium-sized fruits, 4% small fruits, and 1% tiny fruits.
Study Limitations/Implications: This methodology should be evaluated to other tomato varieties using different substrate mixtures and rates of chemical and organic fertilizers to evaluate water response and crop yield.
Findings/Conclusions: Increasing the osmotic potential of the nutrient solution, during phenological stages of maximum water and nutrient demand and the removal of old leaves had a positive response by increasing fruit number, size, and yield.

Keywords: physical characteristics, biochemical components, number of stems, yield.

INTRODUCTION
The osmotic potential (Ψo) of nutrient solution (NS) can influence crop growth and production. However, the effect depends on the o magnitude and nutrient uptake capacity of each specie (Chamú-Juárez *et al.*, 2020). Several studies have focused on the

improvement of crop production (Mundo *et al.*, 2020) and fruit quality (Pérez-Díaz *et al.*, 2020). Nevertheless, there are no studies relating the response of tomato to the Ψo of nutrient solution under greenhouse conditions that could influence higher production compared with the commonly used growing systems.

In Mexico, about 50,900 ha are used for protected agriculture, greenhouses, and crops grown under a shade mesh (SAGARPA, 2020). Tomato (*Solanum lycopersicum* L.) is one of most popular produce worldwide, and mainly grown in greenhouses (SAGARPA, 2020). The main crops produced under this system are: tomato (71%), pepper (17%), and cucumber (11%) (SAGARPA, 2020). Production systems change depending on varieties, growth habits, planting density, number of stems, substrates, irrigation, nutrition, and pest and disease control (Mendoza-Pérez *et al.*, 2022). The production technique based on the number of stems of plants grown in Mexican greenhouses is relatively new and it has impacted fruit productivity, profitability and quality during the last few years (Mendoza-Pérez *et al.*, 2018a; Flores-Velázquez *et al.*, 2022). Protected agriculture is a production system developed to provide plants with the ideal conditions for their development, encouraging their maximum yield potential (Vargas-Canales *et al.*, 2018).

Meanwhile, a balanced nutrient solution can help to achieve an optimal plant growth and development. In addition, it decreases the excessive use of chemical fertilizers to avoid the pollution of aquifers and soil salinization (Villarreal *et al.*, 2006). Tomatoes are a source of vitamins, minerals, carbohydrates, and bioactive compounds that benefit human health. Fresh tomatoes can be consumed in many ways and they are also an important raw material for the processing industry (Martínez-Rodríguez *et al.*, 2017). Ripeness is fundamental to determine the right harvesting moment of this fruit (Martínez-González *et al.*, 2017). Klee and Tieman (2013) have shown that several changes in fruit chemical composition occur during this process that determines organoleptic properties such as texture, scent, taste, and color. The typical red color of these fruits indicates their freshness and lycopene content (Farneti, 2014). A two-step ripening process takes place during the final stages of fruit growth and development: physiological maturity occurs when the fruit reaches its maximum size and seed vigor; while consumption stage occurs with changes in fruit color, texture, sugar, organic acids and volatile compounds and become more sensitive to the attack of pathogens associated with the loss of cell wall integrity (Seymour *et al.*, 2013; Dos Santos *et al.*, 2015).

Physical quality is based on the fruit appearance (size, shape, color, brightness, firmness, and lack of defects and damages). However, biochemical components such as total soluble solids, titratable acidity, vitamin C content and pH are key parameters in fruits used by the agroindustry (Flores-Velázquez *et al.*, 2022). Increasing the osmotic potential of nutrient solution during stages of peak demand also increases tomato yield and fruit quality.

The number of stems per plant is one of the agronomical variables associated with tomato productivity. A higher yield is expected from a greater number of stems. However, other response variables that determine tomato quality can be impacted. Therefore, the objective of this study was to evaluate the biochemical components, physical characteristics (number of stems and fruits), and yield of Saladette tomato, var. Cid F1, grown under greenhouse conditions and its response to a constant increase (from 1 to 2.5 dS m^{-1}) in the osmotic potential of nutrient solution during three phenological stages (transplantation, 2nd cluster fruiting, and 6th cluster fruiting) of plants subjected to a single- and two-stem pruning system.

MATERIALS AND METHODS

Crop management

The experiment was conducted in Colegio de Postgraduados at Campus Montecillo, (19° 27' 58" North latitude, 98° 54' 58" West longitude) and 2431 m above sea level during the spring-summer season 2017. Saladette tomato seeds (Var. Cid F1) were germinated in expanded polystyrene seedling trays with 200 cavities. The planting was realized March 14, the transplant on May 15; while, the process ended on November 30, 2017.

The plant material was grown under hydroponic greenhouse conditions in 12 L polystyrene bags with red tezontle as substrate. The transplanting method consisted of the triangular system (tresbolillo) with 40 cm apart from each plant, twin rows (20 m long), 40 cm between rows, and a density of three plants per m^2 for both treatments.

Experimental design and treatments

The dimension of each experimental unit was 5 m^2 with 15 plants, in a randomized complete block design with four replicates. Two treatments were established as a function of the stem number: T1 (single-stem) and T2 (two stems per plant). The osmotic potential of the nutrient solution was increased in three stages: transplant-2th cluster with osmotic potential of −0.036 MPa; 2th-6th cluster with −0.072 MPa, and 2th-9th cluster with −0.096 MPa for both treatments.

Composition and osmotic potential of the nutrient solution in treatments

T1 and T2 were subjected to three subsequent applications of osmotic potential in the nutrient solution during three phenological stages as recommended by Mendoza-Pérez *et al.* (2018b).

The procedure to obtain and modify the nutrient concentration as well as the osmotic potential was proposed by Steiner (1984). The nutrient solutions were prepared with chemical fertilizers and pH was adjusted to 6.5 using H_2SO_4 1N. Micronutrients (ppm) Mn^{2+} (2.30), Zn^{2+} (0.6), Fe^{2+} (2.0), Cu^{2+} (0.06), and B (0.6) were added to the three nutrient solutions (Steiner, 1984). The irrigation water used in both treatments had 6.69

Table 1. Composition and osmotic potential of nutrient solution used on treatments.

Ψs (Mpa)	pH	EC dS m^{-1}	TIC mg	Ca^{2+}	K^+	Mg^{2+}	$NH4^+$	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	ST
				meq L^{-1}							
−0.036	6.5	1	15	4.5	3.5	2	0	6	0.5	3.5	T-2nd C
−0.072	6.5	2	30	9	7	4	0	12	1	7	2nd-6th C
−0.096	6.5	2.5	40	11.2	8.75	5	0	15	1.25	8.75	6th-9th C

Ψs=Osmotic potential, EC=electrical conductivity, pH, TIC=total ionic concentration; T-2nd C=Transplant-2th cluster, 2th-6th C=2th cluster-6th cluster; 6th-9th C=6th cluster-9th cluster; ST phenological stage.

pH and 0.34 dS m^{-1} electrical conductivity. The ion concentrations (meq L^{-1}) Ca^{2+}, K^+, Mg^{2+}, $NH4^+$, NO_3^-, $H_2PO_4^-$, SO_4^{2-}, and HCO^{3-} were 0.8, 0.1, 1.2, 0.0, 0.0, 0.0, 0.1, and 3.2 respectively.

The irrigation was applied along with the nutrient solution through the drip system. EC and pH were monitored every 10 days. Six irrigations of 0.18 L were applied during the first 30 days after the transplant (dat); subsequently, eight irrigations of 0.480 L were applied during vegetative development. Afterwards, 11 irrigations of 1.650 L were applied at the beginning of the harvest (maximum peak demand). Finally, eight daily irrigations of 1.350 L per plant were applied during the final stage (Mendoza-Pérez *et al.*, 2018b).

Evaluated variables

In order to determine yield and number of fruits, eight plants per treatment were selected. Subsequently, the fruits were harvested as they ripened and weighted in a digital scale. Fruit size was determined based on their equatorial diameter and was measured with a digital caliper (RFAIKA model). The fruits were divided into five categories: extra-large (>71 mm), large (61-71 mm), medium-sized (51-60 mm), small (38-50 mm), and tiny (26-37 mm) according to the Mexican standard for tomato diameter (NMX-FF-031-1997).

Fruit firmness and color are two of the physical characteristics analyzed and was measured with a FDV30 texturometer (Greenwich, CT 06836, USA), which is equipped with an 8mm threaded pin. Two readings were taken from opposite sides of the equatorial region of the fruit and recording the values in Newtons (N). Fruit color was measured in the skin of the equatorial area using a colorimeter "HunterLab D25A®" (HunterLab Virginia, USA). Meanwhile, tomato biochemical components were also evaluated. Total soluble solids (°Brix) of tomato juice were measured with a digital refractometer Pr-100 (ATAGO, Guang-zhou, China).

In addition, EC and pH of tomato juice were measured with a potentiometer (Corning 12 Scientific Instruments, USA). Titratable acidity (TA) was measured by homogenizing 10 g of pulp in 50 mL of deionized water. Subsequently, a 10 mL aliquot was taken and neutralized with NaOH at 0.1 N using phenolphthalein as an indicator (AOAC, 2010); the results were recorded as a percentage of citric acid.

In order to estimate vitamin C (ascorbic acid) concentration, 20 g of fresh pulp was homogenized in 30 mL of oxalic acid solution (0.5%). Subsequently, a 5 mL aliquot was taken and it was titrated in a 2,6-dichloroindophenol standard solution (0.05 g/100 mL). In addition, ascorbic acid was used as pattern and the result was expressed as mg of ascorbic acid in 100 g of sample (AOAC, 2010). The maturity index was obtained from the ratio of total soluble solids (TSS) and the titratable acidity (TA).

Lycopene was estimated with the equation proposed by Arias *et al.* (2000), which used colorimetry data, such as L, a*, and b*. A colorimeter "HunterLab D25A®" (Virginia, Sunset Hills Rd, Reston, VA, USA) was used to obtain the data; which was also calibrated to determine the L, a*, and b* color measurements reported on the International Commission on Illumination (CIE). The lycopene content of the harvested fruits was calculated with Equation 1 described by Arias *et al.* (2000).

$$Lycopene\left(mg\,100g-1\right)=11.848*\left(a*/b*\right)+1.5471 \qquad \text{Equation (1)}$$

Statistical analysis

Analysis of variance and Tukey mean separation test were performed for all evaluated variables using Minitab statistical software (Minitab, 2017).

RESULTS AND DISCUSSION

Yield evaluation

T1 attained a yield of 28.59 kg m^{-2}. This result showed a positive response to the increase of the osmotic potential in nutrient solution during the stage of highest water and nutrient demand. Mendoza-Pérez *et al.* (2018b) reported a yield of 20 kg m^{-2} per plant on treatments with a single stem tomato and osmotic potential of −0.072 MPa. Meanwhile, Núñez-Ramírez *et al.* (2017) found a yield of 19.3-21.2 kg m^{-2} using different nitrogen fertilization rates.

Corella *et al.* (2013) reported a yield of 23.82 kg m^{-2} on six harvested clusters conducted on treatments with single stem. Espinosa-Espinosa-Palomeque *et al.* (2019) reported yields from 4.9 to 8.5 kg m^{-2} on plants with different nutrient solution concentrations. Plants on T2 recorded a total yield of 37.74 kg m^{-2}, of which, 23.76 kg m^{-2} were obtained from the main stem with 10 clusters and 13.98 kg m^{-2} from the secondary stem with 8 clusters. This treatment also showed a positive response to the increase of the osmotic potential. However, plants with a secondary stem produced more medium-sized fruits. This result was higher from that reported by Mendoza-Pérez *et al.* (2018b) who conducted plants with two stems and attained a yield of 18 kg m^{-2} on both stems. Meanwhile, Corella *et al.* (2013) reported a yield of 21.39 kg m^{-2} harvested from six clusters in two-stem tomato plants. According to these results, the plants had a positive effect on yield and fruit quality when the concentration of nutrient solution was enhanced during the stages of higher nutrient demand. In addition, management practices such as pruning or leaf removal at senescence were carried out simultaneously.

Number of fruits per cluster

T1 produced the greatest number of medium-sized fruits in the first two clusters. However, a greater quantity of large fruits was obtained from the third to the sixth cluster. Subsequently, the plant turned to produce more medium-sized fruits. A total of 86 fruits per plant were obtained: 37 large, 37 medium-sized, 10 small and 2 tiny fruits (Figure 1). This result is higher than that reported by Mendoza-Pérez *et al.* (2018a) who harvested 62 fruits per plant. Additionally, the maximum yield potential was recorded on the seventh and eighth clusters, obtaining 11 and 12 fruits per cluster respectively. According to these results, this response is a consequence of the increase of the osmotic potential (−0.096 MPa) of the nutrient solution and leaf pruning. The response of plants on this trial is attributed to the increase in the osmotic potential of nutrient solution (−0.096 MPa) and the pruning of leaves. It is observed that water and nutrients are transported to the young leaves influencing their development and fruit filling. On the other hand, Núñez-Ramírez

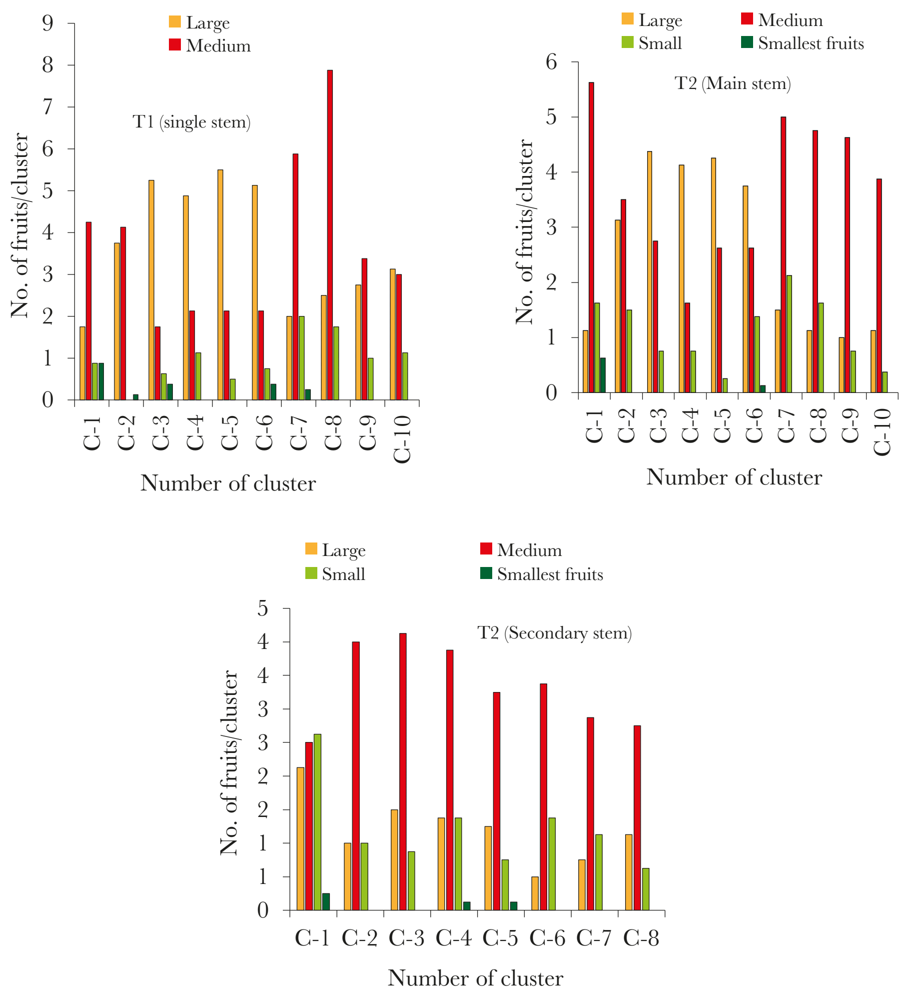

Figure 1. Number of fruits harvested from the treatments.

et al. (2017) found that the application of very high nitrogen rates on this crop increases the number of fruits, but the size of the fruits decreases.

It was found that a greater number of medium-sized fruits was harvested from the first two clusters of the main stem on T2. From the third to the sixth cluster, a greater number of large fruits were harvested and then the plant subsequently produced more medium-sized fruits. A total of 75 fruits per plants were harvested: 26 large, 37 medium-sized, 11 small, and 1 tiny. In that aspect, Mendoza-Pérez *et al.* (2018a) reported 78 fruits harvested from 10 clusters. They also observed that plants produced greater number of medium-sized fruits in all the clusters from the secondary stem of the same treatment. A total of 48 fruits were obtained: 10 large, 27 medium-sized, 10 small fruit, and 1 tiny. As previously observed, increasing the osmotic potential of the nutrient solution from -0.076 to -0.096 MPa during the fruiting stage of the sixth cluster also increased the number, size, and yield of both treatments. There was evidence that increasing the osmotic potential of the nutrient solution and removing the leaves during senescence enabled the transport of water and nutrients to the developing organs, which significantly contributed to the results obtained in this research. In that sense, Arébalo-Madrigal *et al.* (2018) reported that plants with single stem produce fruits with better quality indexes (weight and size), while two-stem or unpruned plants produce more fruits. Nevertheless, they do not reach the right size or desirable quality due to competition for sunlight, water, and nutrients.

Color

Color is a quality attribute of food that impacts the consumer acceptance, taste, and perception (Althaus and Blanke, 2021). The fruits recorded average hue values of 62.31 (very intense red). It also recorded a value of 30.62 for brightness and 24.64 chrome value, which indicated the purity of color. According to the intervals proposed by Cantwell *et al.* (2007), hue values from 35 to 40 match an intense red color, while brightness values from 39 to 41 belong to different tomato varieties (Table 1).

Physical characteristics of the fruits

According to firmness values, T1 recorded 4.42 N, while T2 obtained 4.13 N in the main stem treatments and 4.11 N in the secondary stem treatment. Mendoza-Pérez *et al.* (2018a) reported that single stem plants intercepted a higher amount of radiation than two-stem plants. This phenomenon favored the development of a thicker and more resistant cuticle, which protects fruits from direct damage of solar radiation, increasing their shelf life. The same authors reported 4.43 N for single stem plants and 4.19 N for two-stem plants (main and secondary stems). Whereas, Navarro-López *et al.* (2012) obtained 4.21 and 4.52 N firmness values.

Fruit size

T1 recorded the best fruit size, reaching 76, 19, 4, and 1% large, medium-sized, small, and tiny fruits respectively (Figure 2). The fruits obtained on this treatment attained the size established by the NMX-FF-031-1997 rule for export products. Núñez-Ramírez *et al.* (2017) recorded 28, 31, 23, and 18% extra-large, large, medium-sized, and small fruits, respectively. Meanwhile, Mendoza-Pérez *et al.* (2018b) obtained 68, 23, 8, and 1% large, medium-sized, small, and tiny fruits, respectively. Finally, Núñez-Ramírez *et al.* (2012) reported values of 20% extra-large, 24% large, 20% medium-sized, and 36% small fruits on single-stem globe tomato plants.

Table 2. Effect of the number of stems on tomato fruit color (Cid F1).

Treatments	Number of stems	Brightness (L)	Purity (chroma)	Hue
T1 (single stem)	Main stem	30.81 a	24.19 a	61.83 a
T2 (two stems)	Main stem	30.53 a	25.68 a	61.99 a
	Secondary stem	30.53 a	24.07 a	63.13 a
SD		0.16	0.90	0.71
CV (%)		0.53	3.64	1.14

SD=Standard deviation; CV=Coefficient of variation (%). Different letters in each column indicate significant differences ($p \leq 0.05$).

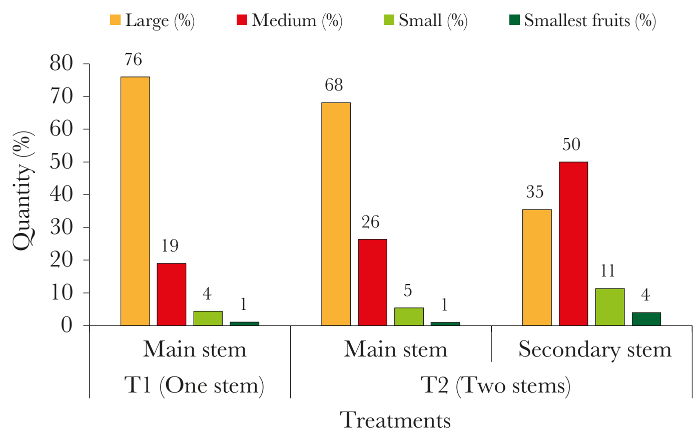

Figure 2. Quantity classification based on fruit size.

Plants with main stem on T2 recorded 68, 26, 5, and 1% large, medium-sized, small, and tiny fruits. The fruits obtained from this treatment are considered for export quality standards. Plants with secondary stem recorded 35, 50, 11, and 4% large, medium-sized, small, and tiny fruits, respectively. These fruits did not accomplish the export standards. In addition, the reduction on fruit size was mainly attributed to stem reduction, since its smaller diameter diminishes the vessel capacity to transport water and nutrients to the fruits. These results coincide with those of Mendoza-Pérez *et al.* (2018b), who reported 49, 33, 17, and 1% large, medium-sized, small, and tiny fruits. Villamán (2015) indicated that a second stem left in the plant competes for solar radiation, water, and nutrients and consequently affects the development of the main stem, causing a delay in maturity and harvest. Pruning plants with two-stems increases the number of medium-sized fruits. However, their quality is lower as compared to unpruned plants. This effect is due to the high demand for nutrients that plants require to nourish two stems and produce fruits.

Biochemical components

The total soluble solid values were of 4.33 °Brix for both treatments, without variations, despite the increase in the number of stems per plants (P 0.05) (Table 3). Navarro-López *et al.* (2012) reported that EC of 4.5 dS m^{-1} in the nutrient solution causes a reduction in the water flux transported to the fruit, leading to salinity stress. Tomato fruits under this type of stress mainly store ions and organic molecules (increase of fructose and glucose concentration) (Kubota, 2006). Pérez *et al.* (2016) recorded 5.1 °Brix values in single stem plants and 5.0 °Brix in two-stem plants with osmotic potential of −0.072 MPa in the Steiner nutrient solution. T1 recorded a titratable acidity of 0.38%; while T2 treatments recorded 0.45% and 0.46% for main and secondary stems (Table 3). In that aspect, Pérez *et al.* (2016) reported 0.8 and 1.0% titratable acidity for single and two-stem plants respectively.

Vitamin C values of 5.54 mg, 4.49 and 4.81 mg 100 g^{-1} ascorbic acid for T1 and T2 (main and secondary stem) (Table 3). These results are lower than the range found on 30 different varieties of cherry tomato (29-73 mg 100 g^{-1}) as reported by Ceballos-Aguirre *et al.* (2012) and to the interval of 6.1 to 16.1 mg 100 g^{-1} reported by Crisanto-Juárez *et*

Table 3. Total soluble solids, titratable acidity, vitamin C, and lycopene of the fruits.

Treatments	NS	Total soluble solids (°Brix)	Tritatable acidity (%)	Vitamin C (mg 100 g^{-1})	Lycopene (mg 100 g^{-1})
T1 (single stem)	TP	4.30 a	0.38 a	5.54 a	14.61 b
T2 (two stems)	TP	4.30 a	0.45 a	4.49 a	16.40 a
T2 (two stems)	TS	4.40 a	0.46 a	4.81 a	16.10 ab
SD		0.06	0.04	0.54	0.96
CV (%)		1.33	10.14	10.88	6.10

NS=Number of stems; SD=standard deviation; CV=coefficient of variation (%). Different letters in each column indicate significant differences ($p \leq 0.05$).

al. (2010) for different wild tomato varieties. Núñez-Ramírez *et al.* (2017) reported values of 0.32 and 0.35 g 100 g^{-1} of citric acid on tomato. This study recorded higher lycopene concentrations on T2 (main stem) with 16.40 mg 100 g^{-1}. No differences were found on treatments with the secondary stem (Table 3) but it was statistically different ($p<0.05$) with respect to T1.

The lycopene accumulation is related to the number of stems: as the number of stems increases, the leaves intercept more photosynthetic active radiation with respect to single stem plants (Mendoza-Pérez *et al.*, 2018b). Pérez *et al.* (2017) found 18.5 mg 100 g^{-1} lycopene values for the Cid F1 variety grown under greenhouse conditions. While, Luna-Guevara and Delgado-Alvarado (2014) found that temperature and light intensity directly influence lycopene accumulation.

The pH values of the juice were 4.40, 4.35, and 4.43 for T1 and T2 (main and secondary stems) (Table 4). If the osmotic potential increases above 2.5 dS m^{-1}, also increases electrical conductivity due to fertilizer accumulation in the substrate. Consequently, higher values can cause negative effects in the fruit quality variables, such as a reduction in fruit size and increase in pH of the juice. Pérez *et al.* (2016) and Mendoza-Pérez *et al.* (2018a) reported pH of 4.47 and 4.30 in tomatoes harvested from single stem and two-stem plants.

Electrical conductivity (EC) recorded 3.17 dS m^{-1} from the juice of fruits harvested from T1, 3.14 dS m^{-1} from the fruits of T2 (main stem) and 2.93 dS m^{-1} from the fruits of the secondary stem. These results are within the range reported by Barrera-Puga *et al.* (2011) who found values of 0.68-3.05 dS m^{-1} EC in tomato fruits.

The maturity index was 11.29 (T1), 9.91 and 9.8 for T2 (main and secondary stem). This index is directly related to quality, taste, firmness, and post-harvest period. Al-Yahyai *et al.* (2010) recorded 13.16 and 12.60 for the ratio of total soluble solids and titratable acidity with EC 6 and 9 dS m^{-1} EC of the nutrient solution.

The maturity index values found on this study are lower than those found by Al-Yahyai *et al.* (2010) and are attributed to a lower osmotic potential of nutrient solution applied (Table 4). Brasiliano *et al.* (2006) proved that the ratio of total soluble solids and titratable acidity can increase if saline irrigation water is used or if the plants are subjected to a moderate water stress.

Table 4. pH, electrical conductivity, and ripeness index of tomatoes.

Traeatments	Number of stems	pH	EC (dS m^{-1})	Maturity index
T1 (single stem)	Main stem	4.40 a	3.17 a	11.29 a
T2 (two stems)	Main stem	4.35 a	3.14 a	9.91 a
T2 (two stems)	Secondary stem	4.43 a	2.93 a	9.88 a
SD		0.04	0.13	0.81
CV (%)		0.92	4.25	7.78

SD=Standard deviation; CV=Coefficient of variation (%). Different letters in each column indicate significant differences ($p \leq 0.05$).

CONCLUSIONS

Increasing the osmotic potential of the nutrient solution during the stages of maximum water and nutrient demand and removing leaves during the senescence of Saladette tomatoes (var. Cid F1) enhanced the number, size, and yield of fruit. The biochemical components were not affected by increasing the osmotic potential or pruning the plants.

This increase lead to a reduction of fruit size, preventing tomatoes from reaching the right export size. It is advisable to adopt the practice of a single stem plants in order to produce larger tomatoes with quality export.

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