

SODIUM CHLORIDE AND SILICON AFFECT YIELD AND QUALITY OF TOMATO FRUITS

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) is a glycophyte species with medium sensitivity to salts, tolerating electrical conductivity values in the soil solution of up to 2.5 dS m⁻¹. Silicon (Si) is a beneficial element that can act as an inorganic biostimulant in plants subjected to salinity. In this research, the main effects of two study factors were evaluated: a) salinity by NaCl (0, 50, and 100 mM) in the nutrient solution and b) biostimulation by Si, applied to the leaves (0, 75, and 150 mg L⁻¹), as well as the interaction of both factors on yield and quality in fruits of the second cluster of tomato plants cv. Río Supremo grown hydroponically under greenhouse conditions. Yield was significantly reduced in the saline treatments, and was not affected by the application of silicon. Compared with the control, the NaCl concentrations evaluated reduced the fruit pH value by 6.2 %, but increased titratable acidity (TA) by 64.8 %, electrical conductivity (EC) by 72.9 %, and total soluble solids (TSS) by 80 %. Consequently, the NaCl treatments increased the TSS/TA ratio, compared to the control. The application of 75 mg Si L⁻¹ through the leaves reduced the pH of the fruit by 0.6 %, while the dose of 150 mg Si L⁻¹ increased the EC and the TSS/TA ratio in fruits. In plants treated with 50 mM NaCl and with both doses of Si, an increase in fruit pH was recorded, while treatments with 100 mM NaCl with both doses of Si significantly reduced the TA values. The TSS/TA ratio increased with both doses of Si in the treatments with 100 mM NaCl. It is concluded that the combination of saline treatments with silicon can improve some quality attributes of tomato cv. Río Supremo fruits.

Keywords: *Solanum lycopersicum* L., beneficial element, salinity, pH, titratable acidity, electrical conductivity.

INTRODUCTION

In Mexico, tomato (*Solanum lycopersicum* L.) production is of great economic importance, as it is cultivated in 27 states of the federation. Sinaloa is the main Mexican state producer and exporter of this vegetable, and concentrates 21 % of the total national production, with a production volume of 677 612 Mg. The states of San Luis Potosí, Michoacán, and Jalisco follow in importance with productions of 440 876,

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283 259, and 197 679 Mg, respectively. In 2021, Mexico advanced to ninth place as a tomato-producing country in the world, producing 3.3 million Mg, compared to 2015, the year it ranked tenth. This is because in the last ten years the average annual rate of production of this vegetable increased positively 1.8 % (SAGARPA, 2015; SIAP, 2021). In 2021, Mexico set a record in the export of red tomatoes, reaching a value of 829 million US dollars, which meant an increase of 5.1 % year-on-year (AMHPAC, 2021). However, tomato cultivation faces water supply problems for its production, and the level of salts in irrigation water has increased in recent years due to the effect of global climate change (Khamidov *et al.*, 2022).

The increase in salinity in irrigation water and cultivated land is a global phenomenon that is severely affecting agricultural production. It is estimated that in the world there are 831 million hectares with salinity problems (FAO, 2015). In Mexico, the northern and coastal states are the most affected by this stress factor. Salinization is a factor that most often occurs naturally, although it can also be caused by human activities. This phenomenon negatively affects the growth and development of crops, since the increase in the salt content in the root zone causes toxicity and imbalance of cations such as Na^+ , Ca^{2+} , and K^+ (Mata-Fernández *et al.*, 2014; CONAGUA, 2018).

To counteract the effects of abiotic stress factors such as salinity, inorganic biostimulants such as silicon (Si) are currently being used. Silicon is the second most abundant element on earth, it represents 28.8 % concentration in the earth's crust; it forms part of the soil and rock particles, in combination with oxygen, and in silicate metals. Si is also found in the soil solution, as silicic acid (H_4SiO_4). The application of Si has shown beneficial effects in various crops, mainly cereals, which are characterized for their ability to store Si both in vacuoles and in the cell wall. Plant species of the Poaceae and Cyperaceae families register the highest Si content, with values greater than 4 % on a dry matter basis. Likewise, it has been reported that Si mitigates negative effects caused by abiotic stress factors such as drought and salinity in plants (Bauer *et al.*, 2011; Hernández-Apaolaza, 2014; Dehghanipoodeh *et al.*, 2015; Weber *et al.*, 2018; Trejo-Téllez *et al.*, 2022). The supply of Si in tomato plants under boron (B) stress improves the average weight of the fruit (Kaya *et al.*, 2011). In cucumber plants (*Cucumis sativus*), the application of Si generated significant increases in fruit yield and higher dry matter and total soluble solids contents (Jarosz, 2013). Under saline stress conditions, Si increased the firmness and intensity of the green color of cucumber fruits (González-Terán *et al.*, 2020). The objective of this study was to evaluate the effects of leaf application of Si to tomato plants exposed to salinity, on the individual yield of the first three clusters and their accumulated yield, as well as on quality variables of the second cluster of fruits.

MATERIALS AND METHODS

Experiment location and experimental conditions

The experiment was carried out in a tunnel-type greenhouse with a zenith window, plastic cover and anti-aphid mesh on the side walls, in Montecillo, State of Mexico, at

19.46° north latitude, 98.90° west longitude, and 2250 m altitude. During the research, the mean daytime and nighttime temperatures were 31.7 and 15.1 °C. The relative humidity during the day was 30 %, and 87 % during the night. The duration of the photoperiod was, on average, 11.3 h with a mean light intensity of 137 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Plant material

Hybrid cv. Río Supremo tomato seedlings were used, of determined growth, obtained from seed sowing in 200-cavity trays with peatmoss (Premier Horticulture Inc., ProMix FLX, Canada) as substrate. For the treatment test, a hydroponic system was established in a greenhouse, with seedlings, 32 days after sowing (das), with five true leaves. The hydroponic system was established in black polyethylene bags, caliber 400, 30 x 30 x 30 cm, using local volcanic gravel known as tezontle as inert substrate, with a particle size between 5 and 6 mm. The characteristics of this substrate have been previously reported (Trejo-Téllez *et al.*, 2013).

Treatment design of and experimental design

To test the proposed treatments, a completely randomized experimental design was used in a 3² factorial arrangement. The first study factor was the concentration of sodium chloride (NaCl; Sigma Aldrich, St. Louis, MO, USA) added in the nutrient solution (NS) at three levels: 0, 50, and 100 mM, corresponding to electrical conductivities of 2, 7, and 12 dS m⁻¹ considering the composition of the NS. Steiner's universal solution was used (Steiner, 1984). The second study factor was the foliar application of Si, from SiO₂ (Sigma Aldrich, St. Louis, MO, USA) at three levels: 0, 75, and 150 mg L⁻¹. By combining the factors with the evaluated levels, nine treatments were obtained, each with nine replicates. The experimental unit consisted of a single plant 61 days after sowing, transplanted into a black polyethylene bag to support the plant material. The plants were staked with agricultural black raffia and axillary buds were pruned to bring them to a single stem.

The experimental units were placed in the greenhouse at a distance of 0.3 m between plants and 0.8 m between rows. The addition of NaCl concentrations to the nutrient solution started 61 das. Irrigation was carried out using a spaghetti drip system. For this, nine 200 L tanks were placed, each container had a 0.5 HP pump, a PVC branch with a return to the tank, regulated with a valve and with an outlet with a ring filter, which connected with the primary conduit (16 mm diameter black agricultural hose). This conduction line contained four crossheads that connected to four pipes, each ending in a stake. Five 1-min irrigations per day were carried out (from 07:00 to 19:00 h, every 3 h), with a volume of 100 mL per stake.

Foliar sprays with Si started 62 das. All the applications were made at 06:00 h, spraying the plants up to the point of dripping, with an average solution volume of 50 mL per plant. For greater adherence of the sprayed solution to the leaf blade, Tween® 20 surfactant (SigmaAldrich, St. Louis, MO, USA) was added at a concentration of 0.5 g L⁻¹. A total of eight leaf applications were made at intervals of 10 days among applications. The pH of the sprayed solutions was adjusted to 4. The experiment lasted 80 days, that is, the plants reached 142 das.

Evaluated variables

The individual yield of the first three clusters and their accumulated yield were evaluated, harvesting the fruits in the state of maturity known as red according to UPOV (2001). The quality variables were evaluated only in fruits of the second cluster with the degree of maturity described above.

In the fruit juice, obtained with an extractor (Hamilton Beach, 67606-MX, China), pH and electrical conductivity (EC) were determined using a portable meter (Conductronic PC18, Puebla, Mexico). Titratable acidity (TA) was also determined, using the methodology proposed by AOAC (1990), taking 5 mL of the juice that was brought to volume to 50 mL with deionized water. From this solution, a 10 mL aliquot was taken and titrated with 0.01 N NaOH. The percentage of acidity, based on citric acid, was calculated with the following formula: citric acid (%) = [(mL spent NaOH) (N NaOH) (meq of citric acid) (V) (100)] / [(sample weight) (aliquot)]; where: N = normality of NaOH; meq = milliequivalents of the acid found in the highest proportion in the fruit, which is citric acid = 0.064; V = total volume.

Total soluble solids (TSS) were measured with a digital refractometer (ATAGO, PR-100 0-32; Tokyo, Japan), placing a drop of juice in the reading cell of the device. The relationship of TSS and TA was determined by dividing the TSS value by the TA value.

Statistical analysis

With the results obtained, analyses of variance and comparison of means tests (Tukey, $p \leq 0.05$) were performed with the SAS software (SAS Institute, 2011).

RESULTS AND DISCUSSION

Yield

The yield of the three clusters and the accumulated yield was significantly influenced by the NaCl factor; although not so by the Si factor. The interaction of the study factors NaCl $\times$ Si had an influence on the yield of the third cluster (Table 1).

Table 1. Significance of the study factors NaCl, Si, and their interactions, on the yield of three clusters of fruits and accumulated yield in tomato (*Solanum lycopersicum*) cv. Río Supremo plants.

Source of variation	Yield			
	First cluster	Second cluster	Third cluster	Three-clusters accumulated
NaCl	<0.0001 *	<0.0001 *	<0.0001 *	<0.0001 *
Si	0.8265 ns	0.8105 ns	0.1185 ns	0.6609 ns
NaCl $\times$ Si	0.3527 ns	0.9226 ns	0.0002 *	0.6598 ns

* = significant ($p \leq 0.05$); ns = not significant ($p > 0.05$).

The absence of effect from Si on tomato yield observed in this study (Table 1) coincides with that reported in wheat (*Triticum aestivum*), a crop in which foliar applications of Si did not affect yield or grain quality in five cultivars analyzed (Segalín *et al.*, 2013).

Significant effects of NaCl on performance. Compared to the control, the applications of 50 and 100 mM NaCl decreased the yield of the first cluster by 63.8 and 81 %, respectively; the decreases in the second cluster were 70 and 80.7 %; while, in the third cluster, they were 60.9 and 88.8 %, respectively (Figure 1A). In the accumulated yield of the three clusters, the reduction was 64.6 and 84.1 % with the addition of 50 and 100 mM NaCl, respectively, compared to the control (Figure 1B). These results coincide with those obtained in a similar study, where four tomato races (Campeche, Oaxaca, Puebla, and Veracruz) and a commercial hybrid (Vengador) were treated with four salinity levels (0, 30, 60, and 90 mM NaCl), and resulted in that the yield per plant decreased for the four races and the hybrid with increasing salinity levels (Ladewig *et al.*, 2021). In watermelon (*Citrullus lanatus*), the application of saline solutions from 2.0 to 5.2 dS m⁻¹ decreased the average fruit weight and total yield (Colla *et al.*, 2006). In chili (*Capsicum annuum*), saline applications of 4 and 8 dS m⁻¹ decreased the fresh weight of the fruit (Grimaldo-Pantoja *et al.*, 2017). Lines of common bean (*Phaseolus vulgaris*) evaluated in saline soil with an EC value of 5.8 dS m⁻¹, reduced the number of pods and grains per plant, which was attributed to the involvement of biochemical pathways in physiological processes, as well as to changes in the concentration and in the relationship of endogenous hormones that intervene in plant growth and development (López-Sánchez *et al.*, 2018).

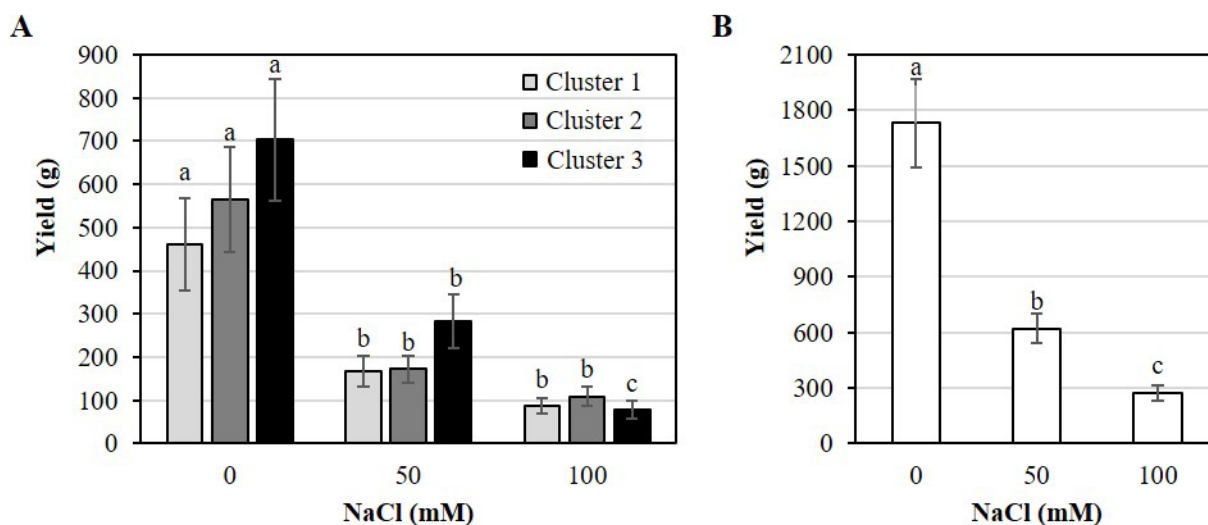


Figure 1. Yield per cluster (A) and accumulated yield of three clusters (B) in tomato plants (*Solanum lycopersicum*) cv. Río Supremo treated with different concentrations of NaCl. Yield means per cluster and accumulated $\pm$ SD with different letters indicate significant statistical differences (Tukey, $p \leq 0.05$).

Significant effects of the NaCl × Si interaction on yield. The yield of the third cluster was reduced due to the interaction of the study factors (Figure 2). In the absence of salt, Si reduced yield. In the rest of the salinity levels, there were no differences among treatments from the addition of Si (Figure 2). Several studies show the beneficial influence of Si on the yield of tomato plants when they are subjected to some type of stress (Toresano-Sánchez *et al.*, 2012; Jarosz, 2014). In our study, the addition of 150 mg Si L⁻¹ in plants exposed to 50 mM NaCl tended to increase this parameter, although the differences were not significant.

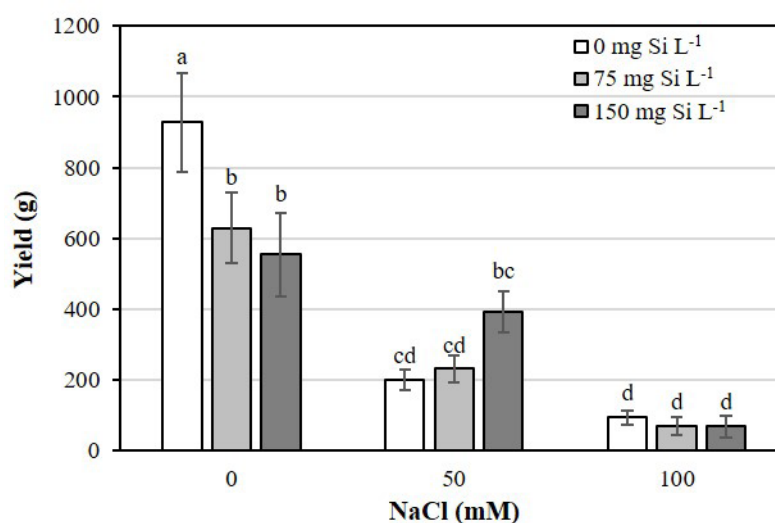


Figure 2. Yield of the third cluster of tomato (*Solanum lycopersicum*) cv. Río Supremo plants treated with different concentrations of NaCl and Si. Means ± SD with different letters indicate statistically significant differences (Tukey, $p \leq 0.05$).

Fruit quality

The NaCl factor and its interaction with Si had significant effects on all the fruit quality parameters evaluated. As an individual factor, the leaf application of Si only affected the values of pH, EC and TSS/TA ratio (Table 2).

Table 2. Significance of the study factors NaCl, Si, and their interactions, on the chemical properties of fruit quality evaluated in tomato (*Solanum lycopersicum*) cv. Río Supremo.

Source of variation	pH	EC	TSS	TA	TSS/TA
NaCl	<0.0001 *	<0.0001 *	<0.0001 *	<0.0001 *	<0.0001 *
Si	0.0017 *	0.0001 *	0.8497 ns	0.2828 ns	0.0344 *
NaCl × Si	<0.0001 *	<0.0001 *	<0.0001 *	<0.0001 *	<0.0001 *

* = significant ($p \leq 0.05$); ns = not significant ($p > 0.05$). EC: electrical conductivity; TSS: total soluble solids; TA: titratable acidity.

Significant effects of NaCl on fruit quality. Some tomato fruit quality indicators are positively affected when plants are exposed to saline stress (Zhang *et al.*, 2016). In this study, the pH of the fruit was reduced with the salinity doses evaluated (Table 3). Tomato fruits produced for the industry must have a value of pH of 4.4 to inactivate pathogenic microorganisms (Villegas-Espinoza *et al.*, 2018). In our study, the pH values of the fruits were lower than those reported, which is indicative of higher quality and possible longer shelf life.

Table 3. Main effect of the NaCl study factor on the chemical properties of fruit quality evaluated in tomato (*Solanum lycopersicum*) cv. Río Supremo.

NaCl (mM)	pH	EC (dS m ⁻¹)	TSS (°Brix)	TA (% citric acid)	TSS/TA ratio
0	4.17 ± 0.015 a	5.12 ± 0.078 b	4.99 ± 0.069 c	0.44 ± 0.027 b	11.65 ± 0.420 b
50	4.05 ± 0.032 b	8.91 ± 0.593 a	9.17 ± 0.411 a	0.72 ± 0.045 a	13.05 ± 0.285 a
100	4.03 ± 0.018 b	8.80 ± 0.570 a	8.81 ± 0.482 b	0.73 ± 0.082 a	12.52 ± 0.695 a

Means ± SD with different letters in each column indicate statistical differences among treatments (Tukey, $p \leq 0.05$). EC: electrical conductivity; TSS: total soluble solids; AT: titratable acidity.

The applications of 50 and 100 mM NaCl increased the EC of the juice by 74 and 71.9 % with respect to the control. There were also increases of 83.8 and 76.6 % in the TSS, with respect to the control. The addition of NaCl to the nutrient solution also increased the TSS/TA ratio on average by 9.7 %, with respect to the control (Table 3). These results are consistent with what has been reported by other investigations (Li *et al.*, 2001; Liu *et al.*, 2014; Zushi and Matsuzoe, 2015; Zhang *et al.*, 2016; Villegas-Espinoza *et al.*, 2018). As a consequence of the high concentration of salts in the roots (osmotic effect), the flow of water to the aboveground parts is inhibited and the concentration of carbohydrates (total soluble solids) is increased, in order to reduce the oxidative stress caused by the lack of water in cells (Zahra *et al.*, 2011). Moderate salinity promotes the activity of the enzyme sucrose invertase that allows the release of hexoses during ripening, which results in a greater accumulation of sugars in the fruit (Lu *et al.*, 2012; Moles *et al.*, 2019). Due to reduced water transport caused by salinity, plants increase the production of organic acids (oxaloacetic and α -ketoglutaric), in order to synthesize amino acids such as glutamate, asparagine, γ -aminobutyric (GABA) and proline, which carry out an antioxidant and osmoprotective function (Sato *et al.*, 2006). Applications of NaCl increased the acidity of tomato juice by an average of 64.8 %, compared to the control (Table 3). Increased acidity is a common response to salinity, since it promotes the activity of the Krebs cycle (Zushi and Matsuzoe, 2015).

Significant effects of Si on fruit quality. Fruit quality is critically affected by pH, since it can inactivate spoilage pathogens and decrease the respiration rate, which prolongs the shelf life of the fruit (Turhan *et al.*, 2011; Tigist *et al.*, 2013). The leaf application of

75 mg Si L⁻¹ significantly decreased the pH of the fruit juice by 0.6 %, compared to the control (Table 4). The pH range obtained in our study oscillated between 4.08 and 4.10, lower values than those reported in tomato by various authors: 4.12-4.35 (Turhan *et al.*, 2011), 4.21-4.80 (Giannakoula and Ilias, 2013), and 4.09-4.21 (Korkmaz *et al.*, 2018). In chili, the treatment with Si causes fruit pH ranges from 5.53 to 5.70 (Jayawardana *et al.*, 2014) and in cucumber from 5.21 to 5.23 (González-Terán *et al.*, 2020). Similarly, the 150 mg Si L⁻¹ dose decreased the electrical conductivity of the fruit by 6.1 %, compared to the control (Table 4). This trend was also observed in aloe vera (*Aloe barbadensis*) (Xu *et al.*, 2015) and in cucumber (González-Terán *et al.*, 2020).

Table 4. Main effect of the study factor Si on the chemical properties of fruit quality evaluated in tomato (*Solanum lycopersicum*) cv. Río Supremo.

Si (mg L ⁻¹)	pH	EC (dS m ⁻¹)	TSS/TA ratio
0	4.10 ± 0.044 a	7.6 ± 1.096 a	12.03 ± 0.609 b
75	4.08 ± 0.042 b	7.6 ± 1.040 a	12.17 ± 0.389 ab
150	4.09 ± 0.059 ab	7.1 ± 1.223 b	12.55 ± 0.330 a

Means ± SD with different letters in each column indicate statistical differences among treatments (Tukey, $p \leq 0.05$). EC = electrical conductivity; TSS = total soluble solids; TA = titratable acidity.

The addition of Si to plants under salt stress adjusts the osmotic potential of the cells through a greater accumulation of osmolytes such as inorganic ions, soluble sugars, and proline (Coskun *et al.*, 2016). The leaf application of 150 mg L⁻¹ Si increased the TSS/TA ratio by 4.3 %, with respect to the control (Table 4). Similar effects were found in tomato (Stamatakis *et al.*, 2003; Iglesias *et al.*, 2015) and strawberry (*Fragaria × ananassa*) (Weber *et al.*, 2018). On the contrary, in four varieties of mango (*Mangifera indica*), the application of 1.5 mM Si significantly increased the TA of the fruits, but did not affect the TSS content (Helaly *et al.*, 2017). Meanwhile, the application of 50 and 100 mg Si L⁻¹ to seedlings of two tomato varieties caused significant reductions in the TSS and TA values (Weerahewa and David, 2015). In cherry tomato cv. Unicorn fruits treated with 20 mM Si, a decrease in TSS and an increase in TA were observed (Islam *et al.*, 2018).

Significant effects of the NaCl × Si interaction on fruit quality. The effects of the interaction of the study factors NaCl and Si show significant trends in the evaluated fruit quality parameters (Figures 3 and 4). On the one hand, the higher Si dose evaluated increases the pH of fruits of plants without salinity stress by 1.3 % compared to the treatment without Si and without salinity (Figure 3A). However, in the absence of salinity, the titratable acidity increased significantly with the treatments with 75 and 150 mg Si L⁻¹ (Figure 3B). This effect was similar to that reported by Baninaiem *et al.* (2016), when applying 1 to 4 mM Si in tomato cv. Baraka. In our study, the titratable

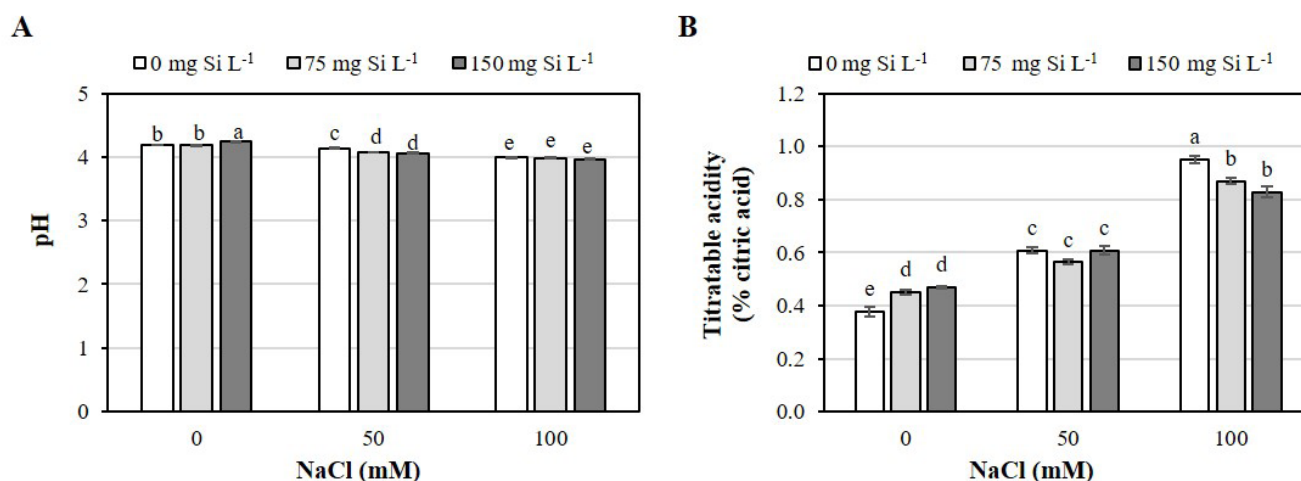


Figure 3. Effects of the interaction of the study factors (NaCl × Si) on the pH value (A) and titratable acidity (B) in tomato (*Solanum lycopersicum*) cv. Río Supremo. Means ± SD with different letters in each subfigure indicate statistical differences among treatments (Tukey, $p \leq 0.05$).

acidity was significantly reduced in plants treated with 100 mM NaCl, in the presence of 75 and 100 mg L⁻¹ Si (Figure 3B). An opposite effect was reported in tomato plants irrigated with saline water (12 dS m⁻¹) when applying up to 400 ppm K₂SiO₃, which increased TA values (Elkhatib *et al.*, 2017).

In the present study, plants treated with 50 mM NaCl and sprayed with 75 or 150 mg L⁻¹ produced fruits with pH values 1.6 % lower than those observed in the fruits of plants exposed to 50 mM NaCl without Si (Figure 3A).

In plants treated with 150 mg Si L⁻¹ and 50 mM NaCl, the electrical conductivity of the fruits was reduced by 13.4 %, compared to the treatment without Si and with 50 mM NaCl (Figure 4A). Likewise, in the absence of salinity, leaf treatment with 150 mg Si L⁻¹ increased TSS concentration in fruits by 14.1 % (Figure 4B). This effect was also observed by Jarosz (2013) in cucumber cv. Unicum grown in substrate (peat-sand) when adding 750 mg Si L⁻¹ in the nutrient solution. The TSS were not influenced by the addition of Si with the levels of 50 and 100 mM NaCl (Figure 4B), which agrees with the reports by Korkmaz *et al.* (2018) and Costan *et al.* (2019) in tomato, and those of Tabatabaei (2016) in strawberry.

The TSS/TA ratio is an indicator of sensory quality (taste) in fruit (Mikulic-Petkovsek *et al.*, 2012; Weber *et al.*, 2018). In this study, both levels of Si (75 and 150 mg Si L⁻¹) in combination with high salinity (100 mM NaCl) increase the value of the TSS/TA ratio by an average of 12.8 % compared to the control treatment without NaCl and without Si (Figure 5). This may be due to the fact that salinity reduces the amount of water in the fruit and Si limits the portion of water that passes through the root via apoplastic pathway, which reduces the entry of Na⁺ (Stamatakis *et al.*, 2003; Wasti *et al.*, 2017), and generates a greater accumulation of TSS in the fruit (Qin *et al.*, 2016).

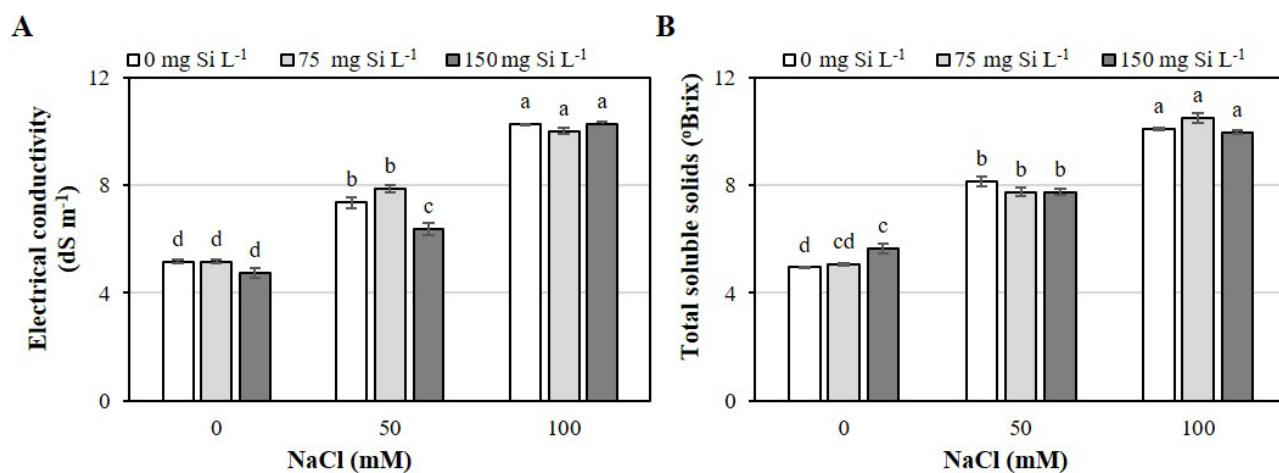


Figure 4. Effects of the interaction of the study factors (NaCl × Si) on electrical conductivity (A) and total soluble solids (B) in tomato (*Solanum lycopersicum*) cv. Río Supremo. Means ± SD with different letters in each subfigure indicate statistical differences among treatments (Tukey, $p \leq 0.05$).

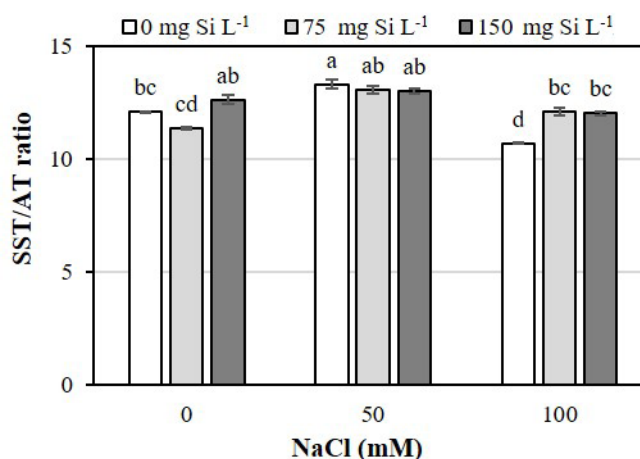


Figure 5. Effects of the interaction of the study factors (NaCl × Si) on electrical conductivity (A) and total soluble solids (B) in tomato (*Solanum lycopersicum*) cv. Río Supremo. Means ± SD with different letters indicate statistical differences among treatments (Tukey, $p \leq 0.05$).

CONCLUSIONS

As individual factors, sodium chloride (NaCl) reduced tomato fruit yield, but silicon (Si) did not affect this parameter. The interaction of both factors decreased yield only in the third cluster evaluated. The quality variables were differentially affected by the NaCl levels tested, with beneficial effects on electrical conductivity and concentration

of total soluble solids. Foliar Si applications increased the TSS/TA ratio. The interaction of the factors showed that the effects of foliar Si applications are dependent on saline treatments. It is concluded that, under salinity conditions, the application of Si improves tomato quality attributes, at the expense of yield.

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