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Silicon and titanium affect the percentage of juice and color attributes in tomato fruits of plants exposed to salt stress

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ABSTRACT

Objective: To evaluate the leaf application of silicon (Si) and titanium (Ti) in three doses (0, 75, and 150 mg L^{-1}), independently, on tomato plants cv. Río Supremo, subjected to saline stress (0, 50, and 100 mM NaCl), on the percentage of juice and color attributes of the fruit.

Design/methodology/approach: Two independent essays were carried out under a completely randomized experimental design in a 3^2 factorial arrangement, where the first study factor was the NaCl concentration in the nutrient solution and the second factor was the leaf application of Si or Ti. The percentage of juice and color attributes in fruits were determined. An analysis of variance and the comparison of means by Tukey ($p \leq 0.05$) with the SAS software were performed.

Results: Salinity was found to reduce the percentage of juice, the color index, and the ratio of "a/b" indexes. Regarding the interactive effects, NaCl with both Ti and Si increases the "b" index. Leaf applications of Si increased the "b" index and reduced the percentage of juice, the color index, and the ratio of "a/b" indexes. Also, Ti improved the color index and the "b" index.

Limitations of the study/implications: The results were obtained in the Río Supremo tomato variety under greenhouse conditions. Other varieties should be tested too.

Findings/conclusions: Si and Ti applied to the leaves have positive effects on the color of the fruits of tomato plants under saline stress.

Keywords: beneficial elements, inorganic biostimulants, saline stress, quality of *Solanum lycopersicum* fruits.

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INTRODUCTION

In 2018, the global area of saline soils was 397 million ha; of which, 45 million ha were irrigated soils affected by salinity, which represented a third of those used for food production [1]. In 2022, 833 million ha of soils with saline problems were estimated, which represents 8.7% of the Earth's soil, most of which are found in arid and semi-arid

zones. Similarly, between 20 and 50% of irrigated soils located on all continents are highly saline [2]. In the Americas, the total area devoted to crops is approximately 3.9 million, 65.1% of which has salinity problems [3]. In Mexico, this problem has increased due to the high rates of evaporation in shallow groundwater areas, the use of brackish irrigation water, saline intrusion into the groundwater table in coastal areas (50 in total), the over exploitation of 157 aquifers, and the effects of climate change [4, 5].

Excess salts in the soil are a stress factor that affects metabolic processes in the plant, since the osmotic pressure generated in the rhizosphere induces less water absorption, causing ionic and nutritional imbalances. The excessive accumulation of sodium and chloride in the cytosol increases oxidative stress, interferes with the absorption of potassium and calcium, in addition to unbalancing the absorption and translocation of nitrate [1], all of which negatively affects crop growth and development, in addition to limiting production and reducing yield [6].

Tomato has a medium tolerance to salinity. Because it is a glycophyte species, it supports electrical conductivities no greater than 2.5 dS m^{-1}. Salinity affects seed germination, reduces lateral and vertical elongation of the root, induces a decrease in bioactive compounds and antioxidant capacity, reduces chlorophyll content, photosynthetic capacity, and decreases the size and number of fruits. However, salinity may improve organoleptic attributes by increasing organic acids and sugars [7-10].

Both Si and Ti are non-essential elements with the ability to promote growth and development of plants, thus they are classified as biostimulants within the group of inorganic compounds. Biostimulants are materials that, in small quantities, stimulate nutritional absorption, increase tolerance to abiotic stress, and improve the quality of crops. Biostimulation is an integral process in crop systems that has gained momentum in recent years, by optimizing production through physiological adjudgments of plants [11, 12].

Si is one of the most abundant elements in the Earth's crust (second only after oxygen) with 27% of its composition. Various investigations have shown its beneficial role in alleviating the negative effects of abiotic stress factors. In addition, Si may constitute between 0.1 and 10% of the plant biomass in dry basis [13, 14]. In tomato plants, it induced tolerance to *Orobanche ramosa* infections [15], improved commercial yield and fruit quality [16], as well as postharvest quality [17]. In avocado (*Persea americana*) trees, K_2SiO_3 applications improved fruit quality and yield [18]. Also, foliar applications of K_2SiO_3 in loquat (*Eriobotrya japonica* Lind.) trees increased fruit set, as well as number, weight, and quality of the fruits [19].

Ti ranks ninth in the Earth's crust with 0.56%. In strawberry (*Fragaria* × *ananassa*) cvs. Selva and Elkat, Ti increased antioxidant capacity, while in the cv. Daewang it improved yield and fruit quality [20, 21]. In peach (*Prunus persica*) cv. Sevilla II and nectarine (*Prunus persica* var. *nucipersica*) cv. Silver King, Ti increased fruit growth and firmness at harvest [22]. In okra (*Abelmoschus esculentus*), it positively influenced germination and chlorophyll content [23]. Furthermore, Ti improved fruit quality characteristics such as the relationship between total soluble solids and titratable acidity (TSS/TA) in tomato cv. Río Supremo [24]. The objective of this study was to evaluate the independent leaf application of Si and

Ti in three doses (0, 75, and 150 mg L^{-1}), to tomato plants cv. Río Supremo, subjected to saline stress (0, 50, and 100 mM NaCl), on fruit quality variables.

MATERIALS AND METHODS

Experimental conditions and plant material

The experiments were carried out in a tunnel-type greenhouse with an anti-aphid mesh and a plastic cover with a roof window. Using a Data Logger (Onset Hobo), the following climatic variables were measured: the mean daytime and nighttime temperatures (31.7 and 15.1 °C, respectively), relative humidity during the day and night (30 and 86.9%), as well as the duration of the photoperiod; it was an average of 11.3 h with a mean light intensity of 137 μmol m^{-2} s^{-1}. Seeds of hybrid tomato cv. Río Supremo of determined size were sown in trays of 200 cavities with peatmoss as substrate. Seedlings, 32 days after sowing (das), were transplanted into 400-gauge black polyethylene bags (30×30×30 cm) containing the local volcanic gravel tezontle as a substrate (particle size ≤ 6 mm).

Design of treatments and experimental design

Two essays were established with a completely randomized experimental design in a 3^2 factorial arrangement. The first study factor was the NaCl concentration in the nutrient solution with three levels (0, 50, and 100 mM NaCl). The nutrient solution (NS) used was the Steiner's universal [25]. The leaf application of Si or Ti was supplied from SiO_2 and TiO_2 (Sigma Aldrich®, St. Louis, MO, USA) respectively, at three levels each: 0, 75, and 150 mg L^{-1}. Si or Ti were considered as the second study factor. With the combination of factors and levels, nine treatments were obtained in each trial, and each treatment had three replicates. The experimental unit consisted of a 61 das plant transplanted in a black polyethylene bag.

An experiment with a spaghetti drip irrigation system was established; for this, nine 200 L tanks were placed, each container had a ½ HP pump, a PVC branch with a return to the tank regulated with a valve and an outlet line with a ring filter, which was connected to a 16 mm black agricultural hose with three drippers per container. Each dripper had a crosshead for four tubes and each tube with a stake that went directly to the experimental unit.

The leaf sprays with Si and Ti for each experiment began 62 das in the morning (6:00 h). For greater adherence of the sprayed solution to the leaf blade, the Tween™ 20 surfactant (Hycel; Gualajara, Mexico) was added at a concentration of 0.5 g L^{-1}. Eight leaf applications were carried out at intervals of 10 days between one and the next applications.

Variables evaluated

The quality variables were evaluated in fruits of the second bunch in the state of maturity known as "red" according to UPOV [26]. Whole fruit weight was determined using an analytical scale (ADAM, model CQT1501, Kingston, UK). Subsequently, the tomato juice was obtained with an extractor (Hamilton Beach, model: 67606-MX, China) and the percentage of the total fruit weight that corresponded to the juice was estimated.

The color indexes, "a" and "b", were obtained using a colorimeter (Hunter Lab, model D25-PC2, Reston, VA, USA). The measurement was determined at two opposite points of the equatorial zone of each fruit. The ratio of the "a/b" indexes was calculated with the data obtained from the colorimeter as proposed by Domene and Segura [27].

Statistical analysis

With the results obtained, analysis of variance and Tukey's means comparison tests ($p \leq 0.05$) were performed, using the SAS software [28].

RESULTS AND DISCUSSION

NaCl and Si in juice percentage and color parameters of tomato fruits

Juice percentage. Crops affected by salinity show osmotic stress at the root level; that is, high salt concentrations in the soil solution reduce the water potential in the rhizosphere of the plant, causing less water absorption and water deficit in its organs [29]. In this study, NaCl significantly affected the percentage of fruit juice, which decreased by 24.2 and 20.9% with the addition of 50 and 100 mM NaCl, respectively, compared to the control (Table 1).

The absorbed Si tends to be deposited in leaf cells; this deposition has been observed in the cell wall of guard cells, causing slight deformations and structural changes that affect the opening of the stomata, reducing conductance and transpiration flow [30, 31]. It is possible that the doses used in this research affected the moisture content of the plant, as well as that of the fruits, as it was observed that the 75 and 150 mg Si L^{-1} doses decreased the percentage of juice in fruits; however, only the 12.7% decrease with the 75 mg Si L^{-1} dose was significant compared to the control (Table 1). These results are not consistent with those of other studies. For example, in orange (*Citrus sinensis*) cv. Olinda Valencia treated with K_2SiO_3 in doses of 2 and 4%, the fruits showed higher juice content at harvest time, compared to control [32]; and in 40-year-old pomegranate (*Punica granatum*) trees cv. Manfalouty, where the juice percentage was higher when leaf doses were applied with 0.5 and 1% of K_2SiO_3, compared to the control [33].

The interactive effect of the study factors was significant; the doses with Si decreased the juice percentage even in combination with NaCl compared to the treatment without NaCl and without Si (Table 1).

Color Index (CI). The color of fruits is associated with organoleptic characteristics such as aroma, flavor, and texture. These sensory properties are indicators of freshness and quality, which determine if the consumer's preferences [34]. CI values between 20 and 40 indicate that the fruit is in a coloration from "orange" to "dark red" [27]. In this research, the results obtained exceeded this interval (both treatments and the control). Nevertheless, 50 and 100 mM NaCl were significantly lower, by 50.9 and 41.8% when compared to the control (Table 1). The application of 75 and 150 mg Si L^{-1} decreased the CI of the fruits by 13 and 16%, respectively, compared to the control. However, only the high dose of Si was significant. In the interactive effect, there were no significant differences among treatments tested (Table 1).

Table 1. Main effects and interaction of NaCl and Si on the juice percentage and color parameters of tomato (*Solanum lycopersicum*) cv. Río Supremo.

NaCl (mM)	Juice (%)	Color Index	"a" Index	"b" Index	"a/b" Index Ratio
0	57.4±5.9 a	70.5±6.22 a	35.6±3.6 a	17.7±0.9 a	2.0±0.27 a
50	43.5±4.4 b	34.6±6.70 b	19.6±3.9 c	17.6±2.4 a	1.2±0.28 b
100	45.4±4.8 b	41.0±1.85 b	25.0±1.1 b	17.6±1.6 a	1.4±0.13 b
Si (mg L^{-1})	**Juice (%)**	**Color Index**	**"a" Index**	**"b" Index**	**"a/b" Index Ratio**
0	52.1±7.7 a	53.9±8.2 a	29.8±3.5 a	16.2±1.6 b	1.8±0.21 a
75	45.5±6.0 b	46.9±7.6 ab	25.4±3.8 a	17.5±1.2 ab	1.4±0.23 b
150	48.7±2.5 ab	45.3±12.0 b	25.1±5.8 a	19.1±2.1 a	1.4±0.36 b
NaCl (mM) - Si (mg L^{-1})	**Juice (%)**	**Color Index**	**"a" Index**	**"b" Index**	**"a/b" Index Ratio**
0-0	70.7±3.2 a	75.7±3.4 a	39.0±1.8 a	16.9±0.5 ab	2.31±0.18 a
0-75	54.3±4.1 b	62.8±8.4 a	31.7±5.0 abc	18.8±1.1 ab	1.75±0.34 abc
0-150	47.0±1.9 bc	73.0±4.5 a	36.3±2.7 ab	17.3±0.7 ab	2.12±0.23 ab
50-0	45.3±3.2 bc	44.0±1.0 b	24.3±0.7 cde	13.7±0.9 b	1.78±0.09 abc
50-75	37.1±5.5 c	35.0±1.4 bc	20.0±1.4 de	17.0±0.5 ab	1.18±0.09 d
50-150	48.1±2.6 bc	24.9±9.7 c	14.6±5.9 e	22.0±2.9 a	0.80±0.31 d
100-0	40.1±4.6 bc	42.0±0.5 bc	26.0±0.6 bcd	18.0±2.1 ab	1.48±0.12 bcd
100-75	45.1±5.5 bc	43.0±1.3 bc	24.5±1.2 cde	16.8±1.6 ab	1.48±0.11 bcd
100-150	51.0±2.9 bc	38.0±2.3 bc	24.5±1.5 cde	18.0±1.4 ab	1.40±0.16 bcd

Means±SD with different letters in each column and study factor indicate significant statistical differences (Tukey, $p \leq 0.05$).

"a" Index. In this study, the treatments with NaCl (50 and 100 mM) significantly reduced the "a" index of the fruits (44.9 and 29.8% with respect to the control). That is, the fruits of plants without saline treatment showed the highest value of index "a" (35.6), and this value was 34.8% higher than 26.4 (referred to the "bright red" color), so they enter the classification of "dark red" [35]. With the saline treatments, the values obtained in index "a" were 20 (50 mM NaCl) and 25 (100 mM NaCl), which were within the rage of "bright red" classification. The independent effect of Si and the interactive effects of the study factors (NaCl×Si) were not significant for this variable (Table 1).

"b" Index. For the "b" index, values below 20.7 (classified as "dark red") are considered ripe fruits with acceptable quality [35]. In this study, the treatment without Si (control) showed the lowest value of the "b" index (16.2), which is less than 20.7 by 21.7%. The doses of Si applied to the leaves progressively increased the variable with means of 17.5 (75 mg Si L^{-1}) and 19.1 (150 mg Si L^{-1}) which meant an increase of 8 and 17.9%, where only the high dose of Si (150 mg L^{-1}) had a significant difference with the control. Although these values are still below the "dark red" classification, it can be seen that Si improved this variable. The independent effect of NaCl and the interactive effects of the study factors (NaCl×Si) were not significant for the variable (Table 1).

Ratio of the "a/b" indexes. The ratio between the "a" and "b" indexes was significantly affected by salinity, since the 50 and 100 mM NaCl doses decreased this ratio by 40 and 30%, respectively, compared to the control. Likewise, the application of Si in concentrations of 75 and 150 mg L^{-1} significantly decreased this variable by 22.2%. Regarding the interactive effects, in the treatment with 50 mM NaCl and 150 mg Si L^{-1}, the lowest and most significant value was observed (55.1% compared to the 50 mM NaCl and 0 mg Si L^{-1} treatment, and 65.4% when compared with the 0 mM NaCl and 0 mg Si L^{-1} treatment), as shown in Table 1.

The maximum organoleptic quality of a tomato fruit is in its maturity state with a "bright red" coloration, which is the result of the synthesis of carotenoids, mainly lycopene. Within the intervals proposed by Cantwell *et al.* [35], the values in "a" and "b" indexes for the stage of "bright red" coloration of the fruit are 26.4 and 23.1, respectively.

NaCl and Ti in juice percentage and color attributes of tomato fruits

Juice percentage. When a plant absorbs salts in excessive amounts, it transports them through the transpiration flow to the leaves, where it stores them. The overaccumulation of ions such as Na^+ and Cl^- induces cell toxicity causing ionic stress. High concentrations of cytoplasmic Na^+ affect the absorption of K^+, an important ion involved in stomatal opening and closure; when the activity of the guard cells in the stomata is affected, the flow of masses is reduced, decreasing the percentage of humidity in the various organs of the plant, such as the fruits [29, 36]. This effect was reflected in this study only with the 50 mM NaCl dose, which caused a 31.9% decrease in the percentage of fruit juice compared to the control (Table 2).

The doses of 75 and 150 mg Ti L^{-1} non-significantly increased the juice percentage by 4.6 and 6.3%, respectively, compared to the control (Table 2).

The interaction of the study factors did not show significant differences, except for the 100 mM NaCl with 75 mg Ti L^{-1} treatment, which increased the percentage of juice by 15.3% with respect to the treatment without NaCl and without Ti (Table 2).

Color Index (CI). The perception of color by the human eye depends on the passage of light through the cornea and the processing of information by the brain. The CI is a parameter that mathematically describes the colors by means of the CIE-L*a*b* color space and serves to evaluate the color of the fruits, determining the consumer's acceptance. In tomato, chlorophyll degradation and lycopene synthesis in chloroplasts dictate the color change from green to red [37, 38]. In this experiment, the CI was decreased by 33.9 and 41.7% with the 50 and 100 mM NaCl doses, compared to the control (Table 2). This is consistent with the results obtained with the lycopene variable (data not shown), since the lycopene concentration decreased under saline stress.

The 150 mg Ti L^{-1} dose increased the CI by 20.5% when compared to the control (Table 2). Regarding the interactions of the study factors, the treatments consisting of 50 mM NaCl with 75 or 150 mg Ti L^{-1} decreased the color index by 33.2 and 20.2%, respectively, compared to the treatment without NaCl and without Ti (Table 2).

"a" Index. The color change in the ripening process (chlorophyll degradation and carotene synthesis) can be measured with the "a" (red) and "b" (yellow) indexes, with values of 26.4 and 23.1, respectively, for the classification called "bright red" [35, 39]. In the fruits of plants treated with the 50 and 100 mM NaCl doses, the "a" index was reduced

Table 2. Main effects and interaction of NaCl and TiO_2 on the juice percentage and color parameters of tomato (*Solanum lycopersicum*) cv. Río Supremo.

NaCl (mM)	**Juice (%)**	**Color Index**	**"a" Index**	**"b" Index**	**"a/b" Index Ratio**
0	57.4±5.9 a	70.5±6.2 a	35.6±3.6 a	17.7±0.9 b	2.06±0.2 a
50	39.1±9.2 b	46.6±8.6 b	25.4±4.4 b	20.8±1.9 a	1.30±0.2 b
100	65.5±7.9 a	41.1±2.2 b	26.0±1.3 b	19.1±2.2 ab	1.42±0.1 b
Ti (mg L^{-1})	**Juice (%)**	**Color Index**	**"a" Index**	**"b" Index**	**"a/b" Index Ratio**
0	52.1±3.8 a	48.7±11.2 b	27.6±5.3 b	18.2±2.2 b	1.6±0.3 a
75	54.5±8.4 a	51.2±7.2 ab	27.8±3.3 ab	18.8±1.4 ab	1.5±0.2 a
150	55.4±6.8 a	58.4±7.4 a	32.1±2.9 b	20.6±1.7 a	1.6±0.2 a
NaCl (mM) - Ti (mg L^{-1})	**Juice (%)**	**Color Index**	**"a" Index**	**"b" Index**	**"a/b" Index Ratio**
0-0	70.7±3.2 ab	75.9±3.4 a	39.0±1.8 a	16.9±0.5 b	2.3±0.1 a
0-75	54.3±4.1 abc	62.8±8.4 ab	31.7±5.0 abc	18.8±1.1 b	1.7±0.3 ab
0-150	47.0±1.9 abc	73.0±4.5 a	36.3±2.7 ab	17.3±0.7 b	2.1±0.2 a
50-0	45.3±3.2 abc	28.6±7.9 b	17.5±4.7 d	21.3±3.2 ab	0.9±0.3 b
50-75	28.2±5.4 c	50.7±5.3 b	25.7±4.4 bcd	21.3±1.1 ab	1.2±0.1 b
50-150	43.7±10.5 abc	60.6±1.7 ab	33.1±1.7 abc	19.8±0.6 ab	1.6±0.2 ab
100-0	40.1±4.6 bc	41.7±0.7 ab	25.2±0.7 cd	16.5±2.2 b	1.5±0.1 ab
100-75	81.5±10.3 a	40.0±1.1 ab	26.0±0.8 bcd	16.2±0.6 b	1.6±0.1 ab
100-150	75.4±9.3 ab	41.5±3.8 ab	26.9±2.0 bcd	24.6±1.0 a	1.1±0.1 b

Means±SD with different letters in each column and study factor indicate significant statistical differences (Tukey, $p \leq 0.05$).

by 27.8% on average, compared to the control (Table 2). That is, the control treatment obtained a high value (36), which places it well above the "dark red" classification (value of 27.5; Cantwell *et al.* [35]); while the values obtained with both saline doses (25.5, on average) place them within the "bright red" classification (Table 2).

The applied doses of Ti did not show significant effects on the variable (Table 2).

The 50 mM NaCl with 150 mg Ti L^{-1} treatment obtained a value of 33, this meant an 89.1% increase in the "a" index with respect to the 50 mM NaCl treatment without Ti, which obtained a value of 17.5. This indicates that the treatment with the medium dose of salinity and with the high dose of Ti, produced fruits classified as "dark red" in comparison with the treatment without NaCl and without Ti located in the color "pink orange".

"b" Index. Regarding the "b" index, the effect of NaCl was only significant with the 50 mM dose, which obtained a value of 21, and represented a 17.5% increase in the variable compared to the control (Table 2).

The application of 150 mg Ti L^{-1} significantly increased the "b" index by 13.2% compared to the control (Table 2).

The increases described above suggest that both salinity and Ti application caused the fruits to be classified as "bright red".

The 100 mM NaCl and 150 mg Ti L^{-1} treatment increased the "b" index by 49.1 and 45.6% compared to the 100 mM NaCl treatment without Ti and the treatment without NaCl and without Ti, respectively (Table 2).

Ratio of the "a/b" indexes. The reduction in the values of the ratio of the "a" and "b" indexes indicates a greater accumulation of green pigments; in ripe fruits with reddish coloration, the values tend to increase [40]. In fruits treated with 50 and 100 mM NaCl, the values of the ratio were 1.3 and 1.4 respectively; that is, the "a/b" index ratio was reduced by 36.9 and 31.1%, when compared with the control (2.1) (Table 2). In other words, the NaCl-treated fruits were not a "dull red" color, but "bright red".

The independent effect of Ti and the interactive effects of both study factors were not significant (Table 2).

CONCLUSIONS

The fruits of tomato plants cv. Río Supremo treated with 50 and 100 mM NaCl are differentially affected in the juice percentage and color parameters. On the one hand, in the experiment with NaCl×Si, salinity reduces the juice percentage, the color index and the "a/b" index ratio of the fruits. Although, the "b" index is increased. In the study with NaCl×Ti, salinity decreased the juice percentage and color index variables, and it improved the indexes and "a/b" index ratio.

The foliar applications of Si increased the "b" index. Although, they reduce the juice percentage, the color index, and the "a/b" index ratio. In the interactive effects of the study factors, decreases were only found in the juice percentage and the "a/b" index ratio. It is concluded that the application of NaCl and Si improve some quality variables in tomato fruits cv. Río Supremo.

On the other hand, the leaf-applied Ti improves the color index and the "b" index of the fruits. These effects may be due to the fact that the TiO_2 contained in both plants and fruits modifies color characteristics in the latter, since it is considered a photocatalyst that is activated by ultraviolet light.

In the interactive effects of the study factors NaCl and Ti, the positively affected variables were juice percentage, color index, and the a and b indexes. Ti can improve color indicators that optimize the quality of tomato fruits. However, the action mechanisms of Ti at the molecular level are still unknown.

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