Article

Silicon as a salinity mitigator in the physiological variables of germination of three varieties of *Solanum lycopersicum*

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Abstract

At present, agricultural soils are affected by salinity due to the excessive use of synthetic fertilizers and poor quality of the water for agricultural irrigation. Currently, products based on silicon (Si) are being applied to help the sustainability of agriculture, in addition, Si benefits plants to have greater tolerance to pests and diseases, helps against heavy metal toxicity and acts against water and salt stress. Therefore, the aim of the study was to evaluate the effect of silicon as a salinity mitigator on seed germination and initial growth of tomato seedlings. The work was carried out in the Germplasm laboratory of the Autonomous University of Baja California Sur, Mexico. The selected tomato varieties were cherry (*Solanum lycopersicum* var. Cerasiforme), beef (*Solanum lycopersicum* var. Floradade) and saladette (*Solanum lycopersicum* var. Río Grande). The experimental design was completely randomized with a 2 x 3 factorial arrangement, where factor A was saline concentrations (0, 25, 50 mM) of sodium chloride (NaCl) and factor B was silicon dilutions (0, 1, 2 mM). Each treatment included four repetitions of 25 seeds each. Tomato cultivars showed different effects regarding salinity. The cherry cultivar showed decreases in its germinative variables with increasing salinity, indicating that the Floradade and Río Grande cultivars are more tolerant to salinity. In this same sense, silicon presented a protective effect in the interaction (NaCl + Si), showing positive effects by increasing the variables evaluated.

Keywords: *Solanum lycopersicum* L., silicon dioxide, sodium chloride.

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Introduction

Tomato (*Solanum lycopersicum* L.) is the most preferred vegetable worldwide (Infoagro, 2017). It has high contents of bioactive compounds such as: folate, ascorbate, polyphenols, carotenoids, vitamins, and other essential nutrients, which is why it is palatable for human health (Ahmed *et al*., 2017). FIRA (2019) mentions that, worldwide, the tomato is grown on approximately 5 million hectares (ha), with a production of 170.08 million tonnes (t) of fresh tomato, where China ranks first in the world with a tomato production of 46.2% of the total, while Mexico ranks tenth with a production of 1 878 289 t year^{-1}.

Salinity affects 1 125 million ha worldwide (Hossain, 2019). This condition generates problems that agriculture faces worldwide, particularly due to the presence of NaCl, which limits the optimal development of plants of commercial interest (Durukan and Demirbas 2018). Mexico has an area of 54% of arid zones throughout the national territory, located mainly in the northern and northeastern regions of the country (Briones *et al*., 2018), which are affected with a high degree of salinity, where sodium (Na^+) cations displace calcium (Ca^+) of the clay-humic complex, thus increasing the osmotic potential of the soil solution (Cisneros *et al*., 2020).

Currently, various alternatives are being sought to mitigate the negative effects of salinity, such as obtaining tolerant varieties, natural products such as biofertilizers and biostimulants that favor the growth and development of plants and benefit the environment (Mazón *et al*., 2020).

Si is a mineral element that protects the plant against biotic and abiotic stress, in addition, chemically active Si restores damage and optimizes soil fertility, keeps nutrients available to the plant and improves cation exchange capacity, especially at pH greater than 7 (Meunier *et al*., 2018). Therefore, the objective was to evaluate the effect of Si as a salinity mitigator on germination and initial growth in seedlings of three tomato varieties.

Materials and methods

The research was conducted in the germplasm laboratory of the Autonomous University of Baja California Sur (UABCS, for its acronym in Spanish). The biological material used was three tomato cultivars: cherry (*Solanum lycopersicum* var. Cerasiforme), beef (*Solanum lycopersicum* var. Floradade) and saladette (*Solanum lycopersicum* var. Río Grande), the beef and saladette varieties are commercial varieties, while cherry is a landrace reproduced at the Autonomous University of Baja California Sur. Germination tests were carried out in sterilized Petri dishes (150 x 15 mm), covered at the bottom with a layer of absorbent paper. Each dish was moistened with 5 ml of the solution resulting from the combination of sodium chloride (NaCl) (0, 25 and 50 mM) and amorphous silicon dioxide (SiO_2) (0, 1 and 2 mM), the application of the solution was made every four days, distilled water was used for the control treatment. The germination tests were performed for 14 days, in a germination chamber (Seedburo, Model 549, NY, USA) at a temperature of 25 °C ±0.5 °C and 80% relative humidity, which were monitored daily if applicable.

Variables evaluated

Germination percentage. it was recorded daily using the following formula of Al-mudaris (1998). Where: GP (%)= $\left(\frac{\text{germinated seeds}}{\text{total seeds}}\right)$ x100. Seeds were considered germinated when the radicle had a minimum length of 2 mm. The germination rate was calculated using the formula of Maguire (1962), where n1, n2, n30 are the number of seeds germinated at times t1, t2, t7 (in days). While the germination energy was calculated using the following formula of Maguire (1962): GE= $\frac{N1}{D1}+\frac{N2\text{-}N1}{D2}+\frac{N2\text{-}N1}{D1}$. Where: N= indicates the number of seeds germinated on the counting date; D= the number of days. In turn, the mean germination time was carried out by the formula proposed by Orchard (1977) MGT= $\frac{\sum(N\text{x}D)}{\sum N}$. Where: N= indicates the number of seeds germinated on day D.

For its part, the germination index was calculated by the formula proposed by Scott *et al*. (1962), GI= $\frac{\sum(n,t1)}{N}$. Where: n= indicates the number of seeds germinated on day 1; t1= number of days after sowing; N= is the total number of seeds sown. While the germination speed was determined by the formula of Maguire (1962), M= $\sum(\frac{n1}{t})$. Where: n= indicates the number of seeds germinated on day 1, t= is the germination time from sowing to germination of the last seed.

Germinated seeds were kept for 14 days and 10 seedlings per repetition were randomly selected. Each seedling was measured stem and radicle length with a digital caliper (AutoTec, Rhos, 2002 EC). Subsequently, the fresh and dry biomass was weighed, using an analytical balance (Ohaus, model PA224C). The plant tissues were placed in paper bags and placed in a drying oven (Ríos Rocha model EO-50) at a temperature of 70 °C for 72 h until complete dehydration.

Experimental design

The experimental design was completely randomized with a 3^2 factorial arrangement, where factor A was the saline concentrations of NaCl (0, 25 and 50 mM) and factor B was the dilutions of Si (0, 1 and 2 mM). Each treatment had four repetitions of 25 seeds each.

Statistical analysis

The data obtained were analyzed for variance. A test of orthogonal polynomials was performed in the variables where there were significant differences. Differences between the mean treatments were compared with Tukey's multiple range test ($p\leq 0.05$) of confidence level. Statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS) version 22.0 (IBM Corp, 2013).

Results and discussion

The statistical analysis showed that the effect of NaCl, Si and the interaction between these factors was statistically different ($p\leq 0.05$) in each tomato variety (Table 1).

Table 1. Values of F (F) and significance levels (*p*) observed in the analyses of variance for germination and growth variables.

Variables	Cherry			Floradade			Río grande		
	NaCl	Si	NaCl*Si	NaCl	Si	NaCl*Si	NaCl	Si	NaCl*Si
				%GP					
F	3.737	0.712	1.017	1.004	0.049	1.25	2.497	0.113	1.061
p	0.037	0.5	0.416	0.38	0.952	0.314	0.101	0.893	0.395
				GE					
F	12.339	2.932	1.624	0.454	0.125	1.309	1.5	0.001	0.891
p	<0.001	0.07	0.197	0.64	0.883	0.292	0.241	0.999	0.483
				GRI					
F	11.124	9.312	6.387	5.562	8.677	2.558	7.926	2.138	1.637
p	<0.001	<0.001	<0.001	0.009	<0.001	0.061	0.002	0.137	0.194
				MGT					
F	3.154	0.673	1.051	0.785	0.06	0.936	3.052	0.031	1.054
p	0.059	0.519	0.399	0.466	0.942	0.458	0.064	0.969	0.398
				GI					
F	7.903	1.144	0.917	1.004	0.049	1.25	2.497	0.113	1.061
p	0.002	0.333	0.468	0.38	0.952	0.314	0.101	0.893	0.395
				GS					
F	3.737	0.712	1.017	1.004	0.049	1.25	2.497	0.113	1.061
p	0.037	0.5	0.416	0.38	0.952	0.314	0.101	0.893	0.395
				RL					
F	8.301	2.098	6.109	4.621	5.434	1.571	13.076	10.335	0.667
p	0.002	0.142	<0.001	0.019	0.01	0.211	<0.001	<0.001	0.62
				SL					
F	222.456	119.31	38.123	8.786	12.858	5.975	33.489	10.317	2.152
p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.102
				FB					
F	15.374	1.508	0.786	18.816	4.517	3.268	78.338	12.499	4.93
p	<0.001	0.239	0.544	<0.001	0.02	0.026	<0.001	<0.001	0.004
				DB					
F	16.487	4.737	7.643	6.09	0.89	0.578	4.454	3.794	0.588
p	<0.001	0.017	<0.001	0.007	0.422	0.681	0.021	0.035	0.674

Germination percentage (%GP); germination energy (GE); germination rate (GRI); mean germination time (MGT); germination index (GI); germination speed (GS); root length (RL); stem length (SL); fresh biomass (FB) and dry biomass (DB).

For the cherry variety, the concentration of 50 mM NaCl increased germination energy and germination index. Meanwhile, fresh biomass increased at concentrations of 25 and 50 mM NaCl. However, germination percentage, germination energy, germination index and germination speed were affected at the concentration of 25 mM NaCl, with respect to the control treatment (Table 2).

Table 2. Main effects of NaCl and Si concentrations on the physiological variables of germination of cherry tomato (*Solanum lycopersicum* var. Cerasiforme).

Dose	Variables evaluated					
	%GP	GE	MGT	GI	GS	FB
			NaCl			
0 mM	89.667 a	11.716 ab	0.219	0.152 a	0.897 a	1.41 b
25 mM	82.667 b	10.723 b	0.207	0.14 b	0.827 b	1.47 ab
50 mM	89.667 a	13.002 a	0.219	0.161 a	0.897 a	1.67 a
±SE	2.091	0.325	0.004	0.004	0.021	0.001
Linear	ns	0.009	ns	ns	ns	< 0.001
Quadratic	0.011	< 0.001	ns	0.001	0.009	0.012
Si						
0 mM	86.667	12.348	0.215	0.154	0.867	1.6
1 mM	89.333	11.855	0.218	0.152	0.893	1.48
2 mM	86	11.237	0.212	0.147	0.86	1.47
±SE	2.091	0.325	0.004	0.004	0.021	0.001
Linear	ns	ns	ns	ns	ns	ns
Quadratic	ns	ns	ns	ns	ns	ns

Different literals between the means indicate a significant difference. Germination percentage (%GP); germination energy (GE); mean germination time (MGT); germination index (GI); germination speed (GS); fresh biomass (FB); NS= not significant; ±SE= standard error.

Cuartero *et al*. (2006) reported that the genus *lycopersicum* has a heritable salinity tolerance trait. Vítámvá *et al*. (2007) mentioned that there is a group of proteins inducible by abscisic acid (ABA), which are associated with salinity tolerance and water deficit, which could be explained to what happened in the present work.

Several studies show that increases in the percentage, energy and index of germination have been found at concentrations of 50 mM NaCl in crops such as: spinach *Spinacia oleracea* (Turhan *et al*., 2011), tomato *Solanum lycopersicum* (Doğan *et al*., 2008) and eggplant *Solanum melongena* (Akıncı *et al*., 2004).

On the other hand, Eitel (2021) evaluated the effect of salt stress on the production and quality of tomato seeds, in different concentrations, where it was observed that the germination index decreased significantly. For their part, Ruiz *et al*. (2014) evaluated the germination of eight genotypes of tomato (*Solanum lycopersicum* L.), which were exposed to different levels of NaCl. Where they observed that the fresh and dry biomass of the aerial part increased in the presence of NaCl. Similarly, Can *et al*. (2017) evaluated the germination and initial growth of beans (*Phaseolus vulgaris*) in response to salinity induced with NaCl, sodium sulfate (Na_2SO_4) and sodium bicarbonate ($NaHCO_3$), where they observed that fresh biomass was decreased with the salt type $NaHCO_3$, while NaCl increased it.

Although the impact of Si was not indicated as the main factor, there was a significant effect in the interaction with NaCl. The presence of Si in the germination rate indicates a quadratic effect in the presence of NaCl (Figure 1A). Similar results were found by Haghighi *et al*. (2012), who evaluated the interaction factor of Si + NaCl in the germination of tomato seeds, where they observed that Si stimulated germination variables, especially the germination rate, which increased around 20% with respect to the control treatment. Likewise, Sun *et al*. (2021) observed the effect of Si on corn (*Zea mays*) germination, which significantly increased germination percentage (GP), germination rate (GR), germination index (GI) and vigor index (VI) compared to the control treatment.

The presence of Si in saline conditions (50 mM) generated an increase in root length (Figure 1B). Similar results were reported by Asgari *et al*. (2018), who found a greater increase in stem length, fresh and dry biomass of shoots and roots in oat (*Avena sativa*) plants treated with Si.

However, Gong *et al*. (2006) evaluated the interaction of Si + NaCl in rice (*Oryza sativa*) seedlings. Where they observed that Si did not mitigate the adverse effects of NaCl. A positive effect of Si was observed in the development of the stem (Figure 1C), particularly seedlings in saline conditions (50 mM) increased stem length with the presence of Si. While, in the production of dry biomass (Figure 1D), a positive impact of Si was observed in the non-saline situation, showing a quadratic effect. Haghighi and Pessarakli (2013) evaluated the interaction factor of Si + NaCl in cherry tomato. They observed that Si mitigated the adverse effects of NaCl and increased stem length, fresh and dry biomass, photosynthetic rate and water content.

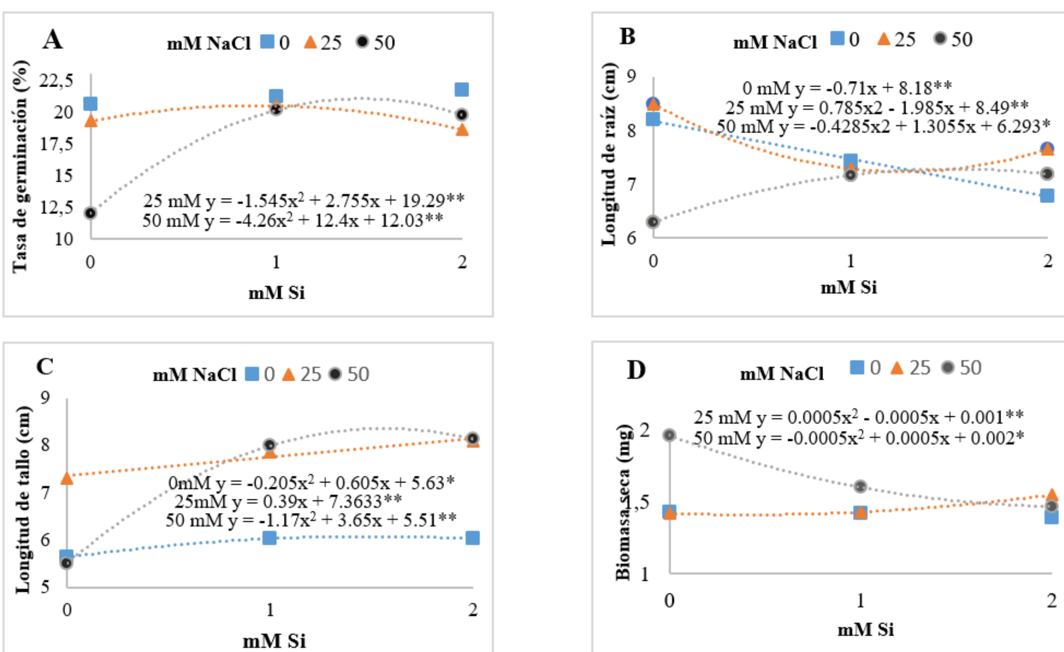

Figure 1. Effect of the interaction of sodium chloride (NaCl) and silicon (Si) on germination rate (A); root length (B); stem length (C); and dry biomass (D) of cherry tomato seedlings after 14 days of establishment of the experiment. The asterisks indicate the levels of significance among treatments 0.01** - 0.05*.

Wang *et al*. (2015) observed that Si promoted the increase in the length of stem, root, and fresh biomass of cucumber (*Cucumis sativus*) plants subjected to NaCl stress. On the other hand, Carballo *et al*. (2019) evaluated the interaction factor of Si + NaCl in the germination of moringa (*Moringa oleifera*). These results showed a positive effect of Si by increasing biomass, vigor index, total phenols, total flavonoids, and antioxidant capacity.

In the Floradade variety, it was observed that the concentration of 50 mM NaCl reduced the germination rate by 14%. Contrary to the above, the concentration of 25 mM NaCl increased the root length by 19%, while the concentration of 50 mM NaCl increased the dry biomass by 19%, both with respect to the control (Table 3).

In this sense, Camejo and Torres (2000) observed an increase in dry biomass in tomato plants under saline conditions. Plants, when exposed in a saline medium, activate their defense mechanism, and raise the levels of enzymes, prolines, amino acids, and antioxidants. The presence of Si, regardless of the concentration, increased germination rate and root length (Table 3).

Table 3. Main effects of NaCl and Si on germination of Floradade tomato (*Solanum lycopersicum* var. Floradade).

Dose	Variables evaluated							
	% GP	GE	GRI	MGT	GI	GS	RL	DB
				NaCl				
0 mM	72.333	13.404	6.5 a	0.132	0.09	0.283	4.034 b	1.44 b
25 mM	72.667	13.658	6.211 ab	0.133	0.091	0.284	4.814 a	1.5 b
50 mM	68	12.925	5.585 b	0.128	0.085	0.266	3.948 b	1.71 a
±SE	2.599	0.553	0.198	0.003	0.003	0.01	0.222	0
Linear	ns	ns	0.003	ns	ns	ns	ns	0.003
Quadratic	ns	ns	ns	ns	ns	ns	0.005	ns
				Si				
0 mM	70.333	13.523	5.458 b	0.13	0.088	0.275	3.675 b	1.57
1 mM	71.333	13.333	6.235 a	0.131	0.089	0.279	4.479 a	1.58
2 mM	71.333	13.132	6.603 a	0.132	0.089	0.279	4.642 a	1.49
±SE	2.599	0.553	0.198	0.003	0.003	0.01	0.222	0
Linear	ns	ns	<0.001	ns	ns	ns	0.005	ns
Quadratic	ns	ns	ns	ns	ns	ns	ns	ns

Different literals between the means indicate a significant difference. Germination percentage (%GP); germination energy (GE); germination rate (GRI); mean germination time (MGT); germination index (GI); germination speed (GS); root length (RL); dry biomass (DB); ns= not significant; ±SE= standard error.

The NaCl-Si interaction showed that the presence of Si increased root length and fresh biomass (Figure 2). Khan *et al*. (2020) evaluated thermotolerance induced by Si in tomato plants at doses of 1 and 2 mM. The results showed that Si significantly improved plant growth, fresh biomass, and root length, compared to the control treatment. Similarly, Mushinskiy *et al*. (2018) found that the application of Si increased the root length of tomato seedlings by 27.8% compared to the control treatment.

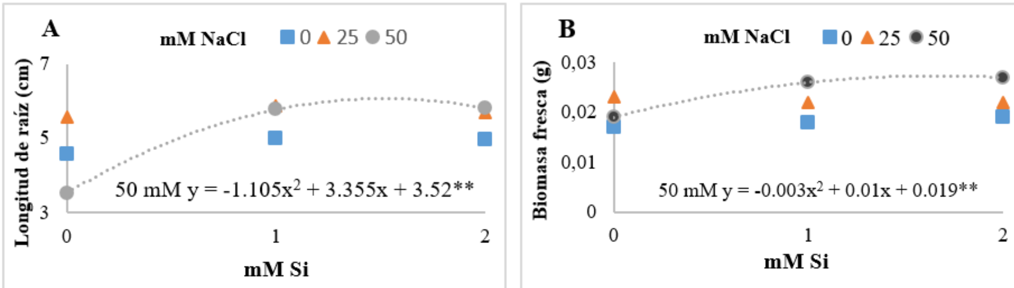

Figure 2. Effect of the interaction of sodium chloride (NaCl) and silicon (Si) on root length (A); and fresh biomass (B) of Floradade tomato seedlings after 14 days of establishment of the experiment. The asterisks (*) indicate significance levels among treatments 0.01** - 0.05*.

In the present study, it was observed that the concentration of 50 mM NaCl significantly reduced the germination rate by 31% compared to the control treatment. Contrary to the above, it was observed that doses of 25 and 50 mM stimulated root length by 36.02 and 27.57% compared to the control treatment. In addition, stem length was also increased by 40% and 26% at these NaCl concentrations (Table 4).

Table 4. Main effects of NaCl and Si on the germination of Río Grande saladette tomato (*Solanum lycopersicum* var. Río Grande).

Dose	Variables evaluated								
	% GP	GE	GRI	MGT	GI	GS	RL	SL	DB
					NaCl				
0 mM	71	13.253	6.169 a	0.132	0.089	0.277	5.744 b	5.351 c	1.85 b
25 mM	67	12.879	5.13 ab	0.128	0.084	0.262	7.813 a	7.494 a	2 ab
50 mM	59.333	11.579	4.253 b	0.116	0.074	0.232	7.328 a	6.766 b	2.13 a
±SE	3.752	0.718	0.341	0.005	0.005	0.015	0.299	0.188	0
Linear	ns	ns	< 0.001	ns	ns	ns	< 0.001	< 0.001	0.006
Quadratic	ns	ns	ns	ns	ns	ns	0.002	< 0.001	ns
					Si				
0 mM	64.333	12.558	4.61 a	0.124	0.08	0.251	5.942 b	5.873 b	2.11 a
1 mM	66.333	12.553	5.442 a	0.125	0.083	0.259	7.091 a	6.68 a	1.86 b
2 mM	66.667	12.601	5.501 a	0.126	0.083	0.26	7.853 a	7.058 a	2.02 ab
±SE	3.752	0.718	0.341	0.005	0.005	0.015	0.299	0.188	0
Linear	ns	ns	ns	ns	ns	ns	< 0.001	< 0.001	ns
Quadratic	ns	ns	ns	ns	ns	ns	ns	ns	0.016

Different literals between the means indicate a significant difference. Germination percentage (%GP); germination energy (GE); germination rate (GRI); mean germination time (MGT); germination index (GI); germination speed (GS); root length (RL); stem length (SL); dry biomass (DB); ns= not significant; ±SE= standard error.

Our results coincide with those obtained by Loudari *et al*. (2020), who observed the effect of NaCl on tomato, which increased the length and diameter of the root. On the other hand, Batista *et al*. (2017) evaluated the effect of NaCl on the germination of three varieties of basil (*Ocimum basilicum* L.). Where they observed a decrease in the percentage and rate of germination. Similarly, González *et al*. (2020) studied the effect of NaCl on the germination of seeds of tomato *cv* 'Río Grande'. They observed that the germination rate decreased significantly compared to the control treatment.

The concentrations of 1 and 2 mM Si had a significant impact by increasing root and stem length, both concentrations were higher than the control treatment (Table 4). It has been shown that Si, despite not being an essential element for plants, favors the growth and development of some species. In this sense, Chourasiya *et al*. (2021) mention that the effect of Si on the germination and initial growth of wheat (*Triticum*) has a positive effect on the variables evaluated.

Si significantly increased fresh biomass (Figure 3). Particularly at the concentration of 50 mM NaCl, the presence of Si generated a positive linear effect. Ahmad *et al*. (2019) evaluated the interaction factor of Si + NaCl in bean seedlings, which improved the adverse effects of NaCl on growth parameters, fresh and dry biomass, pigment synthesis and relative water content.

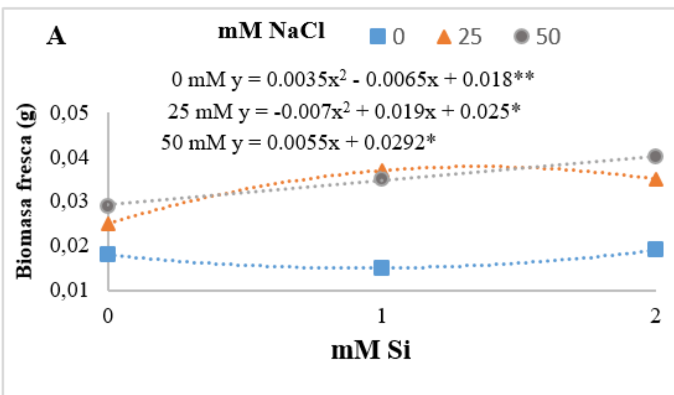

Figure 3. Effect of the interaction of sodium chloride (NaCl) and silicon (Si) on the fresh biomass (A) of Río Grande tomato seedlings after 14 days of establishment of the experiment. The asterisks (*) indicate significance levels among treatments 0.01^{**} - 0.05^{*}.

In addition, Torabi *et al*. (2012) reported that Si positively impacted on the growth of borage (*Borago officinalis*) seedlings, thus increasing their fresh and dry biomass. Therefore, Si, once inside the plant, is found in different structures, diffuses through the tissues, and forms a continuous layer between the cuticle and the epidermis composed of two sublayers, one as Si gel and another in a silicon-cellulose complex, which isolates and defends the plant from adverse environmental factors.

In this sense, Emamverdian *et al*. (2018) mentions that Si has the ability to activate the Lsi1, Lsi2 and Lsi6 genes in plants, the Lsi2 gene is considered an anion transporter and has the ability to express itself in the root endodermis, while Lsi1 and Lsi6 are genes that belong to the aquaporin family and their function is to transport silicon to the tissues of shoots and roots. In addition, when genes express themselves, multiple enzymes are activated, such as: catalases, peroxidases, superoxide dismutases, ascorbate peroxidases and glutathione reductases, which contribute with the plant to relieve stress (biotic or abiotic).

Conclusions

Tomato cultivars showed different effects regarding salinity. The cherry cultivar showed decreases in its germinative variables with increasing salinity, which indicates that the Floradade (beef) and Río Grande (saladette) cultivars had greater tolerance to salinity. Silicon (Si) had a protective effect in the interaction (NaCl + Si), showing positive effects by increasing the variables evaluated. Therefore, Si could be considered as a salinity mitigating agent.

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