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EFFECTS OF SILICON AND CALCIUM APPLICATION ON GROWTH, YIELD AND FRUIT QUALITY PARAMETERS OF CUCUMBER ESTABLISHED IN A SODIC SOIL

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ABSTRACT

Soil salinity is a growing problem that affects crop quality. Cucumber is a vegetable eaten fresh, with great worldwide demand, making its chemical and physical characteristics important. In the present work, the effects of foliar application of silicon (Si: 0 and 2 mM), calcium (Ca: 0 and 2 mM), and the combination of both (Si + Ca: 0 + 0 mM, 2 + 0 mM, 0 + 2 mM and 2 + 2 mM) on dry matter of leaves and stems, yield and fruit quality of cucumbers grown in a sodic soil were studied. Treatments did not affect dry biomass, yield and product size. The obtained results show that applying foliar Ca increases total soluble solids in comparison to the control. Foliar Si application significantly increased fruit firmness in the end towards the peduncle. Moreover, foliar Ca application increased the fruit hue angle (intense green), while foliar Si application increased chroma (dark green), both significantly regarding the control. The individual applications of Si and Ca were proven to differentially improve the fruit quality parameters of cucumber in sodic soil conditions.

Key words: °Brix, titratable acidity, fruit firmness, color attributes of fruit, sodicity, salinity, foliar application

INTRODUCTION

Salinity is one of the main types of abiotic stress affecting agricultural soils, becoming a problem of interest as it has led to considerable losses not only in crop yields but also in crop quality [Hu et al. 2016].

It is estimated that some 34 million hectares of irrigated land worldwide are affected by problems of salinity [FAO 2012]. Adequate mineral nutrition management has proven to be an effective strategy to increase the productivity and quality of crops grown in saline soils [Khan et al. 2017].

As a beneficial element, silicon (Si) may increase stress tolerance in plants, while no inconveniences have been found from its accumulation in soils [Zuccarini 2010]. This element acts by improving the antioxidant system [Savvas and Ntatsi 2015], decreasing the permeability of the plasmatic membrane and its lipid peroxidation, thus maintaining its integrity and functionality [Zhu et al. 2004]. It also prevents Na^+ absorption and transport from the roots to the aerial part [Zhu and Gong 2014]. Silicon may also increase the K^+ content in tissues [Xu et al. 2015] and represents an important element in fruit quality. Nonetheless, even if silicon is present in high concentrations in the soil, it can only be absorbed from the soil solution as silicic acid [$Si(OH)_4$] [Sahebi et al. 2015], which can only happen in acid pH. Therefore, under sodic soil conditions (pH over 8.5), Si availability is very low.

With regard to calcium (Ca), besides being an essential element for plants, with important structural functions in the cell wall and membranes [Bauer et

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al. 2011], it plays a pivotal role in regulatory mechanisms in plants under adverse saline stress conditions [Melgar et al. 2007]. In plants under stress conditions, Ca can activate the antioxidant system and maintain ion homeostasis [Hu et al. 2016]. Also, Ca improves stress tolerance and can help to improve fruit quality and shelf life [Dayod et al. 2010]. The Ca concentration in the cytoplasm is regulated at the apoplast level, which in turn affects cell wall thickness, gene expression, and water relationships of the fruits, giving them better quality [Hocking et al. 2016].

Si and Ca have been widely used as separated elements in order to mitigate stress factors in agriculture. Nonetheless, their combined use has been scarcely studied. To the best of our knowledge, this research the first study reporting the combined use of Si and Ca in foliar application in cucumber, proposing that both elements help to overcome biotic stress imposed by soil salinity.

Cucumber (*Cucumis sativus* L.) is moderately sensible to salts and represents an economically important crop. The objective of the present study was to evaluate the effect of foliar Si and Ca applications, individually and jointly, on fruit quality of cucumber established in sodic soils.

MATERIALS AND METHODS

Experiment location and greenhouse conditions. The experiment was carried in a greenhouse with a metallic structure and a milky white plastic cover, in Texcoco, State of Mexico, Mexico (19°27’ 47.9” NL 98°54’ 12.8” WL, 2250 masl). The experiment period ran from May to August 2016. The mean temperature during the day and night was 30°C and 15°C, respectively, with mean relative humidity during the day and night of 31% and 86%, respectively. The mean light intensity during the day was 137 μmoles m^{-2} s^{-1}.

Plant material, treatments, and experimental design. Seeds of cucumber (*Cucumis sativus* L.) var. Modan were provided by Rijk Swaan®. This is a French, parthenocarpic variety. The effect of foliar application of Si and Ca was studied at two levels of concentration each, 0 and 2 mM. This originated four treatments: (1) control, spraying with distilled water (0 mM Ca and 0 mM Si); (2) 2 mM Si and 0 mM Ca; (3) 0 mM Si and 2 mM Ca; and (4) 2 mM Si and 2 mM Ca. The source of Si used was silicon dioxide (SiO_2) (Sigma-Aldrich®), while the Ca source used was calcium oxide (CaO) (Merck®); both sources of reactive grade. Previous studies by Voogt and Sonneveld [2001], Kaya et al. [2002, 2003], Lolaei et al. [2012], Hojjatnooghi et al. [2014] and Khoshgoftarmanesh et al. [2014], were considered for the doses selection of Si and Ca concentrations evaluated in this research.

Each of the treatments, including the control, was added with Tween 20® 0.05% as surfactant. With the objective of increasing the solubility of the sources of both Ca and Si, the pH of the sprayed solutions was adjusted to 4 using H_2SO_4 0.5 N; this was also done with the control. The H_2SO_4 concentrations in the sprayed solution were the following: 0.090 μM in the control; 0.009 μM in the 2 mM SiO_2 solution; 2.139 μM in the 2 mM CaO solution; and, 2.458 μM in the solution with 2mM SiO_2 and 2 mM Ca. A completely randomized experimental design was used with six replicates. Each experimental unit was made represented by one cucumber plant per bag.

Installation of the experiment. The seedlings, 28-day-old, were transplanted to black polyethylene bags, 35 × 35 cm (10 L), containing a mixture of soil and perlite in a 3 : 1 (v : v) proportion. Given the characteristics of the soil mixed with perlite (Tab. 1; pH 8.59, ESP 18.71, and EC 0.95 dS m^{-1}), it is classified as a sodic soil. The plant density in the greenhouse was 3.1 plants m^{-2}. The perlite was used to prevent compaction and consequently increase aeration and improve water drainage. The foliar treatments began 24 days after transplant and application was repeated weekly at 18:00 h until the end of the experiment.

Crop management. After the transplant, the experimental units were irrigated with Steiner nutrient solution [Steiner 1984] at 50% of the original strength during all the period that the experiment lasted; the solution was prepared with analytic grade reagents. The pH of the nutrient solution was regulated to 5.0 with H_2SO_4.

The first harvest of fruits was done when the fruits reached commercial maturity and weekly thereafter, for a total of 5 harvests. One fruit from each of the 24 experimental units in the third harvest was used for quality evaluations.

Table 1. Characteristics of the soil used in the present research

Parameters	Values
pH	8.59
EC (dS m^{-1})	0.95
Bulk density (g cm^{-3})	0.98
Organic matter (%)	4.58
Total nitrogen (%)	0.18
Phosphorus Olsen (mg kg^{-1})	2.60
CEC ($cmol_{(+)}$ kg^{-1})	46.12
ESP (%)	18.19

EC: electrical conductivity, CEC: cation exchange capacity, ESP: exchangeable sodium percentage

Evaluated variables

Stem, leaf and total dry biomass weight. The leaves were removed from the stem and then dried in a forced-air circulation oven at 72°C for 48 h. Subsequently, the stems and leaves were weighed individually on an analytical balance.

Yield. At commercial maturity the fruits were harvested, counted and weighed on an analytical balance (PCE-BSH 6000, Germany). At final harvest, the total weight of fruits harvested per plant was added to determine yield.

Fruit length and diameter. Each harvested fruit was measured in terms of length and equatorial diameter, the length with a metal ruler graduated to 30 cm, and the equatorial diameter with a digital calibrator (Truper® 14388, CALDI-6MP, China).

Total soluble solids in fruit juice (°Brix). This was determined by placing a juice sample from the equatorial part of the peeled fruit in the cell of a digital refractometer (Atargo N1, Japan).

Electrical conductivity and pH in fruit juice. 10 g peeled cucumber pulp was taken from the equatorial part of the fruits and put in the juice extractor (Hamilton Beach Big Mouth®, 67606-MX, Mexico) and liquated with 50 mL distilled water. The resulting mix was directly measured for EC and pH with portable equipment (Conductronic PC-18, Mexico).

Titratable acidity in fruit juice. From the extract obtained for EC and pH, the volume was measured, and 10 mL filtered samples were taken and titrated with NaOH 0.01 N, using phenolphthalein as indicator, according to the methodology by the AOAC [Boland 1990].

Fruit firmness. The fruits from the third harvest were peeled and evaluated for firmness at three points: one at the end towards the peduncle, one at the middle, and one towards the end near the flower. The measurement was done with a texturometer (Chatillon, USA) with a 0.7 cm base conic point, which was introduced 1 cm into each of the positions, measuring the necessary force for penetration.

Color attributes of fruit. The L, a, and b values were obtained with a colorimeter (Hunter Lab D25-PC2, USA). The measurements were done on both equatorial sides of the fruits from the third harvest. Luminosity corresponds to the L value, which represents clarity and measured from 0 (black) to 100 (white); this value was obtained directly from the colorimeter. The hue angle value was estimated from the a (–green, +red) and b (–blue, +yellow) values using the following formula: Hue (°) = arctan (b/a), while chroma was obtained with the formula: chroma = $(a^2 + b^2)^{1/2}$ [Domene and Segura 2014].

Statistical analysis. An analysis of variance and mean comparison test were done to evaluate the effects of the treatments, with the LSD test using the PROC ANOVA procedure. The normality and homogeneity assumptions were verified with the Shapiro-Wilk test and the Barlett test, respectively. A significance level of 5% was used in the statistical tests. The SAS software was used for these analyses.

RESULTS AND DISCUSSION

Leaf, stem and total dry biomass values were significantly affected by the foliar treatments (Tab. 2). The Si + Ca treatment promoted the highest leaf, stem and total biomass values, and these increases were significant in comparison to the control. The Ca foliar treatment increased the dry biomass weight, with this increase being significant in the leaves, in comparison to the control. Although foliar application with Si increased leaf, stem and total dry biomass, it was not significant in any of the cases. The reduction of growth due to soil salinity is primarily due to osmotic stress, followed by the ionic effect (Na^+) that reduces dry biomass production [Munns and Tester 2008]. Esmat and Hassan [2016] found a greater effect on dry biomass production when treating plants with Si to the soil compared to its application to foliage. Cucumber has also reported increases in plant biomass when treated with Si [Pavlovic et al. 2016, Zhu et al. 2004]. These same effects have been reported in other cucurbitaceae [Savvas et al. 2009, Cooke and Leishman 2016]. Ca has been shown to have positive effects in increasing the dry biomass of various crops under stress [Tuna et al. 2007, Dabuxilatu and Ikeda 2005, Hojjatnooghi et al. 2014, Tzortzakis 2009]. Application of Ca to cucumber plants under stress induces increased activity of the antioxidant system in mitochondria, decreases levels of reactive oxygen species (ROS), and increases the accumulation of enzymes involved in glycolysis and the tricarboxylic acid cycle [He et al. 2015]. Therefore, joint foliar application of Si and Ca may stimulate a greater increase in dry biomass production compared to their individual application.

The tested treatments had no significant effects on fruit yield. Despite the absence of significant differences, the highest yield (1063.1 g) was obtained with the Si + Ca treatment (Tab. 3). Silicon may either increase, maintain or diminish yield, depending on the cultivar studied or the management of the crop [Yaghubi et al. 2016]. According to Kaya et al. [2002] and Tuna et al. [2007], Ca addition can stimulate salt-tolerance mechanisms and increase crop yield. Under these conditions, the positive effect of Ca is due to the fact that this element reduces the permeability of the plasma membrane to Na^+ and increases the absorption of K^+, reducing the possible negative effects of Na^+; once in the plant, Na^+ can compete with Ca^{2+} for membrane binding sites [Tuna et al. 2007], which disrupts the homeostatic growth of the plant.

Fruit growth (length and diameter) was not significantly affected by the applied treatments. Without showing significant differences, the highest fruit length and diameter values were obtained with the Si treatment (Tab. 3). Indeed, cucumber fruit length is not affected by Si addition to the nutrient solution, as compared to the control [Samuels et al., 1993]. In pepper the greatest increase in fruit length and width occurred with Si application to the root rather than the foliage; however, both application methods were not statistically different to the control [Jayawardana et al. 2014].

Treatments tested had significant effects on total soluble solids (TSS) and electrical conductivity (EC) of fruits (Tab. 4). Foliar calcium (Ca) application significantly increased the concentration of total soluble solids in fruit by 14.47, 21.05, and 23.24%, compared against the silicon and calcium (Si + Ca), silicon (Si), and the control, respectively. The degrees Brix express the concentration of total soluble solids (sugars and organic acids), making it an important quality index [Domene and Segura 2014]. Under salinity conditions, soluble solids tend to decrease, although with the addition of Ca in the nutrient solution, this detriment is attenuated [Kaya et al. 2002]. Bouzo and Cortez [2012] reported contrasting results to those obtained herein when treating melon plants with different calcium sources via the leaves. They found no significant effects in the concentrations of soluble solids.

Foliar Ca application also increased the electrical conductivity of the fruit juice, significantly surpassing the treatment consisting of foliar application of Si (Tab. 4). With this same treatment, juice pH decreased, and titratable acidity increased, both compared against the other foliar treatments and the control. However, these latter comparisons showed no statistical significance. In watermelon plants, Colla et al. [2006] reported a link between pH decreases and high fruit quality. Under saline stress conditions (elevated Na^+ levels), the pH of cucumber fruits tends to be less acidic, per-

Table 2. Effect of silicon and calcium foliar application on leaf, stem and total biomass of cucumber plants grown in sodic soil

Foliar treatments	Dry biomass (g plant^{-1})		
	leaves	stem	total
Control	20.643 ±1.438 b	3.977 ±0.215 b	24.620 ±1.653 b
Si	24.256 ±1.45 ab	4.702 ±0.460 ab	28.958 ±2.398 ab
Ca	25.619 ±2.17 a	4.731 ±0.650 ab	30.586 ±2.848 ab
Si + Ca	26.110 ±1.64 a	5.152 ±0.320 a	31.263 ±1.941 a
LSD$_{0.05}$	4.896	1.163	6.025

Data ±SD in each column followed by a different letter were significantly different (LSD, $P \leq 0.05$). LSD: least significant difference test

Table 3. Effect of silicon and calcium foliar application on fruit yield per plant and size of fruits in cucumber established in sodic soil

Foliar treatments	Yield (g plant^{-1})	Fruit length (cm)	Fruit diameter (mm)
Control	995.7 ±124.7 a	22.15 ±1.06 a	49.77 ±1.56 a
Si	897.9 ±42.4 a	23.09 ±0.90 a	52.50 ±1.89 a
Ca	1060.9 ±66.3 a	22.71 ±1.21 a	50.78 ±2.29 a
Si + Ca	1063.1 ±167.0 a	22.48 ±1.38 a	52.07 ±2.39 a
LSD$_{0.05}$	298.83	2.78	4.87

Data ±SD in each column followed by a different letter were significantly different (LSD, $P \leq 0.05$). LSD: least significant difference test

Table 4. Effect of foliar application of silicon and calcium on fruit chemical quality characteristics of cucumber crops established under sodic soil conditions

Foliar treatments			TSS (°Brix)	pH	EC (dS m^{-1})	TA (g 100 g^{-1})
Description	Si (mM)	Ca (mM)				
Control	0	0	3.50 ±0.17 c	5.22 ±0.02 a	1.08 ±0.00 ab	0.635 ±0.014 a
Si	2	0	3.60 ±0.16 bc	5.23 ±0.09 a	1.01 ±0.03 b	0.663 ±0.051 a
Ca	0	2	4.56 ±0.21 a	5.21 ±0.02 a	1.17 ±0.06 a	0.739 ±0.004 a
Si + Ca	2	2	3.90 ±0.05 b	5.23 ±0.05 a	1.05 ±0.05 ab	0.714 ±0.051 a
LSD$_{0.05}$			0.39	0.13	0.10	0.126

Data ±SD in each column followed by a different letter were significantly different (LSD, $P \leq 0.05$). LSD: least significant difference test, TSS: total soluble solids, EC: electrical conductivity, TA: titratable acidity haps due to the presence of elevated Na levels in the fruit [Trajkova and Papadantonakis 2006]. Cucumber pH values above 6.2 indicate extreme fruit immaturity, while values of 5.5 or below indicate longer postharvest lifetime [Gómez-López et al. 2006].

Soluble solids and titratable acidity determine fruit quality and taste, and the increase of these variables by adding Ca to the leaves depends on the source used. The metabolomic analysis of Cherry tomato fruits treated with foliar Ca^{2+} showed changes in primary metabolites (sugars like glucose and fructose), soluble alcohols (arabitol and sorbitol), organic acids (malate and quinate), and amino acids (glycine and beta--alanine) [Michailidis et al. 2017], which is related with fruit quality.

The effect of foliar Si application proved not to be significant on total soluble solids, pH, electrical conductivity and titratable acidity of fruit, compared to the control. Similarly, Si + Ca applications were not significant in any of the fruit chemical quality variables described before; except in total soluble solids, which was greater in comparison to the control. Likewise, other studies have reported no significant effects of Si on total soluble solids, pH, or electrical conductivity of fruits [Jayawardana et al. 2014, Savvas et al. 2009]. According to Toresano-Sánchez et al. [2012], Si can increase as well as decrease the °Brix value, depending on the age of the crops. Under stress conditions, Si can provide a certain degree of firmness to the cells, which may be associated with a decrease in the concentration of soluble solids [Toresano-Sánchez et al. 2012].

The highest fruit firmness values in the three points evaluated were those of the foliar Si treatment (Tab. 5). The effect of the treatments was only significant in the end near the peduncle; at this point, foliar Si application increased fruit firmness by 13.9%. Although at the medium and flower end points the treatments had no significant effects, the Si treatment increased this variable by 10.2 and 14.7%, respectively. Foliar Ca treatment did not significantly affect fruit firmness in all three measurement points, compared to the control. Likewise, when applying Si and Ca together, fruit firmness was not significantly different as compared to any of the evaluated treatments and was itself lower than those promoted by Si and Ca individually. Given the function of Ca as a cementing agent between cell walls in the middle layer, foliar application of this element can increase fruit quality. The crossed links of calcium pectins are the determining factor of fruit structural and physical properties. Under salinity conditions, Na^+ can displace Ca^+ from the pectins, process which can be reverted by adding Ca [Hocking et al. 2016]. Elevated Na^+ levels under salt stress compete with Ca^+ for the union sites in the cell wall, inducing Ca deficiency symptoms [Dayod et al. 2010], which decreases fruit quality. Ca deficiency causes diverse disorders in fruit development. In agronomic crop management, Ca has been applied to both the soil and the leaves. However, efficiency in the use of the applied Ca depends on the physiological mechanisms that the plant uses to regulate the concentration of this element within the cells [Bonomelli and Ruiz 2010]. In some cases, greater fruit firmness can be observed when applying Ca both to the leaves and to the soil. This increase in the firmness of the fruits with foliar Ca application has been attributed to the protective effect of Ca against the activity of polygalacturonases [Michailidis et al. 2017].

Moreover, SiO_2 in plant tissues increases physical and mechanical protection [Luyckx et al. 2017]. In chili pepper crops, foliar Si application increases the thickness of the cuticle and fruit firmness by 50% [Jayawardana et al. 2014]. Polymerized silicon is one of the most rigid components in plant tissue, and it can form much harder structures than those present in unmineralized cell walls [Bauer et al. 2011]. Under stress conditions, Si can provide a certain degree of firmness to the cell [Toresano-Sánchez et al. 2012]. When Si is applied in the nutrient solution, no marked effects of this element on fruit firmness can be expected, as most of the Si is deposited on the leaves, as happens in squash [Savvas et al. 2009].

The effect of the foliar treatments was significant on hue angle and the saturation index (Tab. 6). The hue angle refers to the color hue, represented in degrees in a scale from 0 to 360, and expresses the variations that a single color con have when combining it with another [Domene and Segura 2014]. An increase in the saturation index value (chroma) (0 for achromatic stimuli, 150 or more for monochromatic stimuli) translates as darker or more saturated coloring [Domene and Segura 2014], or that the dominant coloring is more intense [Lancaster and Lister 1997]. Fruit color is a highly im-

Table 5. Effect of foliar application of silicon and calcium on fruit firmness of cucumber crops established under sodic soil conditions

Foliar treatments			Fruit firmness (N)		
Description	Si (mM)	Ca (mM)	at the end towards the peduncle	at the middle	towards the end near the flower
Control	0	0	5.49 ±0.30 b	5.42 ±0.38 a	5.09 ±0.18 a
Si	2	0	6.38 ±0.34 a	6.04 ±0.24 a	5.97 ±0.38 a
Ca	0	2	5.85 ±0.35 ab	5.80 ±0.38 a	5.36 ±0.24 a
Si + Ca	2	2	5.63 ±0.34 ab	5.57 ±0.18 a	5.08 ±0.50 a
$LSD_{0.05}$			0.85	0.79	0.91

Data ±SD in each column followed by a different letter were significantly different (LSD, $P \leq 0.05$). LSD: least significant difference test

Table 6. Effect of foliar application of silicon and calcium on color attributes in cucumber crop fruits established under sodic soil conditions

Foliar treatments			Luminosity (%)	Hue angle (°)	Saturation index (chroma)
Description	Si (mM)	Ca (mM)			
Control	0	0	17.23 ±0.27 a	117.03 ±2.78 b	75.11 ±1.62 b
Si	2	0	17.95 ±0.75 a	120.57 ±1.66 ab	96.79 ±3.03 a
Ca	0	2	17.50 ±0.63 a	125.22 ±2.99 a	78.82 ±3.45 ab
Si + Ca	2	2	17.95 ±0.54 a	123.65 ±1.46 ab	88.32 ±7.51 ab
$LSD_{0.05}$			1.984	7.538	21.466

Data ±SD in each column followed by a different letter were significantly different (LSD, $P \leq 0.05$). LSD: least significant difference test

portant quality parameter [Fahmy and Nakano 2013]. The concentrations of chlorophyll, carotenoids, and anthocyanins result in the presence of the characteristic color of vegetables [Lancaster and Lister 1997]. The highest hue angle value was observed in plants treated with foliar Ca applications, which was significantly higher than the control. The highest chroma value was obtained with foliar Si applications, and it was significantly greater than the control. Even though foliar Si + Ca application showed increases in color characteristics, those increases were not significant.

Foliar Ca applications intensified the green coloring of cucumbers (125.22°), as the higher the hue angle value, the greener the fruit [Jasso-Chaverria et al. 2005]. Greenness (hue angle) in cucumber fruits is related with the accumulation of chlorophyll [Hurr et al. 2009]. Gómez-López et al. [2006] reported hue angle values from 115 to 125° in cucumber of two crop seasons. The increase in the chroma value with foliar Si applications (96.79) translates into dark green coloring [Domene and Segura 2014]. Accordingly, Michailidis et al. [2017] reported that foliar Ca application also increases the fruit chroma value significantly. Regarding luminosity values (L), none of the tested treatments was different to the control. This coincides with Alcaraz-Lopez et al. [2003]. Similarly, Montesano et al. [2016] found no significant effects from Si on the luminosity of green bean pods.

CONCLUSIONS

Foliar Ca application increased the concentration of total soluble solids (TSS) and green coloring (hue angle) of cucumber fruits, while foliar Si application increased fruit firmness at the end towards the peduncle and the intensity of the green color of the fruits (chroma) of cucumber established under sodic soil conditions. Dry matter of leaves and stems, fruit yield and fruit size were not significantly affected by the foliar treatments tested.

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