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RESEARCH ARTICLE

Effect of calcium silicate and moisture content of the substrate on the growth and productivity parameters of cucumber

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ABSTRACT

Water deficits can be mitigated by silicon in plants. Two greenhouse experiments were conducted at the Universidad Autónoma Chapingo to determine whether Si affects the growth, nutrient absorption, and fruit production of a ‘Braga F1’ hybrid cucumber (*Cucumis sativus* L.) under water deficit. A completely randomized design was used with two factors, substrate moisture (55%-65%, 75%-85%, and 90%-100% of container capacity) and Si dose (0, 50, 100 mg L^{-1} SiO_2) applied to the substrate, resulting in nine treatments with four replicates. After transplanting, moisture content was determined on days 30 to 60 (trial I) and 60 to 90 (trial II). Accumulated fruit production (AFP), total soluble solids (TSS), aerial (ADB) and radical dry biomass (RDB), leaf area (LA), and concentrations of N, P, K, and Mg in fruits, leaves, and stems were determined. ANOVA and Tukey tests ($P \leq 0.05$) were performed. For AFP and TSS, ADB and LA (trial II), the interaction between Si concentration and moisture in the substrate was nonsignificant in either trial. Individual Si effects increased fruit production without affecting TSS content. ADB, RDB, and LA production increased under water stress as a result of the interaction between Si concentration and moisture content. Application of 50 mg L^{-1} SiO_2 resulted in 36.5% more ADB, 17.3% more LA, and 46.5% more RDB than 100 mg L^{-1} SiO_2 and 38.8%, 29.6% and 48.9% more than Si alone. The concentration of N, P, K, and Mg in fruits, P and K in leaves, and N and K in cucumber stems also improved.

Key words: *Cucumis sativus*, drought, hydric deficit, silica fertilization, water.

INTRODUCTION

The cucumber (*Cucumis sativus* L.) is, after watermelon, the second most cultivated cucurbit in the world (Pal et al., 2020). The crop has shallow roots and is not tolerant to water stress (Fan et al., 2014), so proper irrigation management is essential for high yields and quality of the fruit (Pal et al., 2020). Cucumber cultivation does better with drip irrigation in greenhouses (Pal et al., 2020). Water stress is a common situation the crop faces during its growth and development stages. Appropriate water management is essential to the crop due to its high susceptibility to unfavorable conditions, where stress situations like water shortage can harm its physiological and biochemical processes (Yuan et al., 2016).

Consequently, its photosynthetic capacity is affected, affecting its growth and eventually reducing its productive capacity (Sharma et al., 2019). As well, membrane integrity, osmotic balance, and plant water states are all negatively affected by water shortage (Jafari et al., 2015). Also, plant cellular and molecular processes can disrupt (Potters et al., 2007). Therefore, it is critical to include alternative sustainable approaches to manage plants’ water stress in agronomic practices.

Despite the benefits of Si usage in agriculture and its abundance in the terrestrial layer, its essentiality remains not yet accepted or confirmed. Although it is an abundant element, its poor solubility implies that only a tiny amount of it is available for uptake by plants as H_4SiO_4 (Toresano et al., 2012). The extraction and accumulation of Si in plant tissues differ by species (Savvas and Ntatsi, 2015) but also by dosage and soil conditions (Ouellette et al., 2017). Cucurbitaceous plants do not consider Si accumulators, although they show selective assimilation of the element, which can differ between species or even at the cultivar level (Toresano et al., 2012). Although Si absorption is low in some plants, its presence can substantially benefit under stress conditions (Toresano et al., 2012). The cucumber is an intermediate Si accumulator plant (Liang et al., 2015; Savvas and Ntatsi, 2015; Dorais and Thériault, 2018). Its foliar Si concentration ranges from 1.8% to 2.9% (Liang et al., 2015). The Si positively influences photosynthetic activity, biomass accumulation in fruits, tolerance to salinity, and environmental stressors such as drought and low and high temperatures (Liang et al., 2015; Savvas and Ntatsi, 2015).

Furthermore, Si protects plants from nutritional imbalance and mineral toxicity (Liang et al., 2015; Savvas and Ntatsi, 2015). The yield of cucumber fertilized with Si can vary according to the element's form and application rate. According to Abd-Alkarim et al. (2017), via the soil or leaves Si enhanced the yield and quality of greenhouse-grown cucumber fruit. Abd-Alkarim et al. (2017) observed that applying Si to the soil increased the yield of marketable cucumber fruit. The Si nanoparticles in cucumber under water shortage and salt stress increased crop production, especially in plants watered up to 85% of their ETc, plant height, chlorophyll content, and fruit output increased by 20%, 51%, and 156%, respectively, compared to untreated plants (Alsaeedi et al., 2019). Alsaeedi et al. (2019) found that high Si content in cucumber leaves aids in regulating water loss through transpiration and mitigates the effects of water shortage and salt stress. Research on cucumber's response to Si under water stress remains scarce. Based on the above, in this work, the effects of different Si dosages and moisture levels in the substrate on the growth, productivity, and nutritional absorption of cucumber under greenhouse conditions were studied.

MATERIALS AND METHODS

Condition and location of the experiment

The experiment was conducted from May to August 2021 in a greenhouse of the Soils Department at the Universidad Autónoma Chapingo (UACh) (19º29' N, 98º53' W).

Two trials were carried out in black perforated polyethylene bags, with 10 L substrate made up of a mixture of peat moss and tezontle in a 3:1 v:v ratio, with the respective chemical compositions described in Tables 1 and 2. The water holding parameters of the substrate were determined according to the De Boodt et al. (1974) approaches. Table 3 presents some physical parameters, and Figure 1 the moisture retention. Figure 2 presents the average temperature, relative humidity, and luminosity recorded inside the greenhouse during the experiment.

Table 1. Chemical properties of Peat moss (ProMix®) according to the provider (Premier Tech Horticulture). SME: Saturated medium extract; EC: electrical conductivity.

Parameter (SME)	Peat moss (ProMix®)
pH	5.2-6.2
EC, dS m^{-1}	1.0-1.8
$N-NO_3$, mg L^{-1}	70-130
$P-PO_4$, mg L^{-1}	5-40
K, mg L^{-1}	50-130
Ca, mg L^{-1}	100-180
Mg, mg L^{-1}	20-45
$S-SO_4$, mg L^{-1}	30-100
Fe, mg L^{-1}	0.8-2.2
Zn, mg L^{-1}	0.1-1.2
Cu, mg L^{-1}	< 0.3
Mn, mg L^{-1}	0.3-1.0
B, mg L^{-1}	< 0.6

Table 2. Chemical properties of tezontle according to Trejo-Téllez et al. (2013). EC: Electrical conductivity.

Parameter	Tezontle
pH	7.35
EC, dS m^{-1}	0.15
N, %	0.61
P, mg kg^{-1}	0.31
K, mg kg^{-1}	2.74
Ca, mol m^{-3}	22.0
Mg, mol m^{-3}	10.09
Na, mg L^{-1}	Not detected

Table 3. Physical and water retention characteristics of the substrate mixture.

Apparent density (D_{ap}), g cm^{-3}	0.43
Water holding capacity (WHC), %	72.97
Total pore space (TPS), %	89.89
Aeration capacity (AC), %	16.91
Readily available water (RAW), %	21.54
Buffering capacity water (BCW), %	11.25
Hardly available water (HAW), %	40.18
Total available water (TAW), %	32.80

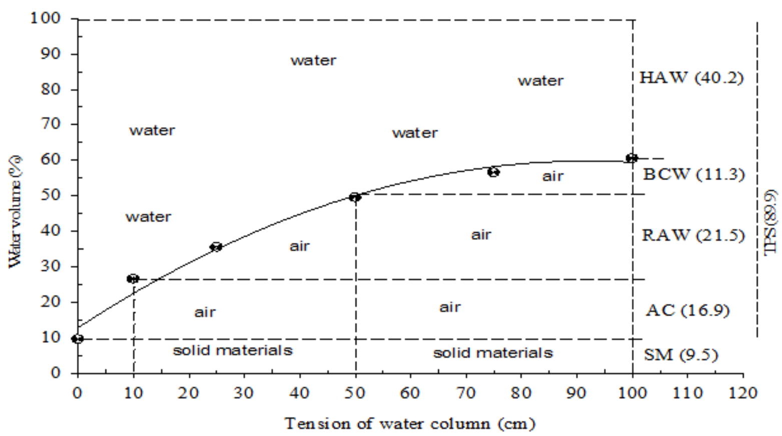

Figure 1. Water release curve of the substrate (peat moss and tezontle in a 3:1 v:v ratio) from 0 to 10 kPa (based on De Boodt et al., 1974). HAW: Hardly available water; BCW: buffering capacity water; RAW: readily available water; AC: air capacity; SM: solid materials; TPS: total pore space.

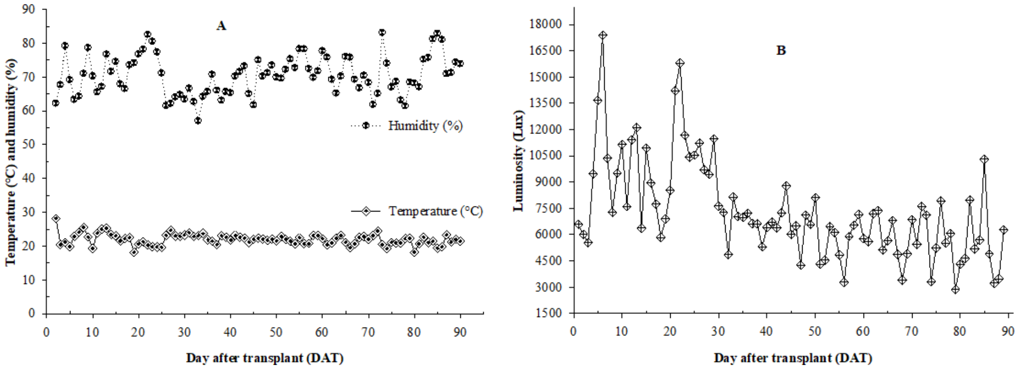

Figure 2. Daily average temperature, relative humidity, and luminosity inside the greenhouse throughout the experiment.

Experimental design, treatments, nutrition, and crop management

Cucumber (*Cucumis sativus* L.) seedlings were grown on seedbeds using 'Braga F1' hybrid seeds and transplanted into the bags of each treatment 22 d later. A completely random design (CRD) was formed from a factorial arrangement with two factors, each with three levels: Moisture in the substrate (55-65%; 75-85% and 90%-100% of container capacity [% CC]) combined with Si dosages (0, 50, 100 mg L^{-1} SiO_2), which generated nine treatments replicated four times each, in total 36 experimental units (3 × 3 × 4 = 36) where each bag with a plant represented an experimental unit.

The plants were evenly watered before and after the timeframes indicated for applying the moisture levels. Controlled watering regimes were performed according to each treatment when applying the moisture levels. The varying moisture levels were applied in the trial I from 30 to 60 d after transplantation (DAT) (Figure 3A) and in the trial II from 60 to 90 DAT (Figure 3B). The moisture levels have been measured using HOBO node Wireless Soil Moisture Sensors (W-SMC, Onset Computer Corporation, Bourne, Massachusetts, USA) inserted into the substrate at a depth of 10 cm in the root environment. Regarding the Si dosages (0, 50, 100 mg L^{-1} SiO_2), 300 mL solution were applied in each bag every 8 d, from the 8th day until the 75th day after transplanting. As Si input, a liquid source of $CaSiO_4$ (Barrier, Cosmocel, Nuevo León, Mexico), with a w/w concentration of 10% Ca, 24% SiO_2, and 66% conditioners and diluents, was employed.

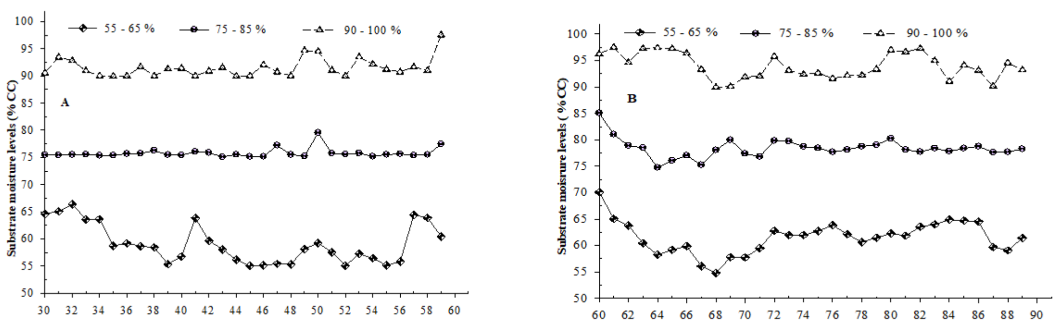

Figure 3. Distribution of the substrate's average moisture levels, trial I (A) and trial II (B).

Plant nutrition has been managed through a fertigation system, preparing the solution according to the recommendations in Table 4. The pH and electrical conductivity (EC) of the nutrient solution used to irrigate the plants, including the control treatment, were maintained between 5.5 to 6.5 and 1 to 2 mS cm^{-1}, respectively. Traps were installed in order to control the prevalence of insect vectors and the occurrence of diseases that may harm the plant's development. Cultural practices such as tutoring, training, and maintenance pruning were carried out, managing the plants to one stem until the cycle's conclusion (90 d after transplantation).

Table 4. Chemical composition of the nutrient solution used to irrigate the plants.

Nutrient	Seedling to 1st fruit	1st fruit-final
	mg L^{-1}	
N	133.00	240.00
P	62.00	62.00
K	150.00	150.00
Ca	130.00	260.00
Mg	50.00	50.00
S	70.00	70.00
Fe	2.50	2.50
Zn	0.09	0.09
Cu	0.10	0.10
Mn	0.62	0.62
B	0.44	0.44
Mo	0.03	0.03

Variables analyzed

Cumulative fruit production. Progressively as the fruits matured, they were harvested and weighted. At the end of the trial, the accumulated fruit production (AFP) per plant was calculated.

Total soluble solids of the fruit. A digital sucrose refractometer (HI96801, Hanna Instruments, Woonsocket, Rhode Island, USA), with a sugar content range of 0% to 85% °Brix, was used to determine the total soluble solids (TSS) percentage. One fruit from the middle part of each plant was selected, cut in half, and squeezed to extract drops of juice where the TSS percentage was determined.

Aerial and root dry biomass. At the end of the experiment, the plant's aerial part was cut at the base of the stem to assess the plant's production of aerial dry biomass (ADB). Plant samples were placed in paper bags and dried in a forced ventilation oven at 70 °C until constant weight. After drying, to determine the biomass on a dry basis, dried plant samples were weighted. The roots of each plant were collected and dried under the same conditions described above, and later the root-dried biomass (RDB) was determined.

Leaf area. After the crop cycle, all leaves from each plant were collected, and the total leaf area (cm^2) per plant was determined using a leaf area integrator (LI-3100C, LI-COR Biosciences, Lincoln, Nebraska, USA).

Analysis of nutrients in fruits and leaf tissue. At the end of the trial, N, P, K, and Mg concentrations in the plant's fruits, leaves, and stems were determined in the Plant Nutrition Laboratory of the Soil Department of the UACh. Nitrogen in foliar tissues by the Kjeldahl method and P by the molybdovanadate colorimetric method, both cases as described by Alcántar and Sandoval (1999). Foliar K determination uses a flame photometer (410, Sherwood Scientific, Cambridge, UK), and Mg uses an atomic absorption spectrophotometer (GBC 932 plus, GBC Scientific Equipment, Braeside, Victoria, Australia).

Statistical data analysis

After verifying the fulfillment of the statistical assumptions of variances normality and residuals homogeneity of the data, they were processed through the statistical program Sisvar 5.6 (Ferreira, 2011) using procedures associated with the ANOVA and followed by Tukey tests ($P \leq 0.05$) for means comparison.

RESULTS AND DISCUSSION

Cumulative fruit production and total soluble solids of the fruit

In both trials, the interaction of the Si doses with the substrate moisture levels was nonsignificant in the accumulated fruit production (AFP) and the content of total soluble solids (TSS) of the fruits (Table 5). In the trial I, silica fertilization did not affect the AFP. However, it influenced fruit yield in the trial II since the applications of 50 and 100 mg L^{-1} SiO_2 increased significantly by 7.89% and 15.56% AFP per plant compared to plants without Si applications. In the trial I, the reduction in water availability to the plant harmed the yield of cucumber fruits, with a significant decrease of 15.24% and 22.23%, respectively, in the lowest moisture level compared to the intermediate and high humidity levels. Similarly, fruit production decreased by 7.79% and 14.05% in the trial II at the lowest moisture level, respectively, compared to the substrate's intermediate and highest moisture levels.

Table 5. Silicon dosage and moisture levels on accumulated fruit production (AFP) and total soluble solids (TSS) of 'Braga F1' hybrid cucumber. Different letters in the same column show significant differences between treatments by Tukey's test ($P \leq 0.05$). % CC: Container capacity.

Treatments	Trial I		Trial II	
	AFP	TSS	AFP	TSS
	g plant^{-1}	%	g plant^{-1}	%
SiO_2, mg L^{-1}				
0	1675.67 ± 78.0^{a}	3.08 ± 0.11^{a}	1524.33 ± 40.0^{c}	2.93 ± 0.08^{a}
50	1796.25 ± 49.5^{a}	3.18 ± 0.18^{a}	1654.92 ± 48.1^{b}	3.18 ± 0.12^{a}
100	1739.83 ± 67.1^{a}	3.45 ± 0.13^{a}	1805.33 ± 50.8^{a}	3.28 ± 0.13^{a}
Humidity, % CC				
55-65	1503.83 ± 45.6^{c}	2.80 ± 0.09^{b}	1534.67 ± 24.4^{c}	3.02 ± 0.1^{a}
75-85	1774.25 ± 152.6^{b}	3.46 ± 0.11^{a}	1664.33 ± 151.6^{b}	3.23 ± 0.1^{a}
90-100	1933.67 ± 76.3^{a}	3.45 ± 0.12^{a}	1785.58 ± 74.9^{a}	3.14 ± 0.1^{a}

Regarding TSS content in the fruits, the Si dosage's separate effects did not affect this variable since all doses of Si generated significantly similar TSS content in both trials. Nor did the moisture levels of the substrate affect the content of TSS in the fruits in the trial II. In the trial I, the two higher moisture levels favored a higher concentration of TSS in the fruits and a 19% decrease in TSS content in the treatment fruits with the lowest moisture level in the substrate.

In the trial II, a favorable response of cucumber to Si was observed regarding AFP, which coincides with the positive effects of Si reported by Wang et al. (2007) and Dorais and Thériault (2018) on the growth and productivity parameters of cucumber crops. Applying a dose of 8 g L^{-1} wollastonite in cucumber plants, Dorais and Thériault (2018) reported a 6.5% increase in plant growth compared to the control treatment. Cucumber fertilization with variable doses of Si increased crop yield between 5.1% and 10.2% (Wang et al., 2007), while in an experiment carried out by Voogt and Sonneveld (2001) in a hydroponic system, cucumber produced its highest yield response in fruit yield to the application of 0.5 mM Si in the plant's root environment. Also, in cucumber plants fertilized with low doses of $(NH_4)_2SiO_3$ or K_2SiO_3, Górecki and Danielski-Busch (2009) reported increased crop yield. Information reported by Jarosz (2013) and Abd-Alkarim et al. (2017) on the yield of cucumber fertilized with diatomite as a Si source corroborated this experiment's results, mainly from the trial II, on the positive influence of Si on increasing yield in cucumber fruit. The accumulated fruit yield per plant in this experiment is much lower than the data reported by Zamora (2017) and Alejo-Santiago et al. (2021). Probably because of the varieties used, the cycle harvest duration since that cucumber is a staggering production crop, as well as the management technologies and environmental conditions under which the plants were developed. Also, the yield reduction observed, in both trials, with the low humidity level coincides with that reported by Grasic et al. (2021). They observed decreased growth and yield of cucumber due to insufficient water supply.

The decrease in soluble sugar concentration observed with the lowest moisture level in the substrate could be due to the plant's water deficit, which has not favored the concentration of soluble organic solutes in the fruits. However, this behavior was not observed in the trial II. Cucumber is not known for having high contents of soluble sugars in their fruits (Moreno et al., 2013). This variable can change between genotypes or fruit quality categories (Chacón-Padilla and Monge-Pérez, 2017). In this experiment, the TSS values range from 2.80% to 3.46% in trial I and 2.93% to 3.18% in trial II. These values are comparable to those obtained by López-Elías et al. (2015) at 3.3%, higher than those obtained by Alejo-Santiago et al. (2021) at 2.48% and 2.72%, and Galindo-Pardo et al. (2014) with 2.5%; and lower than those obtained by Barraza-Álvarez (2015) with values of 3.60% and 4.07% and Chacón-Padilla and Monge-Pérez (2017) with a variation between 3.38% to 3.67% of soluble solids in fruits of six cucumber genotypes grown under greenhouse conditions.

Aerial and root dry biomass

In the trial I, the interaction between the Si doses and moisture levels in the substrate was significant in the production of aerial dry biomass (ADB) of the cucumber crop (Figure 4A). Under limited water supply, compared to treatments without Si and 100 mg L^{-1} SiO_2, ADB increased mainly with 50 mg L^{-1} SiO_2, 38.8% and 36.5% higher, respectively. The ADB generated at the intermediate moisture level reduced considerably for 100 mg L^{-1} SiO_2 compared to the treatments without Si and 50 mg L^{-1} SiO_2. Under the higher humidity level, the absence of Si has not interfered with the plant's ADB production. In the absence of Si, the two highest humidity levels produced similar amounts of ADB but higher than the treatment with the highest water deficit. This tendency is in line with Grasic et al. (2021), who also indicated a reduction in the aerial biomass produced in cucumber cultivation owing to decreased soil water availability. When there is no water limitation and 100 mg L^{-1} SiO_2 is applied, these plants presented higher ADB than those treated with a similar Si dosage and intermediate or low humidity. Water deficit significantly reduces the growth and production of cucumber (Grasic et al., 2021). In this experiment, the dose of 50 mg L^{-1} SiO_2 counteracted the negative effect of water deficit by favoring higher production of ADB in plants with lower humidity levels compared to plants grown with higher humidity levels. The trial II showed that the effect of Si's interaction with the substrate's humidity levels did not affect the production of ADB of the crop. The presence or absence of Si and variations in moisture levels in the substrate did not affect the production of ADB of the plant.

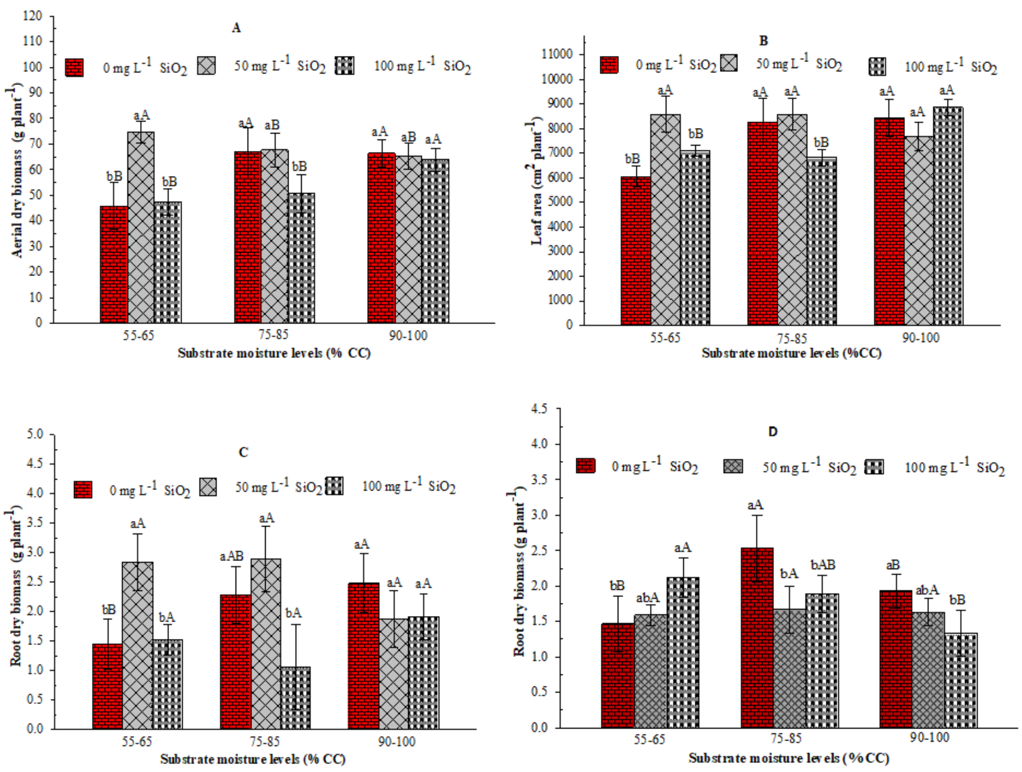

Figure 4. Effect of the interaction between Si dosages and the substrate's moisture levels on the aerial dry biomass production (A), leaf area (B) and root dry biomass (C and D) of 'Braga F1' cucumber hybrid (A, B and C: trial I; D: trial II). Different lowercase letters in the same moisture level indicate differences between SiO_2 doses and different uppercase letters for the same SiO_2 dose indicate differences between moisture levels, by Tukey's test ($P \leq 0.05$).

The interaction between Si and moisture levels in the substrate significantly affected the production of dry root biomass (DRB) in both trials (Figures 4C and 4D). Under the highest humidity level, whether or not Si was applied, there was no effect on the DRB production in the trial I. However, in the trial II, DRB was reduced with 100 mg L^{-1} SiO_2 compared to the treatment without Si. In both tests, the most significant effect of Si occurred at the lowest moisture level in the substrate. The application of Si stimulated the production of radical biomass. At the highest stress, 50 mg L^{-1} SiO_2 increased the root biomass by 48.94% and 46.48% compared to the treatments without Si and 100 mg L^{-1} SiO_2, respectively. In the absence of Si, the higher moisture level generated more DRB than the most stressed moisture level in trial I.

In contrast, the intermediate moisture level surpassed the others in the trial II. In both trials, when 50 mg L^{-1} SiO_2 was applied, the production of DRB was similar between the different moisture levels in the substrate. In the trial I, applying 100 mg L^{-1} SiO_2, all moisture levels presented similar root biomass values. However, in the trial II, although the two lowest moisture levels were significantly equal, the lowest moisture produced root biomass 37.3% higher than the highest moisture level.

The effect of Si on plant biomass production can be affected by the Si source used. A study by Grasic et al. (2021) revealed that the addition of K_2SiO_3 negatively affected the biomass production of the leaf. Ma et al. (2004) observed progressive loss of the green color and severe wilting of the plant leaf at midday in cucumber plants subjected to water stress and Si deficiency. Under the same stress level, the symptoms, as mentioned earlier, were less evident in plants treated with Si. In addition, cucumber plants subjected to water stress and treated with Si accumulated more biomass than plants deficient in Si. Ma et al. (2004) made the same observation as this experiment, mainly in the treatment with higher water stress levels. Likewise, a study by Meng et al. (2021) supports the positive effect of Si on stimulating biomass accumulation in cucumber plants. These findings demonstrate the role of Si in reducing the impacts of drought stress in cucumber plants. According to Ma et al. (2004), under water stress, increased photosynthesis and improved water retention capacity in plants were the main factors responsible for the positive effects of Si on biomass accumulation by plants.

Leaf area

In the trial I (Figure 4B), the leaf area of the crop was significantly affected by the interaction of the Si dosages with the substrate moisture levels. However, in trial II this interaction was nonsignificant (Table 6). Under the highest level of humidity, the leaf area of the crop did not show differences in the doses of Si in the trial I. For the intermediate moisture level, the leaf area decreased by 20.5% and 17.5%, respectively, applying 100 mg L^{-1} SiO_2 compared to 50 mg L^{-1} SiO_2 and the treatment without Si. The 50 mg L^{-1} SiO_2 generated greater leaf area under the lowest humidity level, 29.65% and 17.3% more than the treatments without Si and 100 mg L^{-1} SiO_2, respectively. Without Si, the two highest humidity levels presented similar leaf area values. However, they exceeded the lowest humidity level. With the application of 100 mg L^{-1} SiO_2, the highest humidity level produced a leaf area value 23.1% higher than the intermediate humidity and 19.9% higher than the lowest humidity. Under limited water conditions, 50 mg L^{-1} SiO_2 produced similar leaf area values to plants cultivated without water limitations. This result suggests that the Si impact offsets the detrimental effect of water shortage in plants with water restrictions.

Table 6. Silicon dosage and moisture levels on aerial dry biomass (ADB) production and leaf area (AF) of 'Braga F1' hybrid cucumber. Different letters in the same column show significant differences between treatments by Tukey's test ($P \leq 0.05$). % CC: Container capacity.

Treatments	Trial II	
	ADB	LA
	g $plant^{-1}$	cm^2 $plant^{-1}$
SiO_2, mg L^{-1}		
0	52.87 ± 3.2^a	6906.48 ± 278.13^b
50	57.59 ± 3.2^a	7697.49 ± 224.62^a
100	54.34 ± 2.8^a	7378.56 ± 198.7^{ab}
Humidity, % CC		
55-65	52.59 ± 3.1^a	7182.31 ± 248.85^a
75-85	58.92 ± 3.7^a	7530.90 ± 258.98^a
90-100	53.29 ± 3.1^a	7269.32 ± 206.02^a

Silicon increases plant growth, as can be corroborated mainly by the 50 mg L^{-1} SiO_2. This treatment increased the leaf area by 10.28% compared to the treatment without Si. The isolated effects of moisture levels did not differ regarding the leaf area.

Leaf area can vary depending on the cultivar and the stage of development. Leaf area can be directly related to biomass accumulation and plant performance because it allows better capture of radiant energy. Ortiz-Cereceres et al. (2009) found a positive correlation between leaf area and cucumber yield, observing a production of two more fruits per plant in varieties with a larger leaf area. Ramírez-Vargas (2019) found leaf area values between 433 and 563 cm^2 $plant^{-1}$, much lower than the leaf area (4798 cm^2 $plant^{-1}$) reported by Da Silva et al. (2011) in cucumber plants. The leaf area values obtained for 'Braga F1' at 90 d after transplantation were much higher than those reported by other authors for other cultivars evaluated in earlier stages of development.

Nutrient concentration in different parts of the plant

Fruit. The interaction of the Si dosages with the moisture levels of the substrate slightly influenced the content of N in the fruit in both trials, as well as the contents of P, K, and Mg in the fruits of the trial I (Figure 5). In trial I, under the lowest moisture level and the dose of 50 mg L^{-1} SiO_2, the N concentration was 23.13% higher than the treatment without Si. In contrast, for the two highest moisture levels, the Si dosages did not significantly affect the percentage of N in the fruits. In the trial II, the N concentrations in the fruit for 50 and 100 mg L^{-1} SiO_2 at the lowest moisture level were 13.15% and 14.52% greater than the control treatment. At the intermediate moisture level, 100 mg L^{-1} SiO_2 outperformed the two lowest Si doses, presenting an N concentration of 13.49% and 9.81% higher than the treatment of 50 mg L^{-1} SiO_2 and without Si, respectively.

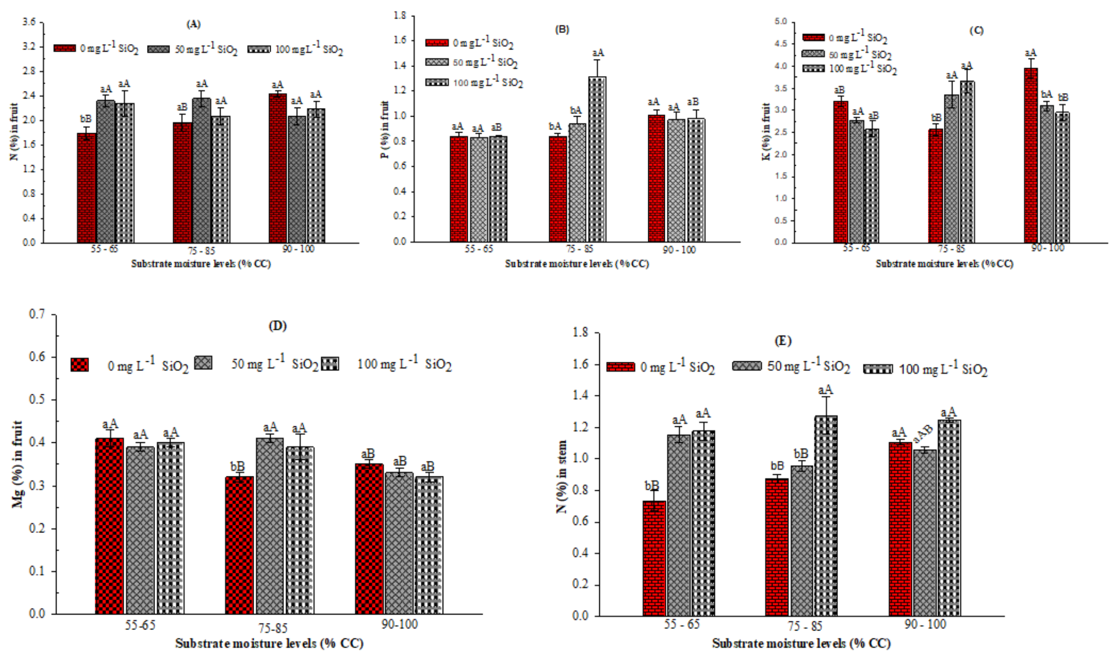

Figure 5. Effect of the interaction between Si dosages and the substrate's moisture levels on the contents of N, P, K and Mg in the fruits (A, B, C, D) and N in the stems (E) of cucumber (trial I). Different lowercase letters in the same moisture level indicate significant differences between SiO_2 doses and different uppercase letters for the same SiO_2 dose indicate significant differences between moisture levels, by Tukey's test ($P \leq 0.05$).

In contrast, the Si doses did not differ at the highest humidity level. The application of Si favored a greater concentration of P, K, and Mg in the fruits in the trial I, but only at the intermediate moisture level; at the other moisture levels, Si had nonsignificant favorable influence on the content of P, K, and Mg in the fruits. Under the intermediate moisture level, fruits of the plants treated with 100 mg L^{-1} SiO_2 had concentrations of P, K, and Mg that were 35.88%, 29.78%, and 17.95% higher than the fruits of the plants that did not receive Si.

Under the intermediate humidity level, when 50 mg L^{-1} SiO_2 was applied, the P percentage in the fruits was significantly similar to the treatment without Si, and higher concentrations of K and Mg, respectively, 28.61% and 21.95% greater as compared to the fruits from the plants without Si. In the trial II, neither the Si dosages' interaction with the humidity levels nor their isolated effect on the concentration of P in the fruits and stems of the plant, K in the fruits, or Mg in the fruits, leaves, and stems of the plant was significant.

Leaf. In the trial I, the interaction of Si doses with the humidity levels did not significantly affect any of the elements analyzed. In the trial II, the concentration of N, P, and K in leaves have been affected by the interaction of the Si doses with the substrate's humidity levels (Figure 6). In the absence of Si, plant leaves had higher N concentration except at the major humidity level, where N concentration in leaves was similar between the control treatment and the treatment with 50 mg L^{-1} SiO_2. Considering that Si showed a greater effect on the plant under higher stress conditions, it is possible that the lower N concentrations in leaves of the plants fertilized with Si are due to a greater transfer of N from leaves to the fruit at lower humidity, which may result in a lower N content in the leaves of the plants fertilized with Si. This explanation is valid only for the interaction of the Si doses with the lowest moisture level and for the interaction of 100 mg L^{-1} SiO_2 with the intermediate moisture level, because the N concentrations in the fruits were similar for the interaction of 50 mg L^{-1} SiO_2 with the intermediate moisture level and both Si doses with the highest moisture level under the respective moisture levels without Si. Although N concentrations in leaves were lower in the interaction of 100 mg L^{-1} SiO_2 with the highest moisture level than in the treatment without Si at that moisture level, no Si transfer from leaves to fruit was evident in fruit. The 50 mg L^{-1} SiO_2 favored a higher concentration of P in the plant leaf at low and intermediate moisture levels while being similar to the 0 and 100 mg L^{-1} SiO_2 under the highest humidity level. Applying 50 mg L^{-1} SiO_2, P concentrations in the leaf were 29.5% and 11.5% higher in comparison to the treatments without Si and 100 mg L^{-1} SiO_2 at the lowest humidity level, and 24.2% and 34.5% higher in comparison to the treatments without Si and 100 mg L^{-1} SiO_2 at the intermediate moisture level. Under the lowest humidity level, the K content in the leaves of plants treated with 50 and 100 mg L^{-1} SiO_2 was 24.4% and 17.4% higher, respectively, than the treatment without Si. The Si treatments did not differ at the other moisture levels.

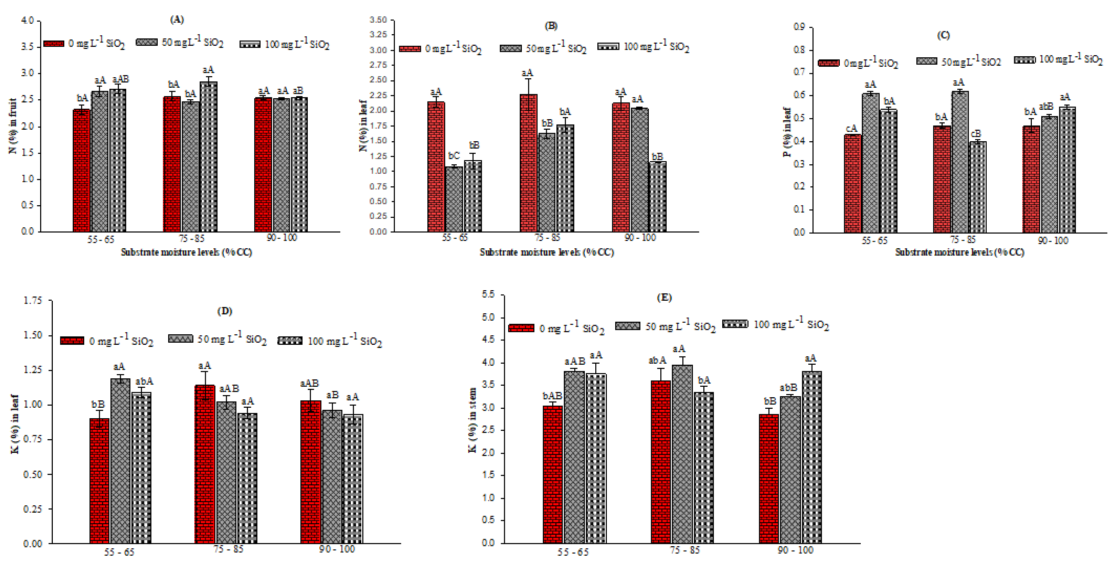

Figure 6. Effect of the interaction between silicon dosages and the substrate's moisture levels on the contents of N in the fruits (A), N, P, and K in the leaves (B, C, D), and K in cucumber stems (E) (trial II). Different lowercase letters in the same moisture level indicate significant differences between SiO_2 doses and different uppercase letters for the same SiO_2 dose indicate significant differences between moisture levels, by Tukey's test ($P \leq 0.05$).

Stem. In the trial I, the combined effect of the Si dosages with humidity levels substantially influences the concentration of N in the stem (Figure 5). Under the highest moisture level, in the trial I, the Si dosages did not differ from each other; however, at the intermediate moisture level, the concentration of N in the stem was 31.5% higher than the treatment without Si and 25.1% higher than the 50 mg L^{-1} SiO_2. Furthermore, under the lowest moisture level, the N concentration in the stem for the treatment without Si was 36.4% and 37.6% lower than the 50 and 100 mg L^{-1} SiO_2 treatments. In the trial I, the significant effect of the interaction between the Si dosages and the humidity levels influenced the percentage of K in the stem (Figure 6). Applying 100 mg L^{-1} SiO_2 increased the concentration of K in the stem by 24.9% and 18.9%, respectively, under the highest and lowest levels of moisture in the substrate, compared to the plants with no Si application. Also, the application of 50 mg L^{-1} SiO_2 and the lower humidity level generated a K concentration 20.2% higher in the plant stem compared to the treatment without Si. Under the intermediate moisture level, Si-treated plants had significantly similar K concentrations in the plant stem compared to the untreated plants.

Based on the nutrient concentration standards analysis of the upper leaves (third to the fifth leaf) in the early stage of flowering recommended for cucumber cultivation, the concentration of N in the different organs of the plant varied between deficient to low, except in the trial II the fruits presented normal levels of N. The concentrations of P were high in the fruits and ranged from standard to high in leaves and stems. Regarding K, its concentration was normal in the fruits, deficient in leaves, and low to normal in the stem. In all organs of the plant, the level of Mg was normal. It is worth mentioning that the analysis of these elements has conducted at the end of the experiment from a sample taken from the total DM produced by the organ. Because of this, the concentrations are subject to significant variations from the recommended standard values. The P and Mg concentrations found in cucumber fruits were quite comparable to those seen in greenhouse cucumber fruits, as by Navarrete (2005). The sequence of concentration of the elements in various plant organs differs by element. The N concentration was higher in the fruit, followed by the leaves, while the stems had the lowest concentration. The fruits had the highest P level, followed by stems and leaves, which had equal P amounts. In terms of K, the fruits had the highest concentration, followed by the stem and leaves.

Epstein (2009) and Jarosz (2013) reported positive effects of Si application on nutrient uptake and distribution in plants, which was not confirmed by the results of this study, except for some exceptions where the content of P and Mg in leaves was higher than the treatment without Si. The Mg concentrations were highest in leaves, then stem, and finally, fruits. The interaction between the two highest doses of Si and the intermediate moisture level presented concentrations of P, K, and Mg in the fruits higher than in the treatment without Si. This investigation revealed a more significant accumulation of K and Mg in the cucumber aerial parts compared to the root part, which agrees with Alsaeedi et al. (2019) and Greger et al. (2018). They also observed a more significant accumulation of K in the cucumber stem compared to the root, indicating a possible involvement of Si in facilitating the movement of these elements toward the aerial part of the plant (Alsaeedi et al., 2019). The examination of the nutrient concentrations in cucumber tissues of this research concurs with Jarosz (2013) in stating that the results of the influence of Si on the absorption and distribution of the elements in plants are frequently conflicting, sometimes revealed as favorable, unfavorable, or simply no impacts of Si.

CONCLUSIONS

The interaction of Si doses with humidity levels in the substrate did not affect fruit production and total soluble solids content. However, the doses of 50 and 100 mg L^{-1} SiO_2 positively influenced cucumber fruit yield, increasing fruit production by 7.89% and 15.56%, respectively, over the control treatment in the trial II.

The decrease in water availability had a detrimental impact on fruit production in both trials and total soluble solids concentration in trial I.

In situations of water stress, particularly in trial I, application of Si improved aerial dry biomass (ADB) production, leaf area, and plant rooting. At the lowest moisture level, application of 50 mg L^{-1} SiO_2 showed advantages over 100 mg L^{-1} SiO_2 and no Si. At 50 mg L^{-1} SiO_2, ADB, leaf area, and radical dry biomass were 36.5%, 17.3%, and 46.5% higher than at 100 mg L^{-1} SiO_2 and 38.8%, 29.6%, and 48.9% higher than without Si.

In the first test, Si interaction with the substrate's humidity and the impacts of the individual factors did not influence the plant's aerial biomass production. However, the dose 50 mg L^{-1} SiO_2 increased the leaf area by 11.45% compared to the control treatment.

At low and intermediate moisture levels in the substrate, Si enhanced the concentration of N, P, K, and Mg in the fruits, P and K in the leaves, and N and K in the cucumber plants' stems, under the conditions of this study.

Author contribution

Conceptualization: G.F. Methodology: G.F. Validation: R.A-R., J.P-P., M.A.V-P. Formal analysis: G.F. Investigation: G.F. Resources: G.F., R.A-R., J.P-P. Data curation: G.F. Writing-original draft: G.F. Writing-review & editing: G.F., R.A-R. J.P-P., M.A.V-P. Supervision: R.A-R., J.P-P. Project administration: G.F, R.A-R., J.P-P., M.A.V-P. Funding acquisition: R.A-R. All co-authors reviewed the final version and approved the manuscript before submission.

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