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Assessment of Two Calcium Silicate Sources on Cucumber Under Water Restriction

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Abstract

Silicon (Si) is beneficial for plants that are under unfavorable conditions. In this study conducted under greenhouse conditions at Chapingo Autonomous University, Si fertilization was tested to examine whether it affected yields, biometrics, physiological parameters, and nutritional attributes of cucumber plants cultivated at different moisture levels in the substrate. Fifteen treatments were tried in a completely randomized design, including three moisture levels (50-60%, 75-85%, and 90-100% of container capacity (CC) and five Si doses (0, 50, 100 mg L^{-1} SiO_2, 2 g L^{-1}, and 3 g L^{-1} Wollastonite). Uniform irrigation was applied until the 18th day after transplantation, and controlled irrigation was applied according to the moisture levels until the end of the experiment. 3 g L^{-1} of wollastonite under 75-85% CC enhanced cucumber yield by 24.9% in comparison to untreated plants, while no Si dose affected fruit length, diameter, weight, and total soluble solids. At 90-100% of CC, 50 mg L^{-1} SiO_2 increased the aerial biomass production (ABP) of the plants by 9.3%, and at 50-60% of CC, 100 mg L^{-1} SiO_2 generated 11.8% more aerial biomass than untreated plants. As Si did not affect root production, mainly at 50-60% of CC, it improved chlorophyll a, b, and the total content of the leaves. Different parts of the plant saw significant increases in N, P, K, Ca, Mg, and Si concentrations because of Si's interactions with moisture levels. When the substrate is low in moisture, Si is likely to improve cucumber yields, physiological, and nutritional characteristics of the plant.

Keywords: *Cucumis sativus*, hydric deficit, silicon fertilizer, stressed plant, water stress

1. Introduction

Water is crucial to the morphological, physiological, and biochemical functions of plants. It provides them with the nutrients and hydration needed to show their full potential, making it an essential part of them (Peçanha, da Cunha-Chiamolera, Chourak, Martínez-Rivera, & Urrestarazu, 2021). Hence, ensuring an adequate supply of water is key for ensuring healthy and thriving plants since its absence significantly impacts their water status, their nutrition (Peçanha et al., 2021), and, consequently, their performance (Sharma, Leskovar, & Crosby, 2019).

As an economically and nutritionally valuable commodity, cucumbers (*Cucumis sativus* L.) have a rapidly growing domestic and foreign market and are widely consumed for their rich vitamin content (Orzolek, Kime, Bogash, & Harper, 2017). A small-scale crop, cucumbers are nutritionally high in water, low in calories, high in phenolic compounds and cucurbitacins, and contain antioxidants, anti-inflammatory, hypoglycemic, and cancer-fighting properties (Mukherjee, Nema, Maity, & Sarkar, 2013; Uthpala, Marapana, Lakmini, & Wettimuny, 2020; Ghafoor et al., 2022). Physiological and biochemical processes of the plant can be damaged by unfavorable conditions, such as stress due to hydric deficit (Yuan, Yang, Li, Liu, & Han, 2016), resulting in reduced yields and decreased quality of the fruits (Pal, Adhikary, Shankar, Kumar, & Maitra, 2020). Multiple effects and benefits of root and foliar applications of silicon sources have been investigated and reported in various plant species (A. Ahmad, Afzal, A. U. H. Ahmad, & Tahir, 2013; Pavlovic et al., 2013; Bityutskii, Pavlovic, Yakkonen, Maksimović, & Nikolic, 2014; Hernández-Apaolaza et al., 2020; Hussain et al., 2021; Martín-Esquinas & Hernández-Apaolaza, 2021). According to Barreto, Schiavon Júnior, Maggio, & Prado (2017), the high concentration of Si in leaf tissue favors yield and tolerance to physicochemical stress. For example, Wenneck, Saath, and Rezende (2022) in an experiment in which they applied to the soil different rates of Si in Cauliflower (*Brassica oleracea* var. botrytis), grown with different levels of water replenishment, increased dry biomass production and Si content in different plant components, with accumulation between 0.5% to 2.19% and 0.29% to 0.9% of Si, respectively in the roots and leaves of the plant. Also, according to González-García et al. (2022), silicon can increase the content of bioactive compounds in cucumbers. They found 15.6% more total soluble solids in treatments with potassium silicate or silicon nanoparticles than in treatments without silicon. The results of Zhu et al. (2016) indicate that 0.3 mM Na_2SiO_3 in nutrient solution increases soluble sugar content (glucose, sucrose, and fructose) in cucumber plants. Also, Hu et al. (2022) corroborated this occurrence with foliar application of 1 mM Na_2SiO_3 in cucumber. In cucumbers, Si regulates the enzymes involved in the acquisition of Fe (Pavlovic et al., 2013). Si-mediated biosynthesis of Fe-chelating compounds in cucumber roots alleviates Fe deficiency and enhances Fe mobilization in roots by increasing apoplastic Fe stores in roots (Pavlovic et al., 2013). Under combined salt and water stress, by adding Si, Zhu, Wei, Li, Qian, and Yu (2004) observed that cucumber plants increased their protein content. Using Si in cucumbers modulates gas exchange, which contributes to drought tolerance (Ma, Li, Gao, & Xin, 2004). Cucumber leaves harbor a high concentration of Si in the cells surrounding the capillary trichome bases (Abe, 2019). In Melon (*Cucumis melo* L.), which is from the same family as cucumber, Nascimento et al. (2020) reported an increase in the absorption of nutrients and their yield due to the application of Si.

In hydroponic systems, De Kreij, Voogt, and Baas (2003) and Kamenidou, Cavins, and Marek (2010) recommend supplementing cucumbers and roses (*Rosa hybrida* L.) with silicon, and according to Ma and Yamaji (2006), the benefits of Si in plants are more evident under stress conditions. In this context, further research on the use of Si as a strategy for mitigating the harmful effects of water scarcity on plants, such as cucumber, is needed. Therefore, in this study, it was investigated whether Si fertilization could reduce the negative impact of water stress on cucumber plant yields, biometrics, physiological as well as nutritional parameters.

2. Method

2.1 Location of the Experiment and Characterization of the Substrate

A greenhouse essay was performed in Texcoco, State of Mexico, at the Chapingo Autonomous University (UACh), located at 19º29′ N, 98º53′ W. The experiment was conducted in perforated black polyethylene bags filled with 12 L of peat (ProMix®) with respective chemical and moisture retention properties, as shown in Tables 1 and 2 and figure 1. The characteristics of substrate water retention were determined according to De Boodt, Verdonck, and Cappaert (1974).

Table 1. Chemical properties of the peat (ProMix®) according to the supplier

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

Note. *SME: saturated media extract.

Table 2. Physical and water retention characteristics of the substrate

Bulk density (B_{ap}), g cm^{-3}	0.14
Water holding capacity (WHC), %	79.78
Total pore space (TPS), %	92.71
Aeration capacity (AC), %	12.93
Readily available water (RAW), %	26.61
Buffering capacity water (BCW), %	13.28
Hardly available water (HAW), %	39.89
Total available water (TAW), %	39.89

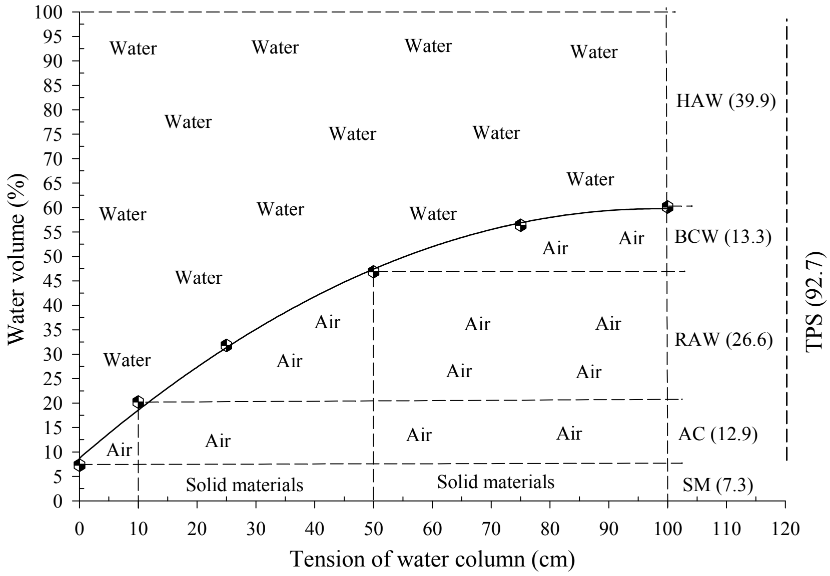

Figure 1. Graphical representation of the water release capacity of the substrate (ProMix®) from 0 to 10 kPa

Note. HAW: Hardly available water; BCW: buffering capacity water; RAW: readily available water; AC: air capacity; SM: solid materials; TPS: total pore space.

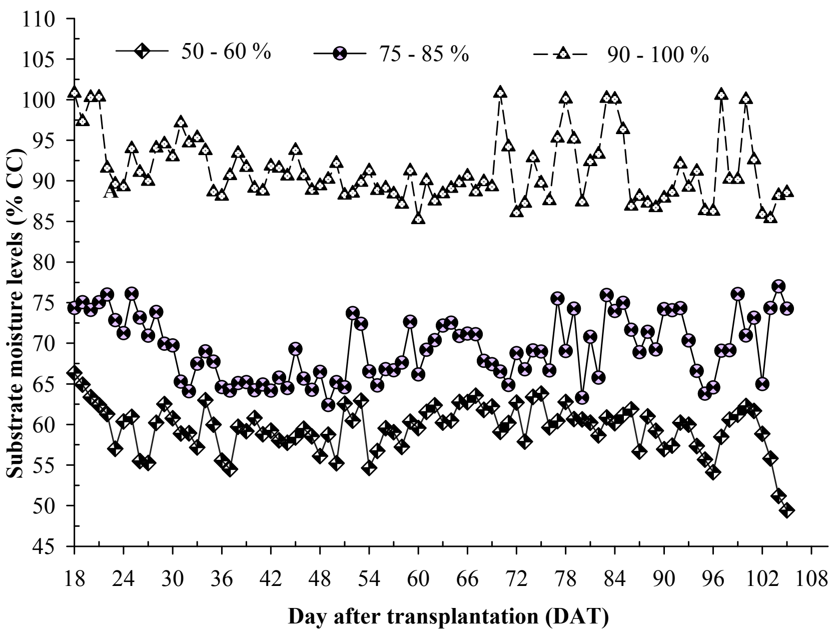

Figure 2. Average daily moisture levels registered in the *substrate*

2.2 Treatments, Experimental Design, and Crop Management

Seedlings of hybrid cucumbers 'Vitaly' (Syngenta AG, Switzerland) were grown in a seedbed and transplanted 18 days after seeding (DAS) into bags for each treatment. The experiment was established following a factorial arrangement of two factors and according to a completely randomized design (CRD), where each bag with a plant represented an experimental unit. The moisture levels in the substrate (50-60%; 75-85%; 90-100% CC), calculated based on its container capacity (% CC) with the doses of Si (0, 50, 100 mg L^{-1} SiO_2, 2 g L^{-1}, 3 g L^{-1} Wollastonite) resulted in fifteen treatments that were replicated four times, totaling 60 experimental units (3 × 5 = 15 × 4 = 60).

In terms of the 0, 50, and 100 mg L^{-1} SiO_2 doses, 300 mL of solution were applied to each bag every 8 days from the day of the transplant until day 63, according to the concentration of the treatment, using a concentrate liquid of calcium silicate, branded Barrier®, produced by Cosmocel, Nuevo León, Mexico, with a chemical composition of 10% Ca, 24% SiO_2, and 66% conditioners and diluents. In the treatment with Si formed with Wollastonite, before transplanting, 24 g of product was applied and mixed with the substrate for the 2 g L^{-1} treatment and 36 g for the 3 g L^{-1} treatment. Wollastonite is a very fine granular calcium silicate, apparent as a powder. Table 3 shows the chemical characteristics of the Wollastonite.

The plants were irrigated uniformly until 18 days after transplantation (DAP) and from this date until the end of the experiment, the moisture levels established in the substrate were maintained by applying controlled irrigation according to each moisture treatment (Figure 2). To monitor moisture levels in the growing medium, wireless HOBOnode soil moisture sensors from Onset Computer Corporation (W-SMC, Bourne, Massachusetts, USA) were installed to a depth of 10 cm in the root environment of the plant. The plants were irrigated and nourished through a fertigation system using a nutrient solution prepared according to the recommendations in Table 4. As part of cultural practices, tutoring, guiding, and pruning tasks were carried out to keep the plants with a single stem until the end of the cycle (105 days after transplanting). Also, when the plant reached around 3 m in height, the terminal growth bud of the plant was cut. Traps were placed to control the presence of insects and disease vectors that could harm the crop.

Table 3. Chemical composition of the Wollastonite, according to the manufacturer

SiO_2 (%)	48-53
CaO (%)	43-46
Al_2O_3 (%)	0.15-0.30
Fe_2O_3 (%)	0.15-0.55
TiO_2 (%)	0.02
S (%)	0.02
P (%)	0.007
LOI* (%)	1-4

Note. LOI*: Loss on ignition.

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

Nutrient (mg L^{-1})	Seedling to 1st fruit	1st fruit to the final of the cycle
N	133	240
P	62	62
K	150	150
Ca	130	260
Mg	50	50
S	70	70
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

2.3 Biometric and Yield Analysis

2.3.1 Cumulative Yield of Fruits

As the fruits matured, they were gradually harvested and weighed to calculate the cumulative yield of fruits (CYF) per plant by adding the production of each harvest.

2.3.2 Average Length, Diameter, and Weight of Fruits

The length of each fruit and the length of its circumference in the central part were measured using a tape measure graduated in cm. The diameter of the fruit was determined by dividing the length of its circumference by π. Finally, with the data from all the fruits, the average length (ALF) and diameter (ADF) of the fruits were calculated. Also, the CYF was divided by the number of fruits produced per plant to determine the average weight of the fruits (AWF).

2.3.3 Concentration of Total Soluble Solids

A digital sucrose refractometer (HI-96801, Hanna Instruments, Woonsocket, Rhode Island, USA), with a sugar concentration range of 0-85% °Brix, was used to determine the concentration of total soluble solids (TSS). For this, two fruits were selected in the middle part of each plant and each one was divided in half and squeezed. With the drops of juice produced, the TSS concentration in each fruit was determined and these values were averaged to determine the TSS content in the fruits.

2.3.4 Aerial and Root Dry Biomass

The aerial portion of the plant was cut at ground level at the end of the experiment to quantify its aerial (leaves and stems) biomass production (ABP). The samples were separated into leaves and stems and placed in paper bags to be dried to a constant weight at 70 °C in a forced ventilation oven. Then, they were weighed, and the amount of aerial biomass per plant was determined. Likewise, after the root of each plant was collected and dried under the same conditions as above, its root biomass (RB) was calculated.

2.4 Relative Water Content of Leaves

Leaf sampling was carried out at 103 DAP, collecting one leaf per plant. Subsequently, 3 leaf punches were removed and weighed individually on an analytical balance to determine their fresh weight (FW). Then, in a Petri dish, they were saturated with distilled water and left at room temperature for 19 hours. Then, excess water was removed from the leaf using a paper towel and its turgid weight (TW) was measured. They were then dried in a forced ventilation oven at 65 ˚C for 48 hours and their dry weight (DW) was determined. The relative water content RWC (%) was determined with the following formula:

$$\text{RWC}\ (\%) = (\text{FW} - \text{DW})/(\text{TW} - \text{DW}) \times 100 \quad (1)$$

2.5 Photosynthetic Pigments of Leaves

At 105 DAP, two leaves were collected at the top of each plant and used to make a composite sample. Subsequently, a subsample of 50 mg of leaf tissue was ground and homogenized in 40 ml of acetone at 80%, filtered, and placed in test tubes. An ultraviolet-visible (UV-Vis) spectrophotometer (Genesys 10-S, Thermo Fisher Scientific, Madison, Wisconsin, USA) was used to measure chlorophyll a, b and total fractions according to Witham, Blaydes, and Devlin (1971) and Lichtenthaler (1987).

2.6 Nutritional Analysis of Fruits, Leaves, Stems and Roots

At the end of the experiment, the dried fruits, leaves, stems, and roots were ground separately and the contents of N, P, K, Ca, Mg and Si in these components of the plants were measured in the Plant Nutrition Laboratory of the Department of Soils at Chapingo Autonomous University. The N in foliar tissues was determined by the Kjeldahl technique and the foliar P by the molybdovanadate colorimetric method, both procedures described by Alcántar and Sandoval (1999). A flame photometer (410, Sherwood Scientific, Cambridge, UK) was used to quantify foliar K and an atomic absorption spectrophotometer (GBC 932 plus, GBC Scientific Equipment, Braeside, Victoria, Australia) to determine foliar Ca and Mg. Also, using the colorimetric method described by Korndörfer, Pereira, and Nolla (2004) Si content was assessed in plant tissues.

2.7 Statistical Analysis

After verifying compliance with the assumptions of normality of variance and homogeneity of residuals, the data of each variable were processed using the statistical program Sisvar version 5.6 (Ferreira, 2014) through analysis of variance (ANOVA) and Tukey tests ($P \leq 0.05$) to compare the means of the treatments. The statistical program

SigmaPlot version 11.0 (Systat Software, Inc., San José California, USA) was used to prepare graphs of results for the variables that presented significant interactions between treatments.

3. Results and Discussion

3.1 Cumulative Fruit yield and Fruit Traits

Cumulative fruit yield (CFY) per plant was significantly affected by the interaction of Si with moisture levels in the substrate (Figure 3). Both at the lowest and highest moisture levels in the substrate, the application of Si did not increase fruit production. However, the application of 3 g L^{-1} of wollastonite, under the intermediate moisture level, favored higher fruit production in relation to the other doses of Si and generated a 24.9% increase in production in relation to untreated plants. Regarding moisture levels, the intermediate moisture level managed to exceed the other levels only when interacting with the 3 g L^{-1} dose of wollastonite. This interaction increased the CFY per plant, respectively, by 26.6% and 17.9% in relation to the lower and higher moisture levels in the substrate. Using 3 g L^{-1} of wollastonite for the intermediate moisture level resulted in the highest average fruit production (4.31 kg $plant^{-1}$); however, using 3 g L^{-1} of wollastonite at the lowest moisture level resulted in the least average fruit production (3.16 kg $plant^{-1}$), with a numerical difference of 26.6% between both treatments. In this study, cucumber fruit production increased with the application of Si as well as Hu et al. (2022) showed an increase in the yield and number of fruits of hybrid cucumber 'Jinyou 315' with foliar application of Si, alone or combined with Se. Likewise, research results by Basirat and Mousavi (2022) agree that Si, applied via foliar to cucumber plants grown under high temperature conditions, improves the total yield of cucumber fruits as well as their quality, with an increase of 36.14% of the total yield and 40.29% more marketable fruits. Similarly, root application of 500 mg dm^{-3} and 750 mg dm^{-3} of Si increased the production of cucumber fruits by 8.60% and 5.89% respectively, according to Jarosz (2013). Consistent with the results of this study, Alsaeedi et al. (2019) reported a 156% increase in fruit yield in cucumber plants under an irrigation regime of 85% ETc and fertilized with 200 mg kg^{-1} of Si nanoparticles. This study, as well as that of other authors, corroborates the positive effects of Si on improving the yield of cucumber fruits under different environmental conditions. These increases may be the result of improvements generated by Si in different components of the plant, such as nutritional aspects.

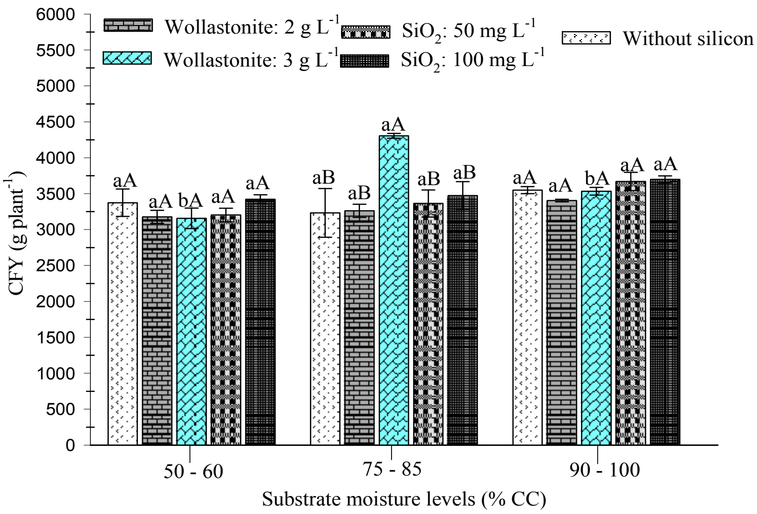

Figure 3. Effect of the interaction between silicon and moisture of the substrate on the average cumulative fruit yield (CFY) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

The interaction of Si with moisture in the substrate does not significantly influence the average length, diameter, weight, and content of total soluble solids in the fruits (Table 5). The length, diameter, weight and content of total soluble solids of the fruits varied between 17.84 to 23.0 cm, 5.0 to 5.67 cm, 243 to 615 g $fruit^{-1}$ and 2.95 to 4.25%, respectively. According to the technical data sheet of the seed, these data fit within the characteristics of the fruit of the 'Vitaly' cultivar. The ALF has not been affected by the silicon dose or by the moisture levels in the substrate. In the same way, the ADF, AWF and TSS of the fruits were not affected by the doses of Si either. However, a slight decrease in ADF and AWF was observed with the decrease in irrigation. As compared to the highest moisture level in the substrate, the fruits of the two lowest moisture levels had slightly higher TSS concentrations. The length, diameter and weight of cucumber fruit can vary mainly according to the variety. In the present experiment, the average length, diameter, and weight of the fruits of the hybrid 'Vitaly' were similar to those found by López-Elías et al. (2011) in Persian type cucumber. The average weight of the fruits in this study was clearly higher than that of the fruits of the varieties 'Reehan' and 'Khassib' evaluated by Alejo-Santiago et al. (2021). According to the report by Dorais and Thériault (2018), Si does not affect the weight of the cucumber fruit, which agrees with what was observed in this study and with Górecki and Danielski-Busch (2009) who reported increased yield in cucumber fruits due to the greater number of fruits produced per plant, not due to differences in the weight of the fruits. The length, diameter and weight of the fruit are phenotypic variables linked mainly to the genetics of the plant material, not to fertilization or the level of irrigation. This observation agrees with what was reported by Corrêa et al. (2018) and Alejo-Santiago et al. (2021) where the K dose variation has not significantly influenced the length and diameter of cucumber fruits, but they have observed differences between varieties for these variables. The bioactive compounds in cucumber fruits can be augmented by applying Si (González-Garcia et al., 2022). As demonstrated by González-García et al. (2022) when applying potassium silicate and silicon nanoparticles to cucumber plants, the TSS content grew by 15.6% in comparison to treatments without Si. Increased contents of phenolic compounds, ascorbic acid, flavonoids, titratable acids, antioxidant activities and lipophilic compounds were also reported (González-García et al., 2022). Similarly, the application of 0.3 mM Na_2SiO_3 in nutrient solution increased the content of soluble sugars (glucose, sucrose, and fructose) in cucumber plants (Zhu et al., 2016). Also, Hu et al. (2022) corroborated it with foliar application of 1 mM Na_2SiO_3 in cucumber. However, there is some evidence that Si application did not affect the TSS content of cucumber fruits. For example, in this study there was no increase in the TSS content in the fruits due to the application of Si, coinciding with the results of Abd-Alkarim, Bayoumi, Metwally, and Rhaka (2017), where the TSS content in cucumber fruits, measured at different stages of plant growth, did not differ significantly between the treatments that received Si and those that did not.

Table 5. Individual effects of silicon and moisture in the substrate on average length (ALF), diameter (ADF), weight (AWF), and total soluble solids (TSS) of 'Vitaly' cucumber

Doses of Si	ALF (cm)	ADF (cm)	AWF (g fruit^{-1})	TSS (%)
0	20.04±0.22 a	5.25±0.03 a	324.76±10.33 a	3.62±0.10 a
2 g L^{-1} Wollastonite	20.78±0.27 a	5.29±0.04 a	360.58±16.66 a	3.60±0.07 a
3 g L^{-1} Wollastonite	20.58±0.27 a	5.30±0.06 a	378.83±10.89 a	3.68±0.11 a
50 mg L^{-1} SiO_2	20.25±0.18 a	5.31±0.04 a	362.07±9.70 a	3.56±0.10 a
100 mg L^{-1} SiO_2	20.01±0.34 a	5.33±0.06 a	350.13±27.17 a	3.59±0.10 a
Humidity (% CC)				
50-60	19.97±0.19 a	5.19±0.03 b	328.72±7.14 b	3.86±0.05 a
75-85	20.53±0.24 a	5.32±0.04 a	364.77±15.94 ab	3.55±0.07 a
90-100	20.50±0.17 a	5.37±0.03 a	372.33±12.33 a	3.52±0.06 b

Note. Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

3.2 Aerial and Root Dry Biomass

Figure 4 shows a significant effect of the interaction between Si doses and moisture levels in the substrate on aerial biomass production (ABP) of the plant. ABP of the plant is positively affected by silicon at high and low moisture levels in the growing medium, whereas non-silicon-treated plants, at the intermediate moisture level, produce aerial biomass similar to those treated with silicon. The application of 100 mg L^{-1} SiO_2 generated dry biomass 11.8% greater than the control treatment at the lowest moisture level. Likewise, at the maximum moisture level, the ABP of the plants fertilized with 50 mg L^{-1} SiO_2 was 9% more when compared to the treatment that did not receive Si. The ABP at the lowest moisture level was 13.3% more than the intermediate moisture level and 10.7% superior in relation to the highest moisture level in the substrate, applied 100 mg L^{-1} SiO_2. While the lowest and intermediate moisture levels in the substrate generated statistically similar aerial biomass values, the intermediate moisture level was 7.7% more than in relation to the highest moisture level, with the application of 3 g L^{-1} of wollastonite.

Regarding the root production of the plant, there was no significant effect of the interaction of Si with moisture in the substrate on the radical biomass (RB) (Table 6). Likewise, the presence or absence of Si did not affect the root production of the plant. However, the reduction of irrigation significantly reduced the amount of root produced by the plant, because the plants grown with the lowest level of humidity produced a root biomass 17.6% lower compared to the plants treated with the highest level of moisture.

According to Grašič et al. (2021), cucumber plants suffer significant reductions in growth and production due to water deficits. For example, Ma et al. (2004) reported decreased growth in cucumber plants grown without Si and subjected to water deficits. The authors stated that in the plants treated with Si the growth reduction was less evident since they obtained a more substantial accumulation of biomass in these plants than in those deficient in silicon. Also, Meng et al. (2021) supports the positive effect of silicon on increasing biomass accumulation in cucumber seedlings. In the same line, although under different stress conditions, cucumber plants under saline stress treated with Si produced 37% more fresh mass than plants not treated with Si (Wang et al., 2015). As described by Ma et al. (2004) and noted in this study, 100 mg L^{-1} SiO_2 can also lead to an increased accumulation of aerial dry mass compared to plants grown without it. This is particularly true for plants at the lowest moisture levels. According to Ma et al. (2004), Si positively affects the accumulation of biomass by the plant under water stress because it increases its photosynthetic and water retention capacities. These results support the influence of silicon to reduce the negative impacts of water stress on cucumber crop growth.

Table 6. Individual effects of silicon and moisture in the substrate on root biomass (RB) production of 'Vitaly' cucumber

Doses of Si	RB (g $plant^{-1}$)
0	2.023±0.165 a
2 g L^{-1} Wollastonite	2.472±0.143 a
3 g L^{-1} Wollastonite	2.385±0.077 a
50 mg L^{-1} SiO_2	2.146±0.121 a
100 mg L^{-1} SiO_2	2.370±0.120 a
Humidity (% CC)	
50-60	2.077±0.101 b
75-85	2.241±0.095 ab
90-100	2.520±0.093 a

Note. Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

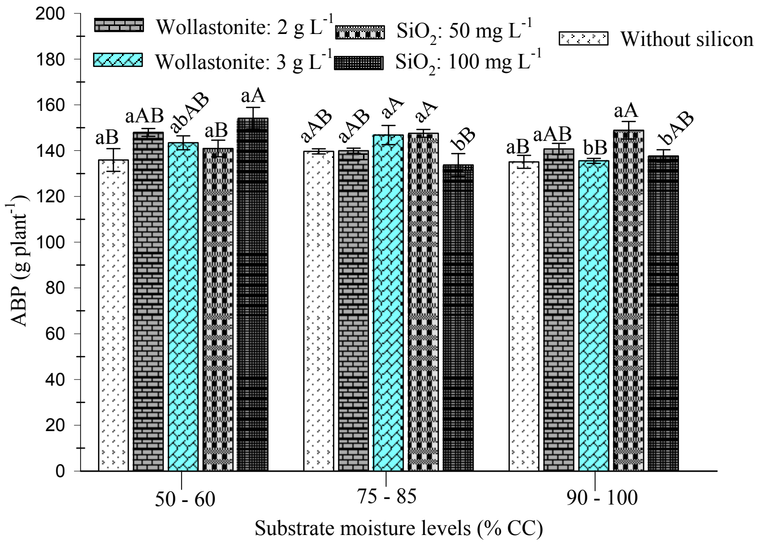

Figure 4. Effect of the interaction between silicon and moisture of the substrate on the aerial biomass production (ABP) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and *upper-case* letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.3 Photosynthetic Pigments and Relative Water Content of Leaves

Chlorophyll a, b and total, and relative water content (RWC) were significantly affected by the interaction between Si and moisture levels of the substrate (Figure 5). At intermediate and high moisture levels, the effects of Si doses did not positively influence the concentrations of chlorophyll a, b and total in the leaves of the plant. For the treatment without Si, the chlorophyll a, b, and total contents were similar to the 2 g L^{-1} wollastonite and 3 g $L^{-}1$ wollastonite doses and, at the same time, higher than the other Si doses, at the intermediate moisture level. At the highest moisture level, the chlorophyll a, b and total values for the treatment without Si and the 100 mg L^{-1} SiO_2 dose were statistically equal but higher than the other Si doses. Si positively influences chlorophyll a, b, and total content in the leaves of plants mainly under the lowest moisture in the substrate. The 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 doses favored concentration of chlorophyll a, respectively, 15.7% and 18.2% higher than the treatment without Si. Likewise, at the lowest moisture level, the 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 doses generated total chlorophyll contents, respectively 14.7% and 18.6% higher than the treatment without Si. Also, under the lowest moisture level, the chlorophyll b content in the leaves of the plants was 19.4% higher than the control treatment and significantly higher than the other doses of Si, with the application of 100 mg L^{-1} SiO_2. The application of Si led to a significant increase in chlorophyll a, b, and total in the leaves of the plants, especially under the lowest moisture level. The foliar spray of Si in tomato increased the chlorophyll content of the leaf as per Xue, Zhang, Sun, Liao, and Chen (2012). Similarly, a significant increase in chlorophyll content in Zn-deficient sorghum plants was reported by Guedes, Prado, Frazão, Oliveira, and Cazetta (2020) due to foliar applications of Si. Ibrahim and Al-Wasfy (2014) confirmed a significant increase in the combined effect of Si with Se, compared to the individual application of Si, on chlorophyll concentrations in orange trees. Along the same lines, Hu et al. (2022) found that the individual application of 1 mM of Si, via foliar, in cucumber plants barely generated a slight, non-significant increase in the concentration of chlorophyll in the leaves, but its combined effect with 0.025 mM of Se significantly increased the concentrations of chlorophyll a and b, respectively 25.2% and 29.8%. Likewise, leaves of melon plants (*Cucumis melo* L.) fertilized with Si had higher chlorophyll content compared to plants not treated with Si (Lu & Cao, 2001). In this study, the plants treated with 100 mg L^{-1} SiO_2 under the lowest moisture level presented the highest chlorophyll a, b and total contents (6.800 g L^{-1}; 3.062 g L^{-1}; 9.864 g L^{-1}, respectively) while the lowest contents of chlorophyll a, b and total (3.070 g L^{-1}; 1.302 g L^{-1}; 4.371 g L^{-1}) were obtained in the treatment resulting from the interaction of 2 g L^{-1} of wollastonite with the highest moisture level. According to Silva et al. (2012), water deficiency significantly reduces the levels of chlorophyll a, b and total in tomato cultivars, while the application of silicon at 0.25, 1.00 and 1.75 µmol in plants with water deficit increases the levels of chlorophyll a, b and total. Chlorophyll a reduction due to water restriction leads to the production of peroxidative enzymes that are associated with chlorophyll a degradation in the thylakoid membrane (Gandul-Rojas, Roca, &

Mínguez-Mosquera, 2004). The increase in chlorophyll a level due to the application of silicon in cultivars with water deficiencies indicates the synthesis of new pigments and the maintenance of existing chlorophyll a (Silva et al., 2012). Silva et al. (2012) observed a positive interaction between leaf water potential and total chlorophyll. In plants under water deficit, the addition of 1.75 µmol of silicon maintained total chlorophyll levels at same levels as those grown without water deficit (Silva et al., 2012). The relationship between leaf water potential and total chlorophyll explains this result, since adequate amounts of water in leaf tissue maintain chloroplast stability along with other functions such as energy absorption and transport (Silva et al., 2012). Silicon has been shown to modify nitrogen metabolism (Watanabe, Fujiwara, Yoneyama, & Hayashi, 2001) and the latter participates in the formation of chlorophyll (Silva et al., 2012). The decrease in total chlorophyll observed in water-deficient plants in the absence of silicon is the result of a decrease in nitrogen uptake since water is responsible for driving nitrogen and other nutrients through the root system. According to Donegá (2009), silicon improves plant architecture and increases photosynthesis. Its deposition in the cell wall increases the resistance of the tissues and the yield of the plant due to the architecture of the leaves and their capacities to intercept sunlight (Lana, Korndörfer, Zanão Júnior, Silva, & Lana, 2003).

The Si favored higher RWC in the leaves of the plant just under the highest level of moisture in the substrate. Under this scenario, the RWC in the leaves of the plants fertilized with 100 mg L^{-1} SiO_2 increases by 11.9% in relation to the leaves of the plants not treated with Si. Conversely, the application or omission of Si does not affect the RWC values in the leaves of the plants under the two lowest moisture levels in the substrate. The highest RWC (90.99%) was observed in plants treated with 100 mg L^{-1} SiO_2 under the highest moisture level, while the lowest RWC (75.25%) was obtained under the lowest moisture level in the substrate in plants without Si treatment. As observed in this study, as well as in that of Qingfang and Chengcang (2002), silicon positively affects RWC in plants. This statement is corroborated by Ma et al. (2004) by attributing the increased resistance to drought stress seen in cucumber plants fertilized with Si to the ability of the element to increase the water content in the leaves, increase biomass production and reduce the rate of plant transpiration. In cucumber plants under intermediate and severe water stress, Ma et al. (2004), after applying 240 ppm of SiO_2, reported RWC 8% and 14% higher than that of deficient plants in silicon. Also, the 120-ppm dose of SiO_2 generated RWC 8% and 3.4% higher than those of a plant deficient in silicon (Ma et al., 2004). In a study by Alsaeedi et al. (2019) the application of Si nanoparticles reduced the negative impacts of water stress in cucumber by improving the water balance in the plant, as also found by Hasanuzzaman et al. (2018) and Jafari, Arvin, and Kalantari (2012) in cucumber and other crops. The effect of silicon on improving the water balance is mainly achieved by favoring better water uptake by the plant (Wang et al., 2015).

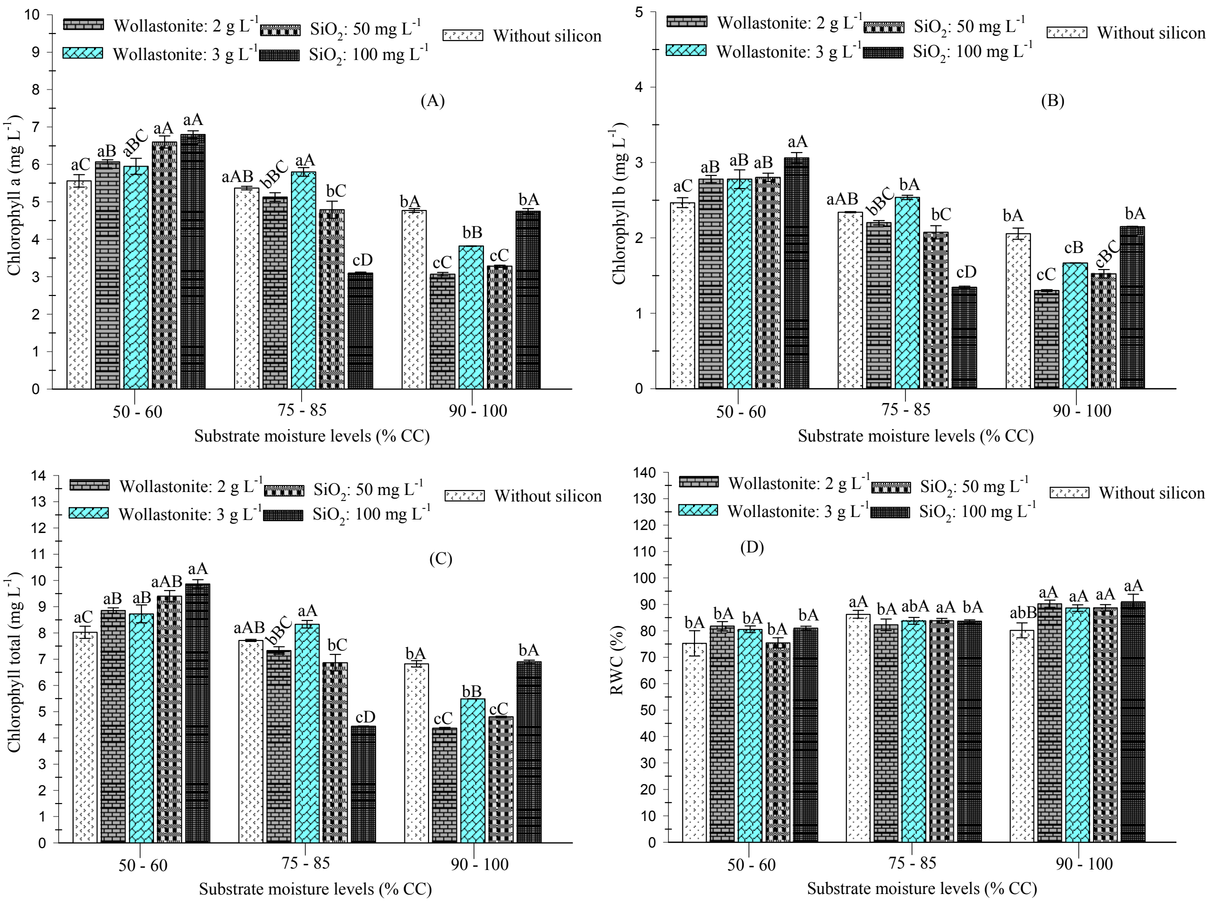

Figure 5. Effect of the interaction between silicon and moisture levels of the substrate on the content of chlorophyll a (A), chlorophyll b (B), total chlorophyll (C) and relative water content (D) in cucumber leaves

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars. RWC: relative water content.

3.4 Concentrations of Nutrients in Different Parts of the Plant

The concentrations of N, P, K, Ca, Mg and Si in the different parts of the plant (fruits, leaves, stem, and roots) were significantly affected by the interaction of Si with the moisture in the substrate, except for the percentages of N in the stem and Ca in the roots. A more significant effect of Si on the concentration of N, P, K, Ca, Mg and Si is observed in different parts of the plant in treatments with the lowest moisture level in the substrate (Figures 6, 7, 8, 9, 10, 11).

3.4.1 Nitrogen (N) Concentration

The application of Si significantly affected the N contents in the different parts of the plant (Figure 6), except in the stem (Table 7). The fruits presented the highest concentration of N (2.2%-2.83%), followed by the stems (1.94%-2.77%), the leaves (1.49%-2.39%) and the roots (1.81%-2.25%). The treatment with 3 g L^{-1} of wollastonite, under the lowest moisture level, produced the greatest N content in the fruits (2.83%), with an increase of 15.3% compared to the treatment without Si. Neither the interaction of Si with the moisture of the substrate nor its individual effects affected the concentration of N in the stem. However, there was more N content in the stem of the plants with the lowest moisture level than at the other moisture levels. The plants grown with the lowest moisture level supplemented with 2 g L^{-1} of wollastonite had the highest level of N (2.4%) in the leaves, which was 26% higher than the plants not fertilized with Si. Also, N levels in the roots increased in response to Si application, mainly with the 3 g L^{-1} wollastonite dose. Respectively, under the lowest and intermediate moisture levels in the substrate, 3 g L^{-1} wollastonite produced a 12.9% and 11.1% higher N concentration in the roots compared to the treatment without Si. Similarly, the 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 doses, under the lowest moisture level, increased the concentration of N in the roots respectively by 21.3% and 19.2% more in relation to the treatment without Si. The application of Si affected favorably the absorption, assimilation, and remobilization of N (Wu et al., 2017; Haddad et al., 2018; Gou et al., 2020, Pavlovic, Kostic, Bosnic, Kirkby, & Nikolic, 2021). It affects N metabolism as well as the C and P stoichiometry in the stem of the plant (Neu, Schaller, & Dudel, 2017; Deus, Prado, Alvarez, Oliveira, & Felisberto, 2020; Pavlovic et al., 2021), and the absorption of nutrients by the roots (Barreto et al., 2017), which enhances the utilization of N in plants (Pavlovic et al., 2021). The greater fixation (Mali & Aery, 2008) and availability of N, increased transcription of the genes involved in its absorption (Haddad et al., 2018), and improved efficiency of its transport are all thought to be contributing factors to the increased absorption of N mediated by Si in different plant species (Sheng, Ma, Pu, & Wang, 2018). Si improves N assimilation (Wu et al., 2017), however various species react differently to silicic fertilization, which varies even within species (Campos et al., 2020; Barreto et al., 2021).

Table 7. Individual effects of silicon and moisture in the substrate on N concentration in the stem of cucumber

Doses of Si	N (%) in stem
0	2.52±0.07 a
2 g L^{-1} Wollastonite	2.36±0.11 ab
3 g L^{-1} Wollastonite	2.20±0.08 b
50 mg L^{-1} SiO_2	2.40±0.06 ab
100 mg L^{-1} SiO_2	2.45±0.07 a
Humidity (% CC)	
50-60	2.59±0.05 a
75-85	2.34±0.03 b
90-100	2.23±0.07 b

Note. Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

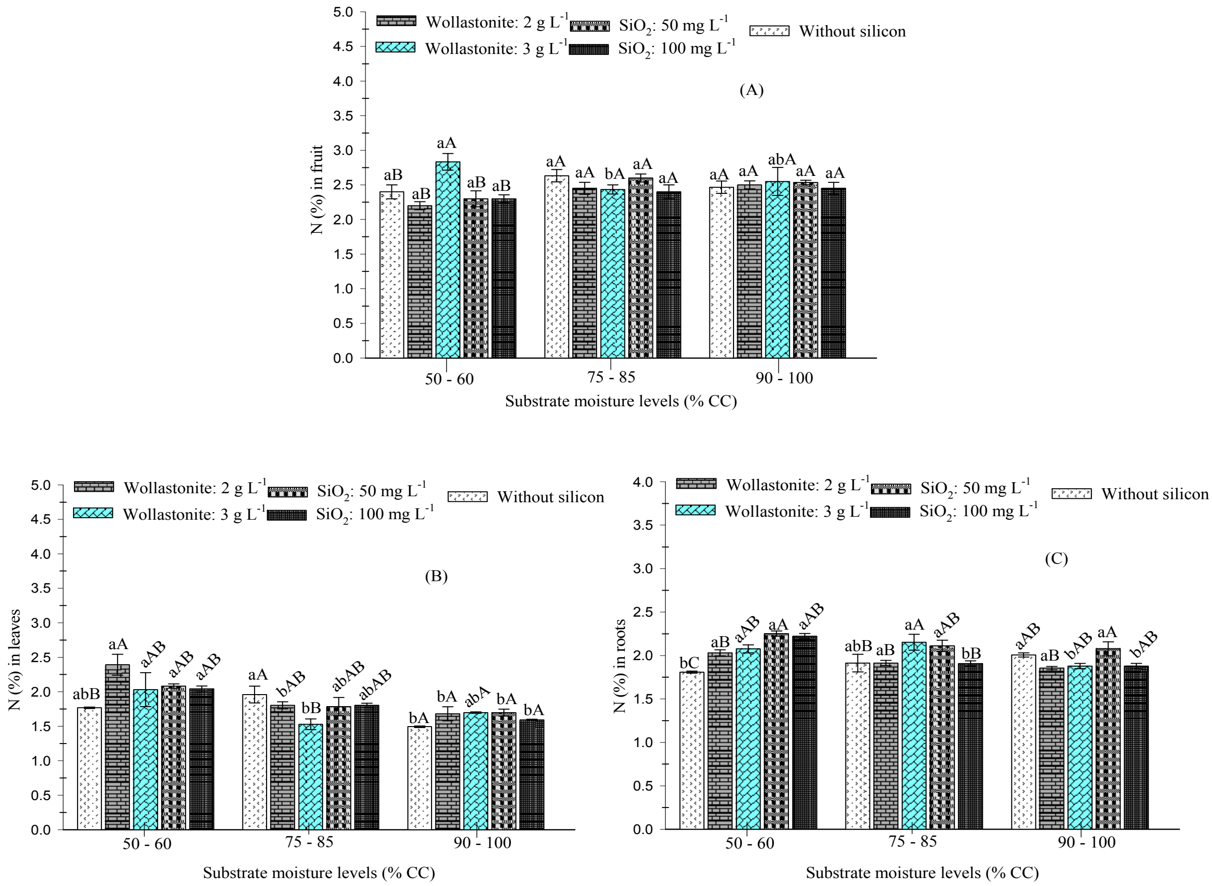

Figure 6. Effect of the interaction of silicon with the moisture of the substrate on the concentration of N in fruits (A), leaves (B), and roots (C) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.2 Phosphorous (P) Concentration

Regarding P, its highest concentration was observed in the roots (0.72%-1.10%), followed by the leaves (0.83%-1.04%), the fruits (0.78%-0.92%) and the stems (0.74%-0.86%). The highest concentration of P in the root (1.10%) is obtained when 50 mg L^{-1} SiO_2 is applied with the lowest moisture level in the substrate (Figure 7). Under this treatment, the P level in the root increased by 10.2% compared to the treatment without Si. In both the leaves and the fruits, no dose of Si resulted in a favorable effect on the concentration of P in these components of the plant. This is because treatments without Si demonstrated equivalent or higher P levels than the leaves or fruits of plants treated with Si. In the stem, there is a significant increase in P concentrations (0.85% and 0.86%) with the 2 g L^{-1} of wollastonite and 50 mg L^{-1} of SiO_2 treatments, respectively, at the lowest moisture level, with higher values of 4.6% and 5.4% compared to the treatment without Si. Si has a favorable impact on P nutrition, but its implications are unclear (Pavlovic et al., 2021). Si reduces P deficiency mainly by increasing P uptake by the roots and its substantial utilization in plant tissues (Pavlovic et al., 2021). Kostic, Nikolic, Bosnic, Samardzic, and Nikolic (2017) have demonstrated that Si promotes the expression of genes linked to inorganic P absorption in wheat crops. In an acid soil with low P content, Pavlovic et al. (2021) claim that Si boosted the expression of inorganic P transporter genes, which increased the uptake of inorganic P. Similarly, Kostic et al. (2017) reported that Si promoted the acquisition of inorganic P by the plant root by enhancing carboxylate exudation. In response to Si's application, Soratto, Fernandes, Pilon, and Souza (2019) observed an increase in the concentrations of soluble inorganic P in the leaves, indicating that Si contributes to plant growth under conditions of low P availability. On the other hand, under an excessive supply of P, it has been observed in several plant species decreased P uptake due to Si application, and Ma (2004) attributed this decrease to the formation of physical apoplastic barriers by Si deposition in the plant root.

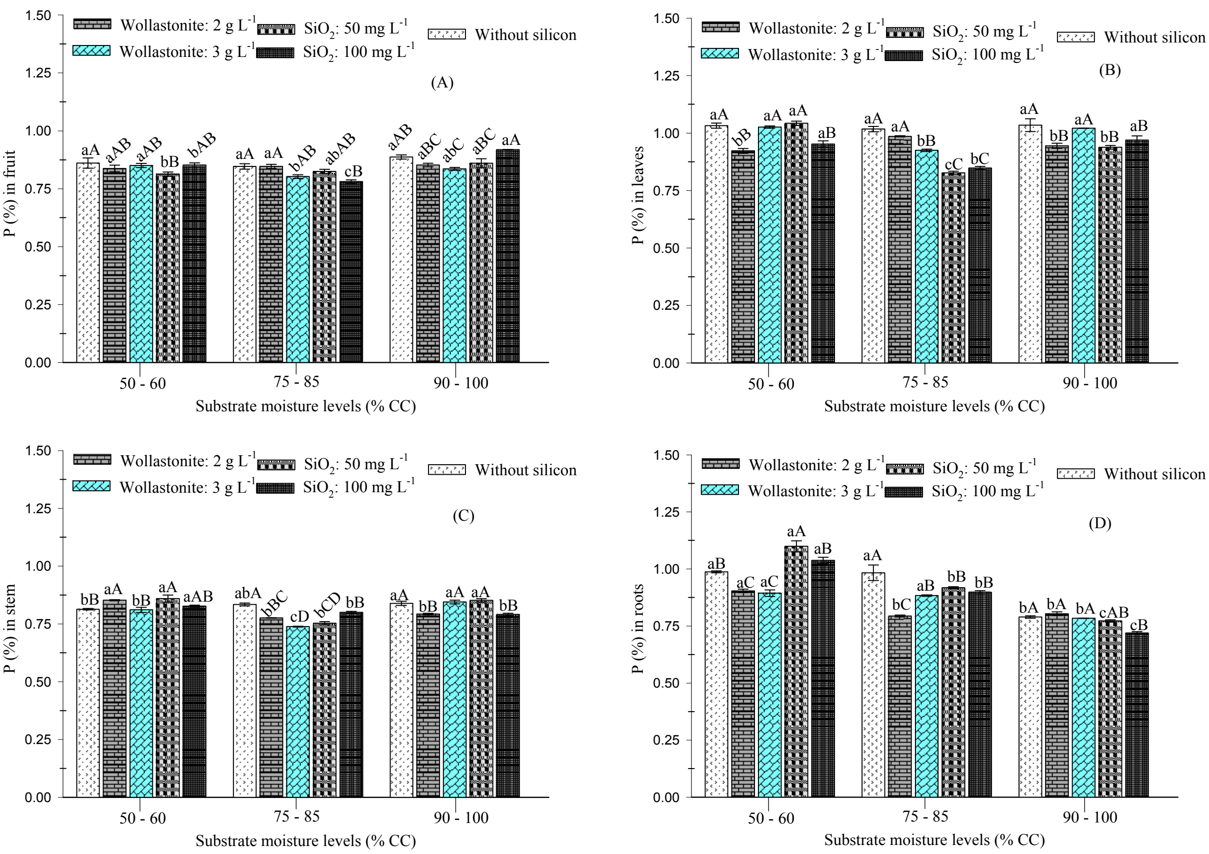

Figure 7. Effect of the interaction of silicon with the moisture of the substrate on the concentration of P in fruits (A), leaves (B), stems (C) and roots (D) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.3 Potassium (K) Concentration

The concentration of K was greatest in the stems (2.57%-4.21%), followed by the fruits (2.42%-3.35%), the leaves (1.56%-1.97%) and the roots (0.71%-1.57%). In reference to the concentration of K in the stem, only the interactions of the lower moisture level with doses of 2 g L^{-1} wollastonite and 3 g L^{-1} wollastonite resulted in higher concentrations of K compared to the other doses of Si. These concentrations were greater than the treatment without Si by 23.9% and 26.6% respectively (Figure 8). In relation to the concentration of K in the fruits, there was no positive effect of the application of Si on this variable. The fruits of the plants not fertilized with Si presented K concentrations equivalent to those of the plants treated with Si. The two highest concentrations of K (1.90% and 1.97%) were observed in the leaves of the plant under the lowest moisture level with the doses 3 g L^{-1} wollastonite and 50 mg L^{-1} SiO_2, being respectively 9% and 12% superior to the K level in the leaves of the control treatment. The silica treatments did not favor the concentration of foliar K under the effect of the intermediate moisture level in the substrate. However, with the 50 mg L^{-1} SiO_2 dose, there was an increase in the concentration of K in the leaves of the plants at the highest moisture level, compared to the plants not treated with Si. In the root, the concentration of K (1.19%) was 39.8% more than in the treatment without Si, with the application of 50 mg L^{-1} SiO_2 at the lowest moisture level. The highest concentration of K (1.57%) in the root was obtained with the interaction of 3 g L^{-1} wollastonite with the highest level of moisture in the substrate. This K concentration was 22.5% higher than in the absence of Si. Under stress situations, such as drought, the concentration of K in plant tissue can be affected by Si (Barreto et al., 2017). Si increases K uptake in K-deficient plants and restores their physiological performance affected by K deficiency (Pavlovic et al., 2021). According to Miao, Han, and Zhang (2010), and Buchelt et al. (2020), the application of Si to soybean and forage crops increased the K content in their leaves. Also, Si modulates antioxidant enzymes, which reduce oxidative stress caused by lack of K, as well as lipid peroxidation of the membrane (Miao et al., 2010; Chen et al., 2016). Under the combined effect of K deficiency and osmotic stress induced by polyethylene glycol (PEG) in Barley (*Hordeum vulgare),* Si does not seem to reduce K deficiency (Hosseini et al., 2017). However, according to the same authors, the likely beneficial effect of Si identified was due to abscisic acid (ABA) homeostasis and increased activity of the cytokinin isopentenyladenine.

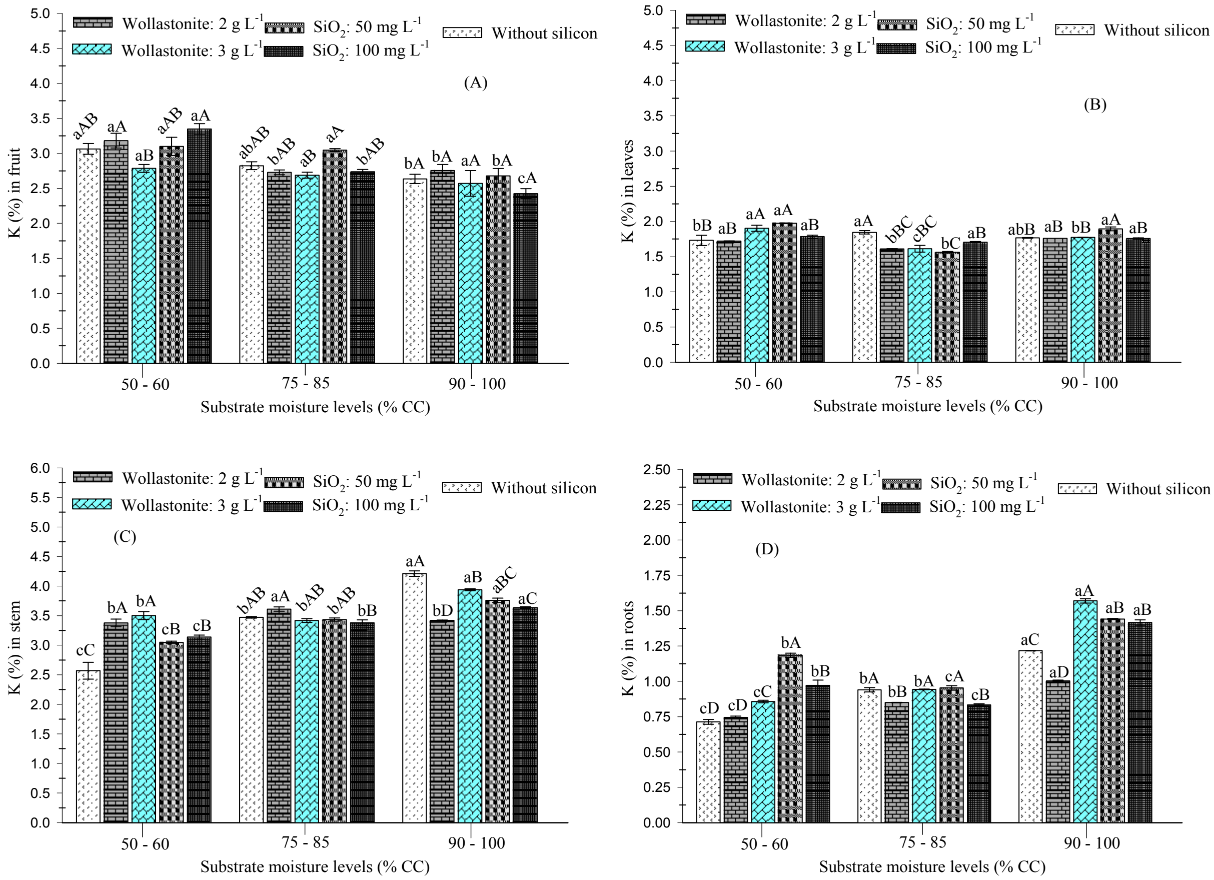

Figure 8. Effect of the interaction of silicon with the moisture of the substrate on the concentration of K in fruits (A), leaves (B), stems (C) and roots (D) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.4 Calcium (Ca) Concentration

The leaves presented the highest concentration of Ca (3.27%-4.63%), followed by the stems (1.53%-2.11%), the roots (0.99%-1.15%) and the fruits (0.33%-0.45%). The interaction of 50 mg L^{-1} SiO_2 with the intermediate moisture level in the substrate favored a higher concentration of Ca (4.63%) in the leaves, 26.9% greater than in the leaves of the plants not treated with Si (Figure 9). On the other hand, the Ca concentrations in the leaves of the plants that were not treated with Si were statistically equal to or greater than those treated with Si, at the low and high moisture levels. The interactions between the lowest moisture level and the 2 g L^{-1} wollastonite and 3 g L^{-1} wollastonite doses presented significantly greater Ca concentrations in the stem compared to the other Si doses. These concentrations were greater than the treatment without Si by 25% and 17.6%, respectively. The interaction between Si and substrate moisture did not affect the percentage of Ca in the root. The individual effect of Si did not affect the concentration of Ca in the root either (Table 8). However, there was a higher concentration of Ca in the root of the plants treated with the two lowest moisture levels compared to the highest moisture level. Regarding Ca in fruits, its largest content (0.45%) has been observed with the application of 50 mg L^{-1} SiO_2 at the intermediate moisture level, with a value 10.4% more in relation to fruits not fertilized with Si. Various factors such as dose, species, type of stress, and study conditions affect the effects of Si on Ca (Pavlovic et al., 2021). In maize under water stress, Kaya, Tuna, and Higgs (2006) found that Si favors Ca absorption, while studies by Brackhage, Schaller, Bäucker, and Dudel (2013), Cooke and Leishman (2016), and Jang, Kim, Khan, Na, and Lee (2018) stated that Si does not affect or even reduce calcium accumulation. The application of increasing doses of Si to rice (*Oryza sativa* L.) and common reed (*Phragmites australis*) decreased the Ca content accumulated in plant tissues (Brackhage et al., 2013; Jang et al., 2018). Dishon, Zohar, and Sivan (2011), and Fleck et al. (2015) attributed this reduction to the effects of the interaction between Si and Ca in the growth medium or in the apoplast of the plant and decreased Ca uptake due to the biosilicification of the root structures of the plant.

Table 8. Individual effects of silicon and moisture in the substrate on Ca concentration in the roots of cucumber

Doses of Si	Ca (%) in roots
0	1.28±0.14 a
2 g L^{-1} Wollastonite	1.18±0.06 a
3 g L^{-1} Wollastonite	1.14±0.05 a
50 mg L^{-1} SiO_2	1.33±0.05 a
100 mg L^{-1} SiO_2	1.24±0.07 a
Humidity (% CC)	
50-60	1.35±0.05 a
75-85	1.35±0.04 a
90-100	1.00±0.04 b

Note. Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

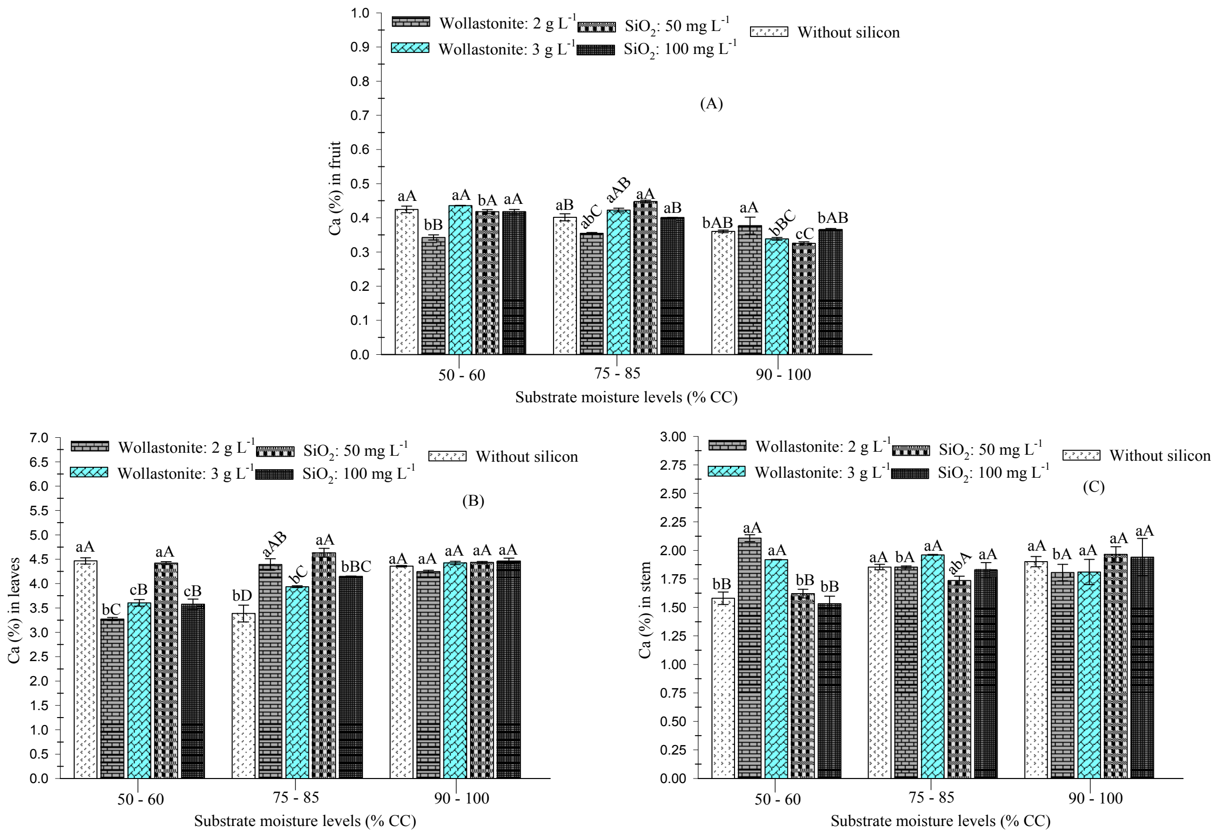

Figure 9. Effect of the interaction of silicon with the moisture of the substrate on the concentration of Ca in fruits (A), leaves (B), stems (C) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.5 Magnesium (Mg) Concentration

The Mg concentration was highest in the leaves (0.79%-1.41%), followed by the stems (0.71%-1.18%), the roots (0.49%-0.83%) and the fruits (0.36%-0.47%). The Mg levels in the leaf increased with the application of Si. The doses of 2 g L^{-1} of wollastonite and 100 mg L^{-1} of SiO_2 were substantially more successful than the treatment without Si at the lowest moisture level, with respective Mg concentrations of 1.29% and 1.27% in the leaves of the plant (Figure 10). Likewise, at the intermediate moisture level, each of the doses of 2 g L^{-1} of wollastonite, 3 g L^{-1} of wollastonite and 50 mg L^{-1} of SiO_2 showed foliar concentrations of Mg (1.34%, 1.41% and 1.35%), greater than the control treatment, respectively. The highest concentration of Mg (1.41%) in the leaves was produced at the intermediate moisture level with the application of 3 g L^{-1} wollastonite. Likewise, the 3 g L^{-1} wollastonite dose outperforms the other treatments at the biggest humidity level. In the stem, Si increases the concentration of Mg at the highest and lowest moisture levels in the substrate. With the application of 3 g L^{-1} of wollastonite or 50 mg L^{-1} of SiO_2, at the biggest moisture level, or 2 g L^{-1} of wollastonite, at the lowest moisture level, the percentage of Mg in the stem was larger than in the treatment without Si. Si did not significantly affect the concentration of Mg in the roots of the plant at either of the two greatest levels of moisture in the substrate. At the lowest moisture level, root magnesium concentration increases for all Si doses. As compared to the treatment without SiO_2, the application of 100 mg L^{-1} SiO_2 at the lowest moisture level favors a higher Mg concentration in the root by 30.8%. The highest Mg content (0.47%) in the fruits, which was 9.6% higher compared to the plants not treated with Si, was promoted by the interaction of 3 g L^{-1} of wollastonite with the intermediate moisture level. Pavlovic et al. (2021) stated that Si seems to influence Mg in different ways depending on species and environmental conditions. In a hydroponic system with optimal nutrient supply, Si increased Mg uptake and accumulation in the shoots of several plant species (Greger, Landberg, & Vaculík, 2018). Under water stress situations, various Si-fertilized sunflower (*Helianthus annuus*) cultivars accumulated higher Mg contents in their shoots compared to stressed plants not fertilized with Si (Gunes et al., 2008). Buchelt et al. (2020) attributed the effect of Si in cultivated forages with Mg deficiency to a greater efficiency in the use of Mg instead of a greater absorption of the element. Hosseini, Rad, Ali, and Yvin (2019) found no effect of Si supply on the absorption or translocation of Mg in maize plants, but according to the same authors its beneficial effects on chlorophyll levels, sugar metabolism and hormonal balance indirectly contributed to the development of Mg deficient plants. According to Pavlovic et al. (2021), so far, no evidence has been found that Si affects the expression of the Mg transporter.

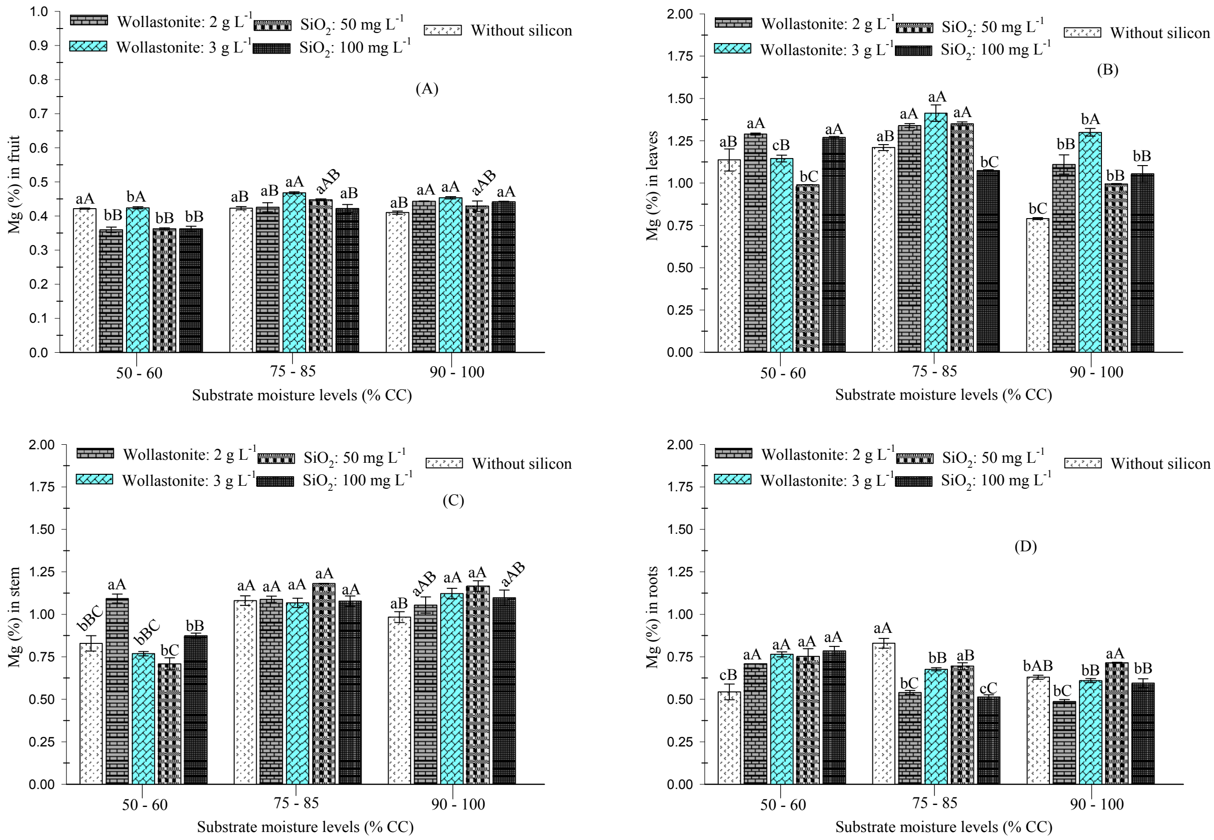

Figure 10. Effect of the interaction of silicon with the moisture of the substrate on the concentration of Mg in fruits (A), leaves (B), stems (C) and roots (D) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.6 Silicon (Si) Concentration

The leaves presented the highest concentration of Si (3.37%-5.36%), followed by the stems (1.04%-1.83%), the fruits (0.30%-1.21%) and the roots (0.52%-1.16%). Regarding the Si concentration in the leaves, only the application of 3 g L^{-1} wollastonite increased the Si content under the effect of intermediate moisture (Figure 11). The doses of Si did not generate an increase in the concentration of Si in the leaves in relation to the treatments without Si at the other moisture levels. In the stem, among the different doses of Si, only 100 mg L^{-1} SiO_2 when interacting with the lowest moisture level favored a more significant Si content. At other moisture levels, there was no difference between the effects of Si doses on the Si concentration in the stem. Under intermediate and higher levels of moisture in the substrate, positive effects of Si on its concentration in the fruit have been observed. With the application of 50 mg L^{-1} SiO_2 and under the highest level of moisture in the substrate, Si content in the fruit has been found to be 22% superior to the treatment without Si. With the intermediate moisture level in the substrate, the doses of 2 g L^{-1} wollastonite, 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 generated Si concentration in the fruit respectively 46.3%, 42.7% and 47.2% more than the treatment without Si, which was not the case for the silicic treatments under the lowest moisture level where Si concentrations in the fruit were lesser than the control treatment. Si does not positively affect the concentration of Si in the roots of the plant at either of the two highest levels of moisture in the substrate. For the concentration of Si in the roots, at the lowest moisture level, there was only an increase in its level in the roots with the dose of 50 mg L^{-1} SiO_2. The application of 50 mg L^{-1} SiO_2 at the lowest moisture level increased the concentration of Si in the root by 53.3% compared to the treatment without Si. Silicon fertilization can increase the concentration of the element in plant tissues, but very high doses can generate an antagonistic effect (Oliveira, et al., 2019). The contents of Si in plant tissues can vary depending on the applied dose (Oliveira et al., 2019), the genetics and the absorption mechanisms of each plant (Hodson, White, Mead, Broadley, 2005). The distribution of Si in the shoots of the plant is regulated by several factors among which is transpiration (Ma and Yamaji, 2006). In leaves of cucumber plants treated with wollastonite, Dorais and Thériault (2018) reported Si content between 0.48% and 3.05%, which were higher than those observed in leaves of plants not supplemented with Si. In the fruits of plants treated with Si, Si concentrations between 0.04 and 0.14% were observed, while in the fruits of control plants Si was not detected (Dorais and Thériault, 2018). Abd-Alkarim et al. (2017) found Si concentration between 1.30% to 1.55% in leaves and between 0.94% to 1.65% in cucumber fruits grown with different doses of Si. The leaves of the cucumber plant accumulate more Si than the fruits, which agrees with the results of studies by Górecki and Danielski-Busch (2009), Terraza et al. (2009), Abd-Alkarim et al. (2017), Dorais and Thériault (2018). However, Shalaby et al. (2021) contradict this trend by reporting a higher Si content in the fruits (9.80% to 10.87%) of cucumber compared to the leaves (6.01% to 7.86%). There is no consistency between authors in the Si concentration data reported in the different parts of the cucumber plant.

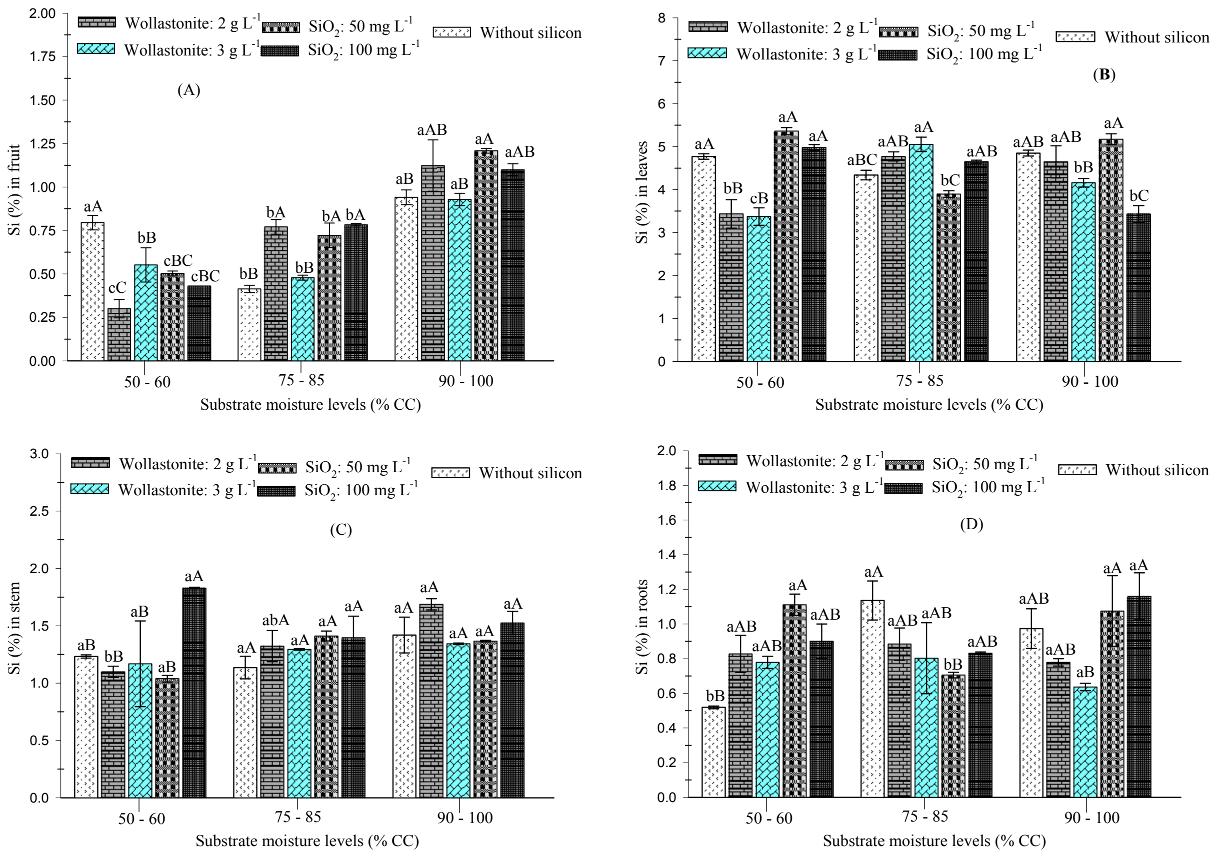

Figure 11. Effect of the interaction of silicon with the moisture of the substrate on the concentration of Si in fruits (A), leaves (B), stems (C) and roots (D) of cucumber

Note. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

4. Conclusion

Under the intermediate moisture level in the substrate, 3 g L^{-1} of wollastonite increased fruit production by 24.9% in comparison to Si-untreated plants.

As moisture levels were reduced, the diameter and average weight of the fruits decreased slightly (3.4% and 11.7%, respectively), while soluble solids concentrations increased (8.8%), and the length of fruits was not affected.

At the lowest moisture level, 100 mg L^{-1} SiO_2 generated 11.8% more dry biomass than the control. Furthermore, when the plant was fertilized with 50 mg L^{-1} SiO_2, aerial biomass production was 9% higher than when no Si was applied.

The presence or absence of Si did not affect the root production of the plant.

Si positively influences chlorophyll a, b, and total content in leaves, specifically at the lowest moisture level in the substrate.

When plants were given 100 mg L^{-1} SiO_2, the relative water content in the leaves increased by 11.9% only when the substrate had the highest moisture level.

The interaction between Si and the moisture in the substrate significantly increased N, P, K, Ca, Mg and Si concentrations in different parts of the plant, with major significant effects under the lowest moisture level in the substrate.

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