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Silicon supplements affect yield and fruit quality of cucumber (*Cucumis sativus* L.) grown in net houses

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Silicon (Si) plays an important role in plant growth and development, but the uptake, accumulation in tissue, and beneficial effects of Si differ greatly between plant species. Net house experiments were conducted with *Cucumis sativus* L. 'Shabah F_1' in 2013 and repeated in 2014 to determine the effects of Si supplementation on yield, fruit quality, and chemical composition. Diatomite (86-89% SiO_2) was applied to cucumber plants three times at two-week intervals after two weeks from transplanting through either foliar spraying (50, 100, 200 mg/l or soil drenching in the root area (500, 1000 and 2000 mg/l). All treatments produced higher early and marketable fruit yield (number and weight) in both years. At all growth stages, application of Si significantly increased fruit firmness, but the effects of Si on total soluble solids varied depending on growth stage and concentration of Si. Significant differences among treatments for ascorbic acid content of cucumber fruits were found in 2013 but not 2014. Tissue analyses showed that Si-treated plants had more Si in the leaves and fruits (% dry wt.), and phosphorus and potassium (% dry wt.) in the leaves compared to untreated controls. We conclude that both foliar sprays and soil drenches of Si have the potential to increase cucumber yield and fruit quality in net house production.

Key words: *Cucumis sativus*, diatomite, foliar spraying, soil drenching.

INTRODUCTION

Cucumber (*Cucumis sativus* L.), is one of the most economically important vegetables in Egypt for local and export markets, with production of 473,700 t in 2014 (FAO, 2017). Fertilizer is necessary for successful crop yields and high fruit quality, and is a major production cost. Fertilizer requirements of cucumber are quite high due to the crop's high plant density per unit area and long production period. Although silicon is not considered an essential element for plant nutrition, Si fertilizers are routinely applied to a variety of plant species including horticultural crops to increase crop yield, quality, and disease resistance (Ma 2004; Hodson et al., 2005).

Silicon-supplemented melon (*Cucumis melo* L.) contained higher chlorophyll levels and reduced transpiration rates compared with untreated plants (Lu and Cao, 2001). Heckman et al. (2003) found calcium

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silicate increased pumpkin yield by 60% and reduced powdery mildew (*Podosphaera xanthii*) severity compared to an untreated control without increasing the cost of production. Applications of a 2.5% monosilicic acid through drip irrigation increased fruit quality in triploid watermelon (*Citrullus lanatus* Thunb. cv. 'Queen of Hearts') grafted onto a squash hybrid (*Cucurbita maxima* × *Cucurbita moschata* cv. 'Strongtosa') (Toresano-Sánchez et al., 2010). Si is considered an agronomically essential element and is recommended for the production of several crops in Japan and Netherlands due to its beneficial effects on growth and quality, photosynthesis stimulation, transpiration reduction, and increased plant resistance to abiotic and biotic stresses (De Kreij et al., 1999; Ma and Takahashi, 2002). However, the Si content in plants varies according to species, cultivar, and tissue. Different plant species differ in their concentrations of Si, and in their accumulation of Si from the soil. Jones and Handreck (1967) classified plants into three major groups on the basis of the SiO_2 content of their leaf tissue on a dry weight basis: dicotyledons generally having the lowest levels of less than 1% (dry weight basis); dryland grasses such as oats and rye (about 1%); and the "wetland" grass, paddy-grown rice (5% or higher).

The beneficial effect of Si is more evident under stress (Ma and Takahashi, 2002). Recent studies have shown that Si is effective in controlling diseases caused by fungi and bacteria in different horticultural crops. For instance, Si increased cucumber resistance to powdery mildew (*P. xanthii*) (Menzies et al., 1992), Corynespora leaf (*Corynespora cassiicola*) (Ma 2004) and *Pythium* spp. (Cherif et al., 1994). Fertilization with Si may provide a new approach to disease control and improve cucumber productivity. Although some studies emphasize the benefits of Si on cucumber growth (Adatia and Besford, 1986; Miyake and Takahashi, 1983), the effect of Si on productivity of cucumber is largely unknown. The objectives of this study were to evaluate the efficacy of foliar and soil applications of diatomite on yield and fruit quality of 'Shabah F_1' cucumber plants grown in net houses in late summer.

MATERIALS AND METHODS

Plants and growth conduction

Net house experiments were conducted during May to August in 2013 and 2014 at the protected cultivation experimental site of the Faculty of Agriculture, Kafr El-Sheikh University. The net house was covered with black shade net (63% shade) made from polypropylene. The net house was 9 m wide, 30 m long and 3.5 m high. Temperatures on the plant canopy ranged from 25 to 39°C and relative humidity (HR) varied from 50 to 95%.

Cucumber (*C. sativus* L.) hybrid 'Shabah F_1' (kindly provided by Al Kalthoum Agricultural Co., El Mansoura, Egypt) was selected for this study because of its productivity under high temperatures, making it the most suitable hybrid for the summer season in Egypt. It is gynoecious (producing only female flowers), and has parthenocarpic fruit with smooth green skin. Seeds were sown in 84-cell seedling trays. After three weeks, seedlings (two true leaves) were transplanted to the net house in May. The plants were watered daily and fertilized twice a week with recommended nutrients at concentrations of 40 kg N, 17 kg P_2O_5, and 30 kg K_2O per feddan [0.42 ha] applied through a drip irrigation system using a venturi injector from the first week of transplanting up to the 14^{th} week (Metwally and Rakha, 2015). Cucumber plants were trained vertically on overhead wires. Once the plants reached the wire they were topped and then pruned using an umbrella system. Other horticultural practices were performed according to the recommendations of the Egyptian Ministry of Agriculture.

Experimental design and silicon treatments

This experiment was set up in a randomized complete block design (RCBD) with four replications. Each plot consisted of a 3 m long bed with two rows of 12 plants spaced 50 cm apart. Beds were 1 m wide (1.5 m between bed centers) and 25 cm high. Aqueous solutions prepared from diatomite contained 86-89% SiO_2. Cucumber plants were treated through foliar spraying (50, 100, 200 mg/l) or soil drenching (500, 1000, 2000 mg/l). Control plants were treated with water and received no additional silicon. Two weeks after transplanting, when the plants were at the 4–5 leaf stage, Si was applied to the leaves and soil three times at two-week intervals.

Data recorded and analysis

Cucumber fruits at a marketable stage were harvested as described by Sevgican (2002) and categorized as marketable or unmarketable fruits. Early yield (number and weight [kg/m^2]) was calculated from the first nine pickings. Marketable and unmarketable fruits for total yield were recorded 3 times a week beginning 4 weeks after transplanting for a total of 27 harvests. We identified unmarketable cucumbers as those that tapered at one end or were excessively curved, as these are signs of stress, disease, poor pollination or insufficient water. Ten female flowers from each plot were labeled and harvested 12-15 days after anthesis to measure fruit firmness and total soluble solids (TSS) at 55, 70 and 85 days from sowing (DAS). Fruit firmness (g/cm^2) was measured using a hand penetrometer (2 mm) on opposite cheeks at the center of each fruit. The probe was inserted to the bioyield point. The TSS in juice of cucumber fruits was estimated by a hand refractometer according to the Association of Official Agricultural Chemists (AOAC, 1965). Ascorbic acid content (mg/100 g fresh weight) was estimated by titration with 2, 6-Dichlorophenol blue at 70 DAS according to AOAC (1965). For the silicon plant tissue analysis, each treatment was analyzed in triplicate and included leaf and fruit samples from each treatment plus the untreated control at 70 DAS using an autoclave-induced digestion method (Elliott and Snyder, 1991). For N, P, and K elements, analyses were performed on leaf tissues. Leaf samples were analyzed for N, P, and K contents in percentage as described by Cottenie (1980).

Statistical procedures were performed using the statistical software SAS (version 9.1; SAS Institute, Cary, NC). Data on yield, fruit quality and leaf chemical content were subjected to one-way analysis of variance (ANOVA) and mean comparisons were made using Duncan's multiple range test (DMRT).

RESULTS AND DISCUSSION

The effects of Si supplements on early yield, marketable and unmarketable yield of cucumber fruit for both years

Table 1. Effects of silicon (Si) supplementation on early yield, fruit yield and unmarketable fruit of *Cucumis sativus* L. 'Shabah F_1' grown in net houses in 2013 and 2014.

Application method	Si supplement Conc. ($mg.L^{-1}$)	Early yield[z]/m^2 Weight (kg)	Early yield[z]/m^2 Number	Marketable yield/m^2 Weight (kg)	Marketable yield/m^2 Number	Unmarketable fruit[y]/m^2 Weight (kg)	Unmarketable fruit[y]/m^2 Number
2013							
Control	0	2.86[bx]	29.64[c]	9.78[d]	109.41[c]	0.5	13.9
Foliar	50	3.41[ab]	35.44[bc]	10.87[bc]	116.09[bc]	0.4	14.0
Foliar	100	3.74[a]	37.7[ab]	11.67[ab]	127.01[ab]	0.4	12.3
Foliar	200	3.91[a]	40.95[ab]	11.78[ab]	132.34[a]	0.4	11.3
Soil	500	3.15[ab]	32.84[abc]	10.69[cd]	111.41[c]	0.4	13.5
Soil	1000	3.90[a]	41.29[a]	11.96[a]	130.73[a]	0.4	13.0
Soil	2000	3.97a	40.64[a]	11.86[a]	130.65[a]	0.5	12.3
F-test		**	**	**	**	ns	ns
2014							
Control	0	2.34[c]	28.41[c]	7.61[b]	77.87[c]	0.23[a]	9.23[a]
Foliar	50	2.62[bc]	29.58[c]	7.61[b]	81.59[c]	0.24[a]	8.19[ab]
Foliar	100	2.80[b]	32.44[ab]	8.03[ab]	86.71[bc]	0.19[ab]	6.58[bc]
Foliar	200	2.93[ab]	34.39[ab]	8.65[ab]	93.21[ab]	0.17[b]	5.81[c]
Soil	500	2.67[bc]	30.36[bc]	7.83[ab]	83.46[bc]	0.21[ab]	7.23[bc]
Soil	1000	2.83[ab]	32.37[ab]	8.12[ab]	85.67[bc]	0.17[b]	5.85[c]
Soil	2000	3.21[a]	36.27[a]	9.43[a]	100.36[a]	0.16[b]	6.84[bc]
F-test		**	**	**	**	**	**

[z] Early fruit yield was determined as number and weight of fruits per square meter from the first 9 pickings.
[y]Unmarketable is fruit that cannot be sold, such as those that taper at one end or are excessively curved.
[x]Means with the same letter within the same column are not significantly different at ($P \leq 0.05$) according to Duncan's multiple range test.

are shown in Table 1. Both foliar spraying and soil drenching significantly increased early fruit number and weight ($p < 0.001$) compared with the untreated controls, except foliar 50 mg/l Si treatment in 2014 was significantly similar to the untreated controls for fruit number. The highest early fruit weight and number was recorded by plants receiving 2000 mg/l Si (soil application) followed by 1000 mg/l Si (soil application) and 200 mg/l Si (foliar application) in both years. Similarly, plants treated with higher Si concentrations through soil and foliar applications exhibited significantly higher marketable fruit number and weight in 2013 and 2014; 1000 and 2000 mg/l Si (soil application) and 200 mg/l Si (foliar application) treatments increased marketable fruit yield up to 2.1 kg/m^2 (by weight) and 23 fruits/m^2 (by number) compared to the untreated control. This result is consistent with previous findings that Si appears to have a positive effect on cucumber yield (Bélanger et al., 1998; Górecki et al., 2009; Jarosz 2013), although different varieties were used in their studies. The mechanism of Si supplementation on cucumber yield is unclear, but Si previously was reported to increase nutrient uptake and photosynthetic activity, which is beneficial for plant growth, development and yield. Ma and Takahashi (1990) found phosphate uptake significantly increased with Si applications in rice, which was positively correlated with growth and yield. Although we did not determine the foliar disease severity, many studies have shown that Si is effective in controlling powdery mildew in cucumber (Ehret et al., 2001; Miyake and Takahashi, 1982), which could have contributed to the increased growth and production of cucumber.

There were no significant differences among Si treatments and the untreated control for unmarketable fruit (weight and number) in 2013 (Table 1). However, most Si treatments significantly decreased unmarketable fruit weight and numbers ($p < 0.001$) compared with untreated controls in 2014. The lowest unmarketable fruit weight was recorded by plants receiving 1000 and 2000 mg/l Si (soil application), and 200 mg/l Si (foliar application). The lowest unmarketable fruit number was determined by plants receiving 200 mg/l Si and 1000 mg/l Si through foliar and soil applications, respectively. However, excessive application of Si may result in poor fruit quality (Samuels et al., 1993; Lieten et al., 2002). Bélanger et al. (1998) reported that the application of higher levels of Si increased hardening of the fruit, resulting in poor fruit quality. In zucchini, Tesfagiorgis and Laing (2013) found that including Si in the nutrient solution did not affect the quality of fruit. As reported by Ago et al. (2008), the response of cucurbits to Si treatments may vary among species or even at the

Table 2. Effects of silicon (Si) supplementation on fruit firmness, total soluble solid and ascorbic acid contents of *Cucumis sativus* L. 'Shabah F_1' grown in net houses in 2013 and 2014.

Application method	Si supplement Conc. (mg.L^{-1})	Fruit firmness (g/cm^2) 55 DAS^z	70 DAS	85 DAS	Total soluble solids (TSS %) 55 DAS	70 DAS	85 DAS	Ascorbic acid (mg/100g fresh wt.)
				2013				
Control	0	340.0^{by}	383.0^c	292.0^b	2.83^b	2.7 0^a	2.33	14.0^c
Foliar	50	511.9^a	485.0^b	510.0^a	3.16^a	2.61^a	2.47	15.5^{ab}
Foliar	100	530.0^a	531.5^b	509.5^a	3.17^a	2.57^b	2.4	15.9^{ab}
Foliar	200	533.0^a	532.5^b	510.3^a	3.09^a	2.65^a	2.41	16.7^a
Soil	500	546.0^a	546.0^{ab}	516.5^a	3.22^a	2.71^a	2.52	14.6^{bc}
Soil	1000	493.4^a	512.5^b	484.8^a	3.25^a	2.59^a	2.42	15.8^{ab}
Soil	2000	564.0^a	601.0^a	501.0^a	3.15^a	2.72^a	2.33	15.2^{bc}
F-test		*	*	*	*	*	ns	*
				2014				
Control	0	432.8^b	426.5^c	450.0^c	3.61	4.15^b	4.26	17.4
Foliar	50	584.8^a	587.5^{ab}	493.8^{bc}	3.75	4.41^b	4.46	16.8
Foliar	100	566.3^a	578.5^{ab}	559.5^a	3.81	4.13^b	4.61	18.2
Foliar	200	615.5^a	606.0^{ab}	571.8^a	3.56	4.36^b	4.11	18.2
Soil	500	542.5^a	541.0^b	521.5^{ab}	3.7	4.73^a	4.31	16.7
Soil	1000	618.0^a	576.3^{ab}	493.5^{bc}	3.69	4.27^b	4.49	17.4
Soil	2000	602.8^a	643.5^a	524.0^{ab}	3.7	4.16^b	4.54	18
F-test		*	*	*	ns	*	ns	ns

[z]DAS days after sowing
[y]Means with the same letter within the same column are not significantly different at ($P \leq 0.05$) according to Duncan's multiple range test

cultivar level.

The effects of Si supplements on fruit firmness, total soluble solids (TSS) and ascorbic acid content of cucumber fruit in 2013 and 2014 experiments are presented in Table 2. Both foliar and soil Si applications significantly increased fruit firmness ($p < 0.001$) compared with the untreated control at 55, 70 and 85 days after sowing (DAS) in both years, but no significant variations were observed among Si treatments at different growth stages. As noted previously, uptake and deposition of Si in the tissue enhances the strength and rigidity of the tissue, which may have contributed to an increase in cucumber fruit firmness (Epstein, 1994). Si concentrations deposited in the fruit were evaluated in leaf and fruit tissue. In general, TSS content of the fruit was not significantly affected by Si applications with the exception of Si treatments at 55 DAS in 2013, which increased TSS content of the fruits. The effect of Si supplements on ascorbic acid content varied; both foliar and soil Si treatments significantly increased the ascorbic acid content compared with the untreated control in 2013, whereas Si treatments did not increase ascorbic acid content in 2014. Previous studies reported that the application of Si can improve the TSS and dry matter in the cucumber fruits (Aziz et al., 2002; Hogendrop, 2008; Jarosz, 2013). It is unclear how Si treatments influence ascorbic acid content. It should be noted that the effect of Si supplementation on plants can vary from beneficial to detrimental, depending on plant species, the source of application, and concentration (Ago et al., 2008; Kamenidou et al., 2008).

Plants differ greatly in their ability to accumulate Si, ranging from 0.1 to 10.0% Si (dry weight) (Epstein, 1999; Richmond and Sussman, 2003). Cucumber accumulates medium levels of Si (2.5%) in the shoot dry weight (Mitani and Ma, 2005; Faisal et al., 2012). In our study, Si treatments increased tissue Si concentrations relative to the control in leaves and fruits (Table 3), but the leaves accumulated higher Si concentrations compared to fruits based on dry weight, supporting earlier results by Górecki and Danielski-Busch (2009) in cucumber. Leaves of un-supplemented control plants contained the lowest values of Si 1.3%, whereas Si-treated plants contained 1.38 to 1.57% Si. Treatments resulting in fruit Si from 1.05 to 1.65% corresponded to increases in fruit firmness, whereas untreated control plants contained the lowest values of Si 0.95% (Table 3). Many of the beneficial effects of Si on agricultural crops are associated with silica gel deposition on leaves, stems and fruits (Ma et al., 2001). Similarly, Si uptake and deposition in cucumber tissue may be responsible for the improved quality observed in some of the Si treatments of this study.

The effects of Si supplements on leaf macronutrient concentrations of cucumber are shown in Table 3. Tissue macronutrient analyses indicated no differences in leaf N concentrations between Si treatments and controls. Both

Table 3. Effects of silicon (Si) supplementation on leaf macronutrient concentrations and plant tissue Si concentration of *Cucumis sativus* L. 'Shabah F_1' grown in net houses in 2013.

Application method	Si supplement Conc. ($mg.L^{-1}$)	Tissue silicon concn. (% dry wt.)		Macronutrients (% dry wt)		
		Leaf	Fruit	N	P	K
Control	0	1.30 [b]	0.94 [c]	4.16	0.13 [b]	1.12 [a]
Foliar	50	1.42 [ab]	1.05 [c]	3.98	0.16 [b]	1.00 [ab]
Foliar	100	1.57 [a]	1.34 [ab]	4.32	0.16 [b]	1.03 [ab]
Foliar	200	1.53 [a]	1.30 [b]	4.84	0.24 [a]	0.83 [bc]
Soil	500	1.53 [a]	1.36 [ab]	4.81	0.25 [a]	0.80 [c]
Soil	1000	1.38 [ab]	1.30 [b]	4.47	0.26 [a]	0.98 [ab]
Soil	2000	1.55 [a]	1.65 [a]	4.71	0.25 [a]	0.98 [ab]
F-test		**	**	ns	**	*

Means with the same letter within the same column are not significantly different at ($P \leq 0.05$) according to Duncan's multiple range test; each value represents the mean of four replicates.

foliar and soil Si treatments significantly increased leaf P concentrations compared with the untreated control, with the exception of foliar 50 and 100 mg/l Si treatments. Brenchley and Maskell (1927) and Fisher (1929) found that Si fertilization made soil phosphorus more available to plants and increased barley yields mainly when phosphorus fertilization was limited. Eneji et al. (2008) also found positive correlations between Si and P uptake and concluded an effect on soil, indicating that Si plays a major role in P uptake. In contrast, foliar and soil Si treatments significantly decreased leaf K concentrations compared with the untreated control. In wheat, Tahir et al. (2011) found that the addition of Si to irrigated saline water significantly improved K uptake. Kamenidou et al. (2008) concluded that there were no differences in the leaf macronutrients (N, P, K, Mg, and Ca), and micronutrients (Al, B, Fe, Na, and Zn) between Si treatments and the control in ornamental sunflower (*Helianthus annuus* L.). Differences in the studies could be due to Si's involvement in metabolic or physiological actions in plants by promoting or suppressing the uptake and transportation of selected elements, depending on the stress conditions (Liang, 1999).

Based on this study, application of Si through soil drenches (1000 or 2000 mg/l Si) gave the highest early yield and total marketable fruit yield (weight and number). Previous studies also found applications of Si increased yield of wheat, rice, sugarcane, and sorghum in the field (Raid et al., 1992; Kaya et al., 2006; Mukkram et al., 2006; Ahmed et al., 2011). Our results indicate that spray and soil application of Si can improve yield and fruit quality of cucumber grown in net houses. Silicon supplementation could also be useful for other vegetable crops.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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