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ORIGINAL PAPER

Effects of Silicon on Growth, Yield and Fruit Quality of Cantaloupe under Drought Stress

Ashraful Alam [1] · Bambang Hariyanto [1] · Hayat Ullah [1] · Krishna R. Salin [2] · Avishek Datta [1]

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Abstract

Silicon (Si) plays an important role in mitigating adverse effects of various biotic and abiotic stresses including drought. Polyhouse experiment was conducted to evaluate the effects of Si on growth, yield and fruit quality of cantaloupe under drought stress. The treatments consisted of four Si fertilizer doses (0, 100, 200 and 400 kg ha^{-1}) applied in the form of silicic acid [H_4SiO_4, 20% Si content] and three soil moisture regimes (100%, 75% and 50% field capacity [FC]). Growth, yield and fruit quality were significantly ($p < 0.01$) affected by decreasing soil moisture level. Yield and water productivity were reduced by 63–69% and 19–34%, respectively, at different Si fertilizer doses when soil moisture was reduced from 100% to 50% FC. Overall, application of Si fertilizer was beneficial at all soil moisture regimes. There was no significant difference in yield and water productivity among four Si fertilizer doses at 50% FC, while these parameters were increased by 18–27% and 16–22%, respectively, at 75% FC and by 10–19% and 2–12%, respectively, at 100% FC with increasing Si fertilizer dose. Flesh thickness and total soluble solids content were also higher in Si-fed plants than the control. Application of silicic acid at 200 and 400 kg ha^{-1} maximized yield at 75% and 100% FC, respectively, and hence could be recommended as optimum doses. Selection of proper Si dose in synchronization with soil moisture level could be critical in cantaloupe production when soil moisture is a limiting factor.

Keywords Abiotic stress · Muskmelon · Quality · Silicon · Water-deficit stress · Water productivity · Yield

1 Introduction

Cantaloupe (*Cucumis melo* L.), commonly known as muskmelon, is a popular fruit in many countries of the world including Bangladesh. It belongs to the Cucurbitaceae family and prefers warm to hot climate. Asia has the highest cultivated area under cantaloupe production [1]. In 2018, China was the largest producer of cantaloupe on a global scale with nearly half of the global production followed by Turkey, Iran, Egypt and India [1]. Like other horticultural crops, cantaloupe also requires proper management practice for producing satisfactory yield with high-quality fruit. The optimum temperature range for cantaloupe cultivation is 22–33 °C and it thrives well in a place receiving sufficient sunlight [2]. Cantaloupe fruit is round to oval in shape and ranges in weight from 0.5 to 5 kg. It is a short-duration crop (less than 3 mo), and growers often face problems related to the quality of fruit setting, size and taste. Poor fruit quality remains a major concern in cantaloupe production, which includes small fruit size, fruit cracking, soft texture and tastelessness of flesh. Maestro and Alvarez [3] reported low quality of fruit setting due to improper and incomplete pollination, very hot weather or water-deficit stress. Various agronomic factors, such as water shortage, injudicious nutrient management, improper farming practices, inferior quality seeds and insufficient and/or improper pest management practices, are largely responsible for the production of low-quality fruit [4–6]. Cantaloupe is susceptible to a range of biotic and abiotic stresses, but very limited published literature is available about its susceptibility and coping mechanism.

✉ Avishek Datta
datta@ait.ac.th; avishek.ait@gmail.com

[1] Agricultural Systems and Engineering, Department of Food, Agriculture and Bioresources, School of Environment, Resources and Development, Asian Institute of Technology, Klong Luang, Pathum Thani 12120, Thailand

[2] Aquaculture and Aquatic Resources Management, Department of Food, Agriculture and Bioresources, School of Environment, Resources and Development, Asian Institute of Technology, Klong Luang, Pathum Thani 12120, Thailand

Among the abiotic stresses, drought is one of the key environmental constraints limiting growth and productivity of all major field and horticultural crops [7–9]. Drought is a condition of physical or physiological unavailability of sufficient water to sustain plant growth and it is one of the most severe abiotic stresses limiting plant growth and yield worldwide [10]. Drought stress adversely affects plant growth and productivity by inducing various morphological, physiological, biochemical and molecular changes within the plant [11, 12]. This has been attributed to decreased stomatal conductivity, restricted CO_2 entry into the leaves for photosynthesis and reduced transpiration [13]. Drought stress induces oxidative stress due to the over-production of reactive oxygen species (ROS) in various cellular compartments [14], and consequently enhances leakage of electrons to molecular oxygen [13, 15, 16]. Normal concentration of ROS is useful for inter- and intra-cellular signaling, but above-normal concentration produced under the influence of drought stress is cytotoxic and damages plant cell. Above-normal concentration of ROS can damage various cellular mechanisms through lipid peroxidation, protein degradation, inactivation of enzymes and damage to nucleic acids, which leads to cell death [13, 16]. The intensity of drought-induced damage varies among plant species depending on various factors, such as stage of life cycle when crop encounters drought situation, frequency, duration and severity of drought stress [17].

Silicon (Si) is among the beneficial nutrients needed for normal growth and development of many plant species, but its function as an abiotic stress-relieving material is often ignored [7]. Silicon when applied in combination with the recommended fertilizer dose has been found effective in enhancing grain yield and nutrient uptake of rice (*Oryza sativa* L.) [18] and in alleviating negative impacts of drought stress in rice depending on proper dose and application timing [7]. Sirisuntornlak et al. [9] reported that soil application of Si enhanced growth and yield of maize (*Zea mays* L.) under water-deficit stress. The Association of American Plant Food Control Officials (AAPFCO) has listed Si as a plant 'beneficial substance' by maintaining the official procedures for computing soluble Si content in fertilizers and plant-available form of Si is now listed on fertilizer labels [19]. Interestingly, an excessive accumulation of Si has no harmful effects on plants [20]. Silicon alleviates both biotic (plant disease, insect pest) and abiotic (drought, salinity, metal toxicity, temperature stress, nutrient imbalance and waterlogging) stresses in a variety of plant species [21–26]. Jana and Jeong [27] and Park et al. [28] reported Si as an important element in horticultural crop production (vegetable, fruit and floricultural crops). The beneficial role of Si as a stress-relieving material has been investigated by various researchers in horticultural crops, such as tomato (*Solanum lycopersicum* L.), carrot (*Daucus carota* L.) and melon [6, 29–31]. Cucurbitaceae species accumulate substantial amounts of Si in their fruit peels or outer surface, which help increase fruit quality and shelf life [32, 33]. Silicon is also known to influence nutrient availability in soils and nutrient use efficiency by plants. In addition, an enhancement in plant metabolism [34, 35] and an improvement in yields in some crops belonging to grass family (Poaceae), such as rice, wheat (*Triticum aestivum* L.), maize and sugarcane (*Saccharum officinarum* L.) have been reported [7, 9, 18, 25, 36–38]. Rizwan et al. [39] reported the beneficial role of Si in the form of improved seed germination, increased biomass production and photosynthetic rate through mechanisms, such as osmotic adjustment, modification of gas exchange attributes, enhanced mineral uptake and increased antioxidant defense system, under water-deficit stress.

Morphological and physiological adaptations and impacts of Si under water-limited environments may vary among crops/cultivars [40], such as an improved root growth in melon [41]. To the best of our knowledge, no published literature is available dealing with the impacts of Si in alleviating water-deficit stress in cantaloupe as its productivity is threatened by multiple stresses including drought. Given this fact, it is critically important to evaluate the impacts of Si in alleviating the deleterious effects of water-deficit stress in cantaloupe. The objective of the present study was to investigate the effects of Si on growth, yield and fruit quality of cantaloupe under drought stress.

2 Materials and Methods

2.1 Experimental Set-up

The experiment was conducted in a polyhouse of the Department of Food, Agriculture and Bioresources, Asian Institute of Technology (14.0791° N, 100.6114° E), Klong Luang, Pathum Thani, Thailand in 2019. The average monthly temperature during the experimental period ranged between 29.9 ° and 31 °C. The soil used for this study was a Bangkok clay soil containing 22% sand, 17% silt, 61% clay, 2.5% organic matter content with a pH of 5.2 (1:1 water) and 0.011% Si, which was measured following the gravimetric method [42]. The soil was air-dried and a total of 15 kg soil was filled in each black plastic pot having a length of 30 cm with top and bottom diameters of 36 and 28 cm, respectively. Seeds of cantaloupe (*Cucumis melo* var. *reticulatus* Cat 697) were soaked in distilled water for 1 d before putting into small polybags filled with the same soil and were placed in the polyhouse for germination. After germination, one uniform, healthy and vigorous seedling at 2–3 leaf stage was transplanted into the pot. All pots were uniformly irrigated for 2 wks after transplanting until the seedlings were established followed by an artificial implementation of water-deficit stress through withholding irrigation until a desired soil moisture level was achieved. Soil moisture content at 100% field capacity (FC) was calculated following Boyd and Van Acker [43] and Datta et al. [44] where 45% soil moisture content was determined at 100% FC. Soil moisture content at 75% and 50% FC was 34% and 23%, respectively. Soil moisture content was monitored daily using a portable soil moisture meter (SM150 Soil Moisture Sensor; SM150, Delta-T Devices Ltd., Cambridge, UK) throughout the crop growing period and pots were re-irrigated when soil moisture level dropped below the desired level to adjust it back to the desired level.

2.2 Experimental Design and Treatments

The treatments were arranged in a completely randomized design with factorial combination and there were four replications. Each pot with one seedling was treated as one replication. The treatments consisted of four silicic acid (SA) doses as a source of Si (0, 100, 200 and 400 kg ha^{-1}) and three soil moisture regimes (100%, 75% and 50% FC). Silicon fertilizer, marketed by Thai Green Agro Co. Ltd., was used in the form of monomeric SA (H_4SiO_4) containing 20% Si. A total of 0, 0.75, 1.5 and 3 g SA (corresponding to 0, 100, 200 and 400 kg SA ha^{-1}, respectively) was applied in each pot at an interval of 2 wks in four equal installments starting from 2 wks after transplanting. All the flowers between the fourth and fifth internodes were manually pollinated, and only one fruit was allowed to grow in each plant. The plants were supported by nylon rope tied with the vertical support.

2.3 Fertilizer Application

A total of 140 kg N ha^{-1} in the form of urea at 304 kg ha^{-1} (2.28 g pot^{-1}), 64 kg P_2O_5 ha^{-1} in the form of triple superphosphate at 140 kg ha^{-1} (1.05 g pot^{-1}) and 60 kg K_2O ha^{-1} in the form of potassium chloride at 100 kg ha^{-1} (0.75 g pot^{-1}) were applied in each pot [45]. Triple superphosphate and potassium chloride fertilizers were applied as a basal dose and were thoroughly mixed with soil 1 wk before transplanting seedling into the main pot. Out of the total N, 40% was applied after 2 wks of seedling transplanting into the main pot and the rest was applied in three equal installments at fourth, sixth and 8 wks after transplanting.

2.4 Data Collection

Growth, yield and its components, irrigation water productivity and fruit quality data were collected. Growth parameters included plant height, number of leaf plant^{-1}, leaf greenness (relative leaf chlorophyll concentration) and shoot and root dry matter. Data on plant height and number of leaf plant^{-1} were collected at 30 days after transplanting. Plant height was measured from the soil surface to the plant tip using a meter scale, while number of leaf plant^{-1} was counted manually. Leaf greenness was measured nondestructively using a SPAD meter (SPAD-502 plus, Minolta Co. Ltd., Japan) from the fully expanded young leaves at 30 days after transplanting. After fruit harvest, shoot dry matter and root dry matter were measured by oven-drying fresh shoot and root samples at 72 °C until constant weight was obtained. Data on days to flowering, days to fruit setting and days to fruit maturity were also collected. Fruit length (cm), fruit diameter (cm), fruit weight (g), flesh thickness (cm) and total soluble solids (°Brix) content were measured in the laboratory after fruit harvest. Irrigation water productivity (kg m^{-3}) was measured using the following formula [46, 47]:

$$\mathrm{IWP} = \frac{\mathrm{Y}}{\mathrm{I}} \tag{1}$$

where *IWP* is the irrigation water productivity in kg m^{-3}, *Y* is the fruit yield in kg and *I* is the amount of irrigation water input in m^3.

2.4.1 Statistical Analysis

The data were subjected to a two-way analysis of variance (ANOVA) and were analyzed using the statistical software Statistix 8. Difference between the treatments means was compared using Fisher's protected least significant difference test at $p < 0.05$. The data for all response variables were presented as means of four replications ± standard errors.

3 Results

3.1 Effect of Silicon-Based Fertilizer and Soil Moisture Regime on Plant Growth

The main effect of SA dose and soil moisture regime was significant on plant height ($p < 0.01$), number of leaf plant^{-1} ($p < 0.05$ and $p < 0.01$, respectively), root dry matter ($p < 0.01$) and shoot dry matter ($p < 0.01$), whereas leaf greenness (SPAD value) was significantly ($p < 0.01$) affected by the main effect of soil moisture regime (Table 1). Maximum plant height was observed at 200 kg ha^{-1} of SA, which was statistically at par with 100 and 400 kg SA ha^{-1}, but 11% higher than the control (Table 1). A progressive decrease in plant height with increasing severity of water-deficit stress was observed, and 100% FC resulted in 14% and 64% taller plants compared with plants at 75% and 50% FC, respectively. Number of leaf plant^{-1} was similar among 100, 200 and 400 kg SA ha^{-1}, which was significantly higher than the control (Table 1). Among three soil moisture regimes, number of leaf plant^{-1} was significantly higher at 100% FC (28.3) than 75% FC (26.3) and 50% FC (21.4). Leaf greenness (SPAD value) progressively decreased with increasing soil moisture

Table 1 Growth of cantaloupe as a function of soil application of silicic acid source of silicon and soil moisture regime

Factor	Plant height (cm)	Number of leaf plant^{-1}	SPAD value	Root dry matter (g plant^{-1})	Shoot dry matter (g plant^{-1})
Silicic acid (kg ha^{-1})					
0	149.7 ± 9.59b	24.5 ± 0.94b	37.7 ± 1.29	0.7 ± 0.08b	6.3 ± 0.54b
100	158.2 ± 9.52ab	25.2 ± 0.91ab	38.0 ± 1.37	1.2 ± 0.15a	7.0 ± 0.64a
200	166.1 ± 8.86a	25.8 ± 0.82a	38.4 ± 1.32	1.4 ± 0.09a	7.5 ± 0.66a
400	163.1 ± 11.39a	25.8 ± 1.06a	38.9 ± 1.29	1.2 ± 0.18a	7.4 ± 0.78a
Soil moisture regime					
50% field capacity	117.3 ± 3.05c	21.4 ± 0.27c	44.2 ± 0.32a	0.6 ± 0.07b	4.3 ± 0.17c
75% field capacity	168.8 ± 3.75b	26.3 ± 0.46b	35.7 ± 0.30b	1.2 ± 0.13a	7.5 ± 0.26b
100% field capacity	191.8 ± 2.35a	28.3 ± 0.25a	34.8 ± 0.35b	1.4 ± 0.11a	9.4 ± 0.23a
Significance					
Silicic acid (SA)	**	*	ns	**	**
Moisture (M)	**	**	**	**	**
SA × M	ns	ns	ns	ns	ns

Means followed by the same letter within a column are not significantly different by least significant difference test at $p < 0.05$; ns, not significant; *$p < 0.05$; **$p < 0.01$; data are means ± standard errors of four replications

level where 100% and 75% FC resulted in significantly lower SPAD values (34.8 and 35.7, respectively) than 50% FC (44.2) (Table 1). Root dry matter and shoot dry matter were the maximum at 200 kg SA ha^{-1}, with a respective increase of 100% and 19% than the control (Table 1). Root dry matter was similar between 100% and 75% FC, which was reduced by 57% and 50%, respectively, at 50% FC. A significant reduction in shoot dry matter was observed with decreasing soil moisture level and 100% FC resulted in 119% and 25% higher shoot dry matter than 50% and 75% FC, respectively. There was no effect of SA dose, soil moisture regime and their interaction on days to flowering, days to fruit setting and days to fruit maturity (Table 2).

3.2 Effect of Silicon-Based Fertilizer and Soil Moisture Regime on Yield Components, Fruit Yield and Irrigation Water Productivity

Fruit length was significantly ($p < 0.01$) affected by the main effects of SA dose and soil moisture regime, whereas fruit diameter ($p < 0.01$), yield ($p < 0.01$) and irrigation water productivity ($p < 0.01$) were significantly affected by the interaction between SA dose and soil moisture regime (Table 3). There was no significant difference in fruit length among 100, 200 and 400 kg ha^{-1} of SA. Fruit length was reduced by 9% at 0 kg SA ha^{-1} compared with 200 kg SA ha^{-1}. Among three soil moisture regimes, 100% FC resulted in the

Table 2 Days to flowering, fruit setting and fruit maturity of cantaloupe as a function of soil application of silicic acid source of silicon and soil moisture regime

Factor	Days to flowering	Days to fruit setting	Days to fruit maturity
Silicic acid (kg ha^{-1})			
0	21.6 ± 0.22	27.7 ± 0.56	59.6 ± 0.98
100	21.7 ± 0.18	27.8 ± 0.32	60.3 ± 0.50
200	21.8 ± 0.20	27.2 ± 0.50	59.9 ± 1.75
400	21.8 ± 0.24	26.9 ± 0.25	59.5 ± 1.26
Soil moisture regime			
50% field capacity	21.6 ± 0.17	27.6 ± 0.36	59.7 ± 0.49
75% field capacity	21.7 ± 0.17	27.4 ± 0.43	59.0 ± 1.33
100% field capacity	21.9 ± 0.20	27.2 ± 0.33	59.3 ± 1.15
Significance			
Silicic acid (SA)	ns	ns	ns
Moisture (M)	ns	ns	ns
SA × M	ns	ns	ns

ns, not significant by least significant difference test at $p < 0.05$; data are means ± standard errors of four replications

Table 3 Yield components, fruit yield and irrigation water productivity of cantaloupe as a function of soil application of silicic acid source of silicon and soil moisture regime

Factor	Fruit length (cm)	Fruit diameter (cm)	Fruit yield (g plant^{-1})	Irrigation Water productivity (kg m^{-3})
Silicic acid (kg ha^{-1})				
0	11.2 ± 0.40b	11.1 ± 0.52b	804.2 ± 91.16b	13.1 ± 0.41b
100	12.1 ± 0.58a	11.4 ± 0.52a	870.0 ± 97.78ab	14.1 ± 0.52a
200	12.3 ± 0.57a	11.4 ± 0.63a	913.3 ± 114.78a	14.3 ± 0.73a
400	12.2 ± 0.62a	11.6 ± 0.69a	922.5 ± 126.18a	14.4 ± 0.80a
Soil moisture regime				
50% field capacity	9.5 ± 0.09c	8.7 ± 0.12c	394.4 ± 8.21c	11.4 ± 0.24b
75% field capacity	12.8 ± 0.23b	12.4 ± 0.10b	1038.1 ± 31.66b	15.1 ± 0.39a
100% field capacity	13.5 ± 0.20a	13.1 ± 0.10a	1200.0 ± 31.39a	15.4 ± 0.25a
Significance				
Silicic acid (SA)	**	**	**	*
Moisture (M)	**	**	**	**
SA × M	ns	**	**	**

Means followed by the same letter within a column are not significantly different by least significant difference test at $p < 0.05$; ns, not significant; *$p < 0.05$; **$p < 0.01$; data are means ± standard errors of four replications

maximum fruit length (13.5 cm), which was reduced by 5% at 75% FC and by 30% at 50% FC. The two-way interaction between SA dose and soil moisture regime for fruit diameter was highly significant ($p < 0.01$) (Table 4). There was no significant difference in fruit diameter among 100, 200 and 400 kg SA ha^{-1} across soil moisture regimes. However, the control (0 kg SA ha^{-1}) had 9% less fruit diameter than 100 kg SA ha^{-1} at 50% FC, while the same (control) had 6% and 5% less fruit dimeter than 400 kg SA ha^{-1} at 75% and 100% FC, respectively. A similar trend of increasing fruit diameter with increasing soil moisture regime was observed regardless of SA doses and 100% FC resulted in 54%, 44%, 55% and 53% more fruit diameter than 50% FC at 0, 100, 200 and 400 kg SA ha^{-1}, respectively.

A highly significant ($p < 0.01$) two-way interaction between SA dose and soil moisture regime was evident for fruit yield, which was statistically similar among four SA doses at 50% FC (Table 4). At 75% FC, fruit yield was the highest at 200 kg SA ha^{-1}, which was reduced by 21% and 7% at 0 and 100 kg SA ha^{-1}, respectively. A progressive increase in fruit yield with increasing SA dose was observed at 100% FC where 400 kg SA ha^{-1} resulted in 19%, 16% and 8% more fruit yield than 0, 100 and 200 kg SA ha^{-1}, respectively. A significantly higher fruit yield was observed at 100% FC across SA doses, which was reduced by 68%, 63%, 68% and 69% at 50% FC with 0, 100, 200 and 400 kg SA ha^{-1}.

Irrigation water productivity was highly significantly ($p < 0.01$) affected by the two-way interaction between SA dose and soil moisture regime, which remained statistically similar across SA doses at 50% FC (Table 4). At 75% and 100% FC, 400 kg SA ha^{-1} had the maximum irrigation water productivity, which was statistically at par with 100 and 200 kg SA ha^{-1}, but 22% and 12% higher than the respective irrigation water productivity at the control. Irrigation water productivity remained statistically similar between 75% and 100% FC across SA doses, whereas 50% FC resulted in 21%, 19%, 29% and 34% less irrigation water productivity than 100% FC at 0, 100, 200 and 400 kg SA ha^{-1}, respectively.

3.3 Effect of Silicon-Based Fertilizer and Soil Moisture Regime on Fruit Quality

Flesh thickness was highly significantly ($p < 0.01$) affected by the main effect of SA dose, soil moisture regime and their interaction; however, total soluble solids content was significantly affected by the main effect of SA dose ($p < 0.05$) and soil moisture regime ($p < 0.01$) (Table 5). Application of SA resulted in significantly higher flesh thickness than the control; however, it was similar among different SA doses regardless of soil moisture regimes (Table 6). Application of SA at 200 kg ha^{-1} had the highest flesh thickness at 50% FC, which was 46% higher than the control. Flesh thickness was the same at three SA doses (100, 200 and 400 kg ha^{-1}) at 75% FC, which was 19% higher than the control. At 100% FC, flesh thickness was 17% higher at 400 kg SA ha^{-1} than the control. There was no significant difference in flesh thickness between 100% and 75% FC across SA doses, while 50% FC resulted in 55%, 45%, 41% and 50% less flesh thickness than 100% FC at 0, 100, 200 and 400 kg SA ha^{-1}, respectively. Total soluble solids (^{o}Brix) content was the highest at 100 kg

Table 4 Interactive effects of soil application of silicic acid source of silicon and soil moisture regime on fruit diameter, fruit yield and irrigation water productivity of cantaloupe

Silicic acid (kg ha^{-1})	Fruit diameter (cm)		
	50% field capacity	75% field capacity	100% field capacity
0	8.3 ± 0.23bC	11.8 ± 0.11bB	12.8 ± 0.20bA
100	9.1 ± 0.20aC	12.5 ± 0.06aB	13.1 ± 0.10abA
200	8.5 ± 0.14abC	12.5 ± 0.21aB	13.2 ± 0.17abA
400	8.8 ± 0.22abC	12.6 ± 0.20aB	13.5 ± 0.16 aA
Significance			
Silicic acid (SA)		**	
Moisture (M)		**	
SA × M		**	
	Fruit yield (g $plant^{-1}$)		
0	360.0 ± 14.71aC	890.0 ± 43.77cB	1115.0 ± 47.34cA
100	420.0 ± 12.24aC	1050.0 ± 34.88bB	1140.0 ± 34.64cA
200	390.0 ± 12.24aC	1127.5 ± 50.22aB	1222.5 ± 61.82bA
400	407.5 ± 12.50aC	1085.0 ± 60.34abB	1322.5 ± 60.60aA
Significance			
SA		**	
M		**	
SA × M		**	
	Irrigation water productivity (kg m^{-3})		
0	11.5 ± 0.43aB	13.2 ± 0.11bA	14.6 ± 0.35bA
100	12.1 ± 0.44aB	15.3 ± 0.72aA	14.9 ± 0.42abA
200	11.2 ± 0.56aB	15.9 ± 0.76aA	15.8 ± 0.56abA
400	10.8 ± 0.44aB	16.1 ± 0.49aA	16.3 ± 0.42aA
Significance			
SA		*	
M		**	
SA × M		**	

Means followed by the same small letter within a column and the same capital letter within a row are not significantly different by least significant difference test at $p < 0.05$; $^{*}p < 0.05$; $^{**}p < 0.01$; data are means ± standard errors of four replications

SA ha^{-1}, which was statistically at par with other SA doses, but 17% higher than the control (Table 5). A progressive decrease in total soluble solids content was observed with increasing soil moisture level and 50% FC resulted in 15% and 21% higher total soluble solids content than 75% and 100% FC, respectively.

4 Discussion

Once assimilated within plants, Si can build up rigidity and impart roughness to the cell wall [48], and sufficiently enhances growth and yields of various cereals, vegetables and fruit crops [42]. The beneficial role of Si in plants belonging to Cucurbitaceae family is well documented against certain biotic and abiotic stresses [49]. It has been reported that Si can alleviate detrimental effects of salinity in both salt-sensitive (cucumber [*Cucumis sativus* L.]) and less salt-sensitive species (bitter gourd [*Momordica charantia* L.]) of cucurbit by decreasing sodium toxicity and enhancing photosynthetic activity resulting in an improvement in growth parameters [50]. Moreover, the application of Si has been reported to significantly increase seed germination index and enhance consequent growth of cantaloupe under autotoxicity stress [51]. The present findings confirm these claims as we observed consistently better results for growth parameters, such as plant height, number of leaf $plant^{-1}$, root and shoot dry matter (Table 1), with the exogenous application of Si-based fertilizer. As the interaction between Si-based fertilizer dose and soil moisture regime was not significant for these growth parameters, the beneficial effect of Si in improving these parameters under water-deficit stress cannot be truly validated. Similarly, fruit length was also increased with Si application (Table 3) indicating the positive impacts of Si on yield contributing

Table 5 Fruit quality of cantaloupe as a function of soil application of silicic acid source of silicon and soil moisture regime

Factor	Flesh thickness (cm)	Total soluble solids (°Brix)
Silicic acid (kg ha^{-1})		
0	2.4 ± 0.16b	7.7 ± 0.28b
100	2.6 ± 0.20ab	9.0 ± 0.35a
200	2.8 ± 0.18a	8.8 ± 0.37a
400	2.6 ± 0.28ab	8.4 ± 0.34ab
Soil moisture regime		
50% field capacity	1.6 ± 0.07b	9.4 ± 0.25a
75% field capacity	2.9 ± 0.06a	8.2 ± 0.28b
100% field capacity	3.1 ± 0.08a	7.8 ± 0.25b
Significance		
Silicic acid (SA)	**	*
Moisture (M)	**	**
SA × M	**	ns

Means followed by the same letter within a column are not significantly different by least significant difference test at $p < 0.05$; ns, not significant; *$p < 0.05$; **$p < 0.01$; data are means ± standard errors of four replications

characters. Fruit diameter was higher in Si-treated plants even at severe (50% FC) and moderate (75% FC) drought stress (Table 4). Yield and irrigation water productivity of Si-treated plants were improved at moderate drought stress (75% FC) and there was no impact of Si on these parameters at 50% FC (Table 4). Higher yield at moderate drought stress might be attributed to longer fruit having more diameter with Si application as total yield was the weight of an individual fruit in a plant since one plant contained only one fruit. Fruit yield increased with increasing Si-based fertilizer dose at 100% FC. Irrigation water productivity remained similar between moderate drought stress (75% FC) and well-watered condition of 100% FC regardless of Si-based fertilizer doses as there was more water savings at 75% FC rather than an increase in yield. Our results are consistent with the findings of do Nascimento et al. [6], who also reported an enhanced fruit number, fruit weight and yield of Si fertilizer-treated melon compared with non-Si-treated plants grown in sandy soils. While examining the impacts of Si on yield of cantaloupe under different irrigation levels, Lozano et al. [52] did not observe any improvement in yield traits of cantaloupe with an increase of Si dose, except the maturity index, which was increased with the maximum irrigation level and was reduced at the lowest irrigation level (water stress) with the application of Si (200 kg ha^{-1} [98% SiO_2]). Although these results are not fully consistent with the present findings, the influence of Si dose and irrigation level on the maturity index of cantaloupe indicated a positive impact of Si fertilization on cantaloupe. Our results for growth parameters are consistent with the findings of Ghani et al. [50], who also reported a significant improvement in cucumber growth with the application of Si in the form of sodium silicate at 100 mg L^{-1} under salt stress. In the present study, irrigation water productivity of Si-fed plants (400 kg SA ha^{-1}) was improved at 75% FC (22%) and 100% FC (12%) compared with the respective irrigation water productivity at the control. Similarly, Buttaro et al. [53] also observed an increase in total fruit yield and water use efficiency (18%) of Si-fed melon plants grown in a soilless culture. This has been attributed to better health of Si-treated melon plants and a reduced water loss by transpiration [53]. The positive impacts of Si fertilization on plant growth and development have also been attributed to correcting soil acidity by reducing H + Al levels, which in turn improves the fertility status of soil resulting in better nutrient acquisition [26]. In addition, various other benefits associated with Si application are highlighted by different researchers, such as (i) increased self-resistance to lodging and strengthended cell wall [32, 54], (ii) restricted fungal disease and insect infestations [26, 55],

Table 6 Interactive effect of soil application of silicic acid source of silicon and soil moisture regime on flesh thickness of cantaloupe

Silicic acid (kg ha^{-1})	Flesh thickness (cm)		
	50% field capacity	75% field capacity	100% field capacity
0	1.3 ± 0.04bB	2.6 ± 0.11bA	2.9 ± 0.07bA
100	1.7 ± 0.10aB	3.1 ± 0.06aA	3.1 ± 0.09abA
200	1.9 ± 0.15aB	3.1 ± 0.07aA	3.2 ± 0.14abA
400	1.7 ± 0.10aB	3.1 ± 0.08aA	3.4 ± 0.21aA
Significance			
Silicic acid (SA)		**	
Moisture (M)		**	
SA × M		**	

Means followed by the same small letter within a column and the same capital letter within a row are not significantly different by least significant difference test at $p < 0.05$; **$p < 0.01$; data are means ± standard errors of four replications

(iii) reduced mutual shading, positive alteration of the leaf angle and extended canopy area [56, 57] and (iv) improved water balance, reduced transpiration and water loss [53]. All or many of the above-mentioned benefits might have contributed to the overall better response of Si-fed cantaloupe plants in the present study.

Drought stress-induced growth reduction is mostly caused by a retarded cell division and cell elongation process [10]. We observed a significant effect of soil moisture regime on all growth parameters (Table 1), yield components and fruit yield (Tables 3 and 4) as well as quality parameters (Tables 5 and 6). Our results indicated that growth and fruit yield were drastically reduced at sever water-deficit condition (50% FC), except for SPAD value. It might be due to reduced photosynthetic and transpiration rates and stomatal closure induced by water-deficit stress [10]. Our findings are consistent with the results of Maestro and Alvarez [3], who also reported an inferior quality of fruit setting in cantaloupe due to very hot weather or water-deficit stress. In the present study, SPAD value was increased by 27% and 24% at 50% FC compared with 100% and 75% FC (Table 1). These findings are consistent with Sirisuntornlak et al. [9], who also reported higher chlorophyll content in Si-fed maize plants under drought stress compared with plants maintained under well-watered condition.

In melon, sugar level positively correlates with total soluble solids content and sugar level largely determines fruit quality [58]. In the present study, fruit quality was significantly affected by the main effects of Si-based fertilizer dose and soil moisture regime (Tables 5 and 6). We observed higher total soluble solids content in Si-fed plants than the control and at 50% FC. Similarly, do Nascimento et al. [6] observed an increasing trend of total soluble solids content of melon from the control plants to higher Si-fed plants. Hajiboland et al. [59] also reported that Si supplementation significantly increased all quality parameters including soluble sugar content of strawberry fruit (*Fragaria ananassa* Duch.), except for titratable acidity, which was slightly reduced in Si-fed plants. Sensoy et al. [60] reported a decrease in melon fruit quality, especially total soluble solids content, with increasing irrigation level. Flesh thickness was higher in Si-fed plants than the control plants; however, it was similar among different Si-based fertilizer doses regardless of soil moisture regimes (Table 6). Flesh thickness was similar between 100% and 75% FC across Si-based fertilizer doses. Similarly, do Nascimento et al. [6] also observed an increase in pulp thickness of Si-fed melon fruits.

5 Conclusion

Growth, yield and fruit quality of cantaloupe were adversely affected by water-deficit stress and the fruits produced at 50% FC were not marketable irrespective of Si-based fertilizer doses. Most growth parameters, yield components and yield were also significantly reduced at 75% FC; however, irrigation water productivity and flesh thickness of fruit were similar between 75% and 100% FC regardless of Si-based fertilizer doses. Application of Si-based fertilizer was beneficial across soil moisture regimes and there was no significant difference among three Si-based fertilizer doses (100, 200 and 400 kg ha^{-1} of silicic acid) for most growth parameters and yield components. The interactive effect between Si-based fertilizer dose and soil moisture regime for yield and irrigation water productivity indicated that Si-based fertilizer application at 200 kg ha^{-1} (40 kg ha^{-1} soluble Si) and 400 kg ha^{-1} of silicic acid (80 kg ha^{-1} soluble Si) could be beneficial to cantaloupe cultivation at moderate drought stress (75% FC) and well-watered condition (100% FC), respectively. Selection of proper Si dose in synchronization with soil moisture level could be critical in cantaloupe cultivation when soil moisture is a limiting factor.

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