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Research article

Silica nanoparticles boost growth and productivity of cucumber under water deficit and salinity stresses by balancing nutrients uptake

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ABSTRACT

The role of amorphous silica nanoparticles (SiNPs) in enhancing growth and yield of cucumber under water deficit and salinity stresses was assessed. A field experiment under greenhouse conditions was established using 4 different levels of SiNPs (100, 200, 300 and 400 mg kg^{-1}) and 3 different watering regimes calculated based on crop evapotranspiration (ET_c) (100, 85 and 70% of ET_c). Electrical conductivity and sodium adsorption ratio of irrigation water were 1.7 dS m^{-1} and 4.63 respectively. The results revealed that SiNPs improved growth and productivity of cucumber regardless of quantity of supplied water; however, the greatest increase corresponded to irrigating cucumber at the rate of 85% of ET_c. Applying SiNPs at rate of 200 mg kg^{-1} showed the greatest increase specially when cucumber plants received 85% of their ET_c causing an increase of 20, 51 and 156% in plant height, chlorophyll and fruit yield, respectively, compared to untreated plants. These increases could be due to alerting nutrient uptake as SiNPs clearly increased contents of nitrogen (by 30%), potassium (by 52, 75 and 41% in root, stem and leaf, respectively) and silicon (by 51, 57, 8 and 78% in root, stem, leaf and fruit, respectively). Otherwise, same treatment reduced sodium uptake by 38, 77 and 38% in root, stem and leaf, respectively; consequently, potassium-sodium ratio increased by 149, 735 and 127% in root, stem and leaf, respectively. The significant role of SiNPs in mitigating water deficit and salinity stresses could be referred to high silicon content found in leaf which regulates water losses via transpiration. Also, high K^+ content found in roots of cucumber helps plants to tolerate abiotic stresses as a result of maintaining ion homeostasis and regulating the osmotic balance as well as controlling stomatal opening which helps plants to adapt to salinity and water deficit stresses.

1. Introduction

In the Earth's crust, silicon exists in most rocks combined with oxygen in the form of quartz as a nonmetallic component by 25.7% (by weight) (Sommer et al., 2006). Also, it may exist in soil as inorganic and biogenic (phytoliths) forms (Cornelis et al., 2011). An amorphous form of quartz, opal, is reported for its possible occurrence in soil and it is expected to have a biological origin (Kabata-Pendias, 2011).

Although the total silicon content in soils is high, the available concentration of silicon in soil solution is very low with ranges between 1 and 200 mg L^{-1} mainly as monosilicic acid (H_4SiO_4. Carlisle et al., 1974). Below pH 9, silicic acid exists in soil solution as non-ionized form with concentration ranges between 0.1 and 0.6 mM and its solubility is 2 mM at 25 °C (Epstein, 2009). Both solubility and mobility of silicon in soils depends on soil and climatic factors. In alkaline soils silicon is more mobile; however, soluble silicon decreases above soil pH 9 (Kabata-Pendias, 2011).

To date, there is no evidence for silicon essentiality for higher plants particularly dicots. Even though, many studies reported that monocots such as wheat and rice uptake and accumulate silicon in high amount within their tissues (e.g., Farooq and Dietz, 2015; Epstein, 2009; Frantz et al., 2008).

Silicon becomes a vital factor in plant protection against many biotic and abiotic stresses such as diseases, pests, drought, salinity and

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heavy metals toxicity (Alsaeedi et al., 2017a, 2018; Ma and Takahashi, 2002). For instance, in rice, a typical silicon absorber, silicon increases the resistance to fungal diseases and improves rice productivity (Datnoff LE et al., 2000). Cucumber plants that lack silicon are found to be more susceptible to infection with powdery mildew disease which causes a large reduction in fruit yield (Miyake and Takahashi, 1983). Silicon deficiency, moreover, can cause defect in growth of the newly developed leaves and results in infertile seeds (Miyake and Takahashi, 1983). Cucumber plants are reported to uptake silicon in much higher amounts compared to gramineous plants when high concentration of available silicon exists in the growth medium (Alsaeedi et al., 2018). In our previous study, silica nanoparticles (SiNPs) were found to enhance all germination parameters of common bean seeds germinated at 5000 ppm Na^{+} when applied at 300 ppm (Alsaeedi et al., 2017b).

Plants take up silicon in many different forms i.e., monosilicic acid (the most commonly absorbed form by plants), amorphous silica and organic complexes (Richmond and Sussman, 2003) and deposit it in their tissues as monosilicic acid (6–38%), polysilicic acid (10–70%) and phytoliths (biogenic silica, 15–79%) based on plant species (Matichenkov et al., 1997). Sangster (1992) reported a layer of 2.5 μm deposited silicon beneath the 1.0 μm cuticle layer making a cuticle-Si double layer. Silicon uptake relies on silicon concentration in soil solution, pH and soil water content. Two possible mechanisms (active and passive) were proposed for silicon uptake by plants. Grasses and many other plants uptake silicon via passive mechanisms (mass flow), while rice was found to have an active pathway due to a gene located in the plasma membrane of the distal side of exodermis and endodermis that can lead to excess silicon accumulation in xylem (Ma et al., 2006). Also, cucumber was reported to take up and transport silicon via active mechanisms (Liang et al., 2005). The deposited silicon in shoots is condensed by transpiration and later transformed into amorphous silica localized in the cell wall of epidermal and vascular tissues causing a reduction in water loss (Ma and Yamaji, 2006). Silicon, also, has great potential improvements in many soil characteristics such as water-holding capacity, soil texture, stability of soil organic matter and soil erosion (Sadgrove, 2006) as well as cation exchange capacity (Camberato, 2001).

Cucumber (*Cucumis sativus* L.), of the Cucurbitaceae family, is one of the most popular vegetable crops worldwide. It is also known for its high economic value. In many regions around the world it is grown all year regardless of the climate, since it can easily and economically grow under greenhouse conditions (Maas and Hoffman, 1977). Cucumber was reported to have high water requirements compared to grain crops, as fruit yield heavily depends on the proper supply with water at all growth stages (Li and Wang, 2000; Mao et al., 2003). The present study aimed at evaluating growth dynamics, nutrient uptake and productivity of cucumber under different watering regimes in presence of silica nanoparticles (SiNPs) as well as the ameliorative effect of SiNPs on water deficit stress was assessed.

2. Materials and methods

The response of cucumber (*Cucumis sativus*) to three different watering regimes and salinity of irrigation water in sandy soil (soil characteristics are presented in Table 1) under greenhouse conditions was investigated in the presence of silica nanoparticles (SiNPs). Five doses of SiNPs (i.e., 0, 100, 200, 300 and 400 mg kg-1) were applied. The water requirements (crop evapotranspiration, ET_c) to be applied for cucumber plants were calculated based on reference evapotranspiration and crop coefficient (K_c) as described by the modified FAO Penman-–Monteith method (Allen et al., 1998). The agro-meteorological inputs to calculate ET_c were measured in greenhouses. Cucumber plants were exposed to three watering regimes i.e., 70, 85 and 100% of ET_c which were equivalent to 4332, 5260 and 6188 $m^3\ ha^{-1}$, respectively, applied from first day after transplantation of cucumber seedlings.

Table 1
Physicochemical characteristics of experimental soil.

Value	Character
7.34 ± 0.05[a]	pH (1: 2.5 soil:water suspension)
2042 ± 79.8	Salinity (ppm)
1.73 ± 0.15	SAR (sodium adsorption ratio)
Soluble cations (meq L^{-1})	
1.24 ± 0.02	Ca^{++}
1.67 ± 0.03	Mg^{++}
2.09 ± 0.22	Na^{+}
0.027 ± 0.001	Total nitrogen (%)
7.87 ± 3.47	Total silicon (mg kg^{-1})
1.59 ± 0.055	Bulk density (g cm^{-3})
2.1 ± 0.1	Particle density (g cm^{-3})
187.28 ± 12.05	Specific surface area ($m^2\ g^{-1}$)
18.73 ± 0.1	Saturation %
Particle size distribution (%)	
99.4 ± 0.05	Sand
0.3 ± 0.05	Silt
0.3 ± 0.05	Clay
Sand	Texture grade

[a] Standard deviation.

2.1. Experimental setup

A drip irrigation system was installed to supply cucumber plants with water treatments; a groundwater with the following characteristics: pH 7.3; electrical conductivity 1088 ppm; sodium adsorption ratio 4.63 was used to irrigate the cucumber plants. The experimental layout was a split-plot design with three replicates with a total of 48 plots (Fig. 1). The experimental field was divided into three main plots (70, 85 and 100% of ET_c); each main plot was divided subsequently into fifteen sub-plots which randomly received the treatments of SiNPs (0, 100, 200, 300 and 400 mg kg^{-1}). Each experimental plot contained 8 plants with 50 cm spacing in a single row and each irrigation rate block consisted of 3 rows on 50 cm spacing. The length of drip tube was 25 m and the distance between drippers was 50 cm. The discharge rate of dripper was 4 L h^{-1}; every three irrigation pipelines, represented one level of watering regimes, were controlled by automatic valve through the main control panel to apply the required amount of water for each main plot. The main control panel was linked with a 1.5 hp (horse power) pump to maintain water pressure in the sub-lines.

2.2. Preparation and addition of silica nanoparticles suspensions

SiNPs were synthesized hydrophilic silica nanoparticles (Aerosil[300], Evonik Industries, Germany). Hydrophilic silica is a white powder of high purity amorphous silica which is moistened with water and can be dispersed in water. The physiochemical characteristics of the SiNPs were provided by the manufacturer and they were: specific surface area (270–330 $m^2\ g^{-1}$), mean diameter (10 nm) and pH (3.7–4.5). SiNPs suspensions were dispersed in deionized water using ultrasonic water bath (Elmasonic E60H, Germany) for 2 h at 45 °C. The added amounts of SiNPs suspensions were calculated for a column of soil (15 cm diameter × 15 cm length) based on bulk density 1.60 ± 0.1 g cm^3. To avoid the surface run off of SiNPs suspension during the application to the soil, we used a cylinder made of polyvinyl chloride (PVC) (15 cm diameter × 10 cm height) and SiNPs suspension was added slowly based on the soil saturation percentage 18.73 ± 0.1%. Furthermore, a round-shaped iron claw consists of 31 nails (15 cm in length) was used to perforate the soil to ensure homogeneous distribution of SiNPs suspensions in plant roots region.

2.3. Seed germination and growing of cucumber seedlings

The plant materials used in the current study were seeds of cucumber (*Cucumis sativus* var Beit Alpha) bought from Bonanza Seeds

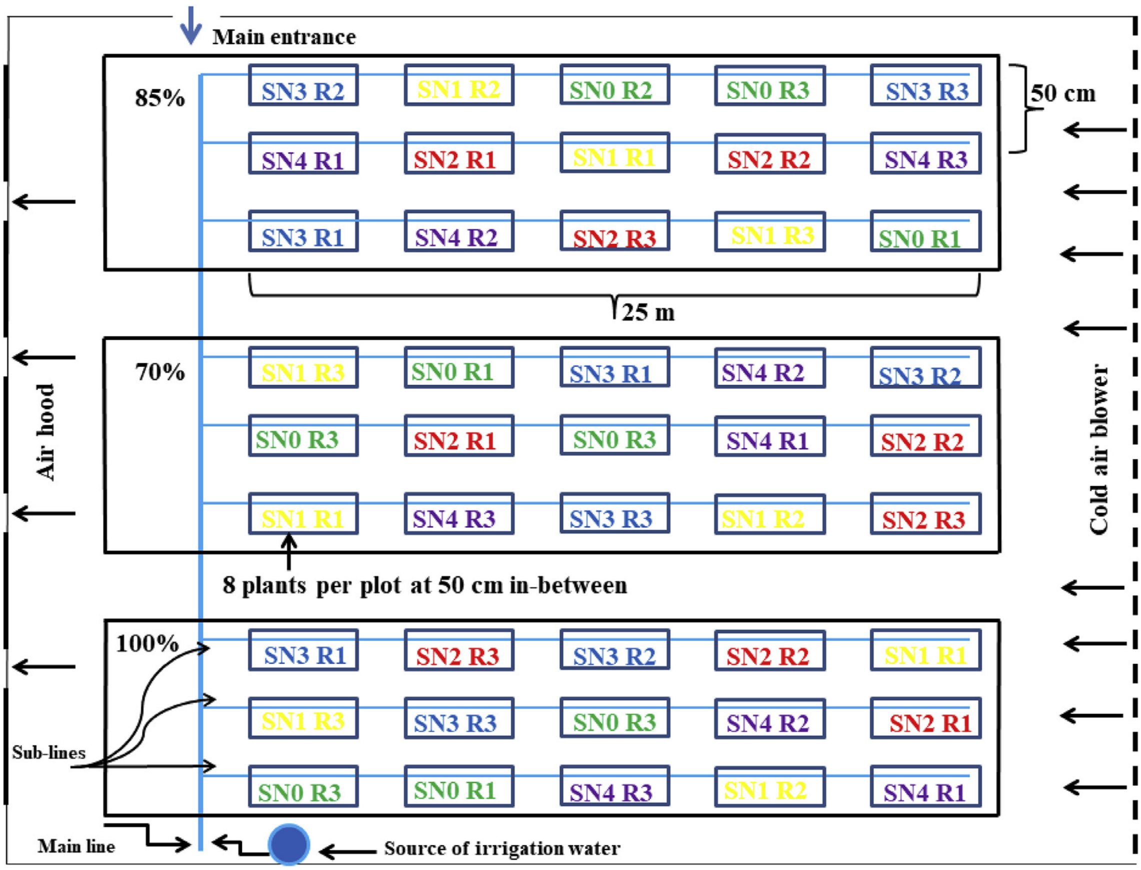

Fig. 1. A schematic diagram for experimental design shows distribution of silica nanoparticles (SiNPs) treatments (SN0 = 0 mg SiNPs kg^{-1}; SN1 = 100 mg SiNPs kg^{-1}; SN2 = 200 mg SiNPs kg^{-1}; SN3 = 300 mg SiNPs kg^{-1} and SN4 = 400 mg SiNPs kg^{-1}) and watering regimes (70, 85 and 100% of ET$_c$) using drip irrigation system.

International, Yuba City, California USA. On 30th March 2016, identical cucumber seedlings (2-leaf stage) were transferred to the experimental field. The mean daily temperature and relative humidity in greenhouse were 23 ± 2 C° and 65–75%, respectively. All agronomic practices such as fertilization and pest control were done. Flowering stage had been started on April 20th' 2016 and fruits harvest had been started on May 7th' 2016 until June 15th' 2016 (end of the experiment). Cucumber fruits were collected twice a week and fruit weight was determined.

2.4. Vegetative parameters

Height of aboveground part was measured from soil surface to shoot tip using metric measuring tape at harvest. Chlorophyll content (SPAD) and leaf area were measured after 5 weeks (May 9th' 2016) from transplantation of cucumber seedlings to the permanent field using Minolta SPAD 502 and Leaf area meter model LI-3000A, respectively; the measurements were done of the fourth mature leaf from shoot tip.

2.5. Preparation of plant samples

Plant samples were washed thoroughly by 0.1M HCl and deionized water to remove any adhered particles and thereafter they were let to air-dry at 23 ± 2 C°. Later, air dried samples were placed in forced-air oven (Binder Model ED115, Germany) at 60 C° for two days. Following that, dried samples were grounded using stainless steel blender and passed through a 60 mesh screen and finally they were stored in plastic bags for further analysis.

2.6. Determination of Na^+, K^+, and Si contents in plant samples

To measure Na^+, K^+ and Si contents in different parts of cucumber plants, 0.5 g ground plant sample was placed into a kjeldahl digestion tube and 5 mL of sulfuric acid (H_2SO_4, 95–97%, 1.84 kg L^{-1}, Merck) were added. Then tubes were placed on heater and temperature increased gradually by 5 C° min^{-1} to reach 170 C°, then digestion continued on this temperature for 2 h. Two mL of 30% H_2O_2 were added to samples after cooling for 30 min and then temperature increased again to 120 C° for additional 1 h until the digestion solution turned clear. Using ultra-pure water the volume of sample was brought to 50 mL in volumetric flask. According to Cottenie (1980), Na^+ and K^+ contents were determined using Atomic Absorption Spectrophotometer (AAS, PERKIN ELMER 3300) with a detection limit of 100 ppb. Si content was measured by spectrophotometer on 650 nm for development of blue color between 10 and 30 min as described by (Frantz et al., 2008) using standard curve as a reference.

2.7. Statistical analysis

Prior to the ANOVA test, Levene's Test for Equality of Variances was performed. The Levene test for different variables at ten treatments was negative, $p < 0.05$, and then the variances are homogeneous. The experimental design was established as a split-plot design with three replicates. Data analysis was performed using Microsoft Excel 2010 (mean values and standard deviation) from experiment. All data were analyzed statistically by the SPSS software package (Version 13). When a significant difference was observed between treatments, multiple comparisons were made by the Duncan's test. Significant differences were accepted at the level $p < 0.05$.

Table 2
Some vegetative parameters and nitrogen content of cucumber plants growing at different levels of silica nanoparticles (SiNPs) under different watering regimes.

Watering regimes[a]	SiNPs (mg kg^{-1})	Leaf area (cm^2)	Chlorophyll (SPAD)	Plant height (cm)	N%
100%	0	47.3 ± 6.7[b]f	23.3 ± 1.4 d	178.7 ± 12.2 bc	2.6 ± 0.02 j
	100	59.5 ± 7.9 e	30.7 ± 2.7 abc	186.3 ± 11.6 ab	3.2 ± 0.02 h
	200	105.1 ± 9.5 a	31.1 ± 0.9 abc	194.0 ± 6.0 a	4.0 ± 0.02 b
	300	70.5 ± 0.2 bcde	31.3 ± 2.9 abc	195.4 ± 1.1 a	3.7 ± 0.04 cd
	400	61.3 ± 1.1 de	30.1 ± 0.5 bc	172.5 ± 1.0 bcd	3.4 ± 0.01 f
85%	0	63.4 ± 3.5 de	22.3 ± 1.6 de	150.1 ± 13.7 f	3.1 ± 0.02 h
	100	66.3 ± 5.5 cde	31.4 ± 0.7 abc	163.6 ± 0.3 def	3.3 ± 0.04 g
	200	97.6 ± 3.9 a	33.6 ± 2.5 a	179.3 ± 6.9 b	4.3 ± 0.03 a
	300	77.4 ± 3.0 bc	32.4 ± 1.0 ab	184.0 ± 3.9 ab	3.9 ± 0.01 b
	400	71.7 ± 2.9 bcd	33.0 ± 0.5 ab	156.1 ± 4.7 ef	3.7 ± 0.01 d
70%	0	62.9 ± 0.6 de	20.1 ± 0.1 e	152.9 ± 4.8 ef	2.3 ± 0.04 k
	100	72.4 ± 10.1 bcd	28.9 ± 0.5 c	160.2 ± 9.8 def	2.8 ± 0.05 i
	200	81.7 ± 7.1 b	32.4 ± 2.5 ab	164.7 ± 6.1 cde	3.7 ± 0.04 c
	300	69.8 ± 11.9 cde	30.2 ± 2.6 bc	150.2 ± 6.7 f	3.5 ± 0.02 e
	400	67.2 ± 6.2 cde	29.9 ± 0.2 bc	154.3 ± 8.2 ef	3.2 ± 0.03 h

[a] Based on crop evapotranspiration (ET_c); 100, 85 and 70% of ET_c. Means in the same column followed by the same letter are not significantly different according to Duncan's test at $p < 0.05$.
[b] Standard deviation.

3. Results

3.1. Development of cucumber plants under different watering regimes in presence of SiNPs

Table 2 provides the results obtained from the measurement of leaf area (cm^2) of cucumber plants. Exposure cucumber plants to water deficit stress by irrigating plants at 85 and 70% of their ET_c resulted in larger leaf area compared to control plants (received 100% of their ET_c). Leaf area of fourth leaf from shoot tip significantly increased from 47.3 cm^2 at watering regime 100% of ET_c to 63.4 and 62.9 cm^2 at 85 and 70% of ET_c, respectively; but, differences between treatment of 85 and 70% were not statistically significant. Application of SiNPs at different levels (i.e., 100, 200, 300 and 400 mg kg^{-1}) resulted in a significant increase of leaf area regardless of watering regimes (Table 2). The larger leaf area corresponded to application of SiNPs at rate of 200 mg kg^{-1} in all watering regimes; however, the largest leaf area (105.1 cm^2) denoted to treatment of 200 mg SiNPs when plants received 100% of their ET_c.

In contrast to leaf area, chlorophyll content (SPAD) responded to the different watering regimes as Table 2 shows, where chlorophyll content decreased as cucumber plants irrigated by less than 100% of their ET_c. chlorophyll content diminished from 23.3 at treatment of 100% of ET_c to 22.3 and 20.1 when cucumber plants were irrigated by 85 and 70% of their ET_c, respectively. Differences were not significant for chlorophyll content between treatments of 100 and 85%; but were significant when plants were irrigated by 100 and 70% of their ET_c as Table 2 shows. The detrimental impacts of water deficit stress on chlorophyll content of cucumber were relieved by application SiNPs to cucumber at different rates. SiNPs, however, enhanced chlorophyll content of cucumber under all watering regimes compared to control plants (no application of SiNPs). Among watering regimes, the highest chlorophyll content was measured for plants irrigated at 85% of their ET_c. Treating cucumber at the rate of 200 mg SiNPs kg^{-1} significantly achieved the highest content of chlorophyll regardless of watering regimes.

In a similar way to chlorophyll content, length of aboveground part (plant height) measured from soil surface to shoot tip at beginning of harvest stage significantly linked to watering regimes, as it decreased when plants were exposed to water deficit stress (i.e., 15 and 30% reduction in ET_c). Plants irrigated by 100% of their ET_c had height of 178.7 cm compared to 150.1 and 152.9 cm when plants were let to grow at 85 and 70% of their ET_c, respectively, as can be seen in Table 2. All plants treated with SiNPs were taller than control plants (no SiNPs) regardless of watering regimes; however, the tallest plants were those irrigated by 100% of their ET_c and treated with either 200 or 300 mg SiNPs kg^{-1}.

What is interesting about data in Table 2 is that application of SiNPs, regardless of its concentration, improved nitrogen use efficiency as nitrogen content in plant tissues increased when cucumber plants were let to grow in presence of SiNPS under all watering regimes; however, the highest values of nitrogen content corresponded to watering regime of 85% of ET_c of cucumber plants. Although all SiNPs levels showed similar effects on nitrogen uptake by cucumber plants and consequently increased nitrogen content in plant tissues, the highest values of nitrogen content were corresponded to treatment of 200 mg SiNPs kg^{-1}.

3.2. Fruit yield of cucumber plants at different levels of SiNPs under different watering regimes

It can be seen from the data presented in Fig. 2 that irrigating cucumber plants with 15% less of water requirements (ET_c) slightly increased fruit yield, *without SiNPs addition*, compared to control plants which received 100% of their ET_c; while increasing water deficit stress to 30% of ET_c resulted in lower fruit yield. However, the differences due

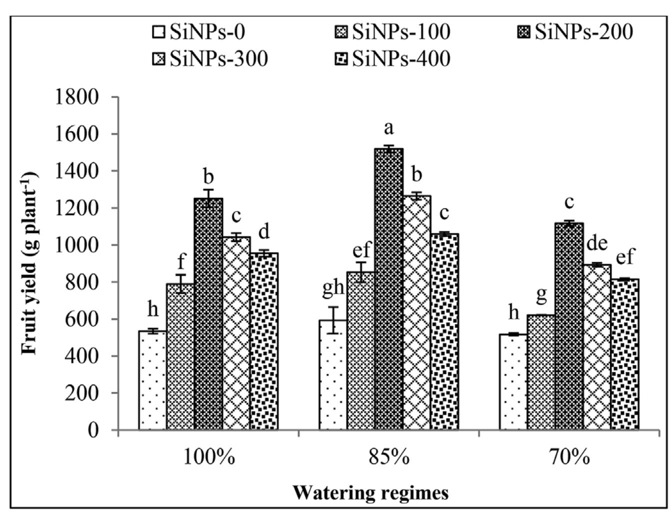

Fig. 2. Yield (g plant^{-1}) cucumber plants after growing under three watering regimes (100, 85 and 70% of ET_c) at five different levels of silicon nanoparticles (SiNPs) i.e., 0, 100, 200, 300 and 400 mg kg^{-1}. Different letters on columns show significant differences according to Duncan's test at $p < 0.05$.

to watering regimes were insignificant as clearly shown in Fig. 2; as the fruit yield ranged from 517 to 593 g plant^{-1}. Strikingly, application of SiNPs significantly enhanced the fruit yield of cucumber plants under all watering regimes (i.e., 70, 85 and 100% of ET_c) regardless of its concentrations. Treated plants with SiNPs produced higher fruit yield than control plants (no addition of SiNPs). Moreover, SiNPs mitigated the damaging impacts of water-deficit stress particularly at watering regime of 85% of ET_c recording higher fruit yield than those plants received 100% of their ET_c. At treatment of 200 mg SiNPs kg^{-1}, the fruit yield was 1251, 1519 and 1117 g plant^{-1} for 100, 85 and 70% of ET_c, respectively.

3.3. Silicon content in different plant tissues

All plant parts possessed the same tendency for silicon accumulation within plant tissues, as silicon content increased with reducing water requirements (increasing water-deficit stress) up to 15% of ET_c; while extreme reduction in water requirements (up to 30% of ET_c) caused significant reduction in silicon uptake and consequently lower accumulation of silicon in plant tissues. Regarding watering regimes, the silicon content is well described as follow: 85% > 100% > 70%. Silicon content in different plant parts of cucumber responded regularly to application of SiNPs, where silicon content increased as application rate of SiNPs increased up to 200 mg kg^{-1}; however, the higher SiNPs concentrations corresponded with lower silicon content in cucumber tissues. However, these values are still higher than those reported for control plants (no addition of SiNPs). Distribution of silicon within the different plant tissues (root, stem, leaf and fruit) is best described as stem > leaf > root > fruit. A very low concentration of silicon was detected in fruit, *the edible part*, regardless of either watering regimes or SiNPs doses (Fig. 3). The highest silicon content measured among all treatments was 0.89% when cucumber plants were irrigated by 85% of their ET_c were treated at 200 mg SiNPs kg^{-1}.

3.4. Sodium content in different plant tissues

Regarding watering regimes, reducing the amount of irrigation water by 15% (85% of ET_c) resulted in the lowest sodium content (%) in all plant parts root (0.65), stem (0.13) and leaf (0.53) when cucumber grew in absence of SiNPs (Fig. 4); increasing water-deficit stress by 30% of ET_c recorded the highest sodium content. In contrast to silicon, sodium content decreased with increasing SiNPs concentration up to 200 mg kg^{-1} then started to increase at higher SiNPs concentration. Nevertheless, the highest sodium content corresponded to cucumber plants grown without SiNPs addition (control) regardless of watering regime. Application SiNPs at rate of 200 mg kg^{-1} significantly reduced the accumulation of sodium in all plant parts regardless of watering regime. Root system, however, had the highest sodium content compared to stem and leaf under all watering regimes with/without application of SiNPs. The accumulation of sodium in different plant parts was in consistency with the following order: root > leaf > stem. It could be concluded that root, stem and leaf of cucumber plants showed similar response towards watering regimes and application of SiNPs (Fig. 4).

3.5. Potassium content in different plant tissues

Fig. 5 displays potassium content in different plant parts (root, stem and leaf) of cucumber plants at the beginning of harvest stage. What stands out in this graph is the high rate of potassium accumulation in all parts of cucumber plants irrigated by 85% of their ET_c compared to 100% ET_c; the lowest potassium content, however, was detected in

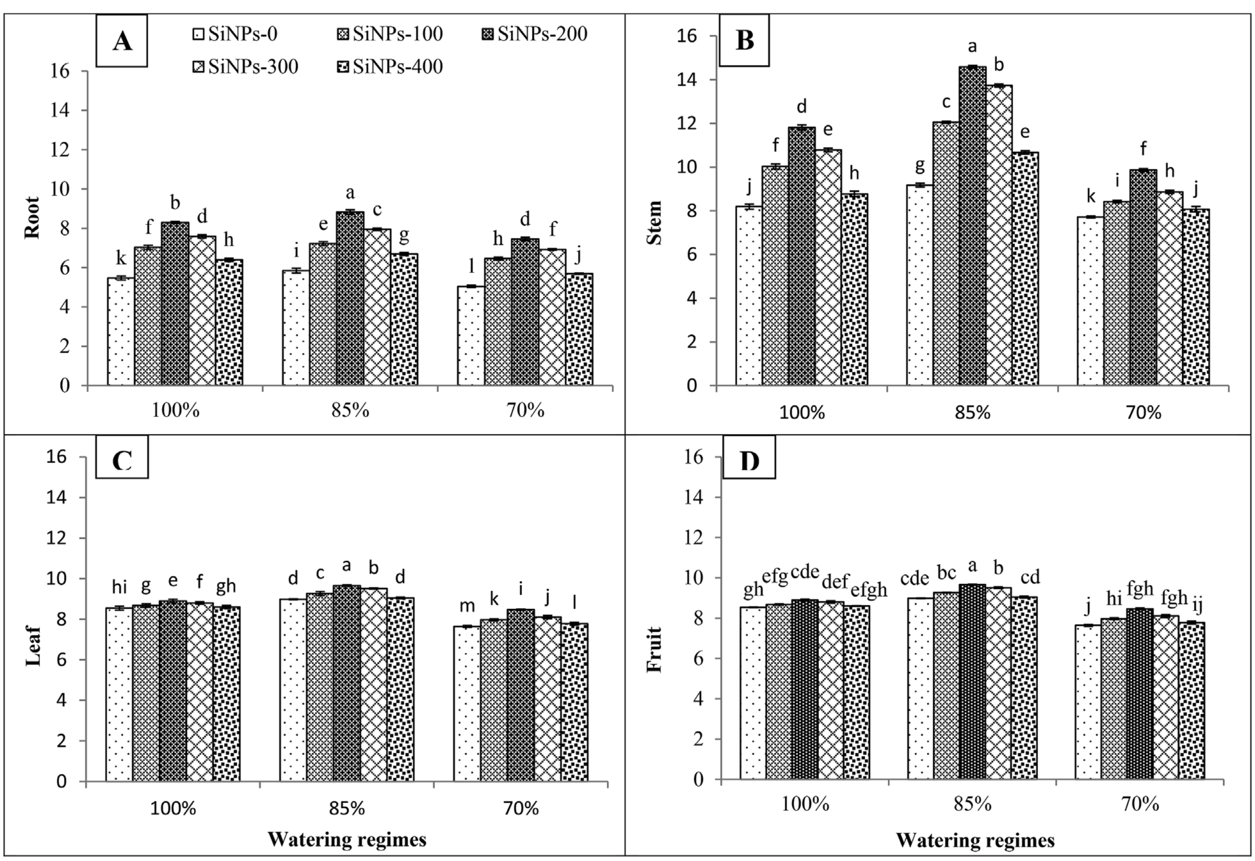

Fig. 3. Silicon content (%) in different plant parts of cucumber (A) root; (B) stem; (C) leaf and (D) fruit at harvest after growing under three watering regimes (100, 85 and 70% of ET_c) at five different levels of silicon nanoparticles (SiNPs) i.e., 0, 100, 200, 300 and 400 mg kg^{-1}. Different letters on columns show significant differences according to Duncan's test at $p < 0.05$.

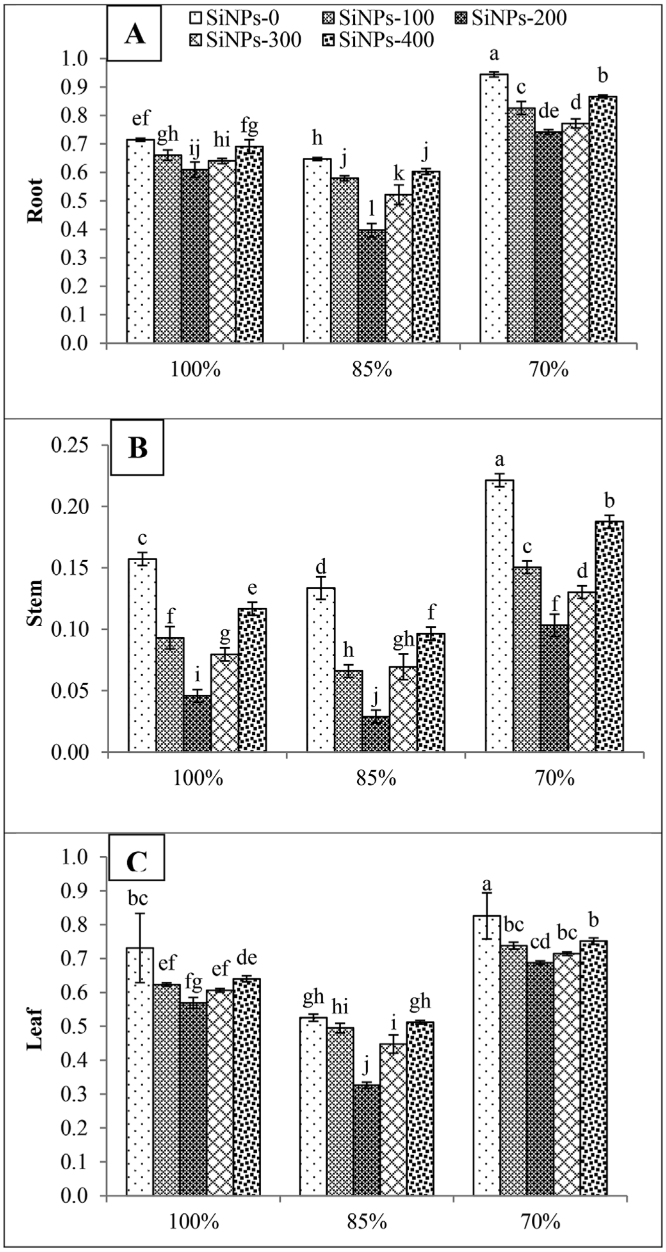

Fig. 4. Sodium content (%) in different plant parts of cucumber (A) root; (B) stem and (C) leaf at harvest after growing under three watering regimes (100, 85 and 70% of ET_c) at five different levels of silicon nanoparticles (SiNPs) i.e., 0, 100, 200, 300 and 400 mg kg^{-1}. Different letters on columns show significant differences according to Duncan's test at $p < 0.05$.

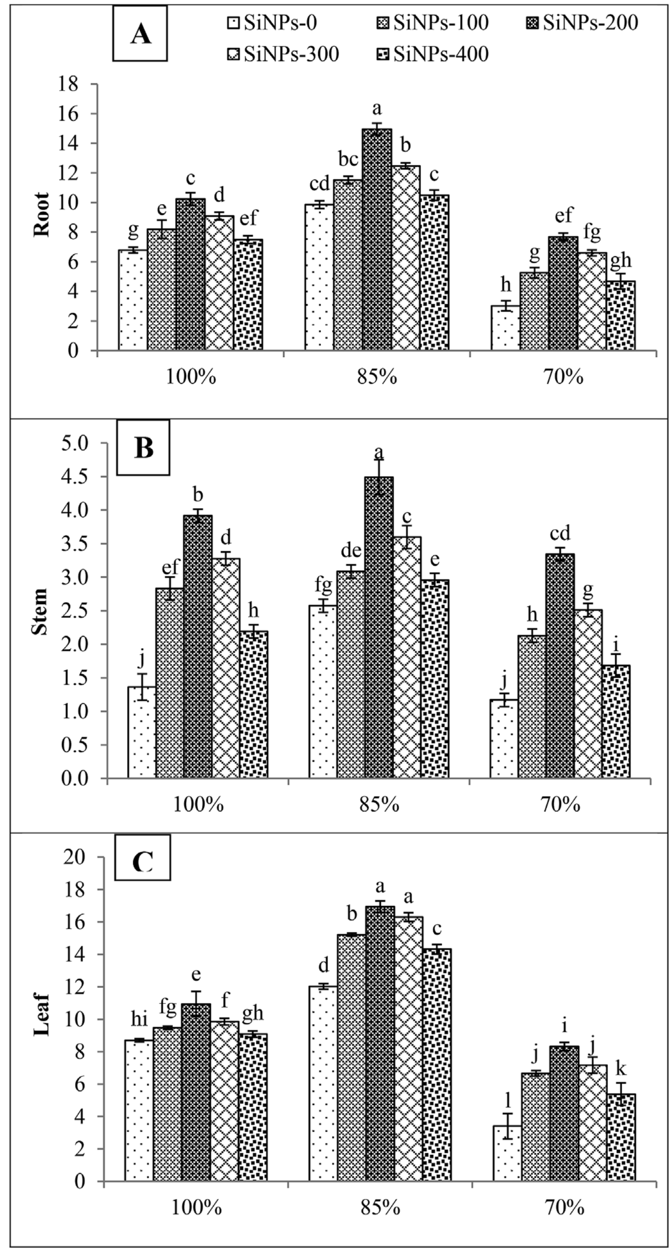

Fig. 5. Potassium content (%) in different plant parts of cucumber (A) root; (B) stem and (C) leaf at harvest after growing under three watering regimes (100, 85 and 70% of ET_c) at five different levels of silicon nanoparticles (SiNPs) i.e., 0, 100, 200, 300 and 400 mg kg^{-1}. Different letters on columns show significant differences according to Duncan's test at $p < 0.05$.

plants received 70% of their ET_c during the growing season. Among separate plant parts, stem possessed the lowest potassium content, while the highest content was corresponded to leaf part (Fig. 5). For instance, at watering regime of 85% (without SiNPs addition) potassium content was 2.57, 9.85 and 12.02% for stem, root and leaf, respectively. From the data presented in Fig. 5, we can see that application of SiNPs at rate of 200 mg kg^{-1} resulted in the highest potassium content in all separate plant tissues regardless of watering regimes; however, strong evidence of applying SiNPs was found when cucumber plants were irrigated by 85% of their ET_c. following the addition of SiNPs, a significant increase ($p < 0.05$) in the potassium uptake and accumulation in different tissues of cucumber plants was recorded. The application of SiNPs to cucumber plants under different watering regimes considerably improved potassium uptake; however, increasing concentration of SiNPs above 200 mg kg^{-1} gradually decreased potassium content in cucumber plants. Nevertheless, potassium content in plant tissues at the highest applied SiNPs concentration is still higher than those measured in control plants (no addition of SiNPs).

3.6. Potassium-sodium ratio in cucumber plants

The results of potassium-sodium ratio (K/Na) in different parts of cucumber plants, as shown in Fig. 6, indicate that watering regimes significantly affected the growth dynamic of cucumber plants through alerting nutrients uptake and accumulation within plants tissues. The highest K/Na was interrelated to watering regime of 85% ET_c, while reducing amount of irrigation water by 30% recorded the lowest K/Na. In absence of SiNPs, K/Na increased from 9.5 to 15.2 (in root system),

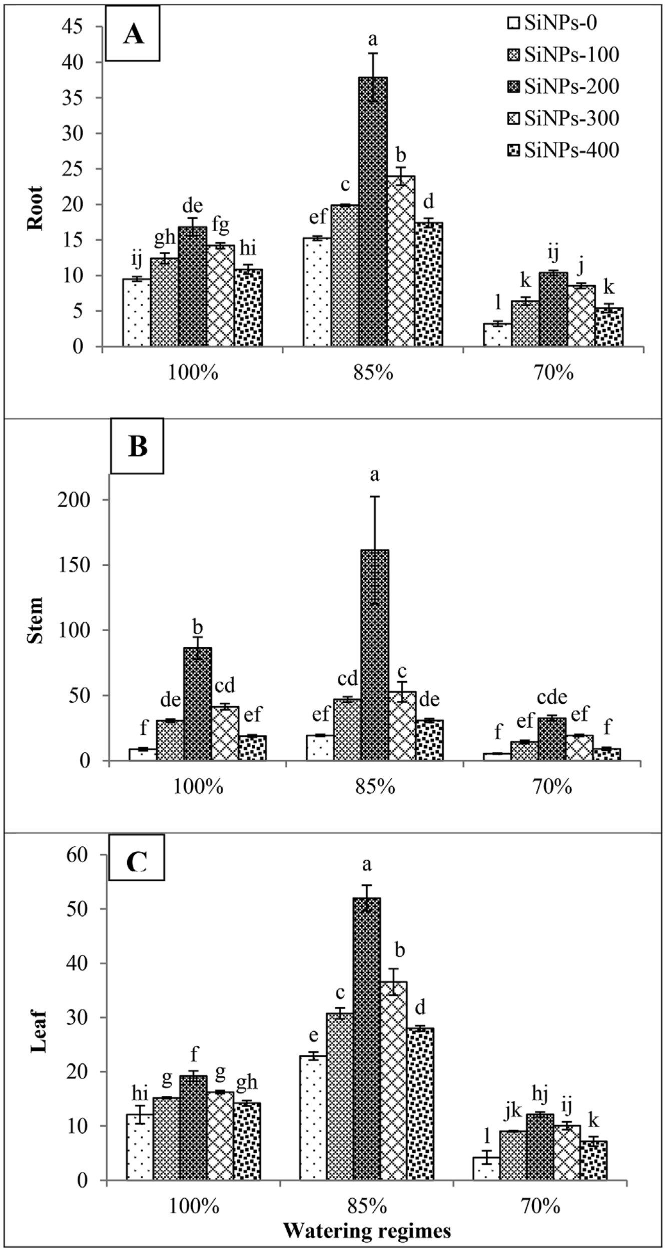

Fig. 6. Potassium-sodium ratio (K/Na) in different plant parts of cucumber (A) root; (B) stem and (C) leaf at harvest after growing under three watering regimes (100, 85 and 70% of ET_c) at five different levels of silicon nanoparticles (SiNPs) i.e., 0, 100, 200, 300 and 400 mg kg^{-1}. Different letters on columns show significant differences according to Duncan's test at $p < 0.05$.

from 8.6 to 19.3 (in stem) and from 12.1 to 22.9 (in leaf) at watering regimes of 100 and 85% of ET_c, respectively; lower values, however, were measured at watering regime of 70%. Surprisingly, all doses of SiNPs, regardless of watering regime, significantly resulted in higher values of K/Na; nevertheless, the highest values of K/Na were noticed when plants were treated with SiNPs at rate of 200 mg kg^{-1}. The most striking results to emerge from this data is that K/Na recorded in different plant parts was in consistent with Si content (stem > leaf > root), while it was in contrast to Na content (root > leaf > stem).

4. Discussion

In the future, a sharp shortage in productivity of irrigated crops (particularly in arid and semi-arid regions) is surely expected due to water scarcity. Consequently, there is a pressing need to improve the water use efficiency by crops to overcome insufficient water supply as well as climate change impacts that are expected to increase the stress on water resources particularly in the Mediterranean basin (Jacobsen et al., 2012).

Alongside optimizing biochemical processes inside plant cells, supply crops with their proper water requirements especially at the critical growth stages enhances nutrients uptake. Otherwise, exposition crops to different degrees of water deficit and/or salinity stresses alters plant growth and yield by changing many growth characteristics such as root/shoot ratio, leaf area, number of leaves and chlorophyll content; in addition to malmetabolism caused by malnutrition (Saif et al., 2003).

Cucumber plants are considered as a water sensitive plant, therefore adequate irrigation water is crucial as water deficiency causes the fall of flowers and fruits (Hashem et al., 2011; Zhang et al., 2011), so fruit yield will be decreased (Sahin et al., 2015). Silicon, applied to the soil in the form of engineered nanoparticles (SiNPs), clearly improved the growth of cucumber plants under all studied watering regimes (i.e., 70, 85 and 100% of ET_c). Moreover, SiNPS significantly enhanced the development of cucumber plants under water deficit stress especially at 85% of ET_c compared to control (100% of ET_c). Treated plants with SiNPS possessed largest leaf area, highest chlorophyll content, tallest plants and highest nitrogen content compared to untreated ones. However, applying SiNPs at the rate of 200 mg kg^{-1} showed the greatest influence among the other SiNPs treatments. This is in accordance with previous studies reported that silicon enhanced the dry mass of cucumber (Alsaeedi et al., 2018), common bean (Alsaeedi et al., 2017a and 2017b), maize (Kaya et al., 2006), wheat (Gong et al., 2003) and soybean (Hamayun et al., 2010). The promotional effect of silicon on plant growth is clearly documented for both monocots (Mehrabanjoubani et al., 2015) and dicots (Li et al., 1989). Furthermore, application of silicon, as SiO_2, significantly increased growth characteristics of rice plants treated at the rate of 100–400 kg ha^{-1}; however, the increase of plant height was not statistically significant (Cuong et al., 2017). Similar responses of rice to silicon addition were reported by Pati et al. (2016). The detrimental impacts of water deficit and salinity stresses on plant growth are due to fast generation of oxidants (free radicals and reactive oxygen species) which cause oxidation of biomolecules mainly proteins resulting in diminished vegetative growth (Ennajeh et al., 2009). In our study silicon showed great capability to induce the growth of cucumber plants under such a biotic stress. However, this positive effect of SiNPs on cucumber plants grew under water-deficit and salinity stresses could be attributed to mitigating the oxidative stress by improving the antioxidant capacity and increase nutrients content in cucumber shoot. Jafari et al. (2012) reported that silicon (added as silicon or salicylic acid) reduced levels of lipid peroxidation, H_2O_2, ion leakage and proline in cucumber plants under osmotic stress. Also, they found silicon enhanced antioxidant capacity of cucumber plants by increase non-enzymatic antioxidants, total phenolic compounds, anthocyanins, flavonoids, and Si, K^+, Ca^{2+} content in shoot as well as phenylalanine ammonia lyase activity.

Low level of silicon (1 g kg^{-1}, added as SiO_2) clearly improved biomass production of wheat plants compared to control; however, higher silicon concentration gradually decreased biomass production of shoot part. On the other hand, grain yield significantly increased at the rate of 10 g SiO_2 kg^{-1} (Neu et al., 2017). Similarly, rice grain yield significantly increased when silicon was applied at the rate of 100–400 kg ha^{-1} (Cuong et al., 2017). In our study, fruit yield of cucumber was higher for lower silicon doses (200 mg kg^{-1}), while higher levels of silicon diminished the fruit yield. Alongside enhancing nutrient use efficiency, silicon also increases the photosynthesis rate through modifying the position and orientation of plant leaves due to precipitation of silicon in cell wall which makes leaves more erect and subsequent improves light interception characteristics (Inanaga et al., 1995). This, of course, will subsequently lead to better plant growth and higher yield.

In general, treating wheat plants with silicon (added as silica nanoparticles) was found to enhance the nutrient use efficiency at whole-plant level (Neu et al., 2017). The most interesting aspect in the current study is that silicon content does not linearly respond to application of SiNPs; silicon content in all plant parts was found to increase as concentration of SiNPs increases up to 200 mg kg^{-1} then regularly decreased with increasing SiNPs concentrations (Fig. 3). This phenomenon could be explained by findings of Mitani and Ma (2005) who cited that increasing silicon content in growth medium resulted in an increase of silicon concentration in the root-cell symplast of rice, cucumber and tomato plants; however, no linear increase was confirm since a saturation state was attended. Silicon, improved nutrient uptake by wheat plants specially nitrogen and phosphorus as well as played an important role in carbon cycle by alerting the carbon transformation when applied at the rate of 1–50 g kg^{-1} as cited by Neu et al. (2017). However, they confirmed silicon did not significantly influence the plant nitrogen content except leaf tissues. Moreover, the highest silicon supply (50 g kg^{-1}) reduced nitrogen content in flag leaf blade, while applying silicon at the rate of 1 and 10 g kg^{-1} increased nitrogen content in subjacent leaf sheaths. The synergetic effect of silicon on phosphorus bioavailability in soil solution is due to competition between silicon and phosphorus for binding sites on soil complexes and subsequent increase phosphorus uptake by plants (Seyfferth and Fendorf, 2012). These results were in accordance with those reported by Cuong et al. (2017) for nitrogen, phosphorus and potassium. Many studies have been reported that silicon enhances uptake of many nutrients such as nitrogen (Singh et al., 2005), phosphorus (Subramanian and Gopalswamy, 1991), potassium (Singh et al., 2005; Pati et al., 2016), iron (Mali and Aery, 2009) and zinc (Curie and Briat, 2003).

Greger et al. (2018) reported that silicon not only affected the availability and uptake of nutrients but also the translocation of nutrients from root to shoot was affected. Interestingly, they found silicon increased the translocation of Mg into shoot part improving photosynthesis rate since Mg is the main element in the structure of chlorophyll.

Many reports have been pointed out that uptake and accumulation of potassium in plant tissues is strongly corresponded to supply plants with silicon at different rates. For instance, applying silicon, particularly under salinity stress, increased potassium uptake by cucumber (Hasanuzzaman et al., 2018; Alsaeedi et al., 2018), sugarcane (Ashraf, 2009), tomato (Al-Aghabary et al., 2004) and barley (Liang et al., 2006). This could be explained as silicon increases the activity of H^+-ATPase located in plasma membrane which increases cellular uptake of potassium through creating electrochemical gradients in the plasma membrane which activates K^+ channels and carriers across the plasma membrane (Liang et al., 2006).

In our recent study potassium accumulation in shoot part of cucumber plants was higher than in root system. These results were in harmony with those reported by Greger et al. (2018). This reveals that silicon may be actively affect the translocation of potassium in shoot part especially leaves. However, this phenomenon is strongly related to plant species as high silicon plant-accumulators were found to uptake more potassium than those take up silicon at low rate (Miyake, 1993).

In the current study, growth development and productivity of cucumber were negatively affected by diminishing quantities of water requirements; however, SiNPs application mitigated the adverse effects of water deficit through alleviating the plant water balance in cucumber plants as found before in many plant crops such as cucumber (Hasanuzzaman et al., 2018; Jafari et al., 2012), sorghum (Kafi et al., 2011), cotton and canola (Mehrabanjoubani et al., 2015) and tomato (Romero-Aranda et al., 2006) particularly under both salt and drought stresses. However, the principle mechanism is still uncertain although there are many mechanisms proposed. Silicon can mediate the plant water status via enhancing water uptake and/or reducing water loss through leaf transpiration (Chen et al., 2018). The proposed mechanisms for the enhancement of water uptake by silicon-treated plants are: i) silicon improves the activity of aquaporin in cell membrane by up-regulation of aquaporin genes in addition to scavenging the reactive oxygen species which inhibit the activity of aquaporin; ii) silicon increases osmosis of root xylem sap through increase the accumulation of osmoregulators such as soluble sugars, amino acids and/or potassium and iii) silicon increases root/shoot ratio due to inducing root growth (Chen et al., 2018; Kafi et al. (2011). Whereas, suppression water loss as a result for silicon application is proved by existence of a precipitated well-thickened layer of silicon in the epidermal cell walls in form of amorphous silica (phytoliths) (Ma, 2004) in addition to enhance stomatal conductance which modifies transpiration rate (Chen et al., 2016). Increase water uptake and/or reduce water loss via silicon application maintains a high relative water content in plant tissues leading to high rate of photosynthesis and enhance plant growth under water deficit stress.

Many higher plants take up silicon, mainly as silicic acid, in a significant amount via either active or passive transportation (Epstein, 2009). Moreover, graminaceous plants such as wheat were shown to translocate 90% of absorbed silicon in their aerial parts (Jarvis, 1987); and in leaves it is deposited as phytoliths due to water loss via transpiration (Ma and Yamaji, 2006). Neu et al. (2017) reported that silicon was precipitated in the form of phytoliths in leaf blades of old leaves of wheat plants treated with silica nanoparticles at the rate of 10 and 50 g kg^{-1}. Moreover, they found that silicon is more deposited in old leaves of wheat plants than younger ones. Interestingly, they cited that flag leaf blade had higher silicon content than subjacent leaf blades; this could be attributed to higher water loss via transpiration due to higher exposure to sunlight and wind (Duda et al., 2001).

Despite silicon is the first element in the Earth's crust after oxygen, the application of silicon to plant crops is really crucial for better plant growth due to many factors (Tubana et al., 2016). First, most silicon forms in soil are insoluble and unavailable, second, silicon in soil solution is maintained at very low concentration, third, dense agricultural systems remove annually significant amounts of silicon (between 210 and 240 million tons annually) (Meunier et al., 2008).

Many mechanisms have been proposed explaining the substantial effect of Si on development of plant crops regardless of growth conditions: i) increase phytohormones (i.e., GA1 and GA4) production (Hamayun et al., 2010); ii) maintain high relative water content (Jafari et al., 2012); iii) promote cell elongation and cell wall extensibility (Hossain et al., 2002); iv) improve nutrients uptake and alerting potassium sodium ratio (Alsaeedi et al., 2018; Neu et al., 2017); v) increase the activity of antioxidant enzymes (Gong et al., 2003); vi) maintain membrane integrity through reducing the permeability of plasma membrane of leaf cell (Liang et al., 2006) and vii) enhance the ultrastructure of chloroplast (Liang, 1998).

5. Conclusion

The present work aimed at assessment of potential role of engineered amorphous silica nanoparticles (SiNPs) to mitigate the deleterious impacts of water deficit stress and salinity using cucumber plants as a model. Results derived from field experiment under greenhouse conditions showed that SiNPs helped cucumber plants to grow normally without any obvious symptoms of irrigating water shortage (85% of cucumber ET_c) during the whole growing season. However, fruit yield per plant was the highest at treatment of 85% of ET_c compared to plants irrigated with full (100%) ET_c. Applying SiNPs at rate of 200 mg kg^{-1} had the highest positive effect on vegetative and yield characteristics of cucumber resulting in the highest recorded increase compared to plants treated with lower or even higher levels of SiNPs. This interesting result could be attributed to the significant role that SiNPs played balancing nutrients uptake beside increase water use efficiency. Results revealed that SiNPs increased uptake of nitrogen, potassium and silicon in all plant tissues; while sodium uptake was diminished in root, stem and leaf parts of cucumber. The recent research highlights and illustrates that SiNPs could be exploit to improve crop productivity under shortage water supply as a possible solution for water scarcity.

Author contributions

Abdullah Alsaeedi Hassan El-Ramady and Tarek Alshaal designed the study. Abdullah Alsaeedi, Mohamed El-Garawany and Awadh Al-Otaibi performed experiments and con-analysisanalyzed data. Abdullah Alsaeedi and Nevien Elhawat wrote initial con-draftdrafts of the manuscript. Nevien Elhawat performed the statistical con-analysisanalysis. Tarek Alshaal and Hassan El-Ramady wrote the final version of the manuscript.

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