The Scientific Journal of King Faisal University

Basic and Applied Sciences

# The Role of Nanosilica in Ameliorating the Deleterious Effect of Salinity Shock on Cucumber Growth

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| LINK | RECEIVED | ACCEPTED | PUBLISHED ONLINE | ASSIGNED TO AN ISSUE |
|---|---|---|---|---|
| https://doi.org/10.37575/b/agr/230026 | 03/04/2023 | 12/05/2023 | 12/05/2023 | 01/06/2023 |
| **NO. OF WORDS** | **NO. OF PAGES** | **YEAR** | **VOLUME** | **ISSUE** |
| 8160 | 9 | 2023 | 24 | 1 |

## ABSTRACT

A greenhouse experiment was conducted to study the influence of the application of four concentrations of silica nanoparticles (NSi) in mitigating the negative effect of salinity shock on cucumber (Cucumis sativus L.). Seedlings were sprayed with NSi (0, 100, 200, and 300 ppm) as the NSi treatment, and the plants were subjected to either no salinity shock (NSCh) or salinity shock (WSCh) 3250 ppm for two days. Yield and vegetative parameters, K+, Na+, K/Na ratio, Si, and proline contents were measured. The NSi treatments prevented the harmful effects of salinity on yield, with a reduction of 9.19% for plants treated with NSi3 under WSCh compared with NSCh. Salinity shock caused an accumulation of proline in the roots and other plant parts as a method of protection. The NSi2 and NSi3 treatments under WSCh prevented the accumulation of Na+, leading to an increase in the K/Na ratio. The Si contents in the roots, leaves, and fruits increased with increased NSi. The results of the interaction treatments showed a significant effect on all traits except for plant length, leaf area, chlorophyll, and root potassium content.

**KEYWORDS**

Cucumber, nanosilica particles, salinity shock, silicon, proline, K/Na ratio

**CITATION**

Al Saeedi, A.H. and Alameer, S.J. (2023). The role of nanosilica in ameliorating the deleterious effect of salinity shock on cucumber growth. *The Scientific Journal of King Faisal University: Basic and Applied Sciences*, **24**(1), 21–9. DOI: 10.37575/b/agr/230026

## 1. Introduction

As an arid and semiarid region, Saudi Arabia is characterized by scarce arable water sources. Saudi Arabia primarily relies on groundwater wells for irrigation.

In agricultural production, abiotic shocks can occur suddenly and without warning. They last for a short period, affecting the optimum growth conditions for plants, causing changes in their metabolism, and leading to harmful effects ranging from minor effects to plant death (Shahbaz and Ashraf, 2013).

Increased soil salinity affects plant production as it leads to changes in plant physiological processes and biochemistry (Singh *et al.*, 2014). Salt stress causes cellular function changes, ion toxicity, and the production of toxic oxygen derivatives, which damage plant cells (Nounjan *et al.*, 2014) and substantially decrease crop yield (dos Santos *et al.*, 2022).

Plants resist these environmental stresses by using processes to modify the accumulation of ions and by creating osmotic substances such as proline to help the plants complete their life cycles (dos Santos *et al.*, 2022). Proline modifies the osmotic properties of a plant, which helps protect the plant against the effects of salinity and drought stresses (Chun *et al.*, 2018). With increasing salinity stress, plants increase proline production in their internal tissues. Proline, more than other amino acids, accumulates in plant tissues when exposed to salinity or drought stresses (Heidari *et al.*, 2011). Proline protects cell membranes by modifying osmotic adjustment, stabilizing and accumulating more of the different enzymes required for the metabolic machinery (Hosseinifard *et al.*, 2022).

Salinity harms crop production, inhibiting the metabolic reactions in photosynthesis (Hameed *et al.*, 2021). Plants tolerate salt stresses by reducing their Na+ and Cl- absorption and the transportation of these ions to the leaves; accordingly, the K/Na ratio increases (Ran *et al.*, 2022). Salt stress increases the production of reactive oxygen species (ROS), namely, $H_2O_2$, $O^{-2}$, and $OH^{-}$, which cause damage to DNA, RNA, and proteins (Ali *et al.*, 2014; Ransy *et al.*, 2020). Plants strengthen their resistance to salinity by decreasing their salt content, accumulating ions, adjusting their osmotic pressure, and stimulating antioxidant enzymes (Arif *et al.*, 2020). The presence of salts in the plant environment leads to the presence of several other problems related to plant nutrition, including the effectiveness of enzymes, the absorption of water and nutrients, and interactions between morphology and physiological and biochemical processes (Akbarimoghaddam *et al.*, 2011; Arif *et al.*, 2020). Excessive sodium accumulation in the cell wall can quickly lead to osmotic stress and cell death (Zhao *et al.*, 2020). The ion imbalance and toxicity that occur in plants under salt stress are attributed to the replacement of potassium with sodium ions (Yao *et al.*, 2021). The ability of plants to maintain high levels of potassium is their most important mechanism in terms of salt tolerance (Yao *et al.*, 2021). The effect of salinity on a plant depends on the intensity of the stress, the time of occurrence, the duration of the exposure to the stress, and the stage of plant growth (Çiçek *et al.*, 2018; El Sabagh *et al.*, 2021).

The presence of Na+ and Cl− leads to certain protein changes. In many enzymes, potassium (K+) acts as a catalyst and cannot be replaced with sodium (Na+) to play the same role as K+. A high potassium concentration is necessary because of its association with RNA, especially in ribosomes, and, thus, protein synthesis. Ion toxicity and osmotic stress cause osmotic imbalance, which in turn leads to oxidation (Chinnusamy *et al.*, 2006).

Salinity mainly affects photosynthesis by reducing the leaf area and chlorophyll content, and by affecting stomatal behavior (Netondo *et al.*, 2004). Salt stress causes a substantial decrease in the wet and dry weights of leaves, stems, and roots. Approximately 80% of the decline in plant growth due to salt stress is caused by a decrease in the effective green leafy surface area, which is used for photosynthesis, thereby negatively affecting the amount of energy absorbed (Chaerle *et al.*, 2005). Increases in the salinity of irrigation water lead to a decrease in the leaf contents of nitrogen (N) and potassium (K), an increase in the sodium content, a decrease in the leaf chlorophyll content, and the inhibition of photosynthesis.

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Silicon is present in the soil in high quantities, but the quantity available to plants is low. Silicon plays an important role in protecting plants from diseases, pests, drought, salinity, and heavy metal toxicity as well as restoring the balance of the elements in the plants (Alsaeedi *et al.*, 2018). Silicon is an essential element of cell walls, increasing their solidity (Głazowska *et al.*, 2018). Silicon plays an effective role in photosynthesis by increasing the contents of chlorophyll a and b, the photosynthetic rate, and stomatal behavior, and decreasing the transpiration rate, which increases photosynthetic efficiency and the accumulation of silicon in the epidermal cells. Silicon positively affects the plant area (Sayed *et al.*, 2022). Silicon works to relieve the effects of abiotic stresses such as saline stress, mineral toxicity, dehydration, radiation, nutrient imbalance, overheating, and cold. Silicon can mitigate the effects of biotic and abiotic stresses in many crops and beneficially affects plants under unstable conditions (Shoman and Bughdady, 2020). Moreover, the Si–enzyme compound that acts as a protective regulator of photosynthesis and affects other enzymatic activities requires silicon (Toresano *et al.*, 2012). The application of silicon to Vicia faba beans by spraying increased the chlorophyll and carotene contents, pod yield, and the number of seeds in each plant under normal and salty conditions (Shoman and Bughdady, 2020).

Nanosilica particles, when applied to cucumber seedlings, have been reported to increase the yield and other growth parameters. These increases may have been due to increases in nutrient uptake, as the nanosilica particles increased the contents of nitrogen and potassium in the roots, stems, and leaves, as well as the content of silicon in the roots, stems, leaves, and fruit (Alsaeedi *et al.*, 2019). The positive function of nanosilica particles in reducing the damage caused by salinity and drought stress may be due to the high $Si^{+4}$ content in the leaves, which regulates water losses via transpiration. In addition, a high $K^+$ content in the roots of cucumber helps these plants to tolerate abiotic stresses by maintaining ion homeostasis, regulating osmotic balance, and controlling stomatal opening, which helps plants to adapt to salinity and water deficit stress. To overcome these unfavorable environmental conditions, plants have developed various protective mechanisms to maintain normal cellular metabolism and to prevent the infection of cellular components, including the accumulation of ions and osmolytes such as proline, changing the potassium/sodium ratio, and increasing the proportion of potassium. This was found by Alsaeedi *et al.* (2017) in their study of the role of nanosilica in reducing the effect of sodium stress on the growth of the common bean (Phaseolus vulgaris) plant.

Cucumber (Cucumis sativus L.) is a popular vegetable in many countries. Cucumber belongs to the Cucurbitaceae family, which contains 118 genera and 825 species (FAO, 2002). It is a major crop grown in greenhouses throughout the Kingdom of Saudi Arabia. According to statistics, in 2018, 2420 hectares of greenhouses produced 43,717 tons of cucumbers in Saudi Arabia (Ministry of Environment, 2021).

The aim of this experiment was to study the effect of different concentrations of nanosilica, which was sprayed on planted cucumber seedlings in a greenhouse, on the ability of cucumber to resist salinity shock. Additionally, the $Na^+$, $K^+$, $Si^{+4}$, and proline concentrations in the cucumber leaves were analyzed, and the K/Na ratio was calculated. The yield, chlorophyll content, plant height, and surface area of the fourth leaf were also recorded.

## 2. Material and Methods

### 2.1. Experimental Design:

This experiment was conducted in a greenhouse and used a split plot with a randomized complete block design with three replicates, where the shock treatments (with and without salinity shock: NSCh and WSCh, respectively) were the main and submain plots, treated with four concentrations of nanosilica (NSi, 0, 100, 200 and 300 ppm). Cucumber seeds (Parthenocarpic Goal F1 species) were presoaked in one of the nanosilica concentrations for 3 h. The seeds were cultivated in plastic pots filled with potting soil and watered to saturation. When the seedling growth was complete (a length of 15 cm was reached), the nanosilica treatments were sprayed on all plants. Salinity shock treatment was then applied to 12 experimental units, after the plants reached a length of 30 cm, by irrigating the plants with salty water obtained from an artesian well with a salt concentration of 3520 parts per million (ppm) for 48 h (at a rate of 4 L $h^{-1}$ for 15 min $day^{-1}$). The rest of the experimental units were left as a control treatment (12 plot units) without salinity shock and were irrigated at the same concentration as normal irrigation water (total soluble salt = 768 ppm).

### 2.2. Preparation of Nanosilica Concentration:

Amorphous hydrophilic nanosilica manufactured by the AEROSIL company was used as a source of nanosilica. The physical specifications of the nanosilica were as follows: specific surface area 270–330 $m^2$ $g^{-1}$, pH 3.7–4.5, loss when drying ≤ 1.5%, density 50 g $L^{-1}$ (0.05 g $cm^{-3}$), and $SiO_2$ content higher than 99.8%. Various concentrations were used to create the nanosilica suspensions, 0 (NSi0), 100 (NSi1), 200 (NSi2), and 300 (NSi3) mg $kg^{-1}$ soil, by directly mixing a specific weight of nanosilica with distilled water into a 50 gallons plastic drum (1 gallon = 4.54 L). Potground H potting soil was used as the growth medium (Klasman Delman, Germany).

### 2.3. The Soil Preparation for Planting:

The greenhouse soil was prepared before planting the seedlings by plowing, leveling, removing plant residues, and sterilization. A drip irrigation network was implemented to irrigate the cucumber crop. Polyethylene irrigation pipes were used, with a distance between sublines of 50 cm and a length of 25 m. The main irrigation line was connected to a dynamo with a 1 hp capacity to maintain water pressure in the sublines, which had a diameter of 16 mm. Irrigation points were installed with a distance of 50 cm between the drippers, and the discharge rate was 4 L $h^{-1}$.

### 2.4. The Experiment Method:

The seeds were presoaked in one of the nanosilica concentrations for 3 h. Then, 30 pots of 16 mL volume were prepared for each nanosilica concentration by filling them with potting soil. The soil was watered until it reached saturation; after that, one seed was sown per pot. When the growth was complete and the plant length was 15 cm, the nanosilica sprinkler treatments were applied to the plants. When the seedling length was 15 cm, the nanosilica was sprayed on all plants according to the treatment. The salinity shock treatment was applied to 12 experimental units containing 60 plants (5 plants per experimental unit) after the plants reached a length of 30 cm by irrigating them with saline water, obtained from an artesian well with a salinity of 3520 ppm, for 48 h (at a rate of 4 L $h^{-1}$ for 15 min every day). The chemical properties of the saline and normal water were analyzed according to the methods reported by Estefan *et al.* (2013).

### 2.5. Yield and Yield Component:

The plant height, chlorophyll content, and fourth leaf area were recorded after 15, 21, and 28 days of treatment. The chlorophyll content was measured using a chlorophyll meter (model MIN LTA SPAD-502), and leaf area was measured with a leaf area meter (model LI-3000A). The mean fruit yield of the middle three plants from every experimental unit was recorded from the 8th to the 30th week after the seedlings were planted, and the fruit yield per plant was calculated.

### 2.6. Preparation of Plant Sample for Elements Determination:

At the end of the harvest, the plants were collected and divided into the vegetative parts (leaves and fruits) and root parts per treatment. The dirt was cleaned from the plant samples with a brush, and the samples were then washed with 0.1 M HCl. Following that, the samples were washed three times using deionized water. Then, the samples were air-dried for 48 h, then dried for two days at 65 °C in an oven, and ground and sieved through a No. 60 mesh sieve. Then, the samples were kept in plastic bags until the contents were quantified. The contents of cucumber fruits were measured from ten fruits from every plant in the experimental unit (three plants); the same procedure was followed for the fourth leaves.

### 2.7. Measuring of Na+ and K+ Content:

A total of 0.5 g of dried plant sample was digested in a 50 mL volumetric flask with 2.5 ml of concentrated sulfuric acid (H2SO4, 95–97%) on a hotplate at approximately 270 °C. H2O2 was repeatedly added until the digest become clear (Cottenie, 1980). After digestion, deionized water was added to the volumetric flask to a final volume of 50 ml. Sodium (Na+) and potassium (K+) contents were determined in the liquid sample via atomic absorption and emission spectrometry (model Shimadzu-AA7000).

### 2.8. Determination of Silicon Si+4 Content in Plant and Fruits:

According to Frantz *et al.* (2008), 0.05 g of powder-dried plant sample was placed into a polyethylene tube. Then, 5 mL of 25 M of NaOH solution was added to the tissue in the tube, which was shaken to mix thoroughly. A capped tube was then placed in an autoclave and heated for 30 min, which was then allowed to cool to room temperature. After cooling, 2 mL of hydrogen peroxide (H2O2) was added to each tube, which was reheated in the autoclave for an additional 30 min. After cooling, 43 ml of distilled water was added to each tube. After additional cooling, 0.1 ml of the digested plant material mixture was added to 10 ml of distilled water. Hydrochloric acid (0.25 ml of 6 M HCl) was added to the tube, along with ammonium molybdate solution (0.5 ml, 10 g/100 ml, pH 7.0); the tube was shaken, and allowed to stand for up to 10 min. Tartaric acid (0.5 ml, 20 g/100 ml) was added; the tube was then shaken and allowed to stand for an additional 3 min. Sodium bisulfate (0.7 ml, 12.5 g/100 ml) was added and mixed in the tube. The developed blue color was measured between 10 and 30 min at 650 nm. Finally, the absorbance was compared with a standard calibration curve of known Si concentrations (0–50 ppm) prepared with soluble Si+4 combined with the previously described reagents.

### 2.9. Proline Determination in Plant:

The proline content was determined according to the method of Bates *et al.* (1973). A total of 1 mg of fresh plant material was placed in a tube and mixed in 20 mL of 40% methanol. Then, the tube was closed with a cap to prevent evaporation and cooled in a water bath for 60 min at 85 °C. To develop the color, the mixture was filtered through Whatman No. 2 filter paper. 1 mL of filtrate was mixed with 2 ml of glacial acetic acid and 2 ml of acid-ninhydrin in a test tube. The mixture was placed in a water bath for 1 h at 100 °C. The reaction mixture was extracted with 4 mL of toluene; the chromophore-containing toluene was aspirated and cooled to room temperature, and the absorbance was measured at 520 nm with a spectrometer. The appropriate proline standards were included for the calculation of the proline content in the samples.

### 2.10. Statistical Analysis:

The obtained data were analyzed using the SAS computer program. Means were differentiated using the Least Significant Difference (LSD) test described by Snedecor and Cochran (1974).

## 3. Result and Discussion

### 3.1. Analysis of Variance of Yield and Growth Characteristics:

The results of the analysis of variance of the cucumber growth characteristics under the treatments with the four different nanosilica levels (NSi), two salinity shock levels, and their interaction are presented in Table 1. The results show significant differences due to the applied NSi for yield and chlorophyll content ($p < 0.0001$), but the differences were not significant for plant height or the surface area of the fourth leaf. These findings are consistent with those of Alsaeedi *et al.* (2017) in their study on the response of cucumber to NSi, where they found that the yield and quality of the fruit were significantly affected by nanosilica treatments. The results showed insignificant effects of the salinity shock treatments on the yield, plant height, surface area of the fourth leaf, and chlorophyll content ($p < 0.05$); the highest values were obtained for yield and chlorophyll content (3.06 kg plant−1 and 24.79, respectively) for the treatments without the salinity shock. The salinity shock treatment reduced the yield by 5.9%. Regarding the length of the cucumber plants, the highest value (120.22 cm) was obtained for treated plants under salinity shock. The shortest plants (106.22 cm) were recorded under salinity shock treatment (Table 1). The effect of the interaction between NSi and salinity shock on yield was significant ($p < 0.05$).

**Table 1: Effect of main treatments (nanosilica concentration and saline shock) on yield (kg per plant), plant height (cm), leaf area ($cm^2$), and chlorophyll (Brix)**

| Treatments | Yield (kg plant−1) | Plant height (cm) | Leaf area (cm2) | Chlorophyll (Spad value) |
|---|---|---|---|---|
| Nanosilica (NSi, ppm) | | | | |
| NSi0 (0 ppm) | $2.18^{c}$ | 105.83 | 137.11 | $21.78^{c}$ |
| NSi1 (100 ppm) | $2.84^{b}$ | 106.58 | 134.55 | $24.63^{b}$ |
| NSi2 (200 ppm) | $3.19^{b}$ | 115.75 | 140.64 | $25.51^{b}$ |
| NSi3 (300 ppm) | $3.66^{a}$ | 124.33 | 156.85 | $26.89^{a}$ |
| $LSD_{0.05}$ | 0.40 | NS | NS | 0.97 |
| Salinity shock | | | | |
| NSCh (no salinity shock) | 3.06 | 106.22 | 141.64 | 24.79 |
| WSCh (with salinity shock) | 2.88 | 120.02 | 142.94 | 24.62 |
| $LSD_{0.05}$ | NS | NS | NS | NS |
| NSi*salinity shock | | | | |
| P | < 0.05 | > 0.05 | > 0.05 | > 0.05 |
| CV% | 10.99 | 19.83 | 27.82 | 3.20 |

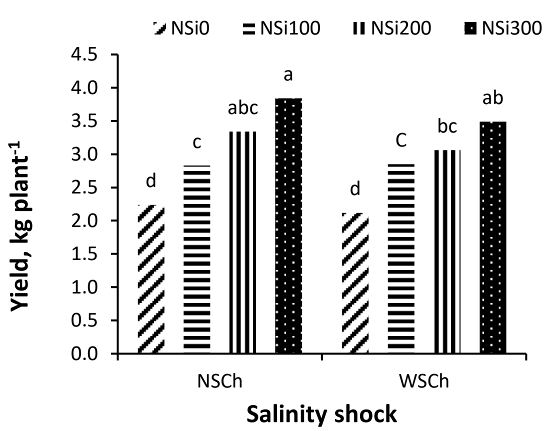
*Any two means under the same treatment not sharing the same letter in a column differ significantly at a 5% probability.
**NSi0 (zero ppm), NSi1 (100 ppm), NSi2 (200 ppm), NSi3 (300 ppm of nanosilica).
***$p < 0.05$ means the probability of signification at 0.05; > 0.05 is not significant at 0.05 according to an analysis of variance.

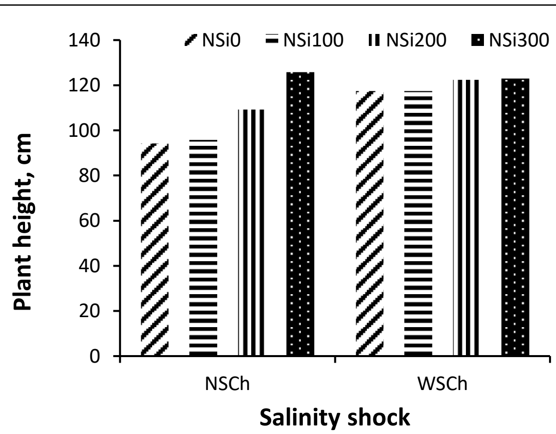
### 3.2. Effect of Nanosilica on the Cucumber Yield, Plant Height, Area of Fourth Leaf, and Chlorophyll Content:

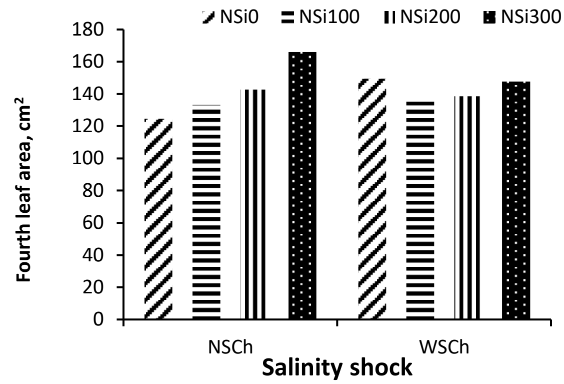
Table 1 presents the mean values of the investigated parameters of the cucumber plants as affected by the preplanting treatment with different concentrations of NSi and salinity shocks. A significant increase in yield was found with increasing NSi concentration, and the highest yield (3.66 kg plant−1) was obtained with the highest concentration (300 ppm). These findings are consistent with those of Alsaeedi *et al.* (2017) in their study on the response of cucumber to NSi, where they found that the yield and quality of the fruit were significantly affected by nanosilica treatments. The yield of the plants without salinity shock treatment (3.06 kg plant−1) was higher than that of plants subjected to shock treatments (2.88 kg plant−1), but not significantly so ($p < 0.05$). The salinity shock (WSCh) decreased the yield by 5.88% relative to that of the NSCh plants. The interaction between NSi and salinity shock (Figure 1) significantly affected the yield. Higher mean yield values were found for NSi3 under the WSCh and NSCh treatments in comparison with those of the control treatment (NSi0 × NSCh).

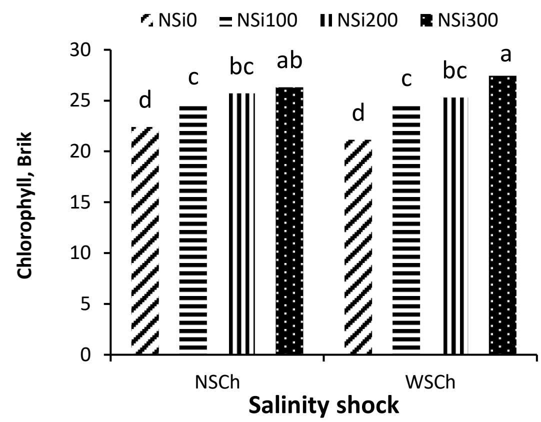
The application of NSi significantly increased the chlorophyll content of the plants (Table 1), which increased by 13.09, 17.13, and 23.46% compared with the control for NSi at concentrations of 100, 200, and 300 ppm, respectively. The results show that the application of NSi insignificantly increased plant height and the leaf surface area. The highest mean plant height and leaf surface area values were obtained with the NSi3 plants. These values followed the same pattern for yield and chlorophyll content, increasing with a gradual increase in the NSi concentration. These increases could be explained by the NSi application strengthening the plants and increasing the uptake of macronutrients. The plant height, surface leaf area, and chlorophyll content were insignificantly affected by the shock treatment. The interaction between NSi and salinity shock had an insignificant effect on the plant height, surface area, and chlorophyll content (Table 1). This indicates that both the NSi and salinity shock treatments increased the yield parameters of cucumber. These parameters increased by 30.4, 18.5, and 22.43%, respectively, under NiS300 × WSCh treatment, compared with the control treatment (NSi0 × NSCh) (Figure 1). This indicates that the plants treated with NSi3 had higher yield and yield parameters, showing that the treatment mitigated the effects of salinity. These results agree with those of Shoman and Bughdady (2020). They found that Vicia faba beans sprayed with silicon had higher chlorophyll and carotene contents, higher pod yields, and a higher number of seeds in each pod under normal and saline conditions.

**Figure 1: Effect of salinity shock (no shock (NSCh) and with shock (WSCh)) and nanosilica concentrations (NSi, 0, 100, 200, and 300 ppm) on yield, plant height, fourth leaf area, and the chlorophyll of cucumber plant. Means of shocks having the same letter are not significantly different at $p < 0.05$ ($LSD_{0.05}$= least significant difference test). Each column without letters means that there is no significant difference between the means.**




### 3.3. Sodium (Na+) Content in Plant (Roots, Leaves, and Fruits):

The data in Tables 2, 3, and 4 show that the application of NSi significantly decreased the sodium contents in the fruits and leaves; there was no significant decrease in the roots. The decrease in the sodium content in the fruits was 3.16, 7.36, and 19.21% compared with the control treatment NSi0 for NSi1, NSi2, and NSi3, respectively; the decreases in the sodium content in the leaves were 12.22, 17.72, and 28.94%, and in the roots 1.66, 2.39, and 1.27% for NSi1, NSi2, and NSi3, respectively, compared with the control treatment.

**Table 2: Effect of nanosilica (NSi, 0, 100, 200, and 300 ppm), salinity shock (no shock (NSCh) and with shock (WSCh) on the Na, K, and K/Na ratio in fruits, fourth leaf area, and roots of the cucumber plants**

| Treatments | Fruits | | |
|---|---|---|---|
| | Minerals concentration, % | | Ratio K/Na |
| | Na | K | |
| Nanosilica (NSi) | | | |
| NSi0 | 0.158ᵃ | 1.283 | 8.502ᵇ |
| NSi1 | 0.163ᵃ | 1.278 | 8.187ᵇ |
| NSi2 | 0.151ᵃ | 1.291 | 9.001ᵇ |
| NSi3 | 0.122ᵇ | 1.302 | 10.461ᵃ |
| $LSD_{0.05}$ | 0.021 | NS | 1.384 |
| Pr | $< 10^{-2}$ | > 0.05 | $< 10^{-3}$ |
| Salinity Shock | | | |
| NSCh | 0.145ᵃ | 1.336ᵃ | 9.557 |
| WSCh | 0.153ᵃ | 1.240ᵇ | 8.613 |
| $LSD_{0.05}$ | NS | 0.063 | NS |
| *Pr* | > 0.05 | $< 10^{-2}$ | > 0.05 |
| Interaction effect between nanosilica and shock treatment | | | |
| NSi*salinity shock | *** | * | *** |
| $LSD_{0.05}$ | 0.011 | 0.126 | 0.957 |
| Pr | $< 10^{-3}$ | < 0.05 | $< 10^{-3}$ |
| CV% | 11.49 | 5.66 | 12.45 |

Means in every column in every treatment followed by different letters are significantly different. *, **, *** indicates significance at the 5, 1, and 0.1% levels, respectively, and NS means insignificant at $p < 0.05$. $LSD_{0.05}$ means least significant difference at 0.05 level of significance. Pr < 0.05, $10^{-2}$, $10^{-3}$, and $10^{-4}$ mean the probability of signification, and CV means the coefficient of variation.

Table 3: Effect of nanosilica (NSi, 0, 100, 200, and 300 ppm), salinity shock (no shock (NSCh) and with shock (WSCh) on the Na, K, and K/Na ratio in fourth leaf area of the cucumber plants

| Treatments | Fourth leaf | | |
|---|---|---|---|
| | Minerals concentration, % | | Ratio K/Na |
| | Na | K | |
| Nanosilica (NSi) | | | |
| NSi0 | 0.090$^{a}$ | 0.368 | 4.202$^{c}$ |
| NSi1 | 0.079$^{b}$ | 0.385 | 5.061$^{b}$ |
| NSi2 | 0.076$^{bc}$ | 0.393 | 5.445$^{b}$ |
| NSi3 | 0.068$^{c}$ | 0.412 | 6.323$^{a}$ |
| $LSD_{0.05}$ | 0.008 | NS | 0.676 |
| Pr | $< 10^{-3}$ | > 0.05 | $< 10^{-3}$ |
| Salinity Shock | | | |
| NSCh | 0.090$^{a}$ | 0.417$^{a}$ | 4.077$^{b}$ |
| WSCh | 0.066$^{b}$ | 0.362$^{b}$ | 6.777$^{a}$ |
| $LSD_{0.05}$ | 0.006 | 0.031 | 0.478 |
| Pr | $< 10^{-3}$ | $<10^{-2}$ | $<10^{-3}$ |
| Interaction effect between nanosilica and shock treatment | | | |
| NSi*salinity shock | ** | * | *** |
| $LSD_{0.05}$ | 0.011 | 0.062 | 0.957 |
| Pr | $< 10^{-2}$ | < 0.05 | $< 10^{-2}$ |
| CV% | 8.35 | 9.25 | 10.50 |

Means in every column in every treatment followed by different letters are significantly different. *, **, *** indicates significance at the 5, 1, and 0.1% levels, respectively, and NS means insignificant at $p < 0.05$. $LSD_{0.05}$ means least significant difference at 0.05 level of significance. Pr < 0.05, $10^{-2}$, $10^{-3}$, and $10^{-4}$ mean the probability of signification, and CV means the coefficient of variation.

Table 4: Effect of nanosilica (NSi, 0, 100, 200, and 300 ppm), salinity shock (no Shock (NSCh) and with shock (WSCh) on the Na, K, and K/Na ratio in fruits, fourth leaf area, and roots of the cucumber plants

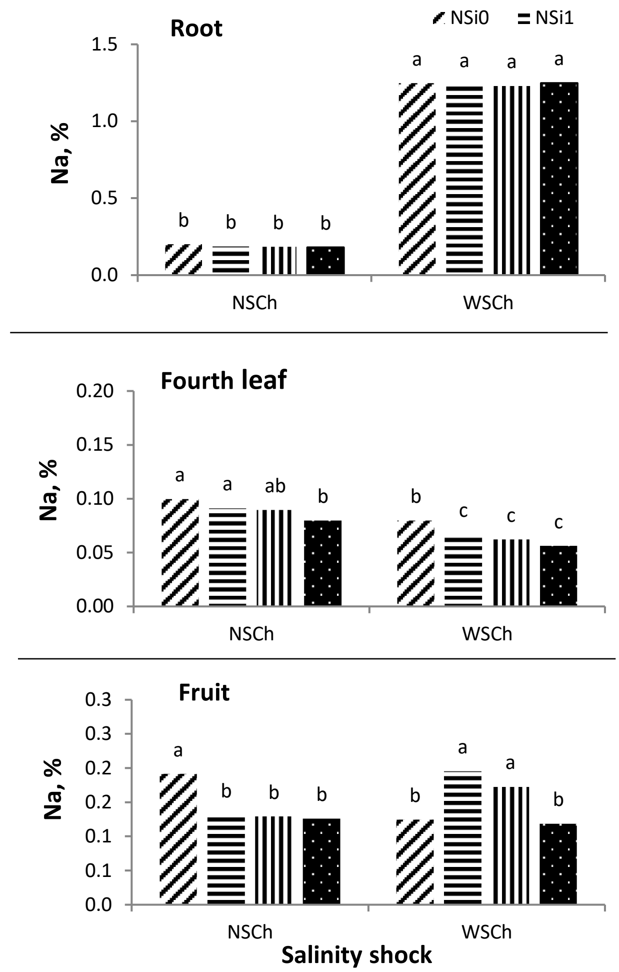
| Treatments | Roots | | |
|---|---|---|---|
| | Minerals concentration, % | | Ratio K/Na |
| | Na | K | |
| Nanosilica (NSi) | | | |
| NSi0 | 0.724 | 0.785 | 2.307 |
| NSi1 | 0.712 | 0.800 | 2.471 |
| NSi2 | 0.707 | 0.791 | 2.556 |
| NSi3 | 0.715 | 0.835 | 2.665 |
| $LSD_{0.05}$ | NS | NS | NS |
| Pr | > 0.05 | > 0.05 | > 0.05 |
| Salinity shock | | | |
| NSCh | 0.188$^{b}$ | 0.819 | 4.367$^{a}$ |
| WSCh | 1.240$^{a}$ | 0.787 | 0.637$^{b}$ |
| $LSD_{0.05}$ | 0.045 | NS | 0.317 |
| Pr | $< 10^{-4}$ | > 0.05 | $< 10^{-4}$ |
| Interaction effect between nanosilica and shock treatment | | | |
| NSi*salinity shock | * | NS | **** |
| $LSD_{0.05}$ | 0.09 | 0.166 | 0.634 |
| Pr | < 0.05 | > 0.05 | $< 10^{-4}$ |
| CV% | 7.32 | 11.98 | 14.64 |

Means in every column in every treatment followed by different letters are significantly different. *, **, *** indicates significance at the 5, 1 and 0.1% levels, respectively, and NS means insignificant at $p < 0.05$. $LSD_{0.05}$ means least significant difference at 0.05 level of significance. Pr < 0.05, $10^{-2}$, $10^{-3}$, and $10^{-4}$ mean the probability of signification, and CV means the coefficient of variation.

Tables 2, 3, and 4 display a significant interaction effect between the NSi and salinity shock treatments on the sodium content in the different parts of the cucumber plants. Comparing the mean sodium contents in the different plant parts under the various salinity shock treatments, a significant effect of the treatments on the sodium content of the leaf and roots is noticed, as well as an insignificant effect on the sodium content of the fruit. In the plants exposed to salinity shock, the sodium contents of the fruits and roots were higher than in the fruits and roots of plants not exposed to salinity shock. The sodium content of the leaves of those plants under WSCh treatment was lower than that of the leaves of those plants under NSCh treatment. These findings indicate that NSi and salinity shock have no individual effects on the sodium content of the cucumber plants.

Figure 2 shows that the sodium content in the roots ranged between 0.201 (NSi0 × NSCh) and 1.249% (NSi3 × WSCh); in the fourth leaf, the sodium content ranged between 0.100 (NSi0 × NSCh) and 0.052% (NSi3 × WSCh). The NSi3 × WSCh treatment decreased the sodium content by 44 and 38.02% (NSi0 × NSCh) in the fourth leaf and fruits, respectively, compared with the control treatment. The sodium content increase in the roots was 83.91% in NSi3 × WSCh compared with the control treatment (NSi0 × NSCh). The above results show that spraying plants with nanosilica led to sodium accumulating more in the roots than in the fruits and leaves, as well as to decreases in the absorption of sodium and its movement through the leaves and fruits, reflecting how cucumber yield increases with chlorophyll content.

Figure 2: Sodium (Na+%) in different parts of cucumber plant (roots, fourth leaf, fruits) under the interaction effect between nanosilica (NSi, 0, 100, 200, and 300 ppm) and shock treatments (no shock (NSCh) and with shock (WSCh)). The same letters for each part of the plant means there is no significant difference between them ($p < 0.05$).

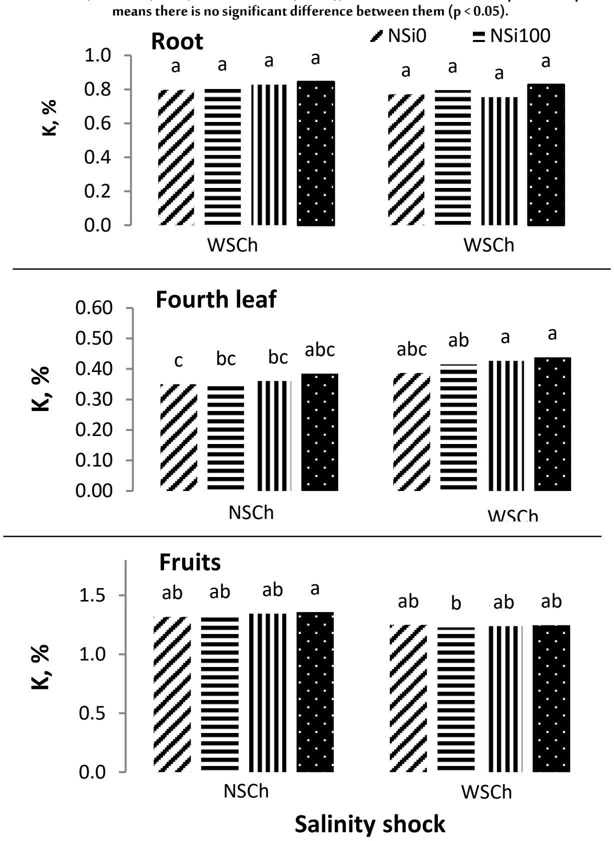



### 3.4. Potassium Content (K+) in Plant (Roots, Leaves, and Fruits):

The results in Table 2, 3, and 4 show that the K+ in the three cucumber parts did not change significantly with NSi treatment. The K+ content in the plants treated with NSi3 increased more than that in those that received other treatments. The K+ of the roots ranged from 1.283 in NSi0 to 1.302% in NSi3. For the leaves, the K+ ranged between 0.368 and 0.412% for NSi0 and NSi3, respectively. The mean K+ content in the roots ranged from 0.785 (NSi0) to 0.835% (NSi3). In general, the K+ content in the different parts increased with increasing NSi concentration. These findings are consistent with the results of Alsaeedi *et al.* (2017) and Alsaeedi *et al.* (2018) in their studies on the response of cucumber and bean to NSi treatment, where they showed that the potassium content of cucumber and bean plants increased with increasing NSi addition from 0 to 300 ppm. The percentage potassium change in fruits was −0.39, 0.62, and 1.48% for NSi1, NSi2, and NSi3, respectively, compared with the control treatment (NSi0).

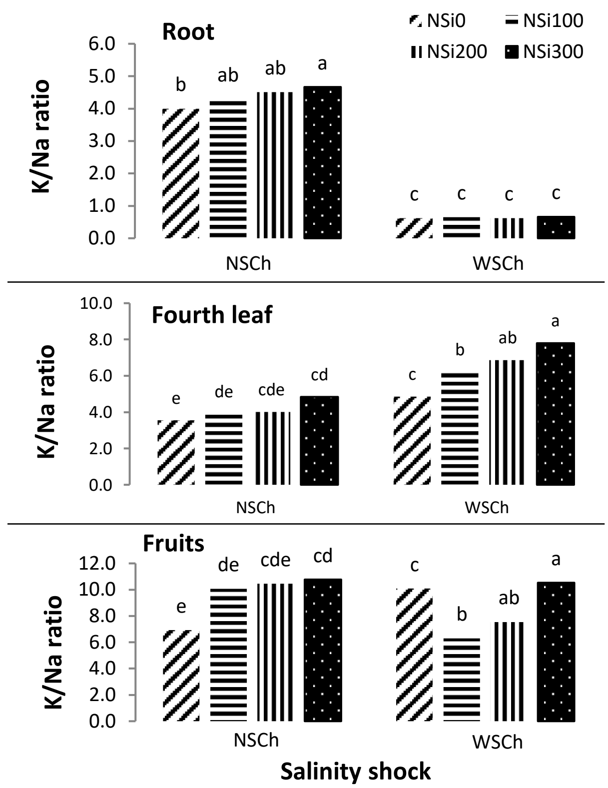
In comparison, the K+ content in the leaves increased by 4.62, 6.79, and 11.96% and that in the roots increased by 1.91, 0.76, and 6.37% in NSi1, NSi2, and NSi3, respectively, compared with the control (NSi0). A significant effect of the treatment on the mean K+ contents of the leaves and fruits was noticed as well as an insignificant effect on the K+ content of the roots. The K+ content was lower in plants exposed to salinity shock than in those not exposed to it. The data presented in Tables 2, 3, and 4 show a significant effect of the interaction between the NSi and shock treatments on the K+ content in all the different parts of the cucumber plants except the roots. These findings indicate that neither NSi nor salinity shock acts individually on the K+ content of the cucumber roots

Figure 3: Potassium (K+) percentage in different parts of cucumber plant (roots, fourth leaf, fruits) under the interaction effect between nanosilica (NSi, 0, 100, 200, and 300 ppm) and shock treatments (no shock (NSCh) and with shock (WSCh)). The same letters for each part of the plant means there is no significant difference between them ($p < 0.05$).




NSCh). The K+ content in the roots increased by 83.91% in NSi3 × WSCh compared with the control treatment (NSi0 × NSCh). The above results show that spraying nanosilica on the plants led to higher sodium accumulation in the roots than in the fruits and leaves, decreased the absorption of sodium, and increased K+ absorption, leading to an increase in the K/Na ratio. These changes in the leaves and fruits reflected the chlorophyll content and the increase in the cucumber yield.

Figure 4: Potassium sodium ratio (K/Na ratio) in different parts of cucumber plant (roots, fourth leaf, fruits) under the interaction effect between nanosilica (NSi, 0, 100, 200, and 300 ppm) and shock treatments (no shock (NSCh) and with shock (WSCh)). The same letters for each part of the plant means there is no significant difference between them ($p < 0.05$).




### 3.5. Ratio of K/Na in Plant (Roots, Leaves, and Fruits):

The results of the effect of NSi treatments on the K/Na ratio of the roots, leaves, and cucumber fruits are presented in Tables 2, 3, and 4. Significant differences are found between the applied NSi treatments (NSi0, NSi1, NSi2, and NSi3) with regard to the K/Na ratios of the fruits and leaves; also, the NSi treatments had an insignificant increasing effect on the K/Na ratio of the roots. The highest K/Na ratios (10.461 in fruits, 6.323 in leaves, and 2.665 in roots) were obtained in the NSi3 treatment. Regarding the K/Na ratio of the fruits, Tables 2, 3, and 4 show that the salinity shock treatments had no significant effect. The effect of salinity shock on the K/Na ratios of the leaves and roots was significant. The exposure of plants to salinity shock resulted in a decrease in the ratio of potassium to sodium in the fruits and roots by 9.88 and 85.41%, respectively, compared with the unshocked plants. In the leaves of the stunned plants, the K/Na ratio increased by 66.22% compared with the control plants (NSCh). The K/Na ratios decreased in the order of fruits > roots > fourth leaves. The interaction between NSi and salinity shock had a significant effect on the K/Na ratio of the fruits ($p < 0.001$), fourth leaves ($p < 0.001$), and roots ($p < 0.0001$). This indicates that nanosilica affected the salinity tolerance mechanisms of the plants. As shown in Figure 4, the K/Na ratio in the roots ranged between 0.66 (NSi3 × WSCh) and 4.66 (NSi3 × NSCh); in the fourth leaves, it ranged between 3.544 (NSi0 × NSCh) and 7.80 (NSi3 × WSCh). For fruits, this ratio was between 6.30 for WSCh × NSi1 and 10.77 for NSCh × NSi3. The NSi3 × WSCh treatment decreased the K+ content by 44 and 38.02% in the fourth leaves and fruits, respectively, compared with the control (NSi0 × NSCh).

### 3.6. Silicon in Plant (Roots and Leaves):

The silicon contents recorded in the different parts of the cucumber plants are shown in Table 5. The results show significant differences in the Si content among the applied NSi treatments (NSi0, NSi1, NSi2, and NSi3) in both the roots and fourth leaves. These results agree with those obtained by Alsaeedi *et al.* (2017) and Alsaeedi *et al.* (2018) in their studies on the response of cucumber and bean to NSi, where they found that the Si content significantly increased with increasing NSi treatment concentration from NSi0 to NSi3. The highest values were found in the roots and fourth leaves in the NSi3 treatment. Concerning the Si+4 content of the roots, the highest value (6.57%) was obtained in the NSi3 treatment, whereas the lowest value (3.417%) was obtained with NSi0 (Table 5). The Si+4 content in the fourth leaves varied between 3.537 and 4.525% for NSi0 and NSi3, respectively. The results overall indicate that increasing the content of Si+4 in the treatment caused an increase in the Si+4 content of the roots and leaves. Salinity shock significantly negatively affected the Si+4 content of the roots and fourth leaves of the cucumber plants, as demonstrated in Table 5. Salinity shock had a nonsignificant negative effect on the Si content of the cucumber roots and fourth leaves, as demonstrated in Table 5. The content of Si+4 slightly decreased by 19.45% in the roots and by 8.09% in the fourth leaves compared with that in the plants not exposed to salinity shock. This shows that the salinity shock decreased the Si+4 contents in the roots and leaves of the cucumber plants. This may have been due to the effect of the salinity on the biotic energy of the plants, as described by Chaerle *et al.* (2005). Table 5 and Figure 5 show that the interaction between treatments (NSi × SCh) significantly affected the Si+4 contents of the roots and fourth leaves. This indicates that these two factors might act dependently on these traits.

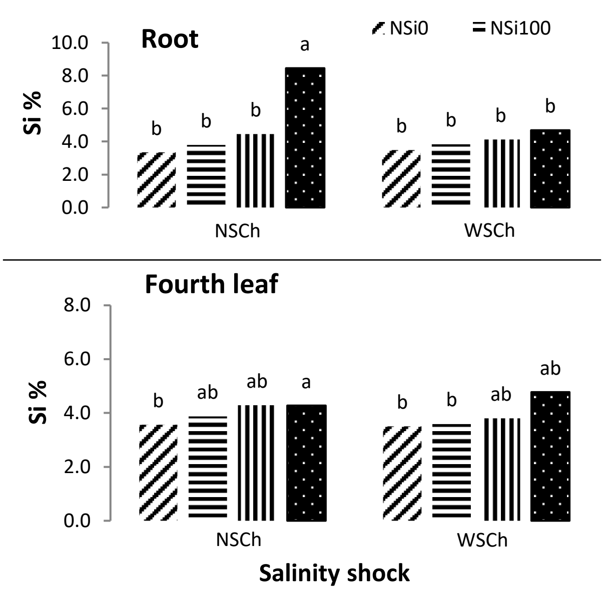
**Table 5: Effect of nanosilica (NSi, 0, 100, 200, and 300 ppm00, and 300), salinity shock (no shock (NSCh) and with shock (WSCh) on the silicon (Si%) and proline (ppm) of roots and fourth leaf of cucumber plant**

| Treatments | Silicon, % | | Proline, ppm | |
|---|---|---|---|---|
| | Roots | Fourth leaf | Roots | Fourth leaf |
| **Nanosilica (NSi)** | | | | |
| NSi0 | 3.417$^{b}$ | 3.537$^{b}$ | 2.230 | 2.630 |
| NSi1 | 3.817$^{b}$ | 3.734$^{b}$ | 2.337 | 4.173 |
| NSi2 | 4.293$^{ab}$ | 4.048$^{ab}$ | 2.927 | 4.710 |
| NSi3 | 6.570$^{a}$ | 4.525$^{a}$ | 3.357 | 5.870 |
| $LSD_{0.05}$ | 2.317 | 0.744 | NS | NS |
| Pr | < 0.05 | < 0.05 | >0.05 | >0.05 |
| **Salinity shock** | | | | |
| NSCh | 5.012 | 4.128 | 2.988 | 6.161$^{a}$ |
| WSCh | 4.037 | 3.794 | 2.437 | 2.531$^{b}$ |
| $LSD_{0.05}$ | NS | NS | NS | 2.324 |
| Pr | > 0.05 | > 0.05 | > 0.05 | < 0.01 |
| **Interaction effect between nanosilica and shock treatment** | | | | |
| NSi*salinity shock | * | * | * | ** |
| $LSD_{0.05}$ | 3.276 | 1.053 | 1.627 | 4.649 |
| Pr | < 0.05 | < 0.05 | < 0.05 | < 0.01 |
| CV% | 41.83 | 15.35 | 34.66 | 61.80 |

**Means in every column in every treatment followed by different letters are significantly different . *, **, *** indicate significant at the 5, 1, and 0.1% levels, respectively; NS means insignificant at $p < 0.05$. $LSD_{0.05}$ means least significant difference at 0.05 level of significance. Pr < 0.05, $10^{-2}$, $10^{-3}$, and $10^{-4}$ mean the probability of signification. CV means coefficient of variation.**

Figure 5 shows that the Si+4 content in the roots ranged between 3.35 (NSi3 × NSCh) and 8.45% (NSi3 × NSCh); in the fourth leaves, the Si content ranged between 3.50 (NSi0 × NSCh) and 4.77% (NSi3 × WSCh). The NSi3 × WSCh treatment increased the Si content by 40.24 and 36.28% in the roots and fourth leaves, respectively, compared with that in the control treatment (NSi0 × NSCh). This means Si treatment can reduce the effects of abiotic stresses in cucumber with a beneficial effects on plants under unstable conditions.

**Figure 5: Silicon concentration (Si%) in different parts of cucumber plant (roots, fourth leaf) under the interaction effect between nanosilica (NSi, 0, 100, 200, and 300 ppm) and shock treatments (no shock (NSCh) and with shock (WSCh)). The same letters for each part of the plant means there is no significant difference between them (p < 0.05).**




### 3.7. Proline:

The proline contents recorded in the roots and leaves of the cucumber plants are listed in Table 5. Insignificant increases were found between the applied NSi treatments (NSi0, NSi1, NSi2, and NSi3) regarding the proline content in both the roots and the fourth leaves of the cucumber plants. These results agree with those obtained by Alsaeedi *et al.* (2017) and Alsaeedi *et al.* (2018) in their studies on the response of cucumber and bean to NSi, where they found that the proline content significantly increased with increasing NSi treatment concentration from NSi0 to NSi3. The highest values were found in the roots and fourth leaves in the NSi3 treatment. Concerning roots, the highest proline content was 3.357 ppm for NSi3, whereas the lowest value (2.230 ppm) was obtained for the NSi0 treatment (Table 5). The proline content in the fourth leaves ranged between 2.630 and 5.870 ppm for NSi0 and NSi3, respectively. The results overall indicate that increasing the level of applied Si caused an increase in the proline contents of the roots and leaves. Salinity shock had a significantly negative effect on the proline content of the fourth leaves of the cucumber plants, as shown in Table 5; however, in the roots, the effect was not significant. The proline content decreased slightly by 18.44% in the roots and by 58.92% in the fourth leaves compared with plants unexposed to salinity shock. This result show that salinity shock had a negative effect on the Si contents of the roots and leaves of the cucumber plants. This may have been due to the effect of salinity on plant biotic energy; Chaerle *et al.* (2005) reported the same. Table 5 and Figure 6 show that the interaction between treatments (NSi × salinity shock) had a significant effect on the proline contents of the roots and fourth leaves. This indicates that each of these two factors might dependently act on these traits.

**Figure 6: Proline content (ppm) in different parts of cucumber plants (roots, fourth leaf) under the interaction effect between nanosilica (NSi, 0, 100, 200, and 300 ppm)and shock treatments (no shock (NSCh) and with shock (WSCh)). The same letters for each part of the plant means there is no significant difference between them (p < 0.05).**

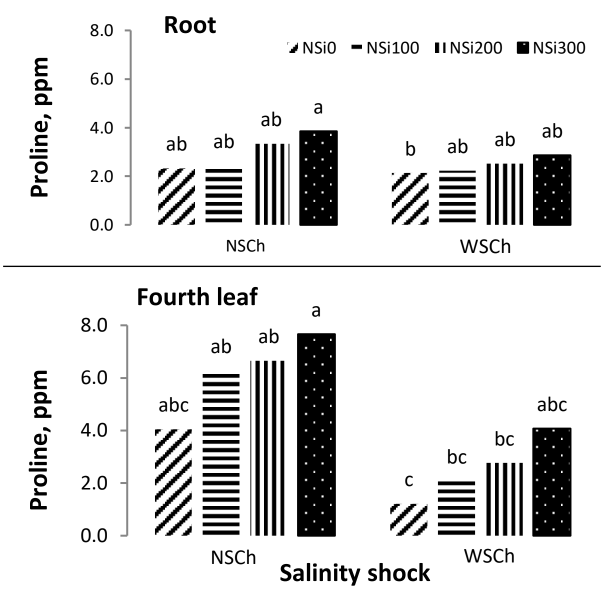



Figure 6 shows that the proline content in the roots ranged between 2.13 (NSi3 × NSCh) and 3.85 ppm (NSi3 × NSCh); in the fourth leaves, it ranged between 1.21 (NSi0 × WSCh) and 7.67 ppm (NSi3 × NSCh). The NSi3 × WSCh treatment increased the proline content in the roots and fourth leaves by 22.75 and 0.74%, respectively, compared with the control treatment (NSi0 × NSCh). This finding indicates that Si application can reduce biotic and abiotic stresses in many crops and can have beneficial effects on plants for cucumber under unstable conditions.

## 4. Conclusion

The use of nanofertilizers in sustainable agriculture can provide unique solutions to improve plant growth under abiotic stresses such as salinity of irrigation water. Such solutions can ameliorate the deleterious effect of salinity shock on plants sensitive to salinity, like cucumbers, by improving the plants' biochemical properties and reducing the impacts of saline water on productivity. Silicon contained in the Si–enzyme compound acts as a protective regulator of photosynthesis and affects other enzymatic activities. Spraying nanosilica at a concentration of 300 ppm resulted in improved yield and yield components against the harmful effect of salinity. Such findings indicate that neither nanosilica nor salinity shock acts individually to influence the decrease of sodium accumulation in leaves, increase the K/Na ratio, or increase proline content in the cucumber plants. Thus, Si can reduce abiotic stress and has beneficial effects on plants under unstable conditions.

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