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Effects of SiO_2 Nanoparticle Pretreatment on Tomato Growth and Physiological Responses under Reduced-Misting Conditions in an Aeroponic System

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ABSTRACT

Nanoparticles of silicon dioxide (SiO_2-NPs) have been demonstrated as possible modifiers of plant responses to abiotic stress. This study investigated the effects of SiO_2-NPs at 0, 50 and 100 mM under normal and water-stress circumstances on the various traits of tomato (*Solanum lycopersicum* L.) seedlings cultivated in an aeroponic system. The trial was done in a factorial layout according to completely randomized design. The measured traits were plant height, root length, root characteristics, proline, chlorophyll pigments, relative water content, anthocyanins, phenolic compounds, activities of antioxidant enzymes, protein, sodium and potassium. The results indicated that the impacts of SiO_2-NPs were variable among traits and water regimes. The 50 mM treatment increased root volume from 13.8 to 15.8 cm^3 under water stress. The 100 mM treatment had higher chlorophylls a and b as well as catalase activity and phenolics. The proline content decreased with increasing nanoparticle concentration; however, ascorbate peroxidase activity did not increase under water stress. Relative water content showed numerical increase at 50 mM but decrease at 100 mM as compared to stressed control. The highest shoot dry weight was recorded in the water-stressed untreated control, followed by the 50 and 100 mM SiO_2-NP treatments, while under non-stress conditions, it decreased at both nano-particle treatments compared with the untreated control. The findings indicated that the reaction of tomato seedlings to SiO_2-NPs application was concentration-dependent and trait-specific, and not a general improvement of tomato seedling performance.

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1. Introduction

Water stress is one of the main environmental factors on crops, affecting water relations, photosynthetic performance, nutrient acquisition, biomass accumulation, and cellular integrity. Tomato (*Solanum lycopersicum* L.) is a horticultural crop whose growth can be adversely affected by inadequate water availability, particularly during early developmental stages. Understanding response of tomato seedlings to water stress and identifying treatments that may alleviate drought effects are therefore important for improving crop establishment (Hao *et al*. 2019). However, the effectiveness of potential protective treatments depends on plant species, treatment concentration, application method, and the severity and duration of stress. Silicon (Si) is considered a beneficial element for many plant species, although it is not classified as needed item for higher plants. Depending on the species and growing conditions, silicon supplementation may influence plant growth, water relations, nutrient balance, photosynthetic activity, and antioxidant defense (Malik *et al*. 2021). Silicon dioxide (SiO_2) is one possible source of silicon, and its nanoparticles (SiO_2-NPs) represent a nanoscale formulation whose biological effects may differ from those of conventional sources.

The behavior of nanoparticles depends on factors such as particle size, surface properties, dispersion, aggregation, concentration, and application route. Previous studies have reported favorable responses to SiO_2-NPs application under certain abiotic stress conditions. Alsaeedi *et al*. (2018), investigated SiO_2-NPs in cucumber under water and salinity stress and reported improvements in plant performance. Hussain *et al*. (2020) also examined foliar-applied SiO_2-NPs in rice in relation to growth and heavy-metal stress. In another study, Salajegheh *et al*. (2020) reported responses involving relative water content and proline accumulation in cumin under drought stress. Also, other investigations suggest that SiO_2-NPs may influence plant responses to environmental stress, although the magnitude and direction of the effects depend on the experimental conditions and the traits evaluated (Panigrahi *et al*. 2025; Sompura *et al*. 2026). Evidence from other species also indicates that the effects of SiO_2-NPs are not uniform across physiological processes. Ashkavand *et al*. (2018) reported that SiO_2-NPs application under drought conditions affected biomass, photosynthesis, and malondialdehyde in hawthorn, whereas changes in relative water content were not significant.

Dawa *et al*. (2020) investigated silicon nanoparticle application in tomato under drought stress and reported responses involving plant growth, yield, water-use efficiency, photosynthetic pigments, and mineral composition. Although, above studies provide a rationale for examining silicon-based treatments under water limitation, differences in plant species, nanoparticle formulations, experimental conditions, and measured variables limit direct comparisons among studies. Several physiological and biochemical indicators can help characterize plant responses to water stress and SiO_2-NPs application. Shoot and root growth reflect biomass allocation and plant development, whereas relative water content provides information about leaf hydration (Frantová *et al*. 2026). Proline, anthocyanins, and phenolic compounds may participate in stress responses, while catalase, ascorbate peroxidase, and peroxidase activities are associated with the regulation of reactive oxygen species (Sood *et al*. 2025).

Increased antioxidant enzyme activity may reflect an induced defense response, whereas decreased activity may reflect reduced oxidative demand, enzyme inhibition, or changes in the broader antioxidant system (Jomova *et al*. 2024). Similarly, a change in relative water content or proline content must be interpreted alongside other physiological measurements rather than being considered definitive evidence of stress alleviation (Saputra *et al*. 2026). Despite reports of beneficial effects in several plant species, the response of tomato seedlings to SiO_2-NPs under contrasting water regimes requires further evaluation. It is important to distinguish responses that occur under non-stress conditions from those that occur under water stress and to determine whether the effects differ between nanoparticle concentrations. Also, evidence of changes in individual growth or biochemical traits should not, by itself, be interpreted as proof of improved drought tolerance. Accordingly, current study investigated the impacts of two SiO_2-NPs treatment concentrations on the various traits of tomato seedlings grown under non-stress and water-stress conditions in an aeroponic system. The objective was to characterize the responses to SiO_2-NPs application under the two water regimes and determine whether these responses differed between concentrations.

2. Materials and methods

2.1. Aeroponic system and plant materials

The effect of silicon dioxide nanoparticles (SiO_2-NPs) on tomato under non-stress and water-stress conditions were evaluated VIA an aeroponic system in controlled-environment conditions. The experimental plant material was tomato cultivar Super Luna (Modesto Seed Co., USA) also called Shomal in some parts of Iran. Tomato seeds were surface-sterilized with 70% ethanol for 2 min and with 0.05% sodium hypochlorite for 10 min. The seeds were washed three times with sterile water and planted in pots of peat moss. Seedlings were grown at a photoperiod of 16 h light/8 h dark, day/night temperature of 25/20 °C and relative humidity of about 85%. They were supplied with nutrient solution of Hoagland and deionized water in turn. After about 2 weeks, when they had two true leaves and were similar in size, they were transplanted into the aeroponic system. The aeroponic system consisted of a

root chamber, a reservoir for the nutrient solution, a pump, and a mist-delivery assembly. Roots were exposed to chamber atmosphere and supplied with water and nutrients by spraying. Tomato plants were cultivated under a 16/8 h light/dark photoperiod, day/night temperatures of 25/20 °C, relative humidity of about 85% and photosynthetic photon flux density (PPFD) of about 375 µmol m^{-2} s^{-1} at the canopy level. The experimental protocol was adopted with a provision of Hoagland nutrient solution and deionized water. The nutrient solution was sprayed to the roots for 20 s at 20 min intervals under the normal condition. In the fifth week after sowing, the misting system of the stress-treatment group was changed from automatic to manual control and water stress was slowly applied over 3 days by reducing the frequency of nutrient-solution application. Spraying was applied to roots on first day for 20 s in intervals of 60 min, on second day for 20 s in intervals of 120 min and on third day for 20 s in intervals of 180 min. The following schedule of misting and duration of stress treatment was followed as per the experimental protocol. Plants were harvested for morphological and biochemical analysis at the end of the sixth week.

2.2. Experimental design.

The SiO_2-NPs experiment was arranged in a 2 × 3 factorial in a completely randomized design with four replications. Experimental factors were misting regime (non-stress and water-stress conditions) and SiO_2-NPs concentration (0, 50 and 100 mM). The SiO_2-NPs were obtained from Pishgaman Nano-Materials Company, Iran, which is reported the primary particle size of the nanoparticles in order to be 20-30 nm and the specific surface area to be >80 m 2 g^{-1}. The suspensions of nanoparticles were prepared by dispersing the required mass of SiO_2-NPs in deionized water. The suspensions were stirred for 40 min. The control was treated with the corresponding solution without the nanoparticles. The aeroponic system was used to apply nanoparticle treatments to the roots during the fourth and fifth weeks of plant growth. The reduced misting treatment was started in the fifth week after sowing as described before. At harvest the plants were separated into roots and shoots for morphological measurements. Further plant material for biochemical analyses was frozen in liquid nitrogen and stored at -80 °C until analysis. Each treatment combination was replicated four times. For each replicate, ten plants were sampled and divided into morphological and biochemical measurements following the experimental sampling protocol.

2.3. Morphological traits.

Plant height (PH) was recorded via a ruler from base to apex. The length of the root (RL) was determined via ruler and expressed in cm. The root volume (RV) was quantified via water displacement, so roots were placed in a graduated container with an overflow spout and the volume of water displaced was measured and recorded as root volume with cm^3 scale. The shoots and roots were separated and dried in an electric oven at 70 °C for two days. Finaly, shoot dry weight (SDW) and root dry weight (RDW) were measured with an analytical balance and expressed in g per plant.

The proline (Pro) was recorded via acid-ninhydrin procedure of Bates *et al*. (1973), whereas leaf sample (0.5 g) was ground in 10 mL of 3% (w/v) sulfosalicylic acid, then 2 mL aliquots of the filtrate were mixed with 2 mL acid-ninhydrin reagent and 2 mL of glacial acetic acid. The mixture was heated at 100 °C for 60 min and then cooled in the ice bath. The colored reaction product was treated with 4 mL of toluene which was added to the mixture and shaken vigorously. The absorbance of the toluene was recorded at 520 nm using toluene as blank. The proline concentration was estimated from L-proline calibration curve as µmol g^{-1} fresh weight (FW) considering the extraction volume, aliquot volume, calibration equation and sample mass (Bates *et al*. 1973).

2.4. Determination of chlorophylls and RWC

Fresh leaves were extracted with 96% ethanol for chlorophyll, while 1 g of fresh leaf material was homogenized in 5 mL of ethanol and the homogenate was centrifuged at 3500 × g for 10 min. The absorbance of the supernatant was read against an ethanol blank at the wavelengths required by the validated ethanol-specific chlorophyll equations. Chlorophyll a and b were calculated from the absorbance readings for each. Pigment concentrations were calculated using the final extraction volume and sample mass, as mg g^{-1} FW. The equations applied must be suitable for the solvent and the exact wavelengths of measurement; equations derived for acetone extracts must not be uncritically applied to ethanol extracts (Lichtenthaler and Wellburn, 1983).

The RWC was calculated according to the following formula: $RWC(\%)= [(FW - DW)/(TW - DW)]\times100$

FW is the weight of a fresh leaf sample without any drying or processing, and TW, is the weight of a leaf sample after being placed in distilled water for 24 hours at 25 °C. This measurement indicates the turgidity or water content of the leaf. DW is the weight of a leaf sample after being dried in an oven at 70 °C for 48 hours.

2.5. Determination of biochemicals

The anthocyanin was determined via procedure of Giusti and Wrolstad (2001), so a leaf extract is taken and divided into two aliquots and then separately diluted with KCl buffer (0.025 M, pH 1.0) and NaOAc buffer (0.4

M, pH 4.5). Absorbance is recorded at 520 and 700 nm after equilibration. Concentration is expressed per mass of tissue using the volume of the extract and the original mass of the sample (Abs 530 g^{-1} FW^{-1}).

For measuring of sodium (Na^+) and potassium (K^+), Plant material was dried and acid extracted or digested before mineral analysis, so sodium and potassium were determined by flame photometry. Sodium and potassium were computed from the respective calibration curves after dilution correction and expressed on a dry-matter basis. If the original procedure was an extraction in 1% (v/v) HNO_3 at 60 °C for 16 h, it should be called an acid extraction, not assumed to be a complete mineral digestion.

Phenolic Content (PE) is quantified via Folin-Ciocalteu procedure (Singleton and Rossi, 1965). A measured aliquot of the plant mixture was added to diluted Folin-Ciocalteu reagent. After about 5 min, Na_2CO_3 is added and incubated in the dark at room temperature for 30 min. Reading of absorbance against reagent blank was done at 765 nm. The concentration of phenolic equivalents is calculated by using a calibration curve with gallic acid. The phenolic content (mg g^{-1} DW) was computed from the volume of the extract, the sample mass and the dilution factor.

Soluble protein was determined by Bradford procedure (Bradford, 1976), so plant tissue was homogenized in an extraction buffer and then centrifuged. The supernatant was divided into aliquots, mixed with reagent and read at 595 nm on a spectrophotometer. Protein was quantified via a standard curve of bovine serum albumin and expressed as µmol g^{-1} FW.

2.6. Measurement of antioxidant enzymes.

The activity of catalase was quantified by determining the absorbance decrease at 240 nm arising from the breakdown of hydrogen peroxide. Enzyme extract is added to KH_2PO_4 buffer (100.0 mM, pH 7.0) containing H_2O_2 and the change in absorbance is recorded over a defined interval using an appropriate blank. CAT amount was estimated from the linear change in absorbance per min via the hydrogen peroxide extinction index of 39.4 M^{-1} cm^{-1} with correction for reaction volume, enzyme-extract volume and optical path length (Aebi, 1984). If expressed per unit fresh tissue mass, activity should be given in a clearly defined unit such as µmol H_2O_2 min^{-1} g^{-1} FW100.0 mM.

Guaiacol peroxidase (POD) activity was quntified spectrophotometrically based on the procedure of Chance and Maehly (1955) with modifications. Leaf sample (100 mg) was crushed in 1 mL of 10 mM KH_2PO_4 buffer (pH 7.0), and centrifuged at 1000 × g for 10 min. The obtained supernatant was used as crude enzyme extract, and enzyme activity was recorded in a 1-mL reaction mixture containing 300 µL of 10 mM KH_2PO_4 buffer, 300 µL of 5 mM H_2O_2, 300 µL of 4 mM guaiacol and 100 µL enzyme extract. The reaction was initiated by adding the enzyme extract and incubated at 25 °C. The absorbance increase at 470 nm was followed during 5 min. A reagent blank was prepared via the same reaction components except that the enzyme extract was replaced with the corresponding extraction buffer. The peroxidase activity was expressed as change in absorbance per minute (ΔA_{470} min^{-1}). Activity was mentioned on a protein basis and computed via the extinction index and normalized to the amount of soluble protein present in the reaction mixture as µmol g^{-1} FW.

Ascorbate peroxidase (APX) was quantified by the oxidation of ascorbate at 290 nm in a reaction mixture containing of KH_2PO_4 buffer (50.0 mM, pH 7.0), EDTA (0.1 mM), ascorbate (0.5 mM), hydrogen peroxide (0.1 mM), and enzyme extract. Hydrogen peroxide is used to initiate the reaction and the decrease in absorbance at 290 nm is recorded over a set time period. The APX activity is expressed with ascorbate extinction index of 2.8 mM^{-1} cm^{-1} (Nakano and Asada, 1981).

2.7. Data analysis.

To determine the normality of the measured traits and analyze the data, statistical tests were done via the IBM-SPSS 27.0 application. The Shapiro-Wilk test was utilized to evaluate the normality of the distribution. For the analysis of variance (ANOVA), a factorial model was conducted in a completely randomized design layout. Also, Levene's test of homogeneity of residuals was used to assess the equality of variances across different groups or treatments. To assess the significance of the differences between the mean scores, the least significant difference (LSD) test was computed, which helps identify statistically significant differences between the means of different treatments at $p<0.05$ probability level.

3. Results

Table 1 indicated that the main effect of SiO_2-nanoparticle (SiO_2-NP) concentration was significant for all of the measured characters except root length (RL), root dry weight (RDW), potassium (K) concentration and phenolic content (PE). The interaction of SiO_2-NP × water-stress was significant for all traits except chlorophyll a (Chl-a). The results indicated that the responses of most measured traits to the SiO_2-NP application depended on the water regime. Thus, the treatment combinations were compared to characterize the responses under water-stressed and non-stressed conditions. The coefficients of variation ranged from 2.2 to 14.4 % (Table 1) indicating

differences in the relative experimental variability among traits, so these low amounts show the adequacy of the experimental design and the validity of the measurements. Lower CV values indicate lower residual variability relative to the trait mean, whereas higher values indicate greater relative variability. However, CV values depend on the biological characteristics and measurement scale of individual traits and should not be interpreted using a single universal threshold.

3.1. Effects of SiO_2-NPs on tomato

3.1.1. Morphological traits

There were different treatment means for PH, RL, RV, SDW, and RDW (Table 2). The highest PH under non-stress conditions was in untreated control, followed by the water-stressed untreated control and 50.0 mM SiO_2-NP treatment under water stress. The minimum PH was seen in non-stressed units received 50.0 mM SiO_2-NPs (Table 2). PH was decreased from 51.3 cm in the untreated control to 44.0 cm at 100.0 mM SiO_2-NPs under water stress, indicating the highest concentration did not maintain the plant height. The root length ranged from 43.4 to 62.5 cm. The RL was maximum in the non-stressed control and in the non-stressed units received 50.0 mM SiO_2-NPs. RL increased from 43.4 cm in the untreated control to 51.8 cm at 100.0 mM SiO_2-NPs under water stress. Root volumes ranged from 8.7 to 15.8 cm^3. The lowest RV was found in non-stressed plants received SiO_2-NPs at 50.0 mM, and the highest value was under water stress at 50.0 mM SiO_2-NPs. The 50.0 mM treatment increased RV to 15.8 cm^3 compared to the water-stressed untreated control (13.8 cm^3), while the 100.0 mM treatment had an RV of 13.3 cm^3 (Table 2).

Shoot dry weight ranged from 1.48 to 5.52 g. The highest value was recorded in the water-stressed treated with 500.0 mM SiO_2-NPs followed by control and 100.0 mM SiO_2-NPs application in the stressed condition (Table 2). Under non-stress condition, SDW decreased at 50 and 100.0 mM SiO_2-NPs, respectively in comparison to control. Root dry weight varied between 0.81 and 1.50 g. The highest values were observed in both the water-stressed untreated control (1.50 g) and water-stressed treatment with 100.0 mM SiO_2-NPs (1.48 g) and the lowest amount was recorded in the non-stressed untreated control (0.81 g). Thus, the effects of SiO_2-NP on morphologic traits were not consistently positive across traits or water regimes.

3.1.2. Proline, chlorophyll and leaf water status

Proline content varied from 0.0027 to 0.0146 µmol g^{-1} FW (Table 2). The highest concentration was observed in the non-stressed untreated control and the lowest values were recorded in plants treated with 100.0 mM SiO_2-NPs under both water regimes. Under water stress, proline decreased from 0.0130 µmol g^{-1} FW in the untreated control to 0.0103 and 0.0029 µmol g^{-1} FW under 50 and 100.0 mM SiO_2-NPs, respectively (Table 2). Thus, a higher SiO_2-NP concentration was associated with lower proline content rather than higher proline accumulation. The chlorophyll a ranged between 1.58 and 3.05 mg g^{-1} FW. Maximum value was seen in non-stressed plants received 100.0 mM SiO_2-NPs (3.05 mg g^{-1} FW^{-1}), whereas minimum was in water stressed plants treated with 50.0 mM SiO_2-NPs (1.58 mg g^{-1} FW^{-1}). Under water stress, Chl-a decreased from 1.92 mg g^{-1} FW in the untreated control to 1.58 mg g^{-1} FW at 50.0 mM, but increased to 2.53 mg g^{-1} FW at 100.0 mM (Table 2). The chlorophyll b varied from 1.71 to 2.11 mg g^{-1} FW. In water stress, Chl-b increased from 1.71 mg g^{-1} FW in the untreated control to 1.96 and 2.11 mg g^{-1} FW at 50 and 100.0 mM SiO_2-NPs, respectively. These results indicate a differential chlorophyll response between pigments and dependence on the concentration of treatment.

Relative water content (RWC) was 73.9-84.3% (Table 2). The maximum value was observed in the non-stressed control (84.3%), followed by non-stressed units received 500.0 mM SiO_2-NPs while the minimum was observed in non-stressed units received 100.0 mM SiO_2-NPs (73.9%). Under water stress, RWC was 77.9 % in untreated control, 79.8 % at 50.0 mM and 74.9 % at 100.0 mM SiO_2-NPs. Therefore, the 50.0 mM treatment caused an increase in RWC compared to the stressed control, while the 100.0 mM treatment resulted in a decrease.

3.1.3. Anthocyanin and phenolics content

The reported anthocyanin measurement ranged from 0.283 to 0.524 absorbance units g^{-1} FW (Table 2). The highest amount was seen in non-stressed units received 50.0 mM SiO_2-NPs (0.524), while the lowest value was obtained in water-stressed plants treated with 100.0 mM SiO_2-NPs (0.283). The reported value decreased from 0.330 in untreated control to 0.338 and 0.283 at 50 and 100.0 mM, respectively under water stress. The phenolic content varied from 1.59 to 2.66 mg g^{-1} DW (Table 2). The highest magnitude in non-stress conditions was observed in untreated control (2.32 mg g^{-1} DW) and phenolic content was reduced to 1.83 and 1.59 mg g^{-1} DW at 50 and 100.0 mM SiO_2-NPs respectively. Under water stress the respective values were 1.70, 2.46 and 2.66 mg g^{-1} DW (Table 2). Therefore, the 50 and 100 mM treatments were linked with higher reported phenolic content under water stress than the stressed untreated control. This pattern suggests a concentration-dependent response to stress, but the identity of the assay and its calibration must be confirmed before the variable can be described as total phenolic content.

Table 1. Analysis of variance for measured traits of tomato in nano SiO_2 trial.

SOV†	DF‡	Mean squares					
		PH	RL	RV	SDW	RDW	Proline
Stress (S)	1	29.3*	839.0**	76.0**	11.10**	0.618**	0.00002194**
Silicon (Si)	2	152.0**	10.3^{ns}	4.7**	9.97**	0.033^{ns}	0.00024972**
S×Si	2	43.8**	205.4**	20.8**	1.96**	0.416**	0.00004150**
Error	18	6.1	4.6	0.7	0.14	0.014	0.00000032
CV		5.3	4.1	6.9	11.6	10.1	7.3
		Chl-a	Chl-b	RWC	Ant	Catalase	Na
Stress (S)	1	2.486**	0.0643**	42.1**	0.10749**	0.0006212**	486.0**
Silicon (Si)	2	1.584**	0.0758**	119.7**	0.01542**	0.0003973**	14.6*
S×Si	2	0.033^{ns}	0.0922**	27.5**	0.01670**	0.0007599**	205.9**
Error	18	0.038	0.0023	2.9	0.00084	0.0000022	3.2
CV		8.4	2.5	2.2	7.6	11.7	5.5
		K	Phenol	Protein	APX	POD	
Stress (S)	1	1768.2**	0.790**	0.00026^{ns}	6.67E-11^{ns}	0.00000023^{ns}	
Silicon (Si)	2	36.4^{ns}	0.041^{ns}	0.07964**	1.80E-08**	0.00000174**	
S×Si	2	4025.3**	1.527**	0.04063**	2.80E-09**	0.00002595**	
Error	18	18.5	0.013	0.00083	7.07E-10	0.00000018	
CV		6.0	5.5	6.0	14.4	13.5	

† SOV, sources of variation; ‡ DF, degrees of freedom; § CV, coefficient of variation.
**, * and ^{ns} denote statistically significant at 0.01 and 0.05 probability level and non- significant, respectively.
Abbreviations are: plant height (PH), root length (RL), root volume (RV), shoot dry weight (SDW), root dry weight (RDW), chlorophyll a (Chl a), chlorophyll b (Chl b), relative water content (RWC), Ascorbate peroxidase (APX) and guaiacol peroxidase peroxidase (POD).

3.2.4. Activities of antioxidants

Catalase activity ranged from 0.0030 to 0.0358 µmol g^{-1} FW^{-1} min^{-1} (Table 2). The highest value was observed in the non-stressed units received 50.0 mM SiO_2-NPs, followed by the water-stressed plants treated with 100.0 mM. The CAT activity was 0.0030, 0.0043 and 0.0153 µmol g^{-1} FW^{-1} min^{-1} in the untreated control, 50.0 mM and 100.0 mM SiO_2-NPs under water stress condition respectively. So, 100.0 mM treatment showed the highest CAT activity among the water-stressed treatments but it did not produce the highest value across all treatments. The response was nonlinear and varied between water regimes. The ascorbate peroxidase (APX) activity ranged between 0.00014-0.00024 µmol g^{-1} FW^{-1} min^{-1} (Table 2). In contrast, the highest APX activity (0.00024 µmol g^{-1} FW^{-1} min^{-1}) was observed in the untreated control under non-stress conditions and decreased at 50.0 mM (0.00014 µmol g^{-1} FW^{-1} min^{-1}) and 0.00018 µmol g^{-1} FW^{-1} min^{-1} at 100.0 mM SiO_2-NPs. Under water stress, APX activity of the untreated control was 0.00024, 0.00017 µmol g^{-1} FW^{-1} min^{-1} at 50.0 mM and 0.00014 µmol g^{-1} FW^{-1} min^{-1}at 100.0 mM. These results indicated that SiO_2-NP application did not increase APX activity under water stress.

The POD activity was between 0.00138 and 0.00551 µmol g^{-1} FW^{-1} min^{-1} (Table 2). The maximum value was recorded in the unstressed untreated control (0.00551 µmol g^{-1} FW^{-1} min^{-1}) and the minimum value was found in the unstressed treated plants with 100.0 mM SiO_2-NPs (0.00138). Under water stress the reported activity increased from 0.00168 µmol g^{-1} FW^{-1} min^{-1} in the untreated control to 0.00260 µmol g^{-1} FW^{-1} min^{-1} at 50.0 mM and 0.00475 µmol g^{-1} FW^{-1} min^{-1} at 100.0 mM SiO_2-NPs. This demonstrates that the response of the recorded peroxidase activity was different in the water regimes.

Table 2. The means of treatment combinations (nano SiO_2 (0, 50, 100mM) versus water stress in the measured traits of tomato.

S¶	Si	PH (cm)	RL (cm)	RV (cm^3)	SDW (g)	RDW (g)	Proline (µmol g^{-1} FW)
	1	52.6±1.11 a	62.0±2.16 a	13.0±0.83 b	3.51±0.311 b	0.81±0.070 d	0.0146±0.00040 a
1	2	41.5±1.29 b	62.5±3.11 a	8.7±0.70 d	1.48±0.240 e	1.22±0.070 b	0.0032±0.00056 d
	3	43.5±4.04 b	52.0±2.94 b	10.5±0.71 c	2.71±0.440 d	1.02±0.074 c	0.0027±0.00022 d
	1	51.3±2.22 a	43.4±0.95 c	13.8±0.38 b	5.52±0.337 a	1.50±0.217 a	0.0130±0.00043 b
2	2	49.0±2.45 a	45.8±1.67 c	15.8±0.95 a	3.34±0.211 bc	1.04±0.114 c	0.0103±0.00089 c
	3	44.0±2.58 b	51.8±1.08 b	13.3±1.33 b	2.93±0.587 cd	1.48±0.099 a	0.0029±0.00065 d

S	Si	Chl-a (mg g^{-1} FW)	Chl-b (mg g^{-1} FW)	RWC (%)	Anthocyanin (Abs 530 g^{-1} FW)	Catalase (µmol g^{-1} FW^{-1} min^{-1})	Na (mg Kg^{-1})
	1	2.69±0.092 b	2.05±0.019 ab	84.3±1.60 a	0.359±0.0175 c	0.0090±0.00018 c	28.0±1.41 d
1	2	2.22±0.193 c	2.00±0.062 bc	82.4±1.22 ab	0.524±0.0347 a	0.0358±0.00250 a	31.8±1.71 c
	3	3.05±0.396 a	2.03±0.066 b	73.9±1.82 d	0.470±0.0276 b	0.0084±0.00064 c	24.3±1.71 e
	1	1.92±0.082 d	1.71±0.048 d	77.9±1.42 c	0.330±0.0440 c	0.0030±0.00022 d	36.3±2.50 b
2	2	1.58±0.043 e	1.96±0.038 c	79.8±1.24 bc	0.338±0.0261 c	0.0043±0.00040 d	31.0±1.83 c
	3	2.53±0.139 b	2.11±0.041 a	74.9±2.59 d	0.283±0.0130 d	0.0153±0.00250 b	43.8±1.26 a

S	Si	K (mg Kg^{-1})	Phenol (mg g^{-1} DW)	Protein (µmol g^{-1} FW)	APX (µmol g^{-1} FW^{-1} min^{-1})	POD (µmol g^{-1} FW^{-1} min^{-1})
	1	54.8±3.10 c	2.32±0.135 b	0.347±0.0269 d	0.00024±0.000026 a	0.00551±0.000648 a
1	2	87.8±7.41 b	1.83±0.072 c	0.641±0.0312 a	0.00014±0.000026 c	0.00273±0.000359 c
	3	48.5±1.91 c	1.59±0.084 d	0.445±0.0192 c	0.00018±0.000041 b	0.00138±0.000213 d
	1	94.5±4.12 a	1.70±0.174 cd	0.517±0.0407 b	0.00024±0.000022 a	0.00168±0.000457 d
2	2	53.3±4.27 c	2.46±0.115 b	0.550±0.0283 b	0.00017±0.000021 bc	0.00260±0.000141 c
	3	94.8±2.75 a	2.66±0.077 a	0.384±0.0214 d	0.00014±0.000017 c	0.00475±0.000480 b

Means (±SD, n =4) with the same letter are not different significantly according to LSD test (P <0.05). Treatments are: S_1, non-water stress condition; S_2, water stress condition; S_1, 0 mM nano SiO_2; S_2, 50.0 mM nano SiO_2; and S_3, 100.0 mM nano SiO_2. Abbreviations are: plant height (PH), root length (RL), root volume (RV), shoot dry weight (SDW), root dry weight (RDW), chlorophyll a (Chl a), chlorophyll b (Chl b), relative water content (RWC), Ascorbate peroxidase (APX) and guaiacol peroxidase (SOD).

3.1.5. Protein, sodium and potassium

The protein varied from 0.347 to 0.641 μmol g^{-1} FW (Table 2). It was high at non-stressed condition 50.0 mM SiO_2-NPs, while it was low in non-stressed untreated control and water-stressed with application of 100.0 mM SiO_2-NPs (Table 2). The concentration of sodium (Na) ranged from 24.3 to 43.8 mg kg^{-1} and that of K from 48.5 to 94.8 mg kg^{-1} (Table 2). Na increased from 36.3 mg kg^{-1} in untreated control to 43.8 mg kg^{-1} at 100.0 mM SiO_2-NPs under water stress, while 50.0 mM treatment had lower value of 31.0 mg kg^{-1}. Water-stressed untreated control had 94.5 mg kg^{-1} potassium concentration, 53.3 mg kg^{-1} at 50.0 mM and 94.8 mg kg^{-1} at 100.0 mM. Thus, the effects were dependent on the measured ion and on the concentration of SiO_2-NPs, whereas higher Na concentrations alone do not show improved drought tolerance and need verified appropriate physiological context.

4. Discussion

The current study indicated that the effects of SiO_2-NPs on tomato growth and biochemical traits were dependent on the concentration and water regime. Some characteristics indicated possible positive responses at specific concentrations, but the treatment means do not support an idea that SiO_2-NPs improved tomato performance under water stress. Water stress resulted in highest root volume at 50.0 mM SiO_2-NPs with an increase from 13.8 cm^3 in stressed untreated control to 15.8 cm^3. Under water stress at 100.0 mM, the root length also increased, so root morphological responses might vary depending on SiO_2-NPs concentrations. Previous studies have reported changes in root traits after silicon-based treatments under water limitation (Ashkavand *et al*. 2015; Siddiqui *et al*. 2020). In contrast, shoot dry weight was reduced in water-stressed untreated control in comparison to 50 and 100.0 mM SiO_2-NPs, respectively. Also, the application of SiO_2-NPs did not increase root dry weight across water regimes. These results contrast with investigations of increased root and shoot biomass after silicon-based treatments (Siddiqui *et al*. 2020), but differences in dose, nanoparticle properties, application timing and experimental conditions may contribute to contrasting responses. The concentrations and physical characteristics of the nanoparticle suspension must be further confirmed before attributing the responses to a beneficial or toxic effect of SiO_2-NPs.

The proline content decreased with increasing concentration of SiO_2-NPs under both water regimes. Although, accumulation of proline is associated with plant response to drought and osmotic adjustment, the extent of proline accumulation is not a general indicator of drought tolerance. Observed reductions may be due to changes in stress response, metabolism, tissue condition or time of sampling. Hence the results show a treatment-associated change in proline content and not that the plants became more or less drought tolerant just on the basis of this compound. Also, the chlorophyll responses depended on concentration and pigment, whereas Chl-a was higher under water stress at 100.0 mM SiO_2-NPs than the untreated control, while Chl-b increased at both concentrations of silicon nanoparticles. This may imply that the two pigments interact differently with exposure to SiO_2-NPs. Silicon-based treatments have been reported to help maintain photosynthetic pigments under abiotic stress in some plant systems (Naing and Kim, 2021). However, pigment concentrations should not be taken as direct measures of photosynthetic performance.

The relative water content was highest in the non-stressed untreated control and lowest in the non-stressed plants supplied with 100.0 mM SiO_2-NPs. With water stress, the 50.0 mM treatment exhibited a slight increase in RWC compared to the stressed control, whereas the 100.0 mM treatment exhibited a lower value. The results indicate that the response was not uniform at different concentrations. Previous studies have related silicon treatments to alterations in plant water relations, but mechanisms differ among experimental systems and should not be deduced from RWC alone (Desoky *et al*. 2025; Shohani *et al*. 2026). Anthocyanins and other phenolic compounds can contribute to antioxidant defense but the response seen depends on the compound class measured and the stress conditions. Similarly, the increased phenolic values recorded at 50 and 100.0 mM under water stress, suggest the possible induction of phenolic-related responses at these concentrations.

The CAT activity was highest in non-stressed plants treated with 50.0 mM SiO_2-NPs, while in water-stressed plants, the CAT activity was highest at 100.0 mM. Such a pattern indicates that the concentration with the highest CAT activity was different between water regimes. The APX activity did not increase with SiO_2-NPs concentration under water stress. The reported peroxidase activity increased with concentration in stressed plants. These differences are physiologically relevant in that antioxidant enzymes have different substrates, regulation and response dynamic (Hasanuzzaman *et al*. 2018; Ferreira *et al*. 2025). However, enzyme activity at a single time point does not by itself establish the capacity of the plant to detoxify reactive oxygen species. The water-stressed treatment supplemented with 100.0 mM SiO_2-NPs showed the highest Na concentration; however, Na accumulation alone does not represent an adaptive osmotic response or increased drought tolerance in tomato. Thus, current findings are best understood as treatment-associated changes in measured ion concentrations rather than evidence for a specific drought-tolerance mechanism.

Finally, current research suggested that the responses of SiO_2-NPs in tomato were concentration-dependent and trait-specific. The higher root volume at 50.0 mM under water stress and the higher CAT activity at 100.0 mM

under water stress are worthy of further studies. However, the decrease in shoot dry weight at both nanoparticle concentrations, the inconsistent APX response and the decrease in proline at higher concentrations indicate that the treatments did not enhance all the traits measured. Further work should confirm the concentrations and characterization of the nanoparticles, evaluate the response at several sampling times and assess whether the observed changes translate into enhanced plant growth and productivity under controlled and field conditions.

Conclusion

Application SiO_2-NPs affected the tomato plants depending on concentration and water regime. Maximum root volume was observed at 50.0 mM SiO_2-NPs under water stress. Higher CAT activity and higher reported phenolic content than the stressed untreated control was observed at 100.0 mM SiO_2-NPs. However, the application of SiO_2-NPs was not always beneficial to plant growth or biochemical responses. Shoot dry weight decreased at both concentrations under water stress, proline content decreased with increasing concentration and APX activity did not increase in particular. Further experiments with additional physiological and growth measurements are required to make a practical recommendation

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human or animal subjects performed by any of the authors.

Consent to publication

Not applicable.

Availability of data and materials

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References

Aebi, H. 1984. Catalase in vitro. In Methods in enzymology (Vol. 105, pp. 121-126). Academic Press. https://doi.org/10.1016/S0076-6879(84)05016-3

Alsaeedi, A., El-Ramady, H., Alshaal, T., El-Garawani, M., Elhawat, N. and Al-Otaibi, A., 2018. Exogenous nanosilica improves germination and growth of cucumber by maintaining K^+/Na^+ ratio under elevated Na^+ stress. Plant Physiology Biochemistry, 125: 164-171. https://doi.org/10.1016/j.plaphy.2018.02.006

Ashkavand, P., Tabari, M., Zarafshar, M., Tomásková, I. and Struve, D., 2015. Effect of SiO_2 nanoparticles on drought resistance in hawthorn seedlings. Leśne Prace Badawcze, 76: 350-359. https://doi.org/10.1515/frp-2015-0034

Ashkavand, P., Zarafshar, M., Tabari, M., Mirzaie, J., Nikpour, A., Bordbar, S.K., Struve, D. and Striker, G.G., 2018. Application of SiO_2 nanoparticles as pretreatment alleviates the impact of drought on the physiological performance of *Prunus mahaleb* (Rosaceae). Boletín de la Sociedad Argentina de Botánica, 53(2): pp.207-219. https://doi.org/10.31055/1851.2372.v53.n2.20578

Bates, L. S., Waldren, R. P., and Teare, I. D. 1973. Rapid determination of free proline for water-stress studies. Plant and Soil, 39: 205–207. https://doi.org/10.1007/BF00018060

Bradford, M. M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Analytical Biochemistry, 72: 248–254. https://doi.org/10.1016/0003-2697(76)90527-3

Dawa, K., Zaghloul, M.M., I Ahmed, H.M. and Hamad, K.H., 2020. Impact of Foliar Application with Iron, Zinc, Silicon Nano Particles and Yeast on Growth, Yield and Water Use Efficiency of Tomato Plants under Water Stress Conditions. Journal of Plant Production, 11(6): 523-530. https://doi.org/10.21608/jpp.2020.106331

Desoky, E. S. M., Mahmood, M., Feng, D., Ahmed, A. F., Al Masoudi, L. M., Alahmari, A. S., and Taha, N. A. 2025. Synergistic effects of clove fruit extract and nano-silicon to enhance drought resilience and productivity

of soybean through improved plant defense mechanisms. BMC Plant Biology, 25(1): 236. https://doi.org/10.1186/s12870-025-06234-1

Frantová, N., Asszonyi, J., Cerkal, R., and Středa, T. 2026. Contrasting root–shoot strategies of spring and winter barley seedlings to PEG-imposed water deficit. Plant Growth Regulation, 106(1): 53. https://doi.org/10.1007/s10725-026-01459-y

Giusti, M. M., and Wrolstad, R. E. 2001. Characterization and measurement of anthocyanins by UV-visible spectroscopy. Current protocols in food analytical chemistry, John Wiley and Sons. USA.

Hao, S., Cao, H., Wang, H., and Pan, X. 2019. The physiological responses of tomato to water stress and re-water in different growth periods. Scientia Horticulturae, 249: 143-154. https://doi.org/10.1016/j.scienta.2019.01.045

Hasanuzzaman, M., Nahar, K., Anee, T. I., Khan, M. I. R., and Fujita, M. 2018. Silicon-mediated regulation of antioxidant defense and glyoxalase systems confers drought stress tolerance in *Brassica napus* L. South African Journal of Botany, 115: 50-57. 10.1016/j.sajb.2017.12.006

Hussain B., Lin, Q., Hamid, Y., Sanaullah, M., Di, L., Hashmi, M.L.U.R., Khan, M.B., He, Z. and Yang, X., 2020. Foliage application of selenium and silicon nanoparticles alleviates Cd and Pb toxicity in rice (*Oryza sativa* L.). Science of the Total Environment, 712: 136497. https://doi.org/10.1016/j.scitotenv.2020.136497

Jomova, K., Alomar, S. Y., Alwasel, S. H., Nepovimova, E., Kuca, K., and Valko, M. 2024. Several lines of antioxidant defense against oxidative stress: antioxidant enzymes, nanomaterials with multiple enzyme-mimicking activities, and low-molecular-weight antioxidants. Archives of Toxicology, 98(5): 1323-1367. https://doi.org/10.1007/s00204-024-03696-4

Lichtenthaler, H. K., and Wellburn, A. R. 1983. Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. Biochemical Society Transactions, 11: 591–592. https://doi.org/10.1042/bst0110591

Malik, M. A., Wani, A. H., Mir, S. H., Rehman, I. U., Tahir, I., Ahmad, P., and Rashid, I. 2021. Elucidating the role of silicon in drought stress tolerance in plants. Plant Physiology and Biochemistry, 165: 187-195. https://doi.org/10.1016/j.plaphy.2021.04.021

Naing, A.H. and Kim, C.K., 2021. Abiotic stress-induced anthocyanins in plants: Their role in tolerance to abiotic stresses. Physiologia Plantarum, 172(3): pp.1711-1723. https://doi.org/10.1111/ppl.13373

Nakano, Y., and Asada, K. 1981. Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplasts. Plant and Cell Physiology, 22(5): 867–880. https://doi.org/10.1093/oxfordjournals.pcp.a076232

Panigrahi, L. L., and Rout, G. R. 2025. Mechanistic insights into micro and nanosilicon for environmental stress mitigation in plant. Discover Nano, 20(1): 208. https://doi.org/10.1186/s11671-025-04387-4

Polle, A., Chakrabarti, K., Schürmann, W., & Rennenberg, H. (1990). Composition and properties of hydrogen peroxide decomposing systems in extracellular and total extracts from needles of Norway spruce (*Picea abies* L., Karst.). Plant Physiology, 94(2): 666–672. https://doi.org/10.1104/pp.94.1.312

Salajegheh, M., Yavarzadeh, M., Payandeh, A. and Akbarian, M.M., 2020. Effects of titanium and silicon nanoparticles on antioxidant enzymes activity and some biochemical properties of *Cuminum cyminum* L. under drought stress. Banat's Journal of Biotechnology, 11(21): 19-25. https://doi.org/10.7904/2068-4738-XI(21)-19

Saputra, H., Soleh, M. A., Hamdani, J. S., and Saryoko, A. 2026. Multivariate association patterns of morpho-physiological responses in soybean under short-term drought at the early vegetative stage using a drought resistance index framework. BMC Plant Biology, 26: 1418. https://doi.org/10.1186/s12870-026-09189-z

Shohani, F., Sarghien, S. H., Taylor, N. L., and Fazeli, A. 2026. Effect of salicylic acid and silicon on physiological parameters and anatomical index of Scrophularia striata L. under drought stress. Scientific Reports, 16: 25732. https://doi.org/10.1038/s41598-026-55665-9

Siddiqui, H., Ahmed, K.B.M., Sami, F. and Hayat, S., 2020. Silicon nanoparticles and plants: current knowledge and future perspectives. Sustainable Agriculture Reviews 41: 129-142. https://doi.org/10.1007/978-3-030-33996-8_7

Singleton, V. L., and Rossi, J. A. 1965. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. American Journal of Enology and Viticulture, 16: 144–158. https://doi.org/10.5344/ajev.1965.16.3.144

Sompura, Y., Bhatt, U., Parihar, S., Shrimali, N. K., Dashora, K., and Soni, V. 2026. Nanoparticles and photosynthesis: a critical mechanistic review of molecular interactions and physiological impacts. npj Science of Plants, 2(1): 13. https://doi.org/10.1038/s44383-026-00024-w

Sood, M. 2025. Reactive oxygen species (ROS): plant perspectives on oxidative signalling and biotic stress response. Discover Plants, 2(1): 187. https://doi.org/10.1007/s44372-025-00275-4