

Silicon dioxide nanoparticles a strategy to improve the growth, physiology, yield, and nutraceutical quality of tomatoes

Juan J. REYES-PÉREZ¹, Luis T. LLERENA-RAMOS¹,
Juan A. TORRES-RODRÍGUEZ¹, Wilmer TEZARA^{1,2,3}, José L.
GARCÍA-HERNÁNDEZ⁴, Pablo PRECIADO-RANGEL⁵, Bernardo
ESPINOSA-PALOMEQUE^{6*}

¹Universidad Técnica Estatal de Quevedo, Av. Quito, km 1.5 vía a Santo Domingo de los Tsáchilas, 120501 Quevedo, Los Ríos, Ecuador; jreyes@uteq.edu.ec; llerenaramos@uteq.edu.ec; jatorres@uteq.edu.ec; wilmer.tezara@utelvt.edu.ec

²Universidad Técnica Luis Vargas Torres, Facultad de Ciencias Agropecuarias, Estación Experimental Mutile, 080102, Esmeraldas, Ecuador

³Universidad Central de Venezuela, Instituto de Biología Experimental, Apartado 47114, Caracas 1041-A, Venezuela

⁴Universidad Juárez del Estado de Durango, Facultad de Agricultura y Zootecnia, Carretera Gómez Palacio-Tlahualilo km 32, Ejido Venecia, 35111 Gómez Palacio, Durango, Mexico; luis_garher@ujed.mx

⁵Tecnológico Nacional de México, Instituto Tecnológico de Torreón, Carretera Torreón-San Pedro km 7.5, 27170, Torreón, Mexico; ppreciador@yahoo.com.mx

⁶Universidad Tecnológica de Escuinapa, Camino al Guasimal S/N, CP. 82400, Escuinapa de Hidalgo, Sinaloa, Mexico; bspinosa@utescuinapa.edu.mx (*corresponding author)

Abstract

The application of nanotechnology in horticultural crops optimizes physiological performance, growth, nutraceutical quality, and resistance to adverse environmental factors. The objective of this study was to evaluate the effect of silica dioxide nanoparticles (SiO₂ NPs) on tomato crops in greenhouses. Three doses were used (25 mg L⁻¹, 35 mg L⁻¹, and 45 mg L⁻¹) along with a control. A randomized block experimental design with three replications was used. The variables analyzed included physiological, morphological, yield, and nutraceutical quality aspects. It was observed that plant height was higher with 45 mg L⁻¹ of SiO₂ NPs, while 25 mg L⁻¹ of SiO₂ NPs showed the highest values for stem diameter, root length and yield. The dose of 25 mg L⁻¹ of SiO₂ NPs caused higher chlorophyll content, net photosynthetic rate, water use efficiency, and leaf water status. Regarding nutraceutical quality (soluble solids, vitamin C, total phenols, flavonoids, carotenoids, and antioxidant capacity), the best results were obtained with 35 mg L⁻¹ of SiO₂ NPs. These findings suggest that SiO₂ NPs at concentrations of 25 and 35 mg L⁻¹ improve the tomatoes' physiological traits, growth, yield, and nutraceutical quality, which is relevant for agricultural production and the promotion of healthy diets.

Keywords: antioxidant activity; fruit quality; nanofertilizer; *Solanum lycopersicum* L.

Received: 05 Mar 2025. Received in revised form: 21 Jun 2025. Accepted: 23 Jun 2025. Published online: 29 Jun 2025.

From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the world's most widely consumed agricultural products and represents a source of bioactive compounds beneficial to human health, such as carotenoids and phenols (Ansari *et al.*, 2023). Its intake has been associated with a reduction in the risk of various diseases, including cancer and chronic non-communicable cardiovascular diseases (Pinedo-Guerrero *et al.*, 2020). However, this crop is characterized by its high nutritional requirements, which is why it depends on high doses of synthetic fertilizers (Marodin *et al.*, 2014) since fertilization via the leaves and/or soil affects the growth, yield, and chemical compounds of this plant species. A sustainable option to reduce the excessive use of agrochemicals, especially pesticides and fertilizers, is the application of agricultural biotechnological and nanotechnological tools (Moshabaki *et al.*, 2019; El-Mahrouk *et al.*, 2024).

In recent years, nanotechnology has become a promising field in agriculture because of its potential to improve productivity and contribute to food security. Nanoparticles, with diameters of less than 100 nm, possess unique properties that facilitate their interaction with plant cells. Nanofertilizers, for example, can increase photosynthetic rate (A), improve nutrient efficiency, and protect plants from biotic and abiotic stresses, resulting in higher agricultural yields (Seleiman *et al.*, 2023; Weisany *et al.*, 2024). It has been reported that nanoparticles can accelerate the seed germination process and can be both soluble and insoluble in suspension. These nanoparticles have been applied at various stages of plant development- from seed germination to plant maturity (Sembada *et al.*, 2023).

For its part, silicon (Si) is a key component in soil and is found in all plants growing in soil. However, the discussion about its essentiality in plant nutrition has been a matter of debate for more than a century (Miyake and Takahashi, 1978). The benefits of Si in tomato plants are still not well determined because this element plays both structural and metabolic roles in plant physiology, which can lead to higher productivity (Marodin *et al.*, 2014). Different doses of Si applied to tomato crops in soil were effective in increasing leaf number, leaf area, stem diameter, chlorophyll index, and fruit titratable acidity (Cazárez-Flores *et al.*, 2023). Silicon biofortified foods are a valuable adjuvant in the protection of bone health. Studies are being carried out to evaluate its bioavailability after in vitro digestion and bone mineral resorption (D'Imperio *et al.*, 2016).

Several experiments with silicon nanoparticles (Si NPs) have demonstrated their ability to improve crop development. Increased concentrations of Si NPs enhance plant growth and improve plant resistance in both field and hydroponic conditions (Sayed *et al.*, 2022). These nanoparticles are effective in mitigating damage from abiotic factors, such as drought, salinity, and heavy metal stress (Weisany *et al.*, 2024). Silicon dioxide-based nanoparticles (SiO₂ NPs) affect plant growth as well as the activity of various defense enzymes, such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and phenylalanine ammonia-lyase (PAL). In addition, they affect the levels of chlorophyll, carotenoids, and proline, key components in plant physiology (Parveen and Siddiqui, 2021).

SiO₂ NPs have a multifaceted role in plant species, e.g., they increase the germination of tomato (Siddiqui and Al-Whaibi, 2014) and sunflower (*Helianthus annuus*) (Janmohammadi and Sabaghnia, 2015) seeds, promote dry matter accumulation, increase the relative water content of leaves, decrease the electrical conductivity of leaves, improve the stability of cell membranes, and increase the metabolism of maize (*Zea mays*) seedlings (Hao *et al.*, 2023). According to Yassen *et al.* (2017), SiO₂ NPs applications increase nitrogen and phosphorus content and uptake and decrease sodium content and uptake, thus showing positive effects on the growth and yield of cucumber (*Cucumis sativa*). Similarly, SiO₂ NPs increased the number, length, and width of shoots, leaf area, leaf chlorophyll content, fruit set percentage, and fruit yield in mango (*Mangifera indica*) (Almutairi *et al.*, 2023). Applying SiO₂ NPs to lentil (*Lens culinaris*) and soybean (*Glycine max*) plants minimized the negative impact of salinity, provoking increases in growth, photosynthetic pigments, primary metabolites, and antioxidant enzymes (El-Mahrouk *et al.*, 2024). Applications of 500 mg L⁻¹ of SiO₂ NPs had positive effects on salt-stressed tomato plants, increasing average fruit weight, fruit yield, and chlorophyll,

phenol, glutathione, and glutathione peroxidase activity (Pinedo-Guerrero *et al.*, 2020). The supply of SiO₂ NPs increases yield, water use efficiency (WUE), yield components, fruit weight, and fruit sugar content in tomato plants when subjected to water stress (Ebrahimi *et al.*, 2024).

In addition to the aforementioned, mesoporous SiO₂ NPs have been reported to be an effective and safe fungicide alternative for the management of early blight (*Alternaria solani*) (Derbalah *et al.*, 2019) and *Ralstonia solanacearum* bacteria in tomato crops (Wang *et al.*, 2022). The SiO₂ NPs produced from sugarcane bagasse (*Saccharum officinarum*) and corn cobs applied to *Eruca sativa* seedlings not only improved the biometry and physiology of the plant but was also effective as an antifungal agent inhibiting *Fusarium oxysporum* and *Aspergillus niger* with inhibition percentages of 73.42 and 58.92 %, respectively (Goswami and Mathur, 2022). The combination of mycorrhizal fungi (*Rhizophagus irregularis*) and SiO₂ NPs caused increases in plant growth and photosynthetic pigments and reduced the rates of diseases, galls, and *Meloidogyne incognita* in carrot plants (*Daucus carota*) (Ahamad *et al.*, 2023). The results obtained with SiO₂ NPs in the improvement of plant nutrition and control of phytopathogens are significant in increasing plant productivity. Furthermore, they could offer an alternative to synthetic insecticides and be applied in powder form without the need for water, which would contribute to the development of new natural insecticides within integrated pest management programs (Alimohamadian *et al.*, 2022). Given the above, the objective of the present study was to evaluate the effect of SiO₂ NPs on greenhouse tomato plants using three doses (25 mg L⁻¹, 35 mg L⁻¹, and 45 mg L⁻¹) along with a control.

Materials and Methods

Study Site

The investigation was carried out in a greenhouse belonging to the “María” Experimental Campus of the State Technical University of Quevedo located 7.5 km along the Quevedo-Mocache road in the Mocache canton, Los Ríos province (01° 04' 48.6" S latitude, 79° 30' 0.04.2" W longitude, and an altitude of 75 masl). The study site is located in a humid tropical climate zone, with an average annual temperature of 24.8 °C, annual precipitation of 2252 mm, relative humidity of 84%, and 894.0 h of sunshine per year.

Plant Material and Growing Conditions

'Floradade' var. tomato seeds were disinfected with 5% sodium hypochlorite for 10 minutes, then washed with distilled water and left to dry at room temperature for 4 hours before sowing. Planting was in 200-cavity polystyrene trays containing black soil and compost (3:1 v/v, soil from a cocoa plantation, sand, and sawdust). Seedlings were transplanted when they reached an average height of 10 to 15 cm. Two seedlings were placed in the center of the 1 kg bags, then one plant per bag. The bags contained a mixture of sand from the river and commercial substrate (1:1 v/v), which were placed in three rows, with a spacing of 0.5 m between rows and 0.3 m between each plant, to obtain a density of 6 plants per m².

After transplanting, irrigation was performed daily, moistening the substrate to its field capacity to avoid water stress in the crop. The crops were managed and cared for according to Peet and Welles (2005) with the exception of the doses of silicon dioxide nanoparticles.

Experimental Design and Treatments

A randomized block experimental design was used with four treatments and three replicates. The experimental unit consisted of 10 plants in each repetition, hence a total of 30 plants per treatment. The treatments used were foliar application of SiO₂ NPs at different concentrations, 25 mg L⁻¹, 35 mg L⁻¹, and 45 mg L⁻¹, plus a control (0 mg L⁻¹). The doses of SiO₂ NPs were mixed with distilled water and agricultural dispersants, then applied with a foliar sprayer at 25, 35, and 45 days after transplant (DAT).

Evaluated Variables

Plant height was measured from the base of the stem to the apical bud with a flexometer (Stanley, Ecuador), and stem diameter was determined at 1 cm from the base of the stem with a vernier (Mitutoyo, Mexico); both phenological variables were evaluated at 30, 45, and 60 DAT. To determine the effect of the applied treatments on the biophysical quality of the fruits, the fruit size variables (polar diameter and equatorial diameter) were evaluated using a vernier. These variables were determined in 30 fruits per treatment. The number of fruits was quantified when 50% of fruiting had occurred in each plant per treatment. The yield (kg ha^{-1}) was obtained by considering the first two harvests obtained in the useful area of each experimental unit. Chlorophyll content was quantified in five different leaves per plant in each treatment with the SPAD-502 Plus chlorophyll meter (Minolta, Japan) at 30, 45, and 60 DAT.

To determine the nutraceutical quality of fruits from plants treated with SiO_2 NPs, the soluble solids content (determined in °Brix) was evaluated with a Carl Zeiss refractometer (Jean, Germany) and total flavonoids using the methodology proposed by Zhishen *et al.* (1999). Polyphenols were quantified using the Folin-Ciocalteu methodology (Singleton *et al.*, 1974), antioxidant capacity with the methodology proposed by Henriquez *et al.* (2002), and vitamin C content using spectrophotometry according to the methodology proposed by Igbokwe *et al.* (2013).

Gas exchange was evaluated as: net photosynthetic rate (A), transpiration rate (E), stomatal conductance (g_s), intercellular CO_2 concentration (C_i), and water use efficiency ($\text{WUE} = A/E$) using a portable infrared gas analyzer model CIRAS 2 (PP Systems, Hitchin, UK). All measurements were taken on fully expanded and healthy adult leaves between the third leaf of the plant. From each clone, 2 plants per block were taken for gas exchange, for a total of 6 plants per treatment ($n = 6$). Measurements were taken between 09:00 and 12:00 h with a photosynthetic photon flux density (PPFD) of $1200 \mu\text{mol m}^{-2} \text{s}^{-1}$, an ambient CO_2 concentration of 420 ± 5 ppm, leaf temperature of 28°C , and a leaf-air vapor pressure deficit (VPD) of 2.0 ± 0.3 kPa.

Leaf water potential (Ψ) was determined by placing a leaf that had been cut with a disinfected knife into a Scholander pressure chamber (PMS, Corvallis, OR, USA), leaving the leaf petiole visible, and then introducing pressurized gas. As the pressure increases, the sap comes out of the xylem and is visualized at the cut end of the leaf and thus visualized with a magnifying glass. These measurements of Ψ were determined between 06:00 and 07:30 h (Ψ_{am}) and at midday (Ψ_{m}) on leaves from three different plants from each treatment ($n = 3$).

The determination of plant hydraulic conductance ($K_L = K_{\text{soil}} - \text{leaf}$) was performed according to Sack *et al.* (2002) and Sack and Scoffoni (2012). K_L was determined by dividing the transpiration rate (E , $\text{mmol m}^{-2} \text{s}^{-1}$) reached a steady state by the driving force of the water potential, i.e., the water potential difference ($\Delta\Psi = \Psi_{\text{am}} - \Psi_{\text{m}}$, MPa): $K_L = E / \Delta\Psi$ ($\text{mmol m}^{-2} \text{s}^{-1} \text{MPa}^{-1}$).

At 30, 45, and 60 days after transplanting, plants were harvested to measure the root length from root apex to stem top with a flexometer. The fresh biomass of the plants was determined with analytical scales (Santorius, USA) by separately weighing the plant organs (stem, leaf, and root system) from 10 plants per treatment and replicates. After recording the fresh weight of the stems, leaves, and root systems, they were put in paper bags and placed in a FED 115 drying oven (Binder, Germany) at a temperature of 65°C for 72 h until a constant weight was reached. The dry weight of plant matter (dry biomass) was determined using the analytical balance.

Statistical Analysis

The results of the variables described above were subjected to the Shapiro-Wilk and Bartlett tests to determine normality and homogeneity of variances, respectively. They were then analyzed by means of an analysis of variance (ANOVA), and in the cases in which statistical differences were found, a comparison of means was made by applying Tukey's test at $p \leq 0.05$ with the SAS 9.0 program.

Results

Plant Height and Stem Diameter

Variations in plant height and stem diameter were observed across the doses of silicon dioxide nanoparticles (SiO₂ NPs) on 'Floradade' tomato on the three sampling dates (30, 45, and 60 DAT) ($p \leq 0.05$) (Table 1). At 30 DAT, the increase in SiO₂ NPs concentration produced greater plant height, the 45 mg L⁻¹ of SiO₂ NPs treatment produced the tallest height (53.26 ± 1.25 cm) with increases of 56.79, 44.41, and 39.85% compared to the control, 25 mg L⁻¹, and 35 mg L⁻¹ of SiO₂ NPs, respectively. Similarly, at 45 DAT, the 45 mg L⁻¹ of SiO₂ NPs treatment with a plant height of 95.10 ± 0.61 cm was 9.10, 13.53, and 9.90% higher than the control, 25 mg L⁻¹, and 35 mg L⁻¹ of SiO₂ NPs, respectively. The greatest plant height at 60 DAT was found in the 45 mg L⁻¹ of SiO₂ NPs treatment with an average of 141.230 ± 2.31 cm, being statistically equal to the control (135.33 ± 0.49 cm) and 35 mg L⁻¹ of SiO₂ NPs (136.17 ± 0.21 cm), however with significant difference to the 25 mg L⁻¹ of SiO₂ NPs treatment (131.60 ± 1.50 cm). Therefore, the 45 mg L⁻¹ of SiO₂ NPs dose was the most effective in promoting plant height growth at 30 and 45 DAT. As time progresses, the difference in plant height between doses of SiO₂ NPs begins to decrease, suggesting that the effect of SiO₂ NPs may have a limited long-term effectiveness on plant height. Regarding stem diameter at 30 DAT, the 45 mg L⁻¹ of SiO₂ NPs treatment presented the highest average with 0.77 ± 0.03 mm, exceeding the control, 25 mg L⁻¹, and 35 mg L⁻¹ of SiO₂ NPs treatments by 30.51, 26.23, and 20.31%, respectively. At 45 DAT, the control, 25 mg L⁻¹ and 35 mg L⁻¹ of SiO₂ NPs treatments showed significant difference compared to the 45 mg L⁻¹ of SiO₂ NPs treatment, which had the smallest average stem diameter. At the last sampling date (60 DAT), the 25 mg L⁻¹ of SiO₂ NPs treatment had the highest stem diameter with an average of 1.64 ± 0.54 mm, being statistically different from the rest of the treatments (Table 1).

Table 1. Effect of silicon dioxide nanoparticles (SiO₂ NPs) on the height and stem diameter of 'Floradade' tomato plants at 30, 45, and 60 DAT

Treatment	PH 30 (cm) [‡]	PH 45 (cm)	PH 60 (cm)	SD 30 (cm)	SD 45 (cm)	SD 60 (cm)
Control	33.97 ± 4.06 b	87.17 ± 3.00 b	135.33 ± 3.96 ab	0.59 ± 0.01 b	0.76 ± 0.02 a	0.49 ± 0.01 b
25 mg L ⁻¹	36.88 ± 2.05 b	83.77 ± 1.21 b	131.60 ± 1.50 b	0.61 ± 0.03 b	0.80 ± 0.03 a	1.64 ± 0.54 a
35 mg L ⁻¹	39.85 ± 3.53 b	86.53 ± 1.15 b	136.17 ± 4.15 ab	0.64 ± 0.04 b	0.80 ± 0.05 a	0.21 ± 0.13 b
45 mg L ⁻¹	53.26 ± 1.25 a	95.10 ± 0.61 a	141.23 ± 2.31 a	0.77 ± 0.03 a	0.56 ± 0.08 b	0.11 ± 0.00 b
<i>p</i> -value	0.0002	0.0003	0.0361	0.0001	0.0011	0.0005
CV (%)	7.1850	1.9797	2.3371	4.0840	6.8379	44.9923
DMSH	7.7004	4.5626	8.3158	0.0696	0.1305	0.7215

[‡]PH 30 = plant height at 30 DAT, PH 45 = plant height at 45 DAT; PH 60 = plant height at 60 DAT, SD 30 = stem diameter at 30 DAT, SD 45 = stem diameter at 45 DAT; SD 60 = stem diameter at 60 DAT. Means ± standard deviation with different letters in the same column indicate significant differences according to Tukey's test ($p \leq 0.05$)

Root Length and Dry Biomass

With respect to the variable root length, a significant difference was shown ($p \leq 0.05$); the control, 25, and 35 mg L⁻¹ of SiO₂ NPs treatments were statistically equal. The plants of the 25 mg L⁻¹ of SiO₂ NPs treatment (46.17 ± 1.07 cm) increased by 10.91% compared to the 45 mg L⁻¹ of SiO₂ NPs treatment (41.63 ± 1.62 cm). Foliar application of SiO₂ NPs affected leaf, root, and stem dry biomass production in 'Floradade' tomato crop ($p \leq 0.05$); the control, 25, and 35 mg L⁻¹ of SiO₂ NPs treatments were statistically equal, yet the control treatment increased root and leaf dry matter by 62.21 and 63.09% compared to the 45 mg L⁻¹ of SiO₂ NPs treatment, respectively. However, for stem dry biomass, the control treatment (109.60 ± 3.51) was statistically equal to the 45 mg L⁻¹ treatment (88.80 ± 17.56), the latter not differing from the 25 and 35 mg L⁻¹ treatments (Table 2).

Table 2. Effect of silicon dioxide nanoparticles (SiO₂ NPs) on root length together with dry root, leaf, and stem biomass in 'Floradade' tomato

Treatment	Root length (cm)	Dry root biomass (g)	Dry leaf biomass (g)	Dry stem biomass (g)
Control	45.93 ± 0.93 ab	68.10 ± 23.24 a	46.07 ± 14.59 a	109.60 ± 3.51 a
25 mg L ⁻¹	46.17 ± 1.07 a	49.83 ± 7.88 ab	32.77 ± 3.58 ab	61.60 ± 9.85 b
35 mg L ⁻¹	45.00 ± 2.70 ab	36.93 ± 7.67 ab	30.13 ± 5.44 ab	61.60 ± 11.07 b
45 mg L ⁻¹	41.63 ± 1.62 b	25.73 ± 3.62 b	17.00 ± 1.84 b	88.80 ± 17.56 ab
<i>p</i> -value	0.0413	0.0201	0.0149	0.0024
DMSH	4.5137	33.9510	21.0280	30.3900
CV (%)	3.8633	28.7590	25.5377	14.4560

Means ± standard deviation with different letters in the same column indicate significant differences according to Tukey's test ($p \leq 0.05$)

Biophysical Quality and Performance

According to the analysis of variance, there was no significant difference between the doses of SiO₂ NPs in the polar and equatorial diameters of the fruits ($p > 0.05$); the highest values were found in the treatments 45 mg L⁻¹ (5.34 ± 0.31) and 35 mg L⁻¹ (6.67 ± 0.58). The number of fruits per bunch and per plant showed statistical differences between SiO₂ NPs doses ($p \leq 0.05$), in that increasing doses decreased the number of fruits. The treatment 25 mg L⁻¹ increased fruits per bunch and per plant by 93.23 and 104.08%, respectively, compared to the control (Table 3).

Table 3. Effect of silicon dioxide nanoparticles (SiO₂ NPs) on fruit polar and equatorial diameter and number of fruits per plant of 'Floradade' tomato crop

Treatment	Polar diameter (cm)	Equatorial diameter (cm)	Number of fruits per plant	Number of fruits per bunch
Control	5.26 ± 0.66	6.46 ± 0.47	1.47 ± 0.15 b	1.33 ± 0.06 b
25 mg L ⁻¹	5.28 ± 0.06	6.50 ± 0.50	3.00 ± 0.52 a	2.57 ± 0.46 a
35 mg L ⁻¹	5.00 ± 0.00	6.67 ± 0.58	2.40 ± 0.17 a	1.97 ± 0.15 ab
45 mg L ⁻¹	5.34 ± 0.31	6.17 ± 0.21	2.63 ± 0.31 a	2.13 ± 0.21 a
<i>p</i> -value	0.6833	0.6318	0.0023	0.0032
DMSH	0.9568	1.2052	0.8439	0.7000
CV (%)	7.0089	7.1478	13.5894	13.3100

Means ± standard deviation with different letters in the same column indicate significant differences according to Tukey's test ($p \leq 0.05$)

In relation to tomato fruit weight, no significant statistical differences were shown between the doses of SiO₂ NPs evaluated ($p > 0.05$); however, the dose of 25 mg L⁻¹ presented an increase of 1.43 and 7.39% compared to the treatment of 35 mg L⁻¹ and 45 mg L⁻¹. As for the yield, the foliar doses of SiO₂ NPs were statistically different ($p \leq 0.05$): the 25 mg L⁻¹ treatment (26.74 t ha^{-1}) showed an increase of 99.70, 28.37, and 21.53% compared to the control, 35 mg L⁻¹, and 45 mg L⁻¹ treatments, respectively (Figure 1)

Chlorophyll content in tomato crop leaves registered significant difference between SiO₂ NPs doses at 30 DAT ($p \leq 0.05$), at which point the 35 mg L⁻¹ of SiO₂ NPs treatment presented the highest chlorophyll content value with 52.20 SPAD units, 17.26% higher than the control treatment (Figure 2). However, at 45 and 60 DAT, there was no significant difference ($p > 0.05$).

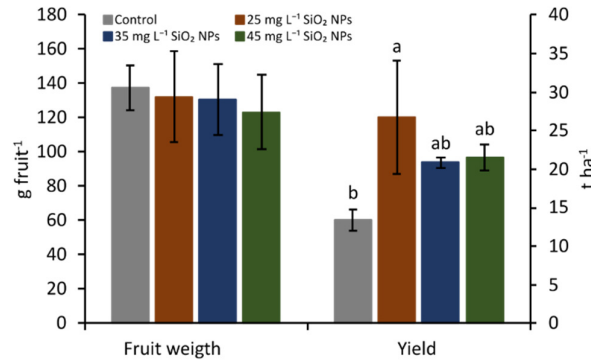


Figure 1. Fruit weight (g fruit^{-1}) and crop yield (t ha^{-1}) of 'Floradade' tomato grown with different foliar doses of silicon dioxide nanoparticles (SiO_2 NPs); \square = control, \blacksquare = 25 mg L^{-1} , \blacksquare = 35 mg L^{-1} , \blacksquare = 45 mg L^{-1} . Means \pm standard deviation with different letters indicates significant difference according to Tukey's test ($p \leq 0.05$)

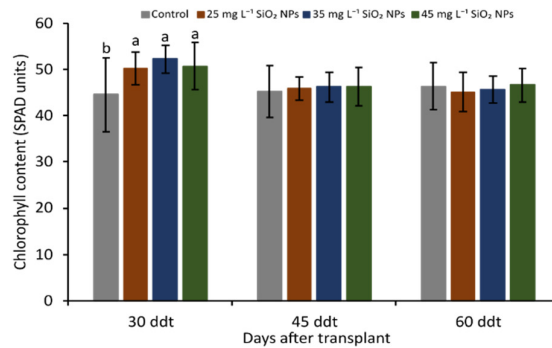


Figure 2. Chlorophyll (SPAD units) content in the leaves of 'Floradade' tomato grown with different foliar doses of silicon dioxide nanoparticles (SiO_2 NPs); \square = control, \blacksquare = 25 mg L^{-1} , \blacksquare = 35 mg L^{-1} , \blacksquare = 45 mg L^{-1} . Means \pm standard deviation with different letters indicate significant difference according to Tukey's test ($p \leq 0.05$)

Nutraceutical Quality

According to statistical analysis, foliar application of SiO_2 NPs positively affected total soluble solids and vitamin C content in 'Floradade' tomatoes ($p \leq 0.05$). In relation to soluble solids, the application of 35 mg L^{-1} of SiO_2 NPs showed an increase of 65.30% in relation to the control; likewise, it presented high quality fruits since tomato for industrial processes and fresh consumption must have a total soluble solids (TSS) value of > 4.5 Brix. Regarding vitamin C, the values obtained in this experiment ranged from 57.96 ± 0.55 to $93.18 \pm 0.95 \text{ mg } 100 \text{ g}^{-1}$. The 35 mg L^{-1} of SiO_2 NPs treatment showed a higher vitamin C content than any other treatment, exceeding the control by 60.77% (Figure 3).

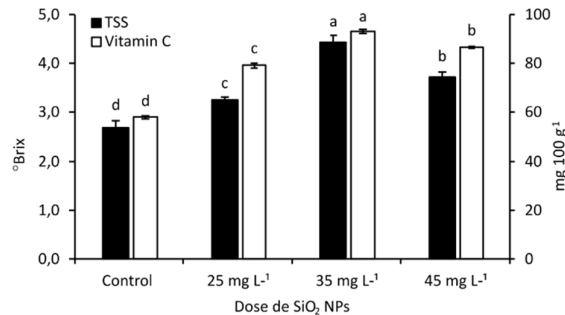


Figure 3. Total soluble solids ($^{\circ}\text{Brix}$) and vitamin C ($\text{mg } 100 \text{ g}^{-1}$) content in 'Floradade' tomatoes grown with different foliar doses of silicon dioxide nanoparticles (SiO_2 NPs); \blacksquare = total soluble solids (TSS), \square = vitamin C. Means \pm standard deviation with different letters indicates significant difference according to Tukey's test ($p \leq 0.05$)

For polyphenol and flavonoid content in tomatoes, there were significant differences between SiO₂ NPs doses ($p \leq 0.05$). The SiO₂ NPs applications presented higher concentrations of polyphenols and flavonoids than the control, with the 35 mg L⁻¹ dose increasing those contents by 52.49 and 59.02% compared to the control (Figure 4).

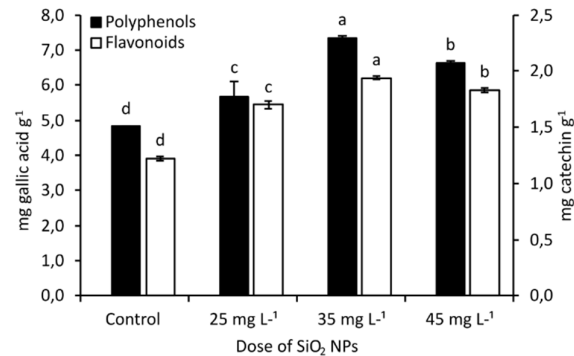


Figure 4. Polyphenol (mg gallic acid g⁻¹) and flavonoid (mg catechin g⁻¹) content in 'Floradade' tomatoes grown with different foliar doses of silicon dioxide nanoparticles (SiO₂ NPs); ■ = polyphenols, □ = flavonoids

Means ± standard deviation with different letters indicate significant difference according to Tukey test ($p \leq 0.05$)

Regarding carotenoids and antioxidant capacity, there was a significant difference between the doses of SiO₂ NPs ($p \leq 0.05$). The highest concentration of carotenoids (175.43 μg βcarotene g⁻¹) and antioxidant capacity (108.33 μmol Trolox g⁻¹) was shown in the 35 mg L⁻¹ treatment, exceeding the control by 67.27 and 17.14%, respectively (Figure 5).

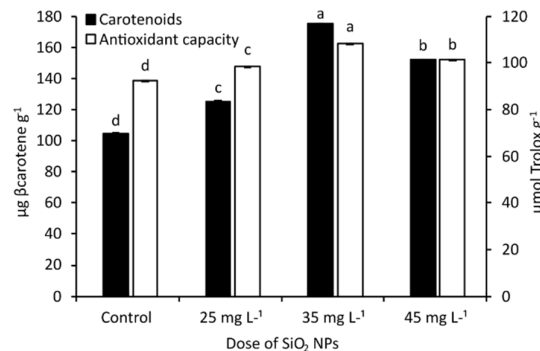


Figure 5. Carotenoids (μg βcarotene g⁻¹) and antioxidant capacity (μmol Trolox g⁻¹) of 'Floradade' tomatoes grown with different foliar dose of silicon dioxide nanoparticles (SiO₂ NPs); ■ = carotenoids, □ = antioxidant capacity

Means ± standard deviation with different letters indicate significant difference according to Tukey's test ($p \leq 0.05$)

Net photosynthetic rate (A), transpiration (E), and water use efficiency (WUA) were statistically different for each of the treatments with the different doses of SiO₂ NPs ($p \leq 0.05$); however, for the variables stomatal conductance (g_s), intercellular CO₂ concentration (C_i), and leaf-air water vapor pressure deficit (VPD), there were no significant differences between treatments ($p > 0.05$). The treatment with the highest net photosynthetic rate and water use efficiency was 25 mg L⁻¹ of SiO₂ NPs. For the transpiration variable, the control treatment presented the highest value, followed by 25 mg L⁻¹ (Figure 6).

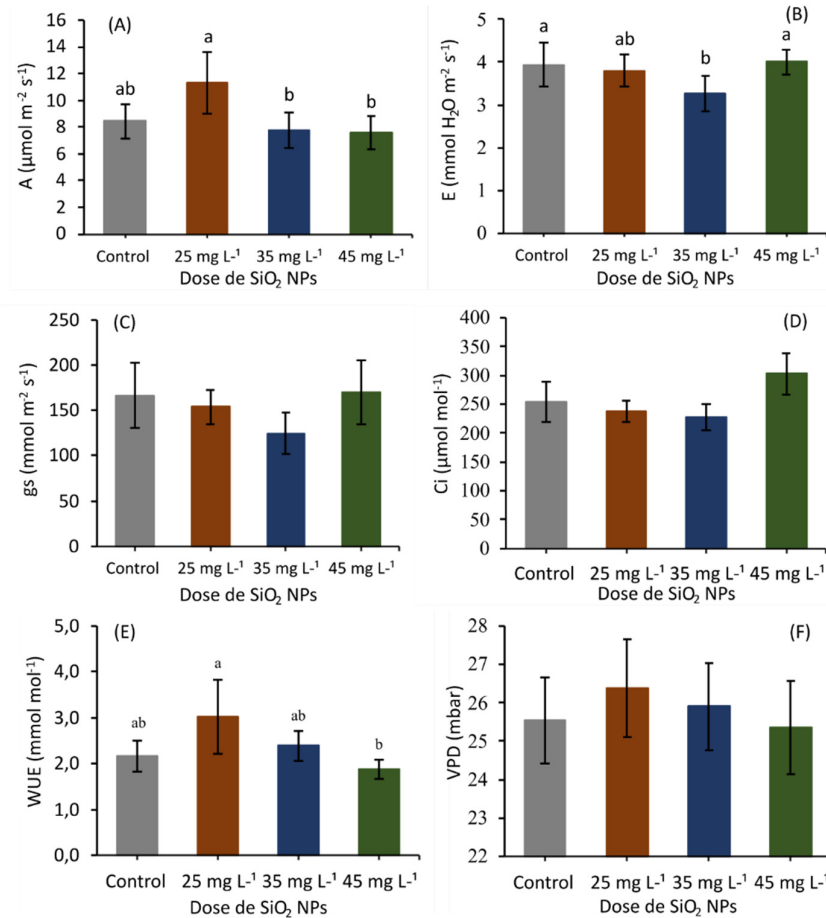


Figure 6. (A) Net photosynthetic rate, (B) transpiration, (C) stomatal conductance, (D) intercellular CO₂ concentration, (E) water use efficiency, and (F) leaf-air water vapor pressure deficit in ‘Floradade’ tomatoes grown with different foliar doses of silicon dioxide nanoparticles (SiO₂ NPs); □ = control, ■ = 25 mg L⁻¹, ▨ = 35 mg L⁻¹, ▩ = 45 mg L⁻¹

Means ± standard deviation with different letters indicate significant difference according to Tukey’s test ($p \leq 0.05$)

Water potential at dawn was statistically different for each of the treatments with SiO₂ NPs doses ($p \leq 0.05$); however, midday water potential, delta of water potential, and plant hydraulic conductivity did not present significant differences among treatments ($p > 0.05$). The treatment with the highest water potential at dawn was 35 mg L⁻¹ of SiO₂ NPs (Figure 7).

Discussion

The results of this study show that SiO₂ NPs doses stimulate plant height and stem diameter in ‘Floradade’ tomatoes under protected agriculture conditions. Another study found that applying 8,000 mg L⁻¹ of SiO₂ NPs improved the vigor of Super Strain B tomato by increasing their germination characteristics; however, higher concentrations caused a decrease in these characteristics (Siddiqui and Al-Whaibi, 2014). This response coincides with the supply of 100 mg L⁻¹ of SiO₂ NPs plus ¾ of NPK base fertilization, which increased plant height by 15.82% and stem diameter by 43.48% in sweet basil (*Ocimum basilicum*) (El-Mahrouk *et al.*, 2024). Similarly, applications of 250 mg L⁻¹ of SiO₂ NPs increased the height of tomato plants subjected to salt stress. This contributes to the hypothesis that SiO₂ NPs confer resistance to plants subjected to abiotic and/or biotic stresses such as insect pests, phytopathogens, drought stress and salt stress (Pinedo-Guerrero *et al.*, 2020).

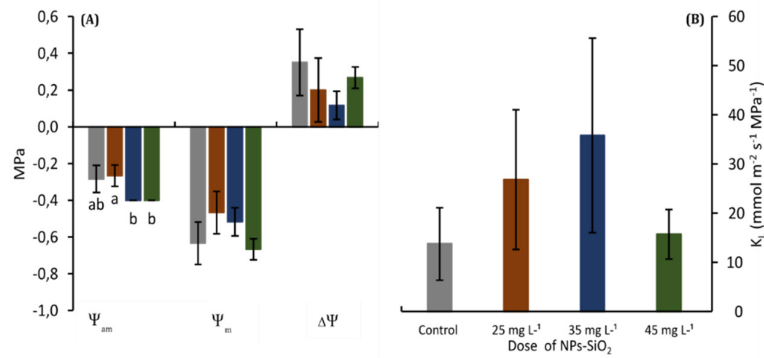


Figure 7. (A) Water potential at sunrise (Ψ_{am}), water potential at midday (Ψ_m), delta of water potential ($\Delta\Psi$), and (B) plant hydraulic conductivity in 'Floradade' tomatoes grown with different foliar doses of silicon dioxide nanoparticles (SiO₂ NPs); ■ = control, ■ = 25 mg L⁻¹, ■ = 35 mg L⁻¹, ■ = 45 mg L⁻¹. Means \pm standard deviation with different letters indicates significant difference according to Tukey's test ($p \leq 0.05$)

Si NPs can regulate the signaling pathways of phytohormones such as salicylic acid (SA), jasmonic acid, and ethylene, which play key roles in biotic stress response and plant acclimation. Foliar spraying of Si NPs enhances SA metabolism by regulating gene expression in tomatoes with a *Ralstonia solanacearum* infection (Yan *et al.*, 2024). Mesoporous SiO₂ NPs represent an effective and safe alternative to fungicides for the management of early blight (*Alternaria solani*) in tomato plants, as they augment plant height, fresh weight, and plant dry weight by 13.73, 49.06, and 55.58%, respectively, compared to plants treated with the synthetic fungicide Metalaxyl. These increases can be attributed to the fact that the SiO₂ NPs reduces the impact of *A. solani* on the leaves, which decreases leaf area damage. This allows the leaves to perform a higher rate of photosynthesis, thus favoring plant growth, which coincides with the present study that the 25 mg L⁻¹ of SiO₂ NPs dose increased the net photosynthetic rate and water efficiency (Derbalah *et al.*, 2019).

Tomato plants with greater height in the initial stage of development tend to be more productive (Moraes *et al.*, 2019). According to Cázarez-Flores *et al.* (2023) and Cázarez-Flores *et al.* (2023), tomato seedling height and stem diameter increased by 31.97 and 7.14% with the application of 30 mg L⁻¹ of SiO₂, respectively, relative to the control. Moreover, the exogenous application of 1 mM of SiO₂ NPs improved the stem diameter of Falcato tomato plants in a greenhouse (Haghighi and Pessaraki, 2013). As plants are treated with Si, the effects of shortages or excesses of nutrients such as manganese and aluminium diminish and the interception of photosynthetically active radiation increases, leading to higher photosynthetic efficiency. There is evidence that Si shows positive effects on germination, growth, biomass production, mineral concentration, and substances of nutritional importance in plants. It also plays a vital role in maintaining ion homeostasis, nutrient absorption, and redistribution, allowing plants to be more efficient with the available resources (Cabezas *et al.*, 2022). Due to the above, the application of SiO₂ NPs improves germination parameter responses, which can be effective in crop growth and yield; this suggests that SiO₂ NPs could be used as a fertilizer for agricultural crop improvement (Sembada *et al.*, 2023; Siddiqui and Al-Whaibi, 2014).

The tallest root length in the present study was recorded with the application of 25 mg L⁻¹ of SiO₂ NPs. This behavior was similar to that reported by Janmohammadi and Sabaghnia (2015), who indicate that the application of 0.4 mM of SiO₂ NPs causes the average root length of Azargol sunflower seedlings (*Helianthus annuus* L.) to increase by 211.11% compared to control. Likewise, *Larix olgensis* seedlings applied with 500 μ L L⁻¹ of SiO₂ NPs promoted greater plant height, diameter at root collar, main root length, and number of lateral roots in seedlings (Bao-shan *et al.*, 2004). Si-based nanofertilizers with a concentration of 3 mM increased root length in Castle Rock VF tomato plants when subjected to 150 mM of NaCl due to the positive regulation of four salt stress genes (AREB, TAS14, NCED3, and CRK1). Furthermore, six genes (RBOH1, APX2, MAPK2, ERF5, MAPK3, and DDF2) were negatively regulated (Almutairi, 2016).

The exogenous addition of Si NPs promoted the expression of gibberellic acid (GA) synthesis (GA20ox1 and GA20ox2) and abscisic acid (ABA) catabolism (CYP707A2) genes while decreasing the expression of genes related to GA deactivation (GA2ox1 and GA2ox2) and ABA synthesis (NCED1, NCED2, and AAO3). This facilitates tomato seed germination under salt stress by regulating GA and ABA homeostasis (Wang *et al.*, 2024). Tomato plants supplemented with Si are better able to tolerate salt stress through the transcription activity of salt stress genes (Almutairi, 2016).

The application of 1,000 mg L⁻¹ of SiO₂ NPs in Sun 7705 tomato plants caused a 49% reduction in root dry weight and 18% reduction in aboveground dry weight compared to the control treatment (González-Moscoso *et al.*, 2021). Increasing from 10 to 2,000 mg L⁻¹ decreased root and stem biomass in cotton (*Gossypium hirsutum* L.) (Le *et al.*, 2014). Similarly, the application of 360 mg kg⁻¹ of SiO₂ NPs decreased the weight of stems and leaves at 50 and 70 days in Icil potato plants (*Solanum tuberosum*), which coincides with the present study in that increasing doses reduces dry matter in the different organs of the crop (Mushinskiy *et al.*, 2018).

Plants treated with Si NPs showed an increase in chlorophyll content (SPAD units) that was similar to the present study at 30 DAT, as well as a higher dry biomass, improved phosphorus and potassium uptake, and a higher activity of antioxidant enzymes, such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). In addition, they show increased expression of SA-related genes (PR-1, PR-5, and PAL) and a reduction in the accumulation of reactive oxygen species (ROS). Si NPs contribute to maintaining ROS homeostasis in plants by enhancing the activity of antioxidant enzymes, mitigating the inhibitory effect of elevated H₂O₂ levels through the SA path-way. Similarly, they induce a high expression of genes associated with this acid, which activates the resistance acquired in plants and increases their resistance to bacterial wilt (Wang *et al.*, 2022).

The values for fruit size (polar and equatorial diameters) obtained in the present study differ from those reported by Reyes-Pérez *et al.* (2023), who indicated that the application of 0.15, 0.25, and 0.35 g plant⁻¹ achieved significant increases in the polar and equatorial diameters of Averado 3059 tomatoes. The efficacy of nanoparticles on seed germination, plant growth, shoot and root biomass, and photosynthetic rate depends on composition, concentration, size, and physical and chemical properties (Shalaby *et al.*, 2016). However, for the variable number of fruits, our results were similar to those reported by Sayed *et al.* (2022), who mention higher fruit numbers, fruit weight, and total yield per plant for Edkawy tomato rootstock combined with 0.5 mg L⁻¹ of nanosilicon treatment compared to the untreated control at three salinity levels. The Edkawy rootstock subjected to salinity of 4,000 and 8,000 mg L⁻¹ of NaCl and 0.5 mg L⁻¹ of nanosilicon produced higher numbers of fruits than the control (0 mg L⁻¹ of NaCl). The application of SiO₂ NPs at concentrations between 30 and 120 mg L⁻¹ increased the number of fruits in Amaco cucumber (*Cucumis melo*) by 66.83% compared to the control (Yassen *et al.*, 2017). SiO₂ nanoparticles increase the accumulation of proline and amino acids in plants, improve nutrient and water uptake, and activate antioxidant enzymes, such as SOD, CAT, POD, nitrate reductase, and glutathione reductase. This strengthens tolerance to stress factors, thus improving agricultural productivity (Shang *et al.*, 2019).

Ebrahimi *et al.* (2024) state that the fresh weight of tomatoes decreases when the plant is subjected to water stress; however, the foliar addition of 100 mg L⁻¹ of Si NPs without water stress increases it by 37.32%. Pinedo-Guerrero *et al.* (2020) employed five applications of 500 mg L⁻¹ of SiO₂ NPs every 15 days upon the growth medium of Cid tomato plants after surface transplanting. They recorded a 17.8% increase in fruit weight compared to the control.

Si application promotes osmotic stress tolerance in both drought-tolerant (LA0147) and drought-sensitive (FERUM) tomato lines. In terms of tolerance, Si increased sulfur (S) and ammonium (NH₄⁺) uptake, resulting in increased production of amino acids such as arginine, methionine, serine, and glycine. In terms of sensitivity, Si significantly stimulated the production of proline and gamma-aminobutyric acid (GABA), reducing the glutathione/glutathione disulfide ratio and balancing redox homeostasis under osmotic stress. The increased production of amino acids - including arginine, methionine, GABA, and proline - favored the

synthesis of free polyamines, such as putrescine and spermidine, thus improving tolerance to osmotic stress (Ali *et al.*, 2018). This indicates the usefulness of Si-based fertilizers in reducing water consumption in tomato cultivation and offers a theoretical basis for their application in agricultural crops grown in arid and semi-arid areas (Shi *et al.*, 2014).

In addition to the above, Marodin *et al.* (2014) indicate that Si fertilization increases the commercial productivity of tomato plants at doses of 400 kg ha⁻¹ of SiO₂ with an estimated productivity of 60.8 t ha⁻¹. SiO₂ NPs have been shown to increase the availability of essential nutrients in the soil, such as phosphorus, potassium, and calcium, favouring their absorption by plant roots. In another study, the foliar application of 0.20 g L⁻¹ of SiO₂ NPs stimulated plant growth, increased photosynthetic pigments (chlorophyll and carotenoids), and reduced the incidence of diseases. Moreover, the use of these nanoparticles improved plant resistance through the increased activation of defense-related enzymes (SOD, CAT, APX, and PAL). Consequently, the foliar application of SiO₂ nanoparticles could be an effective strategy for the management of bacterial and fungal diseases in tomato plants (Parveen and Siddiqui, 2021). SiO₂ NPs have been found to improve the ability of plants to absorb and retain water, even under water stress conditions, resulting in increased biomass development and plant growth (Junedi *et al.*, 2023). The present study is in line with this finding.

Seleiman *et al.* (2023) found that yield characteristics in potato plants (*Solanum tuberosum*) - number of tubers, fresh weight of tubers, and yield per plant - decreased under water deficit conditions; however, foliar applications of 25 and 50 mg L⁻¹ of SiO₂ NPs increased yields compared to water deficit treatments. Likewise, the application of 150 mg L⁻¹ of SiO₂ NPs improved growth attributes, yield, and fruit quality by reducing the effect of stress conditions. The number and length of shoots, leaf area, and leaf chlorophyll in mango (*Mangifera indica*) were increased (Almutairi *et al.*, 2023). SiO₂ NPs improve photosynthesis by obtaining chlorophyll-protein complexes that capture light adequately, particularly when plants are grown under water stress. Si favors plant adaptation to water stress by improving the distribution of light energy between photosystems I and II. This optimization of photosynthesis triggered by Si application promotes enhanced energy dissipation in chloroplasts. In addition, the efficiency of energy dissipation in mitochondria is also increased, which enhances the process in chloroplasts through Si-mediated alternative oxidase (AOX) and the malate/oxaloacetate cycle. As a result, ROS accumulation is reduced due to Si-facilitated energy dissipation (Cao *et al.*, 2020).

The application of SiO₂ NPs in combination with KNO₃ in Strike common beans favored photosynthetic activity, with a 50% increase compared to the control. This increase can be attributed to the regulatory action of Si on stomatal conductance as well as to the strengthening of the antioxidant system and enzymes involved in CO₂ fixation during the dark phase of photosynthesis (Anchondo-Páez *et al.*, 2024). These enzymes include phosphoenolpyruvate carboxylase (PEPC), ribose diphosphate carboxylase (RuBisCO), NADP-malic enzyme (NADP-ME), fructose dehydrogenase (NADP-MDH), and pyruvate phosphate double kinase (PPDK), thus improving the photosynthetic process and promoting plant growth and yield parameters (Hao *et al.*, 2023). The regulation of photosynthetic processes by the action of SiO₂ NPs could explain the higher yields found in these treatments (Anchondo-Páez *et al.*, 2024).

Soluble solids and vitamin C increased with the application of 35 mg L⁻¹ of SiO₂ NPs in the present study. These results are in agreement with the application of 0.35 g plant⁻¹ of Si in Acerado 3059 tomato plants, which increased both total soluble solids and ascorbic acid (vitamin C). However, when the dose was reduced to 0.25 and 0.15 g plant⁻¹ of Si, a decrease in both parameters was observed (Reyes-Pérez *et al.*, 2023). Si supply reduces fruit transpiration, contributing to fruit quality (Sousa *et al.*, 2022). Figueiredo *et al.* (2008) found increases in total sugars and glucose content, hence a higher °Brix content in strawberry fruit pulp developed from Si-treated plants. In addition, these contents act as osmoprotectants, carbon sources, and neutralizers of free radicals in the plants (González-García *et al.*, 2022). The application of Si to Fortuna strawberry plants increased quality (fruit diameter, fruit weight, and glucose and fructose content) and yield, and increased agronomic benefits by improving fruit shelf life without causing distinguishable physicochemical changes

(Peris-Felipo *et al.*, 2020). The application of 2 mM of SiO₂ NPs increased the content of total soluble solids, free amino acids, and proline in Giza 6 common bean plants, with increases of 87, 72, and 52%, respectively. These results suggest a correlation between the accumulation of soluble sugars, proline, and tolerance to osmotic stress (Sorial *et al.*, 2022).

Doses of 250 mg L⁻¹ of SiO₂ NPs caused a 4.85% increase in total phenol content in Sun 7705 tomatoes. In contrast, a dose of 1,000 mg L⁻¹ of SiO₂ NPs reduced phenolic content by 21.74 % compared to the control (González-Moscoso *et al.*, 2019). The application of 500 mg L⁻¹ of Si NPs increased total phenolic content by 25.19% and flavonoid content by 17.9% in Cid tomatoes without salt stress. This effect persisted when plants were exposed to salt stress and 50 mM of NaCl with different levels of increment (Pinedo-Guerrero *et al.*, 2020). Liava *et al.* (2023) indicate that the application of SiO₂ at 92% (w/w) on Heinz 1162 tomato plants generated the highest content of total polyphenols in fruits, reaching 22.5±0.9 mg GAE g⁻¹ in the extracts, which represented an increase of 17.18% compared to the control group. However, they also reported a 7.14% decrease in total flavonoid content relative to the control, which contrasts with the findings of the present study.

Mentha arvensis L. plants treated with 120 mg L⁻¹ of SiO₂ NPs an increased total phenolic content as well as improved photosynthetic efficiency (with an increase of 8.43% in photosystem II maximum efficiency and 19.6% in photosystem II operational efficiency). This enabled the plants to reach greater heights and increased the plants' fresh and dry weight, leaf area, total chlorophyll content, and carotenoid content. Likewise, a higher activity of antioxidant enzymes was noted, including CAT (81.3%), POD (71.9%), and SOD (32%), compared to untreated plants (Aqeel *et al.*, 2024). Coupled with the above, wheat seedlings treated with SiO₂ NPs simultaneously activated several defense mechanisms compared to untreated seedlings. These mechanisms included (i) the induction of defense-related compounds, such as the accumulation of SA and its main biosynthetic enzyme, phenylalanine ammonium-lyase (PAL), and (ii) the activation of both enzymatic (POD, SOD, APX, CAT, and PPO) and non-enzymatic (phenols and flavonoids) antioxidant compounds (Abdelrhim *et al.*, 2021). When SiO₂ NPs were applied to lily leaves (*Lilium orientales*) at a concentration of 1,000 mg L⁻¹, the phenolic content increased by 25.93% in the leaves compared to the control (Sanchez-Navarro *et al.*, 2021). Phenolic compounds play a crucial role in plant defense, protecting against various types of stress, as well as neutralizing free radicals and decomposing peroxides. SiO₂ NPs promote a higher accumulation of phenols in the leaf epidermis compared to untreated leaves. This phenomenon could be related to the accumulation of insoluble silica NPs in the epidermis, which promotes the concentration of constitutive phenols in epidermal cells due to their high adsorption surface (Goswami and Mathur, 2022).

Ahamad *et al.* (2023) state that plant pathogens (*Meloidogyne incognita*, *Alternaria dauci*, and *Rhizoctonia solani*) in carrot plants (*Daucus carota*) cause a reduction in plant growth parameters, chlorophyll, and carotenoid content. But *Rhizophagus irregularis* inoculation in the root system plus the foliar application of 0.10 mg mL⁻¹ of SiO₂ NPs resulted in increased plant fresh weight, dry weight of the shoots, dry weight of the roots, and carotenoid content compared to plants inoculated with *M. incognita*, *A. dauci*, and *R. solani*. Similarly, lentil (*Lens culinaris*) and soybean (*Glycine max*) plants grown under salt stress (600 mM of NaCl) and with 10 g L⁻¹ of Si NPs resulted in an increase in chlorophyll contents of 1.67 and 2.85%, and carotenoid contents of 1.54 and 1.87% compared to the control of each species, respectively. This behavior helps to reduce the negative effects of salinity on plant growth and development attributes (Sarkar *et al.*, 2024). Increases in carotenoids in the edible organs of plants are of utmost importance because they have beneficial effects on human health: reducing the risk of certain forms of cancer, cardiovascular diseases, and macular degeneration, among others (Elvira-Torales *et al.*, 2019). The findings of the present study are consistent with those reported by González-Moscoso *et al.* (2019), who pointed out that the antioxidant capacity in tomatoes increased by 79.59 and 99.17% after applying arsenic plus 250 and 1,000 mg L⁻¹ of SiO₂ NPs compared to the control, respectively. The antioxidant capacity refers to the ability to inhibit the oxidation process, a highly desirable property in food since oxidation is closely related to the development of various diseases and aging. Tomatoes

are widely recognized for their high content of natural antioxidants, such as lycopene, phenolic compounds, and ascorbic acid, which act in a complementary manner to provide antioxidant effects (Vinha *et al.*, 2014).

Conclusions

The foliar application of SiO₂ NPs had a favourable impact on the growth and development of 'Floradade' tomatoes grown in greenhouse conditions. The dose of 45 mg L⁻¹ of SiO₂ NPs was the most effective in increasing plant height in the early growth stages (30 and 45 DAT), although this effect decreased with time. In terms of stem diameter and root length, the 25 mg L⁻¹ dose produced the best results. It also increased fruit yield per plant. Regarding nutraceutical properties, the 35 mg L⁻¹ dose stood out for increasing the contents of soluble solids, vitamin C, polyphenols, flavonoids, and carotenoids, and for its antioxidant capacity in the tomatoes. These results suggest that the application of SiO₂ NPs, especially at concentrations ranging from 25 to 35 mg L⁻¹, has not only the potential to improve yield but also to increase the nutraceutical quality of tomato fruits, which could have important implications for commercial production and healthy eating.

Authors' Contributions

Conceptualization: J.J.R.P. and L.T.L.R.; Data curation: B.E.P.; Formal analysis: B.E.P.; Funding acquisition: J.J.R.P.; Investigation: J.J.R.P.; Methodology: J.J.R.P.; Project administration: J.J.R.P.; Resources: J.J.R.P.; Software: B.E.P.; Supervision: J.J.R.P.; Validation: J.J.R.P., B.E.P. and J.L.G.H.; Visualization; Writing - original draft J.J.R.P., L.T.L.R., J.A.T.R., W.T., P.P.R.; Writing - review and editing J.J.R.P., B.E.P., P.P.R. All authors read and approved the final manuscript.

Acknowledgements

To the Universidad Técnica Estatal de Quevedo, for the support granted through the Fondo Competitivo de Investigación Científica y Tecnológica (FOCICYT) 10th Call, through project PFOC 10-03-2024 "Uso de nanopartículas de calcio y silicio como atenuante del estrés hídrico en cultivos hortícolas"

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

- Abdelrhim AS, Mazrou YSA, Nehela Y, Atallah OO, El-Ashmony RM, Dawood MFA (2021). Silicon dioxide nanoparticles induce innate immune responses and activate antioxidant machinery in wheat against *Rhizoctonia solani*. *Plants* 10(12):1-25. <https://doi.org/10.3390/plants10122758>
- Ahamad L, Siddiqui ZA, Hashem A, Abd-Allah EF (2023). Use of AM fungus *Rhizoglyphus irregularis* and silicon dioxide nanoparticles for the management of *Meloidogyne incognita*, *Alternaria dauci* and *Rhizoctonia solani* and growth of carrot. *Archives of Phytopathology and Plant Protection* 56(6):466-488. <https://doi.org/10.1080/03235408.2023.2207958>

- Ali N, Schwarzenberg A, Yvin JC, Hosseini SA (2018). Regulatory role of silicon in mediating differential stress tolerance responses in two contrasting tomato genotypes under osmotic stress. *Frontiers in Plant Science* 9:1475. <https://doi.org/10.3389/fpls.2018.01475>
- Alimohamadian M, Aramideh S, Mirfakhraie S, Frozan M (2022). Silica nanoparticle: a potential of non-invasive and as a natural insecticide application for beet armyworm, *Spodoptera exigua* Hubner (Lep.: Noctuidae) control. *Agricultural Engineering International: CIGR Journal* 24(2):248-257.
- Almutairi KF, Górnik K, Awad RM, Ayoub A, Abada HS, Mosa WFA (2023). Influence of selenium, titanium, and silicon nanoparticles on the growth, yield, and fruit quality of mango under drought conditions. *Horticulturae* 9(11):1-15. <https://doi.org/10.3390/horticulturae9111231>
- Almutairi ZM (2016). Effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato (*Solanum lycopersicum* L.) seedlings under salt stress. *Plant Omics Journal* 9(1):106-114.
- Anchondo-Pérez J, Sánchez-Chávez E, Ramirez-Estrada CA, Salcido-Martínez A, Ochoa-Chaparro EH, Muñoz M, E (2024). Eficacia de nanopartículas de silicio y Codasil® como potenciales bioestimulantes en frijol ejotero. *Terra Latinoamericana* 42 (1):1-10. <https://doi.org/10.28940/terra.v42i0.1885>
- Ansari M, Ahmed S, Abbasi A, Khan MT, Subhan M, Bukhari NA, ... Abdelsalam NR (2023). Plant mediated fabrication of silver nanoparticles, process optimization, and impact on tomato plant. *Scientific Reports* 13(1):18048. <https://doi.org/10.1038/s41598-023-45038-x>
- Aqeel U, Aftab T, Khan MMA, Gill SS, Naeem M (2024). Silicon dioxide nanoparticles as catalysts for improved growth, enzymatic activities and essential oil production in *Mentha arvensis* L. *South African Journal of Botany* 172:161-174. <https://doi.org/10.1016/j.sajb.2024.06.044>
- Bao-shan L, Shao-qi D, Chun-hui L, Li-jun F, Shu-chun Q, Min Y (2004). Effect of TMS (nanostructured silicon dioxide) on growth of *Changbai larch* seedlings. *Journal of Forestry Research* 15(2):138-140.
- Cabezas GA, Camus AF, Condori WE, González VFA, Mazuela AP (2022). El silicio (Si) y su efecto mitigador del estrés salino en cultivos hortícolas. *IDESIA* 40(1):129-133.
- Cao BL, Ma Q, Xu K (2020). Silicon restrains drought-induced ROS accumulation by promoting energy dissipation in leaves of tomato. *Protoplasma* 257(2):537-547. <https://doi.org/10.1007/s00709-019-01449-0>
- Cazárez-Flores LL, Angulo-Castro A, Vega-Gutiérrez TA, Ayala-Tafoya F, Aguilar- Quiñonez JA (2023). Producción de tomate en respuesta a dosis de silicio. *Ecosistemas y Recursos Agropecuarios* 10(3):1-7. <https://doi.org/10.19136/era.a10n3.3851>
- Cázarez-Flores LL, Velázquez-Alcaraz TJ, Partida-Ruvalcaba L, Ayala-Tafoya F, Zazueta-Torres ND, Yáñez-Juárez MG (2023). Plántulas de pepino y tomate fortificadas con silicio y cloro. *Revista Mexicana de Ciencias Agrícola* 14(1):123-128.
- Derbalah A, Shenashen M, Hamza A, Mohamed A, El Safty S (2019). Antifungal activity of fabricated mesoporous silica nanoparticles against early blight of tomato. *Egyptian Journal of Basic and Applied Sciences* 5(2):145-150. <https://doi.org/10.1016/j.ejbas.2018.05.002>
- D'Imperio M, Renna M, Cardinali A, Buttaro D, Santamaria P, Serio F (2016). Silicon biofortification of leafy vegetables and its bioaccessibility in the edible parts. *Journal of the Science of Food and Agriculture* 96(3):751-756. <https://doi.org/10.1002/jsfa.7142>
- Ebrahimi H, Soltani Mohammadi A, Boroomand Nasab S, Alamzadeh Ansari N, Juárez-Maldonado A (2024). Evaluation the impact of silicon nanoparticle on growth and water use efficiency of greenhouse tomato in drought stress condition. *Applied Water Science* 14(9):1-10. <https://doi.org/10.1007/s13201-024-02256-6>
- El-Mahrouk EM, Atef EAM, Gabr MK, Aly MA, Glowacka A, Ahmed MAA (2024). Application of ZnO NPs, SiO₂ NPs and date pollen extract as partial substitutes to nitrogen, phosphorus, and potassium fertilizers for sweet basil production. *Plants* 13(2):1-24. <https://doi.org/10.3390/plants13020172>
- Elvira-Torales LI, García-Alonso J, Periago-Caston MJ (2019). Nutritional importance of carotenoids and their effect on liver health: A review. *Antioxidants* 8(7):1-23. <https://doi.org/10.3390/antiox8070229>
- Figueiredo CF, Botrel PP, Teixeira CP, Petrazzini LL, Locarno M, de Carvalho JG (2008). Pulverização foliar e fertirrigação com silício nos atributos físico-químicos de qualidade e índices decoloração do morango. *Ciência e Agrotecnologia* 34(5):1306-1311.
- González-García Y, Flores-Robles V, Cadenas-Pliego G, Benavides-Mendoza A, Cabrera De La Fuente M, Sandoval-Rangel A, Juárez-Maldonado A (2022). Application of two forms of silicon and their impact on the postharvest and the content of bioactive compounds in cucumber (*Cucumis sativus* L.) fruits. *Biocell* 46(11):2497-2506. <https://doi.org/10.32604/biocell.2022.021861>

- González-Moscoso M, Martínez-Villegas NV, Cadenas-Pliego G, Benavides-Mendoza A, Rivera-Cruz MDC, Gonzalez-Morales S, Juárez-Maldonado A (2019). Impact of silicon nanoparticles on the antioxidant compounds of tomato Fruits stressed by Arsenic. *Foods* 8(12):612. <https://doi.org/10.3390/foods8120612>
- González-Moscoso M, Martínez-Villegas NV, Meza-Figueroa D, Rivera-Cruz MC, Cadenas-Pliego G, Juárez-Maldonado A (2021). Las nanopartículas de SiO₂ Mejoran la absorción de nutrientes en plantas de tomate desarrolladas en presencia de arsénico. *Revista Bio Ciencias* 8:1-25. <https://doi.org/10.15741/revbio.08.e1084>
- Goswami P, Mathur J (2022). Application of agro-waste-mediated silica nanoparticles to sustainable agriculture. *Bioresources and Bioprocessing* 9:9. <https://doi.org/10.1186/s40643-022-00496-5>
- Haghighi M, Pesarakli M (2013). Influence of silicon and nano-silicon on salinity tolerance of cherry tomatoes (*Solanum lycopersicum* L.) at early growth stage. *Scientia Horticultura* 161:111-117. <https://doi.org/10.1016/j.scienta.2013.06.034>
- Hao Y, Yu Y, Sun G, Gong X, Jiang Y, Lv G, ... Qian C (2023). Effects of multi-walled carbon nanotubes and nano-silica on root development, leaf photosynthesis, active oxygen and nitrogen metabolism in maize. *Plants* 12(8):1-25. <https://doi.org/10.3390/plants12081604>
- Henriquez C, Aliaga C, Lissi E (2002). Formation and decay of the ABTS derived radical cation: A comparison of different preparation procedures. *International Journal of Chemical Kinetics* 34(12):659-665. <https://doi.org/10.1002/kin.10094>
- Igbokwe GE, Anioakor GC, Anagonye CO (2013). Determination of β -carotene & vitamin C content of fresh green pepper (*Capsicum annuum*), fresh red pepper (*Capsicum annuum*) and fresh tomatoes (*Solanum lycopersicum*) fruits. *The Bioscientist Journal* 1(1):89-93.
- Janmohammadi M, Sabaghnia N (2015). Effect of pre-sowing seed treatments with silicon nanoparticles on germinability of sunflower (*Helianthus annuus*). *Botanica Lithuanica* 21(1):13-21.
- Junedi MA, Mukhopadhyay R, Manjari KS (2023). Alleviating salinity stress in crop plants using new engineered nanoparticles (ENPs). *Plant Stress* 9:100184. <https://doi.org/10.1016/j.stress.2023.100184>
- Le VN, Rui Y, Gui X, Li X, Liu S, Han Y (2014). Uptake, transport, distribution and bio-effects of SiO₂ nanoparticles in Bt-transgenic cotton. *Journal of Nanobiotechnology* 12:50. <https://doi.org/10.1186/s12951-014-0050-8>
- Liava V, Chaski C, Añibarro-Ortega M, Pereira A, Pinela J, Barros L, Petropoulos SA (2023). The effect of biostimulants on fruit quality of processing tomato grown under deficit irrigation. *Horticulturae* 9(11):1184. <https://doi.org/10.3390/horticulturae9111184>
- Marodin CJ, Resende TVJ, Morales GFR, Silva LSM, Galvão GA, Zanin SD (2014). Yield of tomato fruits in relation to silicon sources and rates. *Horticultura Brasileira* 32(1):220-224.
- Miyake Y, Takahashi E (1978). Silicon deficiency of tomato plant. *Soil Science and Plant Nutrition* 24(2):175-189. <https://doi.org/10.1080/00380768.1978.10433094>
- Moraes WB, Gonçalves AO, Camara GDR, Silva MA, Damascena AP, Rosas JTF, Junior EM (2019). Resistance induction efficiency of silicon dioxide against *Meloidogyne incognita* in tomato. *Revista Colombiana de Ciencias Hortícolas* 13(1):55-63. <https://doi.org/10.17584/rcch.2019v13i1.7834>
- Moshabaki FI, Tahmourespour A, Hoodaji M, Atabadi M, Mohammadi A (2019). Influence of exopolysaccharide-producing bacteria and SiO₂ nanoparticles on proline content and antioxidant enzyme activities of tomato seedlings (*Solanum lycopersicum* L.) under salinity stress. *Polish Journal of Environmental Studies* 28(1):153-163. <https://doi.org/10.1159/000081206>
- Mushinskiy AA, Aminovsmall a CEV, Korotkova AM (2018). Evaluation of tolerance of tubers *Solanum tuberosum* to silica nanoparticles. *Environmental Science and Pollution Research* 25(34):34559-34569. <https://doi.org/10.1007/s11356-018-3268-4>
- Parveen A, Siddiqui ZA (2021). Impact of silicon dioxide nanoparticles on growth, photosynthetic pigments, proline, activities of defense enzymes and some bacterial and fungal pathogens of tomato. *Vegetos* 35(1):83-93. <https://doi.org/10.1007/s42535-021-00280-4>
- Peet MM, Welles GWH (2005). Greenhouse tomato production. In: Heuvelink E (Ed). *Tomatoes*. CABI: Cambridge, MA, USA.
- Peris-Felipo FJ, Benavent-Gil Y, Hernandez-Apaolaza L (2020). Silicon beneficial effects on yield, fruit quality and shelf-life of strawberries grown in different culture substrates under different iron status. *Plant Physiology and Biochemistry* 152:23-31. <https://doi.org/10.1016/j.plaphy.2020.04.026>

- Pinedo-Guerrero ZH, Cadenas-Pliego G, Ortega-Ortiz H, González-Morales S, Benavides-Mendoza A, Valdés-Reyna J, Juárez-Maldonado A (2020). Form of silica improves yield, fruit quality and antioxidant defense system of tomato plants under salt stress. *Agriculture* 10(9):1-21. <https://doi.org/10.3390/agriculture10090367>
- Reyes-Pérez JJ, Tipán-Torres HC, Llerena-Ramos LT, Hernandez-Montiel LG, Rivas-García T (2023). Silicon increased the growth, productivity, and nutraceutical quality of tomato (*Solanum lycopersicum* L.). *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 53(2):13155. <https://doi.org/10.15835/nbha51213155>
- Sack L, Melcher PJ, Zwieniecki MA, Holbrook NM (2002). The hydraulic conductance of the angiosperm leaf lamina: a comparison of three measurement methods. *Journal Of Experimental Botany* 53(378):2177-2184. <https://doi.org/10.1093/jxb/erf069>
- Sack L, Scoffoni C (2012). Measurement of leaf hydraulic conductance and stomatal conductance and their responses to irradiance and dehydration using the Evaporative Flux Method (EFM). *Jove-Journal of Visualized Experiments* (70):e4179. <https://doi.org/10.3791/4179>
- Sanchez-Navarro JF, Gonzalez-Garcia Y, Benavides-Mendoza A, Morales-Diaz AB, Gonzalez-Morales S, Cadenas-Pliego G, ... Juarez-Maldonado A (2021). Silicon nanoparticles improve the shelf life and antioxidant status of lilyum. *Plants* 10(11):1-16. <https://doi.org/10.3390/plants10112338>
- Sarkar MM, Sarkar A, Roy S (2024). Fertigation of NaCl-stressed lentil and soybean plants with silica nanoparticles improves seed yield and nutritional attributes. *Plant Nano Biology* 8:100068. <https://doi.org/10.1016/j.plana.2024.100068>
- Sayed EG, Mahmoud AWM, El-Mogy MM, Ali MAA, Fahmy MAM, Tawfic GA (2022). The effective role of nano-silicon application in improving the productivity and quality of grafted tomato grown under salinity stress. *Horticulturae* 8(4):1-19. <https://doi.org/10.3390/horticulturae8040293>
- Seleiman MF, Al-Selwey WA, Ibrahim AA, Shady M, Alsadon AA (2023). Foliar applications of ZnO and SiO₂ nanoparticles mitigate water deficit and enhance potato yield and quality traits. *Agronomy* 13(2):1-16. <https://doi.org/10.3390/agronomy13020466>
- Sembada AA, Maki S, Faizal A, Fukuhara T, Suzuki T, Lenggoro IW (2023). The role of silica nanoparticles in promoting the germination of tomato (*Solanum lycopersicum*) seeds. *Nanomaterials* 13(14):1-14. <https://doi.org/10.3390/nano13142110>
- Shalaby TA, Bayoumi Y, Abdalla N, Taha H, Alshaal T, Shehata S, ... El-Ramady H (2016). Nanoparticles, soils, plants and sustainable agriculture. In Ranjan S, Dasgupta N, Lichtfouse E (Eds). *Nanoscience in Food and Agriculture Sustainable Agriculture Reviews*. Springer, Cham 20:283-312. https://doi.org/10.1007/978-3-319-39303-2_10
- Shang Y, Hasan MK, Ahammed GJ, Li M, Yin H, Zhou J (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules* 24(14):1-23. <https://doi.org/10.3390/molecules24142558>
- Shi Y, Zhang Y, Yao H, Wu J, Sun H, Gong H (2014). Silicon improves seed germination and alleviates oxidative stress of bud seedlings in tomato under water deficit stress. *Plant Physiology and Biochemistry* 78:27-36. <https://doi.org/10.1016/j.plaphy.2014.02.009>
- Siddiqui MH, Al-Wahaibi MH (2014). Role of nano-SiO₂ in germination of tomato (*Lycopersicon esculentum* seeds Mill.). *Saudi Journal of Biological Sciences* 21(1):13-17. <https://doi.org/10.1016/j.sjbs.2013.04.005>
- Singleton V, Orthofer R, Lamuela-Raventós RM (1974). Analysis of total phenols and other oxidation substrates and antioxidants by means of Folin-Ciocalteu reagent. *American Journal of Enology and Viticulture* 25(1):152-153.
- Sorial ME, Soliman AA, Abdel-Fattah D, Selim DA-F (2022). Physiological responses of *Phaseolus vulgaris* to some nano bio-stimulants under salt stress conditions. *Annals Of Agricultural Sciences* 60(3):809-820.
- Sousa RMVd, Silva AA, Fonseca GM, Cunha JGd, Lacerda JdJ, Guimarães WP, ... Silva EMD (2022). Silicon increases the production and quality of cherry tomato under different electrical conductivity levels. *Semina. Ciências Agrárias* 43(3):1297-1316. <https://doi.org/10.5433/1679-0359.2022v43n3p1297>
- Vinha AF, Alves RC, Barreira SVP, Castro A, Costa ASG, Oliveira MBPP (2014). Effect of peel and seed removal on the nutritional value and antioxidant activity of tomato (*Lycopersicon esculentum* L.) fruits. *LWT - Food Science and Technology* 55(1):197-202. <https://doi.org/10.1016/j.lwt.2013.07.016>
- Wang L, Pan T, Gao X, An J, Ning C, Li S, Cai K (2022). Silica nanoparticles activate defense responses by reducing reactive oxygen species under *Ralstonia solanacearum* infection in tomato plants. *NanoImpact* 28:100418. <https://doi.org/10.1016/j.impact.2022.100418>
- Wang T, Long H, Mao S, Jiang Z, Liu Y, He Y, ... Yan G (2024). Silicon nanoparticles improve tomato seed germination more effectively than conventional silicon under salt stress via regulating antioxidant system and hormone metabolism. *Horticulturae* 10(8):785. <https://doi.org/10.3390/horticulturae10080785>

- Weisany W, Razmi J, Eshaghabadi AH, Pashang D (2024). Silicon nanoparticles (SiNP): A novel and sustainable strategy for mitigating environmental stresses in plants. *Journal of Soil Science and Plant Nutrition* 24(2):2167-2191. <https://doi.org/10.1007/s42729-024-01790-1>
- Yan G, Huang Q, Zhao S, Xu Y, He Y, Nikolic M, ... Zhu Z (2024). Silicon nanoparticles in sustainable agriculture: synthesis, absorption, and plant stress alleviation. *Frontiers in Plant Science* 15:1393458. <https://doi.org/10.3389/fpls.2024.1393458>
- Yassen A, Abdallah E, Gaballah M, Zaghoul S (2017). Role of silicon dioxide nano fertilizer in mitigating salt stress on growth, yield and chemical composition of cucumber (*Cucumis sativus* L.). *International Journal of Agricultural Research* 12(3):130-135. <https://doi.org/10.3923/ijar.2017.130.135>
- Zhishen J, Mengcheng T, Jianming W (1999). The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chemistry* 64 (1):555-559. [https://doi.org/10.1016/S0308-8146\(98\)00102-2](https://doi.org/10.1016/S0308-8146(98)00102-2)



The journal offers free, immediate, and unrestricted access to peer-reviewed research and scholarly work. Users are allowed to read, download, copy, distribute, print, search, or link to the full texts of the articles, or use them for any other lawful purpose, without asking prior permission from the publisher or the author.



License - Articles published in *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* are Open-Access, distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) License.

© Articles by the authors; Licensee UASVM and SHST, Cluj-Napoca, Romania. The journal allows the author(s) to hold the copyright/to retain publishing rights without restriction.

Notes:

- **Material disclaimer:** The authors are fully responsible for their work and they hold sole responsibility for the articles published in the journal.
- **Maps and affiliations:** The publisher stay neutral with regard to jurisdictional claims in published maps and institutional affiliations.
- **Responsibilities:** The editors, editorial board and publisher do not assume any responsibility for the article's contents and for the authors' views expressed in their contributions. The statements and opinions published represent the views of the authors or persons to whom they are credited. Publication of research information does not constitute a recommendation or endorsement of products involved.