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ORIGINAL ARTICLE

Evaluation the impact of silicon nanoparticle on growth and water use efficiency of greenhouse tomato in drought stress condition

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Abstract

This study focused on the effect of silicon nanoparticles (Si-Nps) use on growth and water use efficiency (WUE) of tomato in hydroponic cultivation under drought stress. Experimental treatments included full irrigation, supplying 85 and 70% of crop water requirement (I_{100}, I_{85} and I_{70}) and use of Si-Nps in three levels of 0, 50 and 100 ppm (N_0, N_{50} and N_{100}) which was performed in a completely randomized design with three replications. Si-Nps were applied in two ways: leaf feeding (L) and root feeding (R). Data analysis showed that different levels of irrigation, Si-Nps and the interaction effect of theirs had a significant effect on fruit weight, leaf fresh and dry weight, stem fresh weight and WUE at 1% level. Si-Nps had a significant effect on stem dry weight at 1% and fruit sugar at 5%. The interaction effect of irrigation and Si-Nps had a significant effect on stem dry weight and fruit sugar at 1%. The maximum fresh fruit weight was related to treatment $I_{85}LN_{100}$ and compared to the control treatment, it was 7.9% more. The maximum WUE was observed in I70RN50 treatment, which was 56.3% higher than control treatment. Generally, applying irrigation $I_{70}RN_{50}$ gives the best result for hydroponic tomato cultivation in greenhouse conditions.

Keywords Drought stress · Irrigation · Silicon nanoparticle · Tomato

Introduction

The scarcity of water resources is one of the important limiting factors of agriculture in the world. Iran is one of the countries that is facing water shortage and drought, and its aggravation in the future will cause economic, social, environmental and political problems (Momenpour et al. 2021). Optimum use of water sources in various sectors, including agriculture, is one of the most essential solutions to prevent the leading challenges and crises in using water sources. In recent years, one of the solutions for optimizing water consumption in crops and producing crops with maximum income under water shortage conditions is the use of deficit irrigation technique. Deficit irrigation is a strategy to increase yield in conditions of reduced agricultural water consumption (Yu et al. 2020) and the main purpose is to increase the efficiency of water use and remove part of irrigation water that does not have a significant effect on increasing yield. Although in deficit irrigation, the yield per unit area may be reduced, it was saved with water. Deficit irrigation can increase the cultivated area with a limited yield reduction and this yield reduction is compensated by a

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significant increase in economic efficiency (Patel and Rajput 2013). Chand et al. (2021) investigated the deficit irrigation on tomato production in the greenhouse and stated that deficit irrigation could lead to a decrease in tomato yield and improve water productivity and yield quality parameters. Cruz et al. (2019) reported an 85% reduction in water consumption and an increase in carotenoids and soluble sugar of tomato under drought stress conditions.

In recent years, silicon nanoparticles (Si-Nps) increased plant resistance in adverse environmental conditions (Rajput et al. 2021). Si-Nps are defined as having at least one dimension less than 100 nm. Over the past decade, Si-Nps have been widely used in industry and agriculture for their unique characteristics such as small size and high surface to volume ratio (Zhu et al. 2018). The use of silicone has a biological effect and has the best results in stress conditions such as salinity, lack or excess of water. Foliar feeding should be introduced as a standard treatment in the management of many crops because it helps to increase crop yield and it is also important that it is environmentally safe (Artyszak 2018). Si-Nps are common for greenhouse plants but also have a positive effect on crops and help against salinity stress, water stress and crop yield (Artyszak 2018).

Many research presented the effect of Si-Nps on the yield and growth of the plant. Zhang et al. (2022) evaluated the effect irrigation (173.66, 372.70 and 528.31 mm) and fertilizer (100, 200 and 300 kg/ha) on tomato growth and concluded that with the increase in irrigation, total dry matter mass first increased and then decreased, while the nutrition and taste indicators of the fruit decreased. Also, the effects of irrigation on tomato yield were greater than that of fertilizer, and with the increase in irrigation, water consumption efficiency decreased, but with the use of more fertilizer, water consumption efficiency first increased and then decreased. Sayed et al. (2022) investigated the impact of using nano-silicon in improving tomato yield in salinity stress condition and suggested using nano-silicon foliar spray in high salinity conditions. Abdullah (2019) investigated the effect of using Kaolin and Pinoline on the growth and efficiency of tomato water consumption under drought stress conditions and stated that the reduction of water consumption significantly increased the efficiency of water consumption and reduced the relative amount of water content in the leaves. Also, Kaolin particles effectively increased physiological activities under reduced irrigation and 25% saving in irrigation water led to 26.24% increase in water efficiency compared to plants without stress. Akhlaghi Mohammadi et al. (2019) announced that the use of silicon nanoparticles in water stress conditions increases the morphological characteristics of tomato plants. Wang and Xing (2017) evaluated the effect of irrigation water and fertilizer use on tomato yield and reported the best yield, efficiency of water consumption and fruit quality in the treatment of 25% deficit irrigation and application of 240 N, 120 P_2O_5 and 150 K_2O kg/ha.

Tomato (*Solanum lycopersicum L.*) is a widely used vegetable. Due to the presence of minerals, vitamins and antioxidant compounds, this product is considered one of the most important products in the world for human nutrition and health (Nuruddin et al. 2003, Cantor et al. 2016, Sayed et al. 2022). The global production of tomatoes in 2020 is about 187 million tons of fresh fruit from about 5.05 million hectares, and Iran is the fifth producer of tomatoes in the world (Faostat 2022). Tomato has a high water requirement, and in areas like Iran, it is necessary to preserve water resources and economic and sustainable use of irrigation water to reduce the problem of water shortage (Nazari et al. 2018).

Due to the inappropriate management of water resources in arid and semiarid regions such as Iran, it is necessary to minimize the damages caused by water shortage and drought stress in the production of agricultural products by providing appropriate management solutions and one of the solutions is the use of nanoparticles. However, the point that should be noted is that the type of nanoparticles and how to use them should be checked separately in each region and for each type of plant and under different environmental stress conditions. Very few studies have been done in Iran in the field of using silicon nanoparticles to increase the resistance of plants against environmental stresses. Therefore, this study was carried out with the aim of investigating the effect of Si-Nps application (leaf and root feeding) on the growth and water use efficiency of tomato under drought stress conditions.

Materials and methods

Experimental details

This research was carried out from 2019 (September 1st) to 2020 (May 20th) in a greenhouse located in Shahid Chamran University, Ahvaz, Iran (located at 31°18′0.22″ Lat. N, 48°39′0.30″ Long. W and altitude 8 m above sea level). The experimental design of this study was a completely randomized with factorial arrangement and three replications. Experimental treatments included full irrigation, supplying 85 and 70% of crop water requirement (I_{100}, I_{85} and I_{70}) and using Si-Nps in three levels of 0, 50 and 100 ppm (N_0, N_{50} and N_{100}). Si-Nps were applied in two ways: leaf feeding (L) and root feeding (R). The 54 pots with a volume of 9 L were prepared and plants were planted in each pot. The method of planting and harvesting was manual. Information was recorded from the time of planting to harvest from each pot.

Si-Nps were used in three stages, the first stage after the formation of the first cluster, the second stage after the formation of the fifth cluster and the third stage after the completion of the seventh cluster.

Irrigation system

In order to perform irrigation and apply different irrigation levels, a drip irrigation system was used. Thus, to apply different percentages of water requirement, three main irrigation lines with a diameter of 32 mm and a length of 3 m were implemented. Then, three branches from each main pipeline were taken at a distance of 1 m by a polyethylene pipe with a diameter of 16 mm and a length of 9 m. In the next step, on the branches with a distance of 50 cm from the main line and dropper distances of 50 cm, a dropper was installed. To accurately measure and control the amount of irrigation, a water volume meter with a measurement accuracy of 100 ml and a solenoid valve was installed at the beginning of each main line. A 4-channel timer for the pump and three solenoid valves were used to adjust irrigation times and automate irrigation. A 500-L tank was used to supply water and a 0.5-HP pump was used to supply the required pressure of the system. Also, a disk filter—130 microns/120 mesh—was used to purify the water.

Preparation of seedlings

Seventy-one seeds were soaked in a plastic container for seven days. After this period, 98.5% of seeds (69) germinated. The seeds were transferred to a culture tray filled with cocopeat and perlite. For irrigation, 10 L of the nutrient solution was prepared based on the amounts in Table 1 (Jones 2014). The nutrient solution was given 100 ml per plant daily at 9 am.

Table 1 Nutrient quantity for 10 L solution

Nutrient	Quantity (g)	Nutrient	Quantity (g)
KNO_3	0.0001	$Na_2MoO_4\ 2H_2O$	0.003
KH_2PO_4	2.19	$ZnSO_4\ 2H_2O$	0.01
$Ca(NO_3)\ 2H_2O$	8.86	Fe(EDTA)	0.115
K_2SO_4	1.28	$CuSO_4\ 5H_2O$	0.01
$MgSO_4$	4.11	H_3BO_3	0.04
$MnSO_4$	0.02		

Bed preparing

In the present study, 50% weight of cocopeat and 50% weight of perlite were used to prepare the plant culture bed. First, the cocopeat was soaked in water in a pan for 12 h. Then, to reduce salinity, it was washed four times. In the next step, it was thoroughly mixed with perliteFirst, the cocopeat was soaked in water in a pan for 12 h. Then, to reduce salinity, it was washed four times. In the next step, it was thoroughly mixed with perliteFirst, the cocopeat was soaked with water in a pan for 12 h. Then, it was washed four times with water to reduce salinity. In the next step, it is thoroughly mixed with perlite. First, all pots were washed with water to remove possible contamination, then pots were filled with the same amount of the prepared mixture (4.7 kg), and to stabilize the culture medium, all pots were watered manually. When the tomato plants reach the five-leaf stage, they are ready to be transferred to the pot. First, a hole, the size of the root volume, was created in the bed of each pot, then each seedling was gently placed in the bed of the pot, and the surrounding area was filled with bed material.

Irrigation planning

In this study, the weight balance method was used to measure the need for daily irrigation. For this purpose, three pots with plants and three pots without plants were used. Every day at 10 o'clock, all six pots were weighed and based on the using Eq. 1, the water required of the plant was obtained and the mean of three pots was considered as a criterion:

$$WU = \left(W_L + W_2\right) - \left(W_I + W_D\right) \tag{1}$$

WU: Water requirement, W_L: Weight of pot, one day before irrigation (g), W_2: Irrigation water weight in 24 h (g), W_I: pot weight one day after irrigation (g) and W_D: Weight of drainage water (g). During the growth period, the required water was given to the plant several times a day. Table 2 shows the number of irrigation times per day and the time of its use.

The total irrigation water used for every pot during the growing season for treatments I_{100}, I_{85} and I_{75} was 351, 301 and 250 L, respectively.

Table 2 Irrigation planning during the tomato growth period

Date	Number of times	Irrigation hours
01/04/2020 to 02/15/2020	3	08:00, 12:00 and 16:00
02/16/2020 to 03/18/2020	4	08:00, 11:00, 13:00 and 15:00
03/19/2020 to 04/08/2020	5	08:00, 10:00, 12:00, 14:00 and 16:00
From 04/09/2020 until the end of cultivation	6	07:00, 09:00, 11:00, 13:00, 15:00 and 17:00

Table 3 Time and amount of application of silica nanoparticles for each pot

Stage	Date	For 100 ppm	For 50 ppm
First	04/02/2020	13.8	7.0
Second	18/03/2020	16.6	8.3
Three	14/04/2020	41.6	21.0

Table 4 The specification of used nanoparticles (NANOSHEL)

Product	Silicon oxide nanopowder
Stock No	NS6130-03–341
CAS	7631–86-9
Purity	99.9%
APS	15–20 nm
Molecular formula	SiO_2
Molecular weight	60.08 g/mol
Form	Powder
Color	White
Density	2.4 g/cm^3
Melting point	1610 °C
Boiling point	2230 °C
Solubility	Insoluble in water

Applying nanoparticle treatment

The amount of Si-Nps for each treatment and stage use, was poured into a specified volume of distilled water and stirred by a stirrer for 1 h. Application of Si-Nps was done in 35, 78 and 115 days after planting the seedlings to the pot with a manual sprayer on the leaf and syringe on the root. The amount of Si-Nps consumption in each stage is given in Table 3. The specification of nanoparticles used in this research is given in Table 4.

Measurement of plant traits

Tomato yield was determined five times by hand. After the last harvest and the end of the growth stage, the leaf length, leaf width, leaf fresh and dry weight, stem dry and fresh weight, fruit weight, fruit sugar, root fresh and dry weight, width and length of root were measured. A caliper was used to measure the length and width of the leaf. To measure fruit sugar, a fully ripe fruit was selected from each treatment and cut in half. Then, two ml of fruit juice was taken from it with a syringe and placed inside the sugar measuring chamber (Model: Pocket Refractometer Pal-1, Brand: ATAGO, Range: 0–53%) and its sugar level was measured. In addition to these traits, water use efficiency (WUE) was calculated. Water use efficiency is derived from Eq. 2:

$$\mathrm{WUE} = Y/\mathrm{IR} \tag{2}$$

WUE: Water use efficiency (Kg / m^3), Y: Yield (Kg) and IR: Irrigation water volume (m^3).

At the end of study, the water use efficiency was calculated by dividing the fruit yield by the volume of water consumed in different treatments.

Statistical analysis

Analysis of variance was done using SAS software (version 4.5) and comparison of means with Duncan's test at 1%. In this research, three replications were used for each treatment. Also, one plant has been tested in each replication and a total of 54 pots were tested.

Results and discussion

The results of the variance analysis are shown in Tables 5 and 7. Also, the mean comparison of the studied treatments is presented in Tables 6 and 8. In these tables, I indicates irrigation treatment and NRL indicates the application of silica nanoparticles. Also, to compare the results, for root feeding treatments, $I_{100}RN_0$ treatment and for spraying on the leaf, $I_{100}LN_0$ treatment has been considered as control.

Schematic diagram of the mechanisms of Si-Nps in tomato plant under drought stress is shown in Fig. 1. As a result, it was found that application of Si-Nps is a useful way to improve drought tolerance and tomato plant yield. It has been reported that the application of Si-Nps impacts the morphology and physiology of plants, which can result in better growth and yield (Rastogi et al. 2019). With application of Si-Nps, plant resistance against drought stress is controlled by increasing antioxidant defense, reducing oxidative damage to membrane molecules and maintaining many physiological and photosynthetic processes (Gunes et al. 2007). Furthermore, Si-Nps can modulate the levels of endogenous phytohormones, positively impact on plant–water relation, and through this, modify plant growth and development, as well as productivity (Mukarram et al. 2022).

Length, width, dry and fresh weight of leaf and stem

The effect of irrigation, Si-Nps and the interaction effect of irrigation and Si-Nps were significant on the length and width of leaf at 1% level (Table 5). According to Table 6, the maximum leaf length and width were obtained in treatments $I_{70}LN_{100}$ (58.2 cm and 64.5 cm) which increased by 23.8% and 57.3%, respectively, compared to the control. The least leaf length and width were determined in $I_{85}RN_{100}$ (40.5

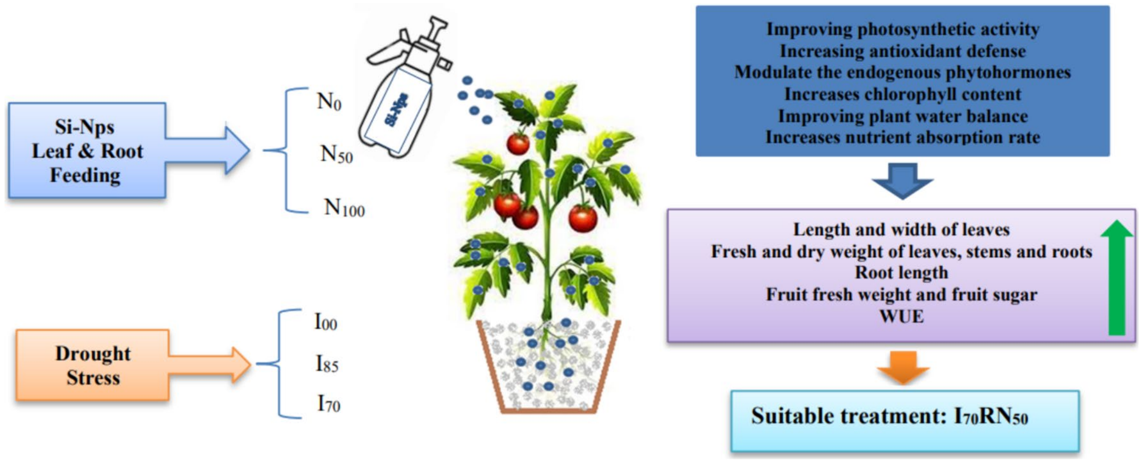

Fig. 1 Schematic diagram of the mechanisms of Si-Nps in tomato plant under drought stress

Table 5 Variance analysis of tomato component yield data

Sources of changes	df	Leaf length (cm)	Leaf width (cm)	Leaf fresh weight (g)	Leaf dry weight (g)	Stem dry weight (g)	Stem fresh weight (g)
I	2	2.31**	0.39**	38,642**	1576**	698.50^{ns}	50.11**
NRL	5	4.37**	4.13**	5263**	198**	359.45**	68.62**
I × NRL	10	7.41**	1.63**	4850**	184**	736.48**	80.54**
Error	36	6.10	9.18	94.00	14.00	208.12	26.76
CV		8.60	2.90	4.40	1.11	4.90	6.30

ns: Nonsignificant, **Significant at $p < 1\%$, *: Significant at $p < 5\%$

Table 6 Mean comparison of tomato component yield in different treatments

I	*N*	Leaf length (cm)	Leaf width (cm)	Leaf fresh weight (g)	Leaf dry weight (g)	Stem dry weight (g)	Stem fresh weight (g)
70	R-N0	54.17^{ab}	54.67^{b}	289.70^{b}	52.22^{a}	40.67^{a-d}	257.67^{ab}
	L-N0	44.67^{e-h}	41.33^{efg}	158.60^{i}	21.90^{g}	36.80^{b-f}	221.43^{f}
	R-N50	53.70^{abc}	53.67^{bc}	299.30^{b}	55.00^{a}	36.67^{b-f}	232.60^{def}
	L-N50	48.53^{cde}	47.53^{b-f}	236.30^{c}	41.40^{b}	34.60^{ef}	225.23^{ef}
	R-N100	53.50^{abc}	52.67^{bcd}	301.00^{b}	36.67^{bc}	32.33^{f}	229.67^{def}
	L-N100	58.20^{a}	64.50^{a}	360.50^{a}	56.83^{a}	38.80^{b-e}	240.17^{cd}
85	R-N0	48.50^{cde}	47.17^{c-f}	205.60^{e}	28.84^{def}	41.67^{abc}	257.67^{ab}
	L-N0	42.17^{gh}	40.17^{g}	168.70^{hi}	25.20^{fg}	35.57^{def}	231.13^{def}
	R-N50	44.00^{e-h}	43.83^{efg}	187.00^{fg}	28.51^{def}	37.20^{b-f}	239.00^{cde}
	L-N50	46.17^{efg}	44.17^{efg}	182.60^{fgh}	25.36^{efg}	38.80^{b-e}	248.33^{bc}
	R-N100	40.50^{h}	41.17^{efg}	179.70^{gh}	25.01^{fg}	32.50^{f}	227.67^{def}
	L-N100	42.67^{fgh}	43.00^{efg}	182.90^{fgh}	25.77^{d-g}	34.60^{ef}	225.23^{ef}
	R-N0	46.67^{d-g}	45.50^{d-g}	204.10^{e}	26.22^{d-g}	34.30^{ef}	248.33^{bc}
100	L-N0	47.00^{d-g}	41.00f^{g}	211.70^{de}	31.67^{cd}	42.43^{ab}	266.10^{a}
	R-N50	51.83^{bcd}	53.50^{bc}	209.30^{de}	31.49^{cde}	44.60^{a}	267.23^{a}
	L-N50	44.17^{e-h}	43.17^{efg}	224.70^{cd}	31.46^{cde}	34.83^{ef}	233.85^{def}
	R-N100	47.67^{def}	48.33^{b-e}	198.50^{ef}	27.45^{d-g}	36.07^{c-f}	249.90^{bc}
	L-N100	43.33^{e-h}	44.83^{efg}	209.50^{de}	29.31^{def}	33.70^{ef}	230.87^{def}

The means with common letters in each column are not significantly different cm) and $I_{85}LN_0$ (40.17 cm) treatment and showed decreased 13.2% and 2% compared to the control, respectively.

According to Table 5, irrigation, Si-Nps and the interaction effect of irrigation and Si-Nps were significant on the fresh and dry weight of leaf at 1% level. The maximum fresh and dry weight of leaf was observed in the $I_{70}LN_{100}$ treatment (360.5 cm and 56.83 cm), which was a 70% and 79% increase compared to the control treatment. The lowest fresh and dry weight of leaf was observed in $I_{70}LN_0$ treatment (158.6 cm and 21.90g) and showed a 25% and 31% decrease control treatment (Table 6). Treatments of irrigation, Si-Nps and the interaction effect of irrigation and Si-Nps were significant on dry and fresh weight of stem at 1% level (Table 5) and the maximum of them was in $I_{100}RN_{50}$ treatments with 44.60 g and 267.23 g, respectively. According to Table 6, the minimum dry and fresh weight of the stem (32.33 g) belongs to $I_{70}RN_{100}$ and $I_{70}LN_0$ (221.43 g). The difference between the $I_{70}RN_{100}$ and $I_{70}LN_0$ for stem fresh weight was not significant.

The results show that the addition of Si-Nps increased the length and width of leaves, the fresh and dry weight of leaves and stem and the maximum increase related to the treatment of I_{70}. With the use of 50 ppm Si-Nps in feeding the roots method and 100 ppm Si-Nps foliar spraying on plant leaves with a 30% reduction in water consumption, it is possible to achieve a higher performance than the control treatment and these two treatments have a significant difference with control treatment.

According to Khalid et al. (2022), the use of Si-Nps is useful for producing maximum yield, and by modulating various physiological molecular processes, it plays an important role in improving plants' tolerance to stresses. When the Si-Nps come into contact with the roots or leaves, they are absorbed, promoted enzyme activity (González-Moscoso et al. 2022) and produced a stimulatory effect on stressed plants. Also it improves plant–water balance, structural changes in leaves, increases chlorophyll content, and improves photosynthetic activity and resistance to environmental stresses (Xu et al. 2022, 2023; Malik et al. 2021). According to Table 6, it can be seen that feeding the roots (R) has better result than foliar spraying on plant leaves (*L*). Probably the better performance in feeding the roots (*R*) method is due to the increase in root length and increased absorption of the elements through the roots. Mahawar et al. (2023) reported that silicon nanoparticles increase water absorption in drought stress conditions by increasing root length. When nanoparticles are applied on the leaves, the stomata of leaves become smaller and water transpiration decreases from the leaf surface. The positive effect of Si-Nps on tomato growth parameters has been observed by Haghighi and Pessarakli (2013), Yassen et al. (2017), Akhlaghi Mohammadi et al. (2019), Smaeil Pour and Akbari (2012), Lu et al. (2016). The result of the study on the effect of Si-Nps on tomato plant growth parameters was consistent with the previous reports.

Width, length, dry and fresh weight of root

Treatments of irrigation, Si-Nps and the interaction effect of irrigation and Si-Nps were significant on the fresh and dry weight of root and root length at 1% but were not significant on root weight (Table 7). The maximum and least root fresh weight was observed, respectively, in treatments $I_{100}LN_{50}$ (203g) and $I_{70}RN_0$ (98.5g) (Table 8). The maximum and least root dry weight was observed, respectively, in treatments $I_{70}RN_{100}$ (79.7 g) and $I_{100}LN_{100}$ (33.3 g) (Table 8). The increase in Si-Nps from 0 to 100 ppm in the method of feeding by roots increased the fresh weight of roots and this increase was more in the treatment of I_{70}. Also, in the spraying on leaf method, the increase in nanoparticles from 0 to 50 ppm caused an increase in the root fresh weight, but an increase in amount of silica nanoparticles from 50 to 100 ppm led to a reduction in it. The increase in Si-Nps from 0 to 100 ppm in both methods of spraying on leaves and feeds by roots increased the dry weight of root in the I_{70} treatment, but in the other two irrigation treatments (I_{85} and I_{100}), the root dry weight decreased with the increase in nanoparticles.

The maximum root length was observed in treatment $I_{85}LN_{50}$ with 66.33 cm and the least root length was observed in treatments $I_{70}RN_{100}$ and $I_{85}LN_0$ with 38.37cm

Table 7 Variance analysis of tomato component yield data

Sources of changes	df	Fruit weight (g)	Fruit sugar (%)	Root dry weight (g)	Root fresh weight (g)	Root width (cm)	Root length (cm)	Water use efficiency (%)
I	2	283,851**	0.165^{ns}	1057**	2850**	2.180^{ns}	0.306**	32.20**
NRL	5	239,876**	0.244*	126**	2460**	7.852^{ns}	5.960**	38.30**
I×NRL	10	203,344**	0.271**	321**	1748**	2.697^{ns}	0.110**	64.20**
Error	36	34,235	0.690	16	57	3.222	1.220	37.00
CV		4.7	4.6	1.9	8.5	6.9	8.9	3.70

ns: Nonsignificant, **Significant at $p<1\%$, *Significant at $p<5\%$

Table 8 Mean comparison of tomato component yield in different treatments

I	*N*	Fruit fresh weight (g)	Fruit sugar (%)	Root fresh weight (g)	Root dry weight (g)	Root length (cm)	Water use efficiency (%)
70	R-N0	2741.0^{abc}	4.57^{ab}	98.5^{h}	41.5^{d-h}	45.33^{c-g}	10.90^{a}
	L-N0	1835.7^{h}	3.97^{def}	115.7^{g}	42.8^{c-g}	44.33^{c-g}	7.34^{fgh}
	R-N50	2741.7^{abc}	4.47^{abc}	150.0^{cd}	55.3^{b}	43.00^{d-g}	10.97^{a}
	L-N50	2271.7^{efg}	4.17^{b-e}	119.0^{g}	48.5^{c}	45.33^{c-g}	9.09^{bcd}
	R-N100	2443.0^{c-f}	4.4^{a-d}	175.7^{b}	79.7^{a}	38.67^{g}	9.77^{b}
	L-N100	2333.3^{d-g}	3.67^{f}	112.3^{g}	48.6^{c}	42.33^{fg}	9.33^{bc}
85	R-N0	2481.3^{b-f}	3.67^{f}	117.6^{g}	39.3^{e-i}	46.00^{c-g}	8.24^{def}
	L-N0	2072.0^{gh}	4.03^{c-f}	112.3^{g}	43.4^{c-f}	38.37^{g}	6.88^{h}
	R-N50	2462.3^{c-f}	3.77^{ef}	122.7^{g}	44.5^{cde}	49.33^{b-f}	8.18^{d-g}
	L-N50	2624.7^{a-d}	4.63^{a}	135.3^{ef}	44.6^{cde}	66.33^{a}	8.72^{cde}
	R-N100	2200.7^{fg}	4.20^{a-e}	138.7^{de}	36.8^{f-i}	51.33^{bc}	7.31^{fgh}
	L-N100	2852.0^{a}	3.80^{ef}	99.5^{h}	34.3^{i}	42.67^{efg}	9.47^{bc}
	R-N0	2462.7^{c-f}	4.10^{c-f}	138.9^{de}	45.4^{cde}	50.67^{bcd}	7.02^{h}
100	L-N0	2644.0^{abc}	4.27^{a-d}	152.9^{c}	47.5^{cd}	49.00^{b-f}	7.53^{fgh}
	R-N50	2770.3^{ab}	4.27^{a-d}	137.8^{de}	35.6^{hi}	50.33^{b-e}	7.89^{e-h}
	L-N50	2571.0^{a-e}	4.20^{a-e}	203.0^{a}	36.6^{ghi}	49.00^{b-f}	7.32^{fgh}
	R-N100	2835.0^{a}	3.97^{def}	124.4^{fg}	33.6^{i}	56.00^{b}	8.08^{d-g}
	L-N100	2520.7^{b-e}	4.03^{c-f}	116.4^{g}	33.3^{i}	51.67^{bc}	7.18^{gh}

The means with common letters in each column are not significantly different

(Table 8). According to Table 8, with the increase in silica nanoparticles, the root length increased and this increase was more in the irrigation treatment of 100%.

The application of Si increases root length and cell wall extensibility in root growing regions (Etesami and Jeong 2018). Between the two methods of nanoparticle application, feeding from the roots has a more significant effect on increasing the length of the roots, which is probably due to the availability of more nutrients compared to spraying on the leaves.

The results of Abdallah (2019) showed that under deficit irrigation, relative leaf water content and market yield of tomato significantly reduced but Kaolin particles effectively increased the physiological processes and production of salable yield. Abolqasemi and Haghighi (2018) showed that the nanoparticles were significant on root dry weight and nanoselenium increased the growth of tomato plant. In Hou et al. (2017) study, full irrigation and partial irrigation of the root area had a significant effect on root fresh weight and root length. Ashkavand et al. (2018) reported that the silicon nanoparticles were significant on root width. Our results are similar to previous studies.

Fruit fresh weight and fruit sugar

According to Table 7, irrigation, Si-Nps and the interaction effect of irrigation and Si-Nps were significant on fruit fresh weight at the 1% level. The maximum and lowest fruit fresh weight was observed in treatments $I_{85}LN_{100}$ (2852g) and $I_{70}LN_0$ (1835.7g) (Table 8), respectively. According to Table 8, with deficit irrigation practices, the fruit fresh weight has decreased, but the addition of Si-Nps has increased it and has been able to partially compensate for the lack of water. This result shows the positive effect of using Si-Nps, which agree with Zhang et al. (2022) and Akhlaghi Mohammadi et al. (2019). Saleh et al. (2007) expressed that the irrigation frequency was significant on fruit weight and the 3-day irrigation had least fruit weight than 1-day irrigation frequency. The addition of Si-Nps in water stress conditions increases chlorophyll on the plant leaf surface (Sadak 2019), photosynthesis and nutrient absorption rate, activates the activity of defensive enzymes and increases anti-stress compounds (Wang et al. 2022), adjusting the osmotic pressure of the cell and thus improving the ability of tissues to absorb and retain water in leaves of plant (Luyckx et al. 2017; Boaretto et al. 2014). Also, silicon nanoparticles reduce stomatal conductance of leaves that led to reducing the stomatal conductance of the leaf which leads to the reduction of water loss in the plant and as a result increases the relative resistance to drought stress conditions (Mahawar et al. 2023).

It was also found that feeding of Si-Nps by roots has better results than spraying on leaves and although the maximum fruit fresh weight was obtained in the $I_{85}LN_{100}$

treatment, there is no significant difference with $I_{100}RN_{100}$ treatment. According to Table 7, it can be seen that irrigation treatment was not significant on fruit sugar at the 5% level, but Si-Nps was significant on it at 5% level, also the mutual effect of Si-Nps and irrigation was significant on fruit sugar at 1%. The maximum amount of fruit sugar was observed in the $I_{85}LN_{50}$ treatment (4.63%) and the least fruit sugar was observed in $I_{70}LN_{50}$ and $I_{85}RN_0$ treatments (3.67%) (Table 8). Although irrigation treatment effect was not significant on fruit sugar, the maximum of it was observed in treatment 85%. The increase in nanoparticles in low irrigation treatment (I_{70}) has more effect than 85% and 100% treatments. This result indicates that spraying Si-Nps on leaves has increased the plant's resistance to drought stress by adjusting the nutritional balance. Similar to fruit fresh weight, feeding of Si-Nps by roots has better results on fruit sugar; although the maximum fruit sugar was obtained in the I85LN50 treatment, there is no significant difference with the I70RN50 treatment.

The results of Hu et al. (2023) showed that the application of silicon improves the growth of tomato plants. Rastogi (2019) reported that silicon nanoparticles increase crop yield under weed, disease and drought conditions. Pinedo-Guerrero et al. (2020) by evaluating the application of K2SiO3 and SiO2 nanoparticles (SiO2 NPs) on the growth and tolerance to salt stress of tomato, stated that the application of SiO2 nanoparticles at 500 mgL^{-1} had positive effects on plants. The results of Korkamaz et al. (2017) showed that NaCl, silicon and their interaction effects on the nutrients and silica levels in leaves were significant in different concentrations, and silicon increased fruit yield. These results are agreed with the results of our study.

Water use efficiency

As shown in (Table 7), the treatments of irrigation, Si-Nps and the interaction effect of irrigation and Si-Nps were significant on WUE at 1% level. The maximum and least WUE was recorded in treatments $I_{70}RN_{50}$ (10.97 kg/m^3) and $I_{85}LN_0$ (6.88 kg/m^3) (Table 8), respectively. It showed a 56.3% increase and it decreased by 8.6% compared to control. The reason for the increase in WUE in the $I_{70}RN_{50}$ treatment is the increase in the weight of the fruit and the decrease in the volume of water used. According to the results of this research, with a 30% reduction in water consumption and the use of silica nanoparticles with a concentration of 50 ppm, the maximum WUE was obtained. In addition, according to the results of Table 3, the use of 30% reduction in the volume of irrigation water and the use of silica nanoparticles with a concentration of 50 ppm as root nutrition had a higher WUE and it was not significant compared to the I70RN0 treatment. Since Si-Nps has biostimulative effects, it reduces transpiration, increases water storage capacity and improves plant–water balance in tomato (Romer-Aranda et al. 2006), also it affects the activity of enzymes and biochemical processes in plant tissues and ultimately reduces water stress and ultimately weight loss.

The results are similar to the results of Yang et al. (2019), that concluded irrigation regimes were significant on water use efficiency. Shokri et al. (2022) concluded that the use of silica nanoparticles increases water use efficiency and increases cucumber yield, also the use of silica nanoparticles with a concentration of 50 ppm can be a good option to increase yield in cucumber. In the research of Abdallah (2019), the use of Kaolin and Pinoline in conditions of applying water stress to tomatoes saved 25% of irrigation water and increased WUE by 26.24%. Al Saeedi (2022) concluded that adding nano-silica particles to sandy soil significantly increases cucumber yield and improves WUE. The results of these studies are similar to the results of the present research.

Conclusions

In this research, the effect of silica nanoparticles (Si-Nps) in three concentrations of 0, 50 and 100 ppm (N_0, N_{50} and N_{100}) and irrigation including supplying 100, 85 and 70% of crop requirement (I_{100}, I_{85} and I_{70}) were investigated on growth and water WUE of greenhouse tomato plant in hydroponic culture. The Si-Nps were applied in two ways: spraying on the leaf (*L*) and root feeding (*R*). Based on the results, the application of Si-Nps improves the yield and water use efficiency and it causes an increase in yield components, fruit weight, fruit sugar and water use efficiency. The results of I_{100} and I_{85} treatments in the presence of the use of Si-Nps were not significantly different compared to the results of the I_{30} treatment and a 30% reduction in water consumption had different results in the yield and WUE compared to the control treatment, so that in the $I_{70}RN_{50}$ treatment, the fruit fresh weight increased by 11.5%, fruit sugar increased by 9%, and WUE increased by 56.3%, but in the $I_{70}LN_{50}$ treatment, fruit fresh weight decreased by 14%, fruit sugar decreased by 2.3%, and WUE increased by 20% compared to the control treatment. Therefore, supplying 70% of the water requirement, using silica nanoparticles with a concentration of 50 ppm and feeding by the roots can be a suitable option to increase the yield and WUE of hydroponic tomato cultivation in the greenhouse.

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Data availability The datasets generated and/or analyzed during the current study are available upon request by contact with the corresponding author.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to publish All authors have read and agreed to the published version of the manuscript.

Ethical approval This manuscript does not involve ethical approval.

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