



Investigating the Effects of Nitrogen and Silicon-dioxide Nanoparticles on Sunflower in the Semi-arid Region

Masoud Aghdam, Mohsen Janmohammadi* and Naser Sabaghnia

University of Maragheh, Maragheh, Iran

Received: September 4, 2024 Accepted: December 23, 2024

OPEN ACCESS

Editor-in-Chief
Praveen Kumar

Associate Editor
V.S. Rathore
P. Santra
R.K. Solanki

Managing Editor
N.R. Panwar

Editors
R.S. Tripathi
S. Soondarmurthy
U.R. Ahuja
R. Sharma
P.P. Rohilla
Raj Singh

Guest Editors
Mahesh Kumar
M.L. Dotaniya
Archana Verma

***Correspondence**
Mohsen Janmohammadi
mohsen_janmohammadi@yahoo.com

Citation
Aghdam, M., Janmohammadi, M. and Sabaghnia, N. 2025. Investigating the Effects of Nitrogen and Silicon-dioxide Nanoparticles on Sunflower in the Semi-arid Region. *Annals of Arid Zone* 64(1): 23-33.

<https://doi.org/10.56093/aaz.v64i1.156022>
<https://epubs.icar.org.in/index.php/AAZ/article/view/156022>

<https://epubs.icar.org.in/index.php/AAZ>

Abstract: A field experiment was conducted to assess the impact of varying levels of nitrogen fertilizer (40, 80, and 120 kg ha⁻¹) and different concentrations of silicon dioxide nanoparticles (50, 100, and 150 ppm) on the growth characteristics of sunflower in Northeast Iran. Results showed nitrogen application improved the plant height, the number of leaves, canopy width and decreased the diameter of the stem. The longest leaves were recorded in the plants grown with application of 80 kg N ha⁻¹ followed by spray of 100 ppm SiO₂. The application of 80 and 120 kg ha⁻¹ nitrogen significantly increased the head diameter, and the foliar application of 100 ppm SiO₂ under high nitrogen application. Nitrogen utilization improved the positive effect of SiO₂ on achene yield components. Maximum head weight was obtained with application of 80 kg N ha⁻¹ followed by spray of 100 ppm SiO₂ while maximum achene weight was achieved for plants grown with application of 80 kg N ha⁻¹ followed by spray of 50 ppm SiO₂. Application of high doses of silicon dioxide nanoparticles (100 and 150 ppm) decreased the weight of achene while nitrogen application increased this component. Foliar application of concentrated Si solution decreased the number of achene in the head. High achene yield was recorded following application of 80 kg N ha⁻¹ with 100 ppm SiO₂ and 120 kg N ha⁻¹ and 50 ppm SiO₂. The results indicated that the application of 40, 80, and 120 kg ha⁻¹ of nitrogen increased the achene yield 21%, 57%, and 52% compared to the control, respectively. Taken together, the results exhibited that the use of 80 kg ha⁻¹ of nitrogen along with foliar spray with a 50 or 100 ppm of silicon dioxide nanoparticles can significantly improve the sunflower performance.

Key words: Achene yield; empty achene; canopy width; nanoparticles; optimum nitrogen dose.

Oilseed products are one of the important sources of energy supply for humans. Sunflower seeds contain 44% of oil and sunflower produces about 10% of the total edible oil in the world. Sunflower has the largest portion in oil production in Iran after soybean and oilseed rape. The cultivated area of this crop in the world is estimated to be about 29.5 mha and about 58.1 mt of achene are annually harvested from these

areas. Nevertheless, the amount of cultivated area of sunflower in Iran is 60,000 ha and the amount of seed production is about 62,000 tons (FAO, 2022).

Despite the relatively high adaptability of sunflower to different climatic conditions, the main reasons for its low yield in semi-arid areas such as northeastern Iran can be attributed to factors such as unsuitable soil conditions, nutrient deficiencies, its cultivation as a second crop after harvesting winter cereals (wheat and barley) and encountering its sensitive reproductive periods with hot and dry periods, unprincipled fertilizers and nutritional management (Naorem *et al.*, 2023).

Nitrogen is considered as one of the main and most effective mineral elements in plants, and its deficiency can directly restrict plant growth. Nitrogen comprises about 2-4% of the dry weight of the plant and this amount is significantly higher than other mineral elements (Hawkesford *et al.*, 2023). Considering the structural role of nitrogen in amino acids, nitrogen deficiency can widely affect the function and structure of enzymatic proteins. RuBisCO as a key photosynthetic enzyme is the *most abundant protein on Earth* (Hawkesford *et al.*, 2023). Therefore, the availability of nitrogen in the soil and the amount of its absorption by the plant root system can affect the rate of photosynthesis, the supply of photo-assimilates, and consequently, the production of oil in the sunflower achene.

However, the soil of semi-arid areas is faced with a nitrogen deficiency (Naorem *et al.*, 2023). It appears that *proper nitrogen* management means application at the right time and in the right amount can improve sunflower growth and the extracted oil quantity and characteristics. The response of sunflower growth and achene production may vary with different doses of nitrogenous fertilizers and the rate of nitrogen application can affect the nitrogen use efficiency and the absorption rate or efficiency of other elements (Ahmad *et al.*, 2018). In this context, it has been reported that among the different levels of nitrogen application, the use of 90 kg N ha⁻¹ could improve the efficacy of fertilizers containing micronutrients (Jarecki, 2022).

Silicon (Si) is a non-essential yet abundant element in soil, ranking as the second most plentiful. While Si is not critical for plant growth,

research has indicated that it can significantly influence various aspects of plant development (Pavlovic *et al.*, 2021). Importantly, the form of silicon present in the soil is not directly accessible to the root system. Plants can only uptake silicon from the rhizosphere in the form of ortho-silicic acid (Si (OH)₄). Notably, silicon is unique among elements, as it does not pose any serious harmful effects, even when accumulated excessively in plant tissues (Ma *et al.*, 2001). The useful impacts of Si are particularly apparent in plants under unfavorable environmental conditions such as drought stress, salinity stress, heavy metals and ultraviolet radiation, also Si plays a critical role in the induction of defense processes against pathogens, seedling establishment, cell wall elasticity and strength, and reducing transpiration (Luyckx *et al.*, 2017). Foliar application of silicon dioxide significantly reduced the penetration of pathogens (Wang *et al.*, 2017). Furthermore, Si had a positive and promising effect on the activity of the superoxide dismutase enzymes and peroxidase enzyme activity (Farouk *et al.*, 2020). The utilization of Si may increase the positive impact of some macronutrients such as nitrogen and phosphorous (Yavaş and Aydın, 2017; Pavlovic *et al.*, 2021).

Due to the soil limitations in semi-arid areas, it appears that the spray of Si can meet the plant's needs and stimulate the plant's defense systems. The use of nanotechnology can be significantly effective. The external use of silicon in nano dimensions (1-100 nm) due to having more external surface area and specific physical and chemical properties compared to similar bulk particles can increase the efficiency of the silicon effect. Nanoparticles have adjustable reactivity and bioavailability in comparison with bulk components. It has been reported that nanoparticles even in low concentrations due to slow and steady release and more targeted delivery were more efficient than bulk or conventional fertilizers (Liu and Lal, 2015). Nano-silicon can be more easily absorbed by plants and due to its small size, it can pass through the barriers such as cell walls and cell membranes compared to bulk silicon. Also, it is easier to load and distribute in the vascular system (Naidu *et al.*, 2023). However, there is still not much information available about the impact of nitrogen fertilizer dose and foliar spraying of different concentrations

of silicon dioxide nanoparticles under semi-arid conditions. The present experiment was designed and implemented to investigate the effectiveness of nano-silicon under different N fertilizer applications on the growth performance of sunflower plants in the northeast of Iran.

Material and Methods

Experimental site

The present experiment was carried out during the spring and summer of 2023 in a private field in the Hashtroud region, East Azarbaijan, Iran. The field was located at 47° 05'E, 37°47'N, at an altitude of 1665 m height above mean sea level. According to the cataloging of Köppen and Geiger, this region is classified as cold semi-dry. The soil of the area was silt loam (69% silt, 20% sand, 11% clay) with a pH of 7.74, electrical conductivity: 2.51 dS m⁻¹, total organic carbon 0.716%, total nitrogen 0.0926%, available phosphorus 37 mg kg⁻¹ and available potassium 213 mg ka⁻¹. The amount of rainfall during the growing season was 71 mm.

Implementation of experimental treatments:

The experiment was conducted as factorial based on randomized complete block design with three replications at a private field in Hashtroud region. The first factor was different levels of nitrogen (40, 80, and 120 kg ha⁻¹ abbreviated as N₄₀, N₈₀, N₁₂₀), and the second factor comprised

of different concentrations of nano SiO₂ (50, 100, and 150 ppm abbreviated as Si₅₀, Si₁₀₀, Si₁₅₀) for foliar spray. The control (intact) plants were sprayed with distilled water. Silicon dioxide nanoparticles with product ID: SOP301 were obtained from Arminano Company, Tehran. The images obtained from electron microscopes (scanning and transmission) confirmed the nano-size of silicon dioxide particles (Fig. 1).

The seeds of sunflower (*Helianthus annuus*), the local mass of Khoi, were purchased and used for cultivation. Before planting, the seeds were surface sterilized and disinfected with Vitavax fungicide. The primary tillage of the field was carried out during the autumn of 2022 with a moldboard plow and 10 t ha⁻¹ of farm yard manure was applied. In the early spring season of 2023, secondary tillage was done using a rotary cultivator and leveler. Then, using a Hiller-Furrower, the top soil was made into a ridge and furrow. The distance between the ridges was 70 cm and the distance between the plants on the row was 20 cm.

Each experimental plot consisted of 8 planting rows with a length of 4 meters. Seed planting was done manually on May 15, 2023. Pre-emergence weed control was done using Treflan (trifluralin) herbicide at the rate of 2.5 L ha⁻¹ of 48% emulsifiable concentrated liquid with irrigation water. The field was irrigated immediately after planting. Irrigation was carried out through polyethylene pipes and

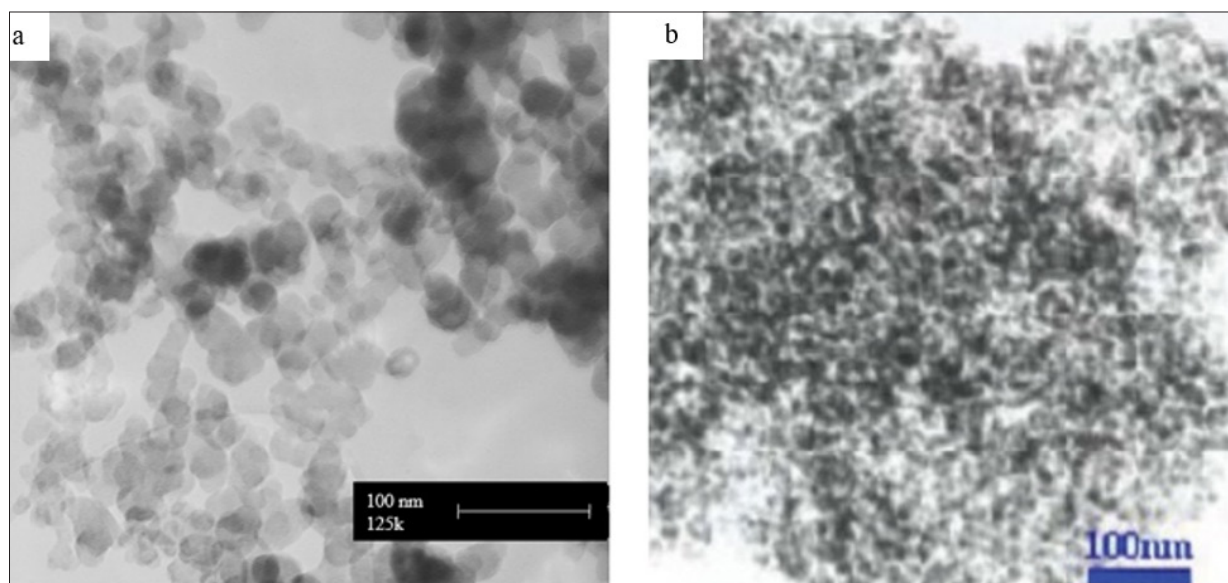


Fig. 1. The images were prepared by scanning electron microscope (a) and transmission electron microscope (b) for utilizing silicon dioxide nanoparticles.

Table 1. Effect of different doses of soil-applied nitrogen and foliar application of different nano silicon dioxide concentrations on morphological trait of sunflower

Treatment		Stem diameter	Plant height (cm)	Total leaves number during the sunflower development	Leaf length (cm)	Leaf weight (g)	Canopy width (cm)
Nitrogen (kg ha ⁻¹)	SiO ₂ (ppm)						
0	0	7.44 ^d	142.00 ^c	19.00 ^d	15.46 ^c	5.16 ^c	46.66 ^d
40	0	9.17 ^{ab}	159.66 ^{bc}	21.93 ^c	16.17 ^b	6.18 ^b	59.33 ^c
80	0	9.57 ^a	164.88 ^b	25.6 ^a	18.46 ^a	7.12 ^a	63.77 ^b
120	0	8.64 ^c	169.77 ^a	24.4 ^{ab}	17.86 ^{ab}	7.43 ^a	73.66 ^a
0	50	9.60 ^a	165.88 ^b	23.46 ^b	17.65 ^b	7.45 ^a	64.33 ^a
0	100	9.52 ^a	171.22 ^a	25.53 ^a	18.20 ^a	6.70 ^b	67.66 ^a
0	150	8.81 ^b	158.66 ^c	22.60 ^{bc}	16.64 ^c	6.58 ^b	64.77 ^a
40	50	8.60 ^d	168.33 ^b	21.80 ^{ef}	15.89 ^{de}	5.50 ^{cd}	55.33 ^c
40	100	10.15 ^a	155.33 ^e	22.80 ^{de}	17.26 ^{bc}	6.21 ^{de}	65.66 ^b
40	150	8.77 ^{cd}	155.33 ^e	20.20 ^{fg}	15.36 ^e	6.08 ^e	57.00 ^c
80	50	10.11 ^a	165.00 ^{cd}	24.80 ^{bc}	18.44 ^e	7.07 ^{bc}	64.00 ^b
80	100	9.23 ^{bc}	174.00 ^b	27.80 ^a	19.40 ^a	7.00 ^{bc}	65.00 ^b
80	150	9.39 ^b	160.00 ^{de}	24.2 ^{bcd}	17.65 ^{bc}	7.29 ^b	63.66 ^b
120	50	8.47 ^d	164.33 ^{cd}	23.80 ^{cd}	18.62 ^{ab}	8.80 ^a	73.66 ^a
120	100	9.16 ^{bc}	184.33 ^a	26.00 ^b	17.96 ^{bc}	6.89 ^{bc}	75.00 ^a
120	150	8.27 ^d	160.66 ^{de}	23.40 ^{cde}	17.01 ^{cd}	6.61 ^{cd}	72.33 ^a
Significance level							
N		0.000	0.001	0.000	0.000	0.001	0.000
S		0.001	0.02	0.002	0.03	0.007	0.05
N×S		0.001	0.009	0.395	0.184	0.002	0.01
CV%		2.77	2.21	3.78	4.02	5.25	3.14

If the p-value is less than 0.01 and 0.05, it is judged as “significant at 1% (**) and 5% (*) level,” and if the p-value is greater than 0.05, it is judged as “not significant (NS)”. The means in each column that have different letters have statistically significant differences at the 5% level.

a drip tape system. After complete seedling establishment and at the stage of 3 to 4 leaves, thinning was done. After planting, irrigation was done every 8 days until the completion of seedling establishment, and in the later stages of development, irrigation was repeated every 4 to 7 days according to climatic conditions and plant requirements. Nano SiO₂ foliar spraying was done during stem growth, elongation of immature bud, and beginning of flowering using portable sprayers. During spraying, the whole plant got wet and it continued until the drops fell from the leaf surface. The *split nitrogen application* was followed with one-third of the amount being applied during seed sowing, one-third during vegetative growth, and the remaining during early reproductive growth. During planting, 80 kg ha⁻¹ of phosphorus was used in the form of triple superphosphate and 40 kg ha⁻¹ of potassium in the form of potassium

sulphate (K₂SO₄) fertilizer as band application 4 cm down and away from the seed.

Measurement of growth traits and yield components: Assuming the shape of the canopy to be elliptical, the width of the canopy was obtained by measuring the distance between the tips of the right and left leaves. The height of the plant was measured from the ground level to the highest point on the plant using a meter scale. To measure the seed yield components, 10 plants were harvested from each plot at the full maturity stage, by removing the marginal effects in the plots, and were transported to the laboratory and kept in an oven at 75°C for 48 hours to reach a constant dry weight. Then, traits such as the number of the achene per head, the diameter of the head, the weight of 1000 achene, and the percentage of empty achene were calculated. To evaluate the achene and biological yield, an area equal to 3 square meters was harvested and after

Table 2. Achene yield component of sunflower under different nitrogen levels and nano silicon dioxide concentration

Treatment		Head diameter	Head weight	Achene number	Thousand achene	Biological yield
Nitrogen	SiO ₂	(cm)	(g)	head ⁻¹	weight (g)	(kg ha ⁻¹)
(kg ha ⁻¹)	(ppm)					
0	0	17.50 ^c	65.88 ^d	719.00 ^c	58.60 ^b	7573.00 ^d
40	0	21.33 ^b	81.89 ^c	872.55 ^b	60.20 ^a	8393.44 ^c
80	0	25.29 ^a	104.93 ^a	885.78 ^a	60.84 ^a	8944.66 ^b
120	0	20.35 ^b	95.32 ^b	885.11 ^a	60.78 ^a	9706.44 ^a
0	50	23.06 ^{ab}	92.24 ^b	891.78 ^a	61.30 ^a	8960.89 ^{ab}
0	100	24.50 ^a	98.51 ^a	892.11 ^a	60.08 ^b	9220.44 ^a
0	150	22.74 ^c	91.39 ^b	859.55 ^b	60.44 ^b	8863.11 ^{bc}
40	50	20.88 ^c	83.32 ^{ef}	822.00 ^c	60.56 ^{bc}	8354.00 ^{ef}
40	100	21.33 ^c	83.83 ^{ef}	926.67 ^a	59.43 ^d	8533.00 ^{de}
40	150	21.80 ^c	78.54 ^f	869.00 ^b	60.63 ^{bc}	8293.33 ^f
80	50	24.36 ^b	91.10 ^{cd}	936.67 ^a	62.10 ^a	9039.00 ^c
80	100	26.99 ^a	115.83 ^a	872.67 ^b	60.43 ^c	9089.67 ^c
80	150	24.53 ^b	107.88 ^b	848.00 ^{bc}	59.99 ^{cd}	8705.33 ^d
120	50	23.96 ^b	102.31 ^b	916.67 ^a	61.25 ^b	9489.67 ^b
120	100	25.20 ^b	95.89 ^c	877.00 ^b	60.40 ^c	10038.67 ^a
120	150	21.90 ^c	87.76 ^{de}	861.67 ^b	60.71 ^{bc}	9591.67 ^b
Significance level						
N		0.001	0.001	0.045	0.004	0.001
S		0.001	0.05	0.013	0.007	0.001
N×S		0.04	0.001	0.005	0.024	0.004
CV%		2.76	3.66	4.24	1.67	6.20

If the p-value is less than 0.01 and 0.05, it is judged as “significant at 1% (**) and 5% (*) level,” and if the p-value is greater than 0.05, it is judged as “not significant (NS)”. The means in each column that have different letters have statistically significant differences at the 5% level. Rows 1 show the averages of the control conditions (no use of nitrogen and silicon nanoparticles), rows 2 to 4 for the main effects of nitrogen, rows 5 to 7 for the main effects of silicon dioxide nanoparticles, and rows 8 to 16 for the mutual effects of nitrogen and Silicon nanoparticles.

threshing, the total biomass and seed weight were weighed. All the collected data were statistically analyzed using SAS software and mean comparisons were made with Duncan's multiple range test at the 5% level. Box plots were prepared using GenStat software. *Principal Component Analysis* (PCA) for identifying a smaller number of uncorrelated variables and as a linear dimensionality reduction technique was performed by Minitab software.

Results and Discussion

The results of the analysis of variance indicated the mutual effect of N×Si was significant for stem diameter. Mean comparison exhibited that the thickest stems were related to plants grown under N₈₀Si₁₀₀, which were about 35% more than the control condition (N₀Si₀). However, regardless of the effects of foliar application of silicon dioxide nanoparticles, nitrogen use decreased the stem diameter, and this trend was

also observed for foliar application with high concentrations of Si (Table 1).

The investigation of plant height displayed that the use of 40, 80, and 120 kg ha⁻¹ nitrogen fertilizer increased this trait by 12%, 16%, and 20%. The tallest plants were recorded under N₁₂₀Si₁₀₀ conditions. However, foliar spraying with medium concentrations of silicon dioxide nanoparticle solutions (Si₁₀₀) and low concentration (Si₅₀) increased the plant height by 21% and 12%, respectively (Table 1).

The evaluation of the leaf length among the treatments indicated that the application of nitrogen significantly increased this parameter. A comparison of leaf length between different concentrations of nano silicon dioxide showed that SiO₂ application also had a positive effect on leaf length (18.20 cm with Si₁₀₀ and 17.65 cm with Si₅₀). Under low nitrogen use conditions, foliar application of Si₁₅₀ had no positive effect

on leaf length. The best effect of foliar spraying was observed with Si₁₀₀. For leaf width, the interaction effect of N×Si was significant and the widest leaves were recorded under the application of high levels of nitrogen along with foliar spray of Si₁₅₀, which were about 70% wider compared to the control (N₀Si₀). Canopy width as one of the most important components of vegetative growth was affected by the investigated factors. The effect of nitrogen, foliar spray of SiO₂ nanoparticles on canopy width was clearly evident (Table 1).

Assessment of achene yield components showed that there are significant mutual effects of N×Si (Table 2). The means comparison for head diameter showed that the largest heads were obtained following simultaneous application of N₈₀Si₁₀₀. The application of N₁₂₀ had less effect on head diameter compared to N₈₀.

Assessment of head weight revealed that the application of N₄₀, N₈₀, and N₁₂₀ increased the head weight by 24%, 59%, and 44% compared to control (N₀), respectively (Table 2). Foliar application of silicon nano-particles also showed a positive effect on head diameter. Foliar spray with high concentrations of silicon dioxide nanoparticles (150 ppm) under N₁₂₀ conditions caused a decrease in head diameter compared to plants grown with N₈₀ and N₄₀. Although the spray of all concentrations of nano-silicon dioxide could improve seed weight, the greatest effect was recorded with the application of Si₁₀₀ with an increase of about 49%. The highest head weight was achieved by application N₈₀Si₁₀₀ condition which was 76% higher than the control condition. However, the effect of the silicon nanoparticles was different in nitrogen levels. Under N₈₀ applied condition, the foliar spray of Si₁₀₀ and under N₁₂₀ applied condition, foliar spray of Si₅₀ had the best encouraging effects on head weight. The examination of the number of achenes in the head showed that foliar spray with low concentrations of silicon dioxide nanoparticles under N₈₀ and N₁₂₀ and foliar spray of Si₁₀₀ under low nitrogen applied conditions resulted in the highest achene number in head (Table 2).

The main effects of nitrogen and foliar spraying of silicon dioxide nanoparticles were significant for the number of leaves in the plant. The highest number of leaves was recorded

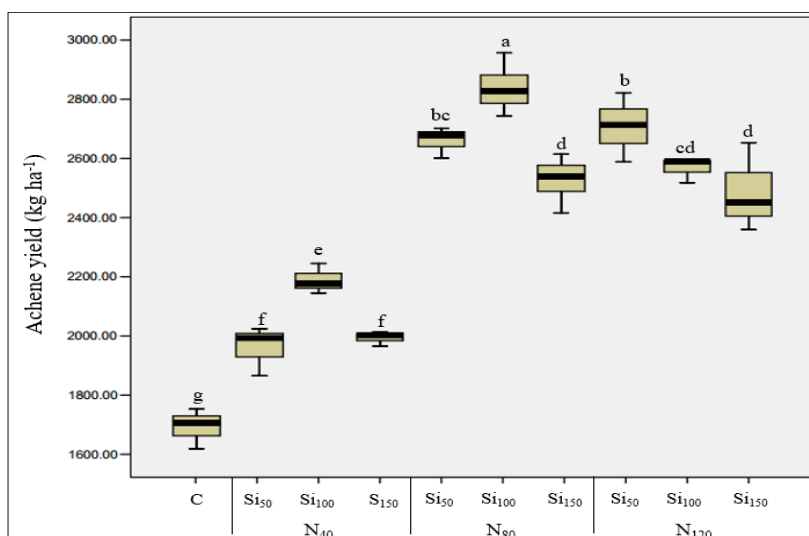
after application of 80 kg N ha⁻¹. Also, foliar spraying of Si₁₀₀ had the maximum positive influence on this trait. The plants grown under the N₈₀Si₁₀₀ condition had 46% higher leaves than the control. The application of the high level of nitrogen (N₁₂₀) compared to the N₈₀ caused a 5% decrease in the number of leaves. Examining the effect of nitrogen application showed that the highest number of leaves (25.6) was obtained with the application of 80 kg per hectare and the lowest number of leaves was recorded in the condition of no nitrogen application (19). Different concentrations of silicon dioxide nanoparticle also had a significant effect on the number of leaves, so that the highest number of leaves (25.53) was obtained with the application of 50 ppm. By increasing the concentration of silicon nanoparticles to 150 ppm, the number of leaves decreased (22.80).

Although the foliar application of silicon nanorod increased the achene yield compared to the control. However, the effectiveness of silicon nanoparticles on achene performance was more evident under nitrogen application conditions. The use of nitrogen resulted in better effects of silicon nanoparticles on achene performance. Evaluation of achene yield showed that nitrogen application and foliar spraying of silicon dioxide nanoparticles caused a significant increase in this component.

However, the effect of foliar spraying with different concentrations of Si was different at levels of nitrogen application. The use of N₄₀, N₈₀ and N₁₂₀ increased the yield by 21%, 57% and 52% respectively, compared to control. However, foliar spray of silicon dioxide nanoparticles under N₄₀ conditions did not have much effect on achene yield. The greatest effect of foliar spray treatments was recorded for Si₁₀₀ with N₈₀.

Comparison of the achene yield among the levels of foliar spraying showed that obtained achene yield under foliar spray with Si₀, Si₅₀, Si₁₀₀ and Si₁₅₀ were 1694.33, 2454.89, 2526.56 and 2343.02 kg ha⁻¹, respectively (Fig. 2).

The use of 80 and 120 kg of nitrogen improved the yield of achene by about 1000 kg ha⁻¹ compared to the condition of not using nitrogen. The use of high amounts of nitrogen decreased the yield of achene compared to the use of medium amounts of nitrogen. In the conditions of application of high amounts of



Boxes with different letters have a statistically significant difference at the 5% level. Control: no nitrogen application and foliar sprayed with distilled water (S_0), N_{40} : application of 40 kg ha⁻¹ nitrogen, N_{120} : application of 120 kg ha⁻¹ nitrogen, Si_{50} , Si_{100} and Si_{150} : foliar spray with solution contains 50, 100 and 150 ppm of silicon dioxide nanoparticles.

Fig. 2. The effect of application different levels of nitrogen in the soil and foliar spray of different concentrations of silicon dioxide nanoparticles on achene yield of sunflower plant grown in the semi-arid region of Hashtroud.

nitrogen, the application of a dilute solution of silicon nanoparticles was more effective (Fig. 2).

The excellent performance in terms of achene number was obtained under $N_{80}Si_{50}$ conditions which was 27% higher than the control condition (N_0Si_0). The investigation of 1000-achene weight showed that the heaviest achene was obtained in the plants grown under $N_{80}Si_{100}$ conditions, which were about 6% heavier than the seeds produced under control conditions (N_0Si_0). The lowest 1000-achene weight was recorded under N_0Si_0

(58.60 g), $N_{40}Si_{100}$ (59.43 g) and $N_{80}Si_{150}$ (59.99 g). Assessment of percentage of empty achene in head revealed that with the use of nitrogen, the portion of hollow and empty achene increased, however, foliar application of Si_{100} under the N_{120} condition reduced the percentage of empty achene by 23% compared to other levels of silicon dioxide nanoparticles under the same conditions of nitrogen application (Fig. 3).

The highest percentage of empty achene was recorded for plants grown under $N_{120}Si_{50}$ conditions, which was 138% higher than control

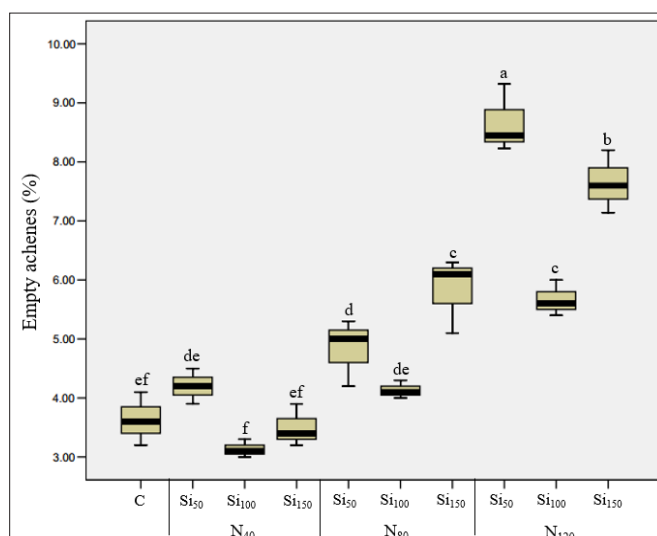
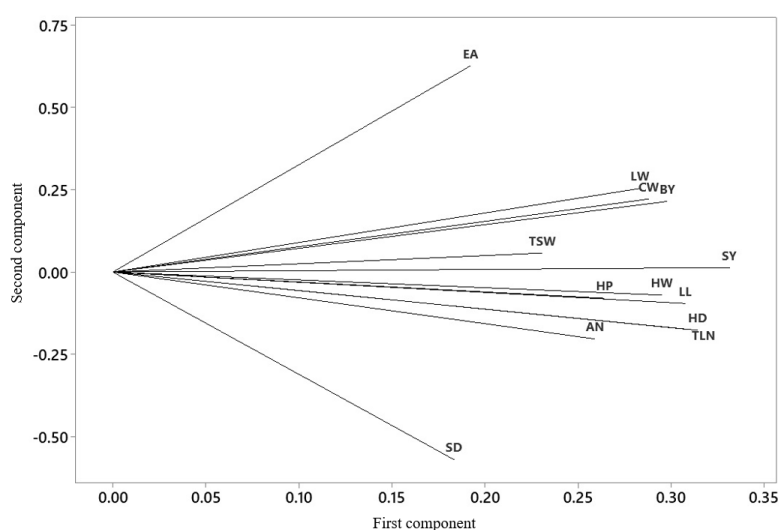


Fig. 3. The effect of the application of different levels of nitrogen in the soil and foliar spray of different concentrations of silicon dioxide nanoparticles on the percentage of empty sunflower achene in the semi-arid region of Hashtroud.



HD: head diameter, HW: head weight, AN: achene number per head, TAW: thousand achene weight, SY: achene yield, BY: biological yield, SD: stem diameter, PH: Plant height, TLN: total leaves number during the sunflower development, LL: leaf length, LW: leaf width, CW: canopy width

Fig. 4. The plot of the first two PCAs shows the relation among various growth characteristics of sunflower grown in a semi-arid region.

conditions (N_0Si_0). The lowest percentage of empty achene was recorded under $N_{40}Si_{100}$ conditions with 3.13% empty achene.

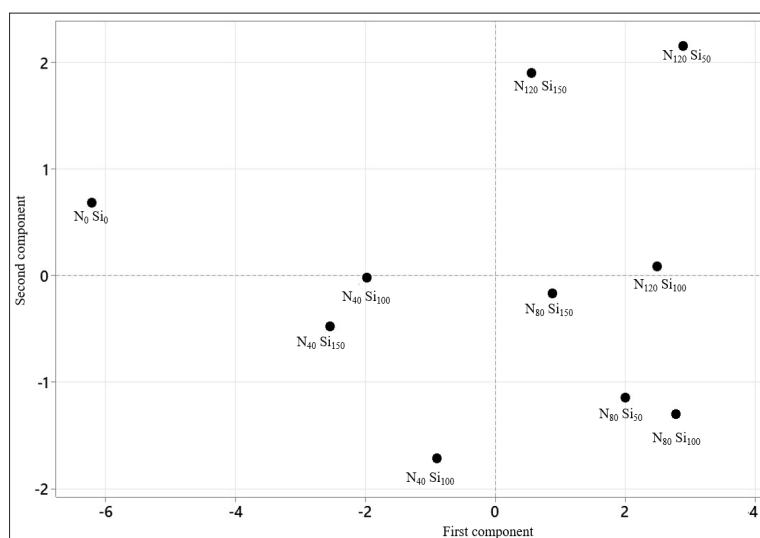
The interaction effect of $N \times Si$ was significant for biological yield. With the increase in nitrogen application, the biological yield increased significantly and the highest biological yield was recorded for plants grown with N and SiO_2 combination of $N_{120}Si_{100}$. Similar to achene yield, foliar spray with high concentrations of silicon dioxide nanoparticles under N_{80} and N_{120} conditions caused a 7% and 2% decrease in biological yield.

Besides, the principal component analysis (PCA) through the angles between the attributes explained the degree of correlations and the results showed that there is a positive and significant correlation between achene yield, 1000-achene weight, head weight, plant height, head diameter, and leaf length (Fig. 4).

However, biological yield showed a strong positive correlation with canopy width and leaf width. Examining the behavior of the traits against the studied treatments showed that the response of traits such as the total leaf number in the plant, head diameter, head weight, and length of the leaf was very similar to the response of the achene yield. Therefore, these traits can be used as suitable biomarkers for the evaluation of sunflower performance. The plot of the first two

PCAs could separate the combined treatments. The first component was able to separate the effective levels of nitrogen from the less effective nitrogen levels (N_{40} , N_0). The second component was also able to distinguish the best-combined treatments that include the use of the medium to low levels of silicon dioxide nanoparticles along with the medium to high use of nitrogen ($N_{80}Si_{100}$, $N_{80}Si_{50}$, and $N_{120}Si_{100}$) from others (Fig. 5).

The data related to the chemical and physical properties of soil in the investigated location indicated that the soil of the region is facing a severe deficiency of nitrogen and organic matter. For this reason, the addition of medium and high amounts of nitrogen (N_{80} and N_{120}) increased the growth characteristics and yield components of sunflower. The results obtained for canopy growth related parameters and achene yield components showed that the application of low amounts of nitrogen had no significant effect. Therefore, it seems that N_{40} could not provide the nitrogen requirements of the sunflower plant appropriately. Application of N_{80} and N_{120} , in addition to stimulating various aspects of growth, could also greatly increase the effectiveness of silicon dioxide nanoparticles. Although previous researches indicated the effectiveness of the external application of silicon nanoparticles in adverse environmental conditions (Wang *et al.*, 2017;



(N₀Si₀: Control or no nitrogen application and foliar spray of distilled water, N₄₀: application of 40 kg ha⁻¹ nitrogen, N₁₂₀: application of 120 kg ha⁻¹ nitrogen, Si₅₀, Si₁₀₀, and Si₁₅₀: foliar spray with solution containing 50, 100, and 150 ppm of silicon dioxide nanoparticles)

Fig. 5. Two-dimensional PCA plot based on the first two components for combined treatment for different levels of soil-applied nitrogen and foliar spray with different concentrations of silicon dioxide nanoparticles.

Farouk *et al.*, 2020; Naidu *et al.*, 2023; Okeke *et al.*, 2023; Boora *et al.*, 2023) the findings of this experiment showed that the effectiveness of SiO₂ nanoparticles can be largely influenced by the management conditions, especially the supply of essential elements. The external application of SiO₂ nanoparticles on plants can lead to a series of internal adjustment networks such as increasing the expression of genes as well as increasing the activity of antioxidant enzymes (such as catalase, superoxide dismutase, peroxidase, and ascorbate peroxidase) or increasing the synthesis of non-enzymatic antioxidants such as ascorbate and glutathione (Riaz *et al.*, 2022). The increase in growth observed with foliar application of SiO₂ nanoparticles can be attributed to the following: increasing the efficiency of photosynthetic systems and photoinduced electron transfer chain in chloroplast and improvement of stomatal conductance (Siddiqui *et al.*, 2014; Kalal *et al.*, 2022), increasing photosynthetic and protective pigments such as chlorophyll and carotenoid (Verma *et al.*, 2022), increasing the biosynthesis of polyamines and delaying the leaf senescence (Yin *et al.*, 2014), improving the plant water status by reducing transpiration and water loss through the cuticle or stomata (Verma *et al.*, 2019), improving the absorption of nutrients and creating a balance in absorption. However, not much information was available in earlier studies about physiological mechanisms and related details to the interaction of

external silicon used on the plant with other elements and the effect of SiO₂ nanoparticles in improving the absorption or impact of other nutrients. The obtained results in the current experiment seem to be consistent with our previous finding about the foliar application of SiO₂ nanoparticles on safflower in the semi-arid region. In the present study, maximum effect of foliar spraying of SiO₂ nanoparticles was observed under improved nutritional conditions (the use of high levels of farmyard manure or the application of NPK chemical fertilizers) and the application of silicon nanoparticles had no positive effect under no fertilizer application (Janmohammadi *et al.*, 2016). In addition, the obtained results emphasized that the influence of SiO₂ nanoparticles not only depended on the nutritional conditions of the plant but also can be affected by the applied concentrations. Although it has already been established that the accumulation of silicon in the plant cannot have toxic effects (Ma and Takahashi, 2002), our results showed that high concentrations of SiO₂ nanoparticles did not have a positive effect on sunflower growth. The present experiment showed that the supply of the medium to high levels of nitrogen (N₈₀ and N₁₂₀) probably affected and modified the source-sink relationship, and by increasing the vegetative growth and the expansion of the leaves, it provides more and better absorption of silicon dioxide nanoparticles. On the other hand, the application of nitrogen by increasing

the conversion of reproductive primordia into achene could increase the size of the sink or even sink activity (Masclaux-Daubresse *et al.*, 2010).

Considering the special conditions of the soils of semi-arid regions and the problems of supply and absorption of nutrients in the rhizosphere, supposedly in addition to foliar spray the design and application of nano-silicon fertilizers may have significant effects. The present experiment was carried out under full irrigation conditions and without restrictions on soil moisture. However, it should be noted that the use of nitrogenous fertilizers increases vegetative growth and it can result in increased water loss through transpiration, and lead to serious limitations in areas with a water shortage problem. Taken together, the obtained results emphasized that with the optimal use of nitrogen fertilizers (N_{80} and N_{120}) and foliar spray of silicon dioxide nanoparticles (Si_{100}), vegetative growth and yield components considerably improved. Considering to the protective effects of silicon nanoparticles, the application of suitable concentrations of silicon is very important, since the sunflower growth coincides with hot and dry summer periods in semi-arid Mediterranean regions. The effectiveness of silicon nanoparticles in plants still needs more investigations, however, our results indicated synergistic effects between nitrogen and silicon nanoparticles.

Conclusions

The results confirmed that for achieving an acceptable achene yield of sunflower in the studied region, the application of moderate levels of nitrogen should be on the agenda. Nitrogen application in addition to direct impact on the growth and yield of sunflower, could also affect the effectiveness of foliar spraying treatments with silicon dioxide nanoparticles. So, the lowest effect of foliar spray was recorded under low nitrogen application (N_0 and N_{40}). The obtained results showed that the spray of silicon dioxide nanoparticles in moderate concentrations (100 ppm) can stimulate both vegetative and reproductive growth. However, the effectiveness of a foliar spray of silicon dioxide nanoparticles probably depends on the nutritional conditions of the plant, and under favorable nutrient management, the application of silicon nanoparticles can significantly

increase sunflower performance. However, according to the distinctive conditions of semi-arid regions, it is necessary to investigate the effectiveness of silicon dioxide nanoparticles in different nutritional and moisture conditions and its possible interaction with the use of other elements, especially micronutrient elements.

Acknowledgments

The authors thank Maragheh University for their financial support. The project was part of the master's thesis in field of Agrotechnology. We hereby thank all the students of Sahand Agricultural Vocational school who helped during the field experiments. We thank Iran Nanotechnology Innovation Council for encouraging support and training courses on applications of nano-materials in agriculture.

Conflicts of Interest

The authors have no conflicts of interest
ORCID

Masoud Aghdam: <https://orcid.org/0009-0006-4669-6615>

Mohsen Janmohammadi: <https://orcid.org/0000-0002-6121-6791>

Naser Sabaghnia: <https://orcid.org/0000-0001-9690-6525>

References

- Ahmad, M.I., Ali, A., He, L., Latif, A., Abbas, A., Ahmad, J., Ahmad, M.Z., Asghar, W., Bilal, M. and Mahmood, M.T. 2018. Nitrogen effects on sunflower growth: a review. *International Journal of Biosciences* 12: 91-101. <https://doi.org/10.12692/ijb/12.6.91-101>
- Boora, R., Rani, N., Kumari, S., Yashveer, S., Kumari, N. and Grewal, S. 2023. Efficacious role of silica nanoparticles in improving growth and yield of wheat under drought stress through stress-gene upregulation. *Plant Nano Biology* 6: 100051. <https://doi.org/10.1016/j.plana.2023.100051>
- FAO 2022. *World Food and Agriculture Statistical Yearbook*. Food and Agriculture Organization of the United Nations. Rome, Italy
- Farouk, S., Elhindi, K.M. and Alotaibi, M.A. 2020. Silicon supplementation mitigates salinity stress on *Ocimum basilicum* L. via improving water balance, ion homeostasis, and antioxidant defense system. *Ecotoxicology and Environmental Safety* 206: 111396. <https://doi.org/10.1016/j.ecoenv.2020.111396>
- Hawkesford, M.J., Cakmak, I., Coskun, D., De Kok, L.J., Lambers, H., Schjoerring, J.K. and

- White, P.J. 2023. Functions of macronutrients. In: *Marschner's Mineral Nutrition of Plants* (Eds. Z. Rengel, I. Cakmak and P.J. White), Elsevier. pp. 201-281. <https://doi.org/10.1016/B978-0-12-384905-2.00006-6>
- Janmohammadi, M., Amanzadeh, T., Sabaghnia, N. and Ion, V. 2016. Effect of nano-silicon foliar application on safflower growth under organic and inorganic fertilizer regimes. *Botanica Lithuanica* 22(1): 53-64. <https://doi.org/10.1515/botlit-2016-0005>
- Jarecki, W. 2022. Effect of varying nitrogen and micronutrient fertilization on yield quantity and quality of sunflower (*Helianthus annuus* L.) achenes. *Agronomy* 12(10): 2352. <https://doi.org/10.3390/agronomy12102352>
- Kalal, P.R., Tomar, R.S. and Jajoo, A. 2022. SiO₂ nanopriming protects PS I and PSII complexes in wheat under drought stress. *Plant Nano Biology* 2: 100019. <https://doi.org/10.1016/j.plana.2022.100019>
- Liu, R. and Lal, R. 2015. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of the Total Environment* 514: 131-139. <https://doi.org/10.1016/j.scitotenv.2015.01.104>
- Luyckx, M., Hausman, J.F., Lutts, S. and Guerriero, G. 2017. Silicon and plants: current knowledge and technological perspectives. *Frontiers in Plant Science* 8: 411. <https://doi.org/10.3389/fpls.2017.00411>
- Ma, J.F. and Takahashi, E. 2002. *Soil, Fertilizer, and Plant Silicon Research in Japan*. Elsevier. <https://doi.org/10.1016/B978-0-444-51166-9.X5000-3>
- Ma, J.F., Miyake, Y. and Takahashi, E. 2001. Silicon as a beneficial element for crop plants. *Studies in plant Science* 8: 17-39. [https://doi.org/10.1016/S0928-3420\(01\)80006-9](https://doi.org/10.1016/S0928-3420(01)80006-9)
- Masclaux-Daubresse, C., Daniel-Vedele, F., Dechorgnat, J., Chardon, F., Gaufichon, L. and Suzuki, A. 2010. Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. *Annals of Botany* 105(7): 1141-1157. <https://doi.org/10.1093/aob/mcq028>
- Naidu, S., Pandey, J., Mishra, L.C., Chakraborty, A., Roy, A., Singh, I. K. and Singh, A. 2023. Silicon nanoparticles: Synthesis, uptake and their role in mitigation of biotic stress. *Ecotoxicology and Environmental Safety* 255: 114783. <https://doi.org/10.1016/j.ecoenv.2023.114783>
- Naorem, A., Jayaraman, S., Dang, Y.P., Dalal, R. C., Sinha, N.K., Rao, C.S. and Patra, A.K. 2023. Soil constraints in an arid environment-challenges, prospects, and implications. *Agronomy* 13(1): 220. <https://doi.org/10.3390/agronomy13010220>
- Okeke, E.S., Nweze, E.J., Ezike, T.C., Nwuche, C.O., Ezorba, T.P.C. and Nwankwo, C. E.I. 2023. Silicon-based nanoparticles for mitigating the effect of potentially toxic elements (PTEs) and plant stress in agroecosystems: A sustainable pathway towards food security. *Science of the Total Environment* 898: 165446. <https://doi.org/10.1016/j.scitotenv.2023.165446>
- Pavlovic, J., Kostic, L., Bosnic, P., Kirkby, E. A. and Nikolic, M. 2021. Interactions of silicon with essential and beneficial elements in plants. *Frontiers in Plant Science*, 12: 697592. <https://doi.org/10.3389/fpls.2021.697592>
- Riaz, M., Zhao, S., Kamran, M., Ur Rehman, N., Mora-Poblete, F., Maldonado, C., Hamzah Saleem, M., Parveen, A., Ahmed Al-Ghamdi, A., Al-Hemaid, F.M. and Ali, S. 2022. Effect of nano-silicon on the regulation of ascorbate-glutathione contents, antioxidant defense system and growth of copper stressed wheat (*Triticum aestivum* L.) seedlings. *Frontiers in Plant Science* 13: 986991. <https://doi.org/10.3389/fpls.2022.986991>
- Siddiqui, M.H., Al-Whaibi, M.H., Faisal, M. and Al Sahli, A.A. 2014. Nano-silicon dioxide mitigates the adverse effects of salt stress on *Cucurbita pepo* L. *Environmental Toxicology and Chemistry* 33(11): 2429-2437. <https://doi.org/10.1002/etc.2697>
- Verma, K.K., Song, X.P., Lin, B., Guo, D.J., Singh, M., Rajput, V.D., Singh, R.K., Singh, P., Sharma, A., Malviya, M.K. and Chen, G.L. 2022. Silicon induced drought tolerance in crop plants: physiological adaptation strategies. *Silicon* 14: 2473-2487. <https://doi.org/10.1007/s12633-021-01071-x>
- Verma, K.K., Wu, K.C., Singh, P., Malviya, M.K., Singh, R.K., Song, X.P. and Li, Y.R. 2019. The protective role of silicon in sugarcane under water stress: photosynthesis and antioxidant enzymes. *Biomedical Journal of Scientific and Technical Research* 15(2): 002685. <https://doi.org/10.26717/BJSTR.2019.15.002685>
- Wang, M., Gao, L., Dong, S., Sun, Y., Shen, Q. and Guo, S. 2017. Role of silicon on plant-pathogen interactions. *Frontiers in Plant Science* 8: 701. <https://doi.org/10.3389/fpls.2017.00701>
- Yavaş, İ. and Aydın, Ü. 2017. The role of silicon under biotic and abiotic stress conditions. *Türkiye Tarımsal Araştırmalar Dergisi* 4(2): 204-209. <https://doi.org/10.19159/tutad.300023>
- Yin, L., Wang, S., Liu, P., Wang, W., Cao, D., Deng, X. and Zhang, S. 2014. Silicon-mediated changes in polyamine and 1-aminocyclopropane-1-carboxylic acid are involved in silicon-induced drought resistance in *Sorghum bicolor* L. *Plant Physiology and Biochemistry* 80: 268-277. <https://doi.org/10.1016/j.plaphy.2014.04.014>

