Silica nanoparticles improve growth, chemical bioactive, and antioxidant enzyme activity of *Dianthus caryophyllus* L., plant

Iman M. El-Sayed, Dina M. Soliman

Ornamental Plants and Woody Trees Department, National Research Centre (NRC), Dokki, Cairo, Egypt

Correspondence to: Dr. Dina M. Soliman, PhD, Ornamental Plants and Woody Trees Department, National Research Centre (NRC), El Buhouth St., Dokki 12622, Cairo, Egypt. Tel: +0100 874 4811; fax: 0020237601877; e-mail: dina123soliman@hotmail.com

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Background
Nanotechnology has provided innovative use of various materials with unique properties. These substances may react positively in plants, and the induction of bioactive compounds and antioxidant activity is particularly remarkable. Ornamental plant production is a positive economic activity of great interest, especially Carnation (Dianthus caryophyllus L.). This plant is more attractive for its various colors, but the flower quality and its longevity can diminish very fast. Thus, examining methods capable of improving flower quality and vase life is crucial. Additionally, carnation can be used to treat coronary and nervous disorders. Carnation contains compounds that calm the nervous system and minimize swelling and inflammation.
Objective
This research aimed to evaluate the effect of silica nanoparticles (SiO_2 NPs) on the growth, bioactive chemical analysis, enzyme activity, and antioxidant accumulation.
Material and methods
The different rates of SiO_2 NPs (0, 150, and 300 ppm) were used in two ways: foliar spray and soil drench; it was applied 3 times. The first application was after 3 weeks of transplanting and repeated with 21-day intervals.
Results and conclusion
The results showed that foliar application of SiO_2 NPs increased all morphological and flowering traits compared with drench and the control, higher levels of photosynthetic pigments and anthocyanin, greater total phenols, total sugars, and total free amino acids were obtained from plants treated with foliar spray 300 ppm followed than 150 ppm. In addition, the greatest levels of enzyme activity were recorded with plants treated with foliar spray of SiO_2 NPs at a rate of 300 ppm, as well as improved anatomical structure of the stem and stomata properties compared with the drench method and control. Similarly, SiO_2 NPs application method is more critical than their concentration. Therefore, it is recommended that foliar spraying of SiO_2 NPs at 300 ppm can enhance plant growth, flowering, bioactive compounds, enzyme activity, and anatomical structure of the stem of carnation plants while adding SiO_2 NPs drench at a rate of 150 ppm had rather acceptable findings.

Keywords:
antioxidant, bioactive analysis, carnation, enzyme activity, flowering, nanotechnology, phenols

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Introduction

Nanoparticles (NPs) are defined as materials less than 100 nm in size in at least two dimensions and are referred to as unique properties. NPs have been used in various applications because of their unique characteristics [1,2]. One of the critical applications of nanotechnology is using nano-fertilizers in plant nutrition [3]. According to reports, silica nanoparticles (SiO_2 NPs) can now be made from natural sources. These particles were made cheaply using rough rice for the first time. Plant roots or leaves can absorb nutrients. Nano-fertilizers can be released gradually and deliberately, allowing them to be absorbed by both organs. Therefore, applying nano-fertilizers is preferred to other fertilizer types due to their faster plant release and absorption [4].

Silicon (Si) is an essential element of the earth's crust. The main silicon source is silica sand, which is easily processed and widely available. Silica substance is referred to by quartz, metamorphic, tridymite, cristobalite, and minerals as silica polymorphs. Silica is used to describe silicon minerals, and 90% of the earth's crust comprises silicates, which are silicon and oxygen compounds [5].

SiO_2 NPs significantly impact plants' physiology, growth, and protection. Since they can positively

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enhance the processes of nutrient supply and water absorption, positively regulate the processes of gas exchange and photosynthesis, and activate metabolism, thus enhancing the nitrogen metabolism and antioxidant defense system [6]. Furthermore, SiO_2 NPs can be used directly as nano-fertilizers, nano-pesticides, and nano-herbicides [4]. In addition, SiO_2 NPs have shown promise in cosmetics, disease diagnosis, drug delivery, and bio imaging due to their great biocompatibility and low toxicity [2].

Ornamental plant production are expanding worldwide industry with excellent potential for continued growth in international markets [7–9]. However, cut flowers generally have a short vase life depending on genetic and environmental factors, which often limits industry development [10,11]. Carnation (*Dianthus caryophyllus* L.) is one of the ornamental industry's most popular and vital cut flowers. It is also useful as an ornamental model plant for which the genome has been sequenced [12,13]. The plant had anesthetic, analgesic, insecticidal, anticancer, and antiviral properties. In traditional European herbal medicine, it was used for cardiac problems. The blossoms were thought to have nervine, alexiteric, cardiotonic, diaphoretic, and antispasmodic effects. In China, the plant has been employed as a vermifuge [14]. Typically, carnations have a short vase life of around 5–10 days, depending on the cultivar. Prolonging vase life and maintaining flower quality is excessively prominent since quality and longevity are economically essential factors for carnation commercialization due to their short vase life after or before deterioration and harvest, which causes difficulties for long-distance decrease and transport in market value [15]. However, more information needs to be provided about using SiO_2 NPs in carnation experiments in open areas to enhance flower quality and vase life. Therefore, this work aimed to evaluate the effect of SiO_2 NPs in carnation plants precisely to determine the best method and concentration to use SiO_2 NPs to stimulate morphological parameters, flowering characteristics, antioxidant accumulation, and anatomical stem structure.

Material and methods

Establishment of plant and experiment treatments

An experiment was conducted during two successful seasons (2021-2022) under greenhouse conditions at National Research Centre (NRC), using *Dianthus caryophyllus* L. cv, (Ciremson Tempo) seedlings. The transplant was performed in 25 cm plastic containers with a peat moss/perlite mixture in a 2 : 1 ratio. The treatments consisted of SiO_2 NPs at levels 0, 150, and 300 ppm. The control plants received equal distilled water spraying for foliar and without any treatments. SiO_2 NPs were applied using foliar spray and drenches. Two applications were applied 3 times, starting 21 days after planting seedlings and repeated with 21 days intervals.

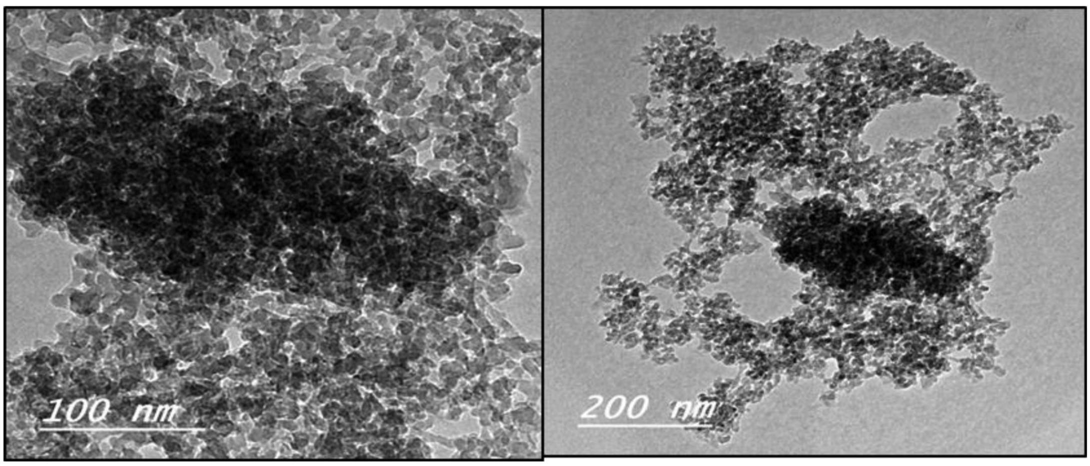
Specification of silica NPs

Obtained SiO_2-NPs from Sigma Cor., USA, According to Zafar *et al.*, [16], Silica NPs are distributed in substantial distilled water, and characterized in an Electron of National Research Centre (NRC) microscopy unit. SiO_2 NPs are demonstrated according to their specification in Table 1 and Fig. 1.

Morphological and flowering parameters

Some morphological and flowering parameters were record by the end of the experiment i.e. the plant height

Figure 1



Scanning electron microscopy image of silica nanoparticles at 100 and 200 nm.

Table 1 Specification of used silica oxide nanoparticles

Specification	Test method	
Phase	Silica gel	XRD
Particle size	<50 nm	TEM
Surface area	>200 m^2/gm	BET (P/Po: up to 0.35)

(cm), number of leaves, stem diameter (cm), leaf area (cm^2), fresh and dry weight of shoot (g), fresh and dry weight of roots (g), diameter of flowers (cm), fresh and dry weight of flower (g), and flowers vase life (days).

Bioactive chemical analysis

Photosynthetic pigments

Chlorophyll a, b, and total carotenoids (mg/g F.W.) were determined in fresh leaf samples according to Saric *et al.*, [17].

Anthocyanin content

The extraction of fresh petals was done with an ethanol hydrochloric acid solution (15 ml 1.5 N HCl+85 ml ethanol 95%) according to the method of Fuleki and Francis, [18].

Total free amino acid content (mg/g F.W.)

The content of total amino acid was measured by using the ninhydrin reagent in the fresh shoots, according to Moore and Stain [19].

Total phenolic and total sugar content (mg/g F.W.)

In the fresh shoot samples of each treatment, the total phenolic content was determined by Swain and Hillis [20] method, and the total sugar content was described by Dubois *et al.*, [21].

Extraction and assessment antioxidant enzymes activities

Fresh leaf samples were used to extract the enzymes according to Mukherjee and Choudhuri [22]. The activity of Catalase (CAT) EC1.11.1.6 and Peroxidase (POD) EC 1.11.1.7 were measured by the method of Kar and Mishra [23]. Superoxide dismutase activity (SOD) EC1.15.1.1 according to Marklund and Marklund [24] was determined.

Determination of proline

The content of proline was determined by the method of Bates *et al.*, [25] in fresh shoot samples.

Macro-and micronutrient determination

Nitrogen determination (%): Extract for the nitrogen content was collected from dried shoot. Nitrogen content was described by the modified Kjeldahl method as described by Cottenie *et al.* [26]. Phosphorus determination (%): using the ammonium molybdate method Snell and Snell [27]. Potassium assessment (%): using a flame photometer according to Snell and Snell [27] method. Ca% was assessed by using atomic absorption spectroscopy (PerkinElmer 100 B, US) using the method of Cottenie *et al.* [26]. Silicon, according to Wolf [28] was determined the silicon content.

Anatomical study

Throughout the first growing season after second treatment, stem samples were collected from plants exposed to different concentrations of silica NPs (150 and 300 ppm) by both methods. The samples were fixed and killed in a 70% formalin, ethyl alcohol, and acetic acid solution for 48 h. Following fixation, samples were rinsed in 50% ethyl alcohol, dehydrated using a series of butyl alcohols, and then embedded in paraffin wax (melting point, 56–58°C). Leica Rotary Microtome was utilized to cut stem cross sections (20 microns thick).Sections were mounted in Canada balsam after being dyed with crystal violet-erythrosine [29]. Cross slices were examined under a microscope and photographed. The stem anatomical parameters (μm), Stem diameter, Epidermis thickness (μ), Cortex thickness (μ), Phloem thickness (μ), Xylem thickness (μ), and Pith thickness (μ). The Scanning electron microscopy and anatomy were carried out in the CURP Research Park, Fac. of Agric., Cairo Univ., Giza, Egypt.

Scanning electron microscopy (SEM)

To observe stomata parameters, fresh leaf samples were collected after 63 days from transplanting (third treatment) and prepared for scanning electron microscopy (SEM). Recut leaf samples 4–10 mm length segments to measure stomata parameters sample segments were attached to aluminum stubs using electron-conductive cement (Neubauer Chemikalien, Germany). Five image of each sample were collected from different locations images J software was used to process the SEM images [30].

Experiment design and statistical analysis

The pot experiment was organized in three replications of each treatment, established in a randomized block design (RBD). Statistical analysis was performed using COSTATV-63 least significant difference method ($P \leq 0.05$). The differences in treatments means were separated, according to new multiple-range testes according Duncan [31].

Results

According to our findings, SiO_2 NPs' significantly influence morphological and flowering parameters, chemical composition, antioxidant accumulation, and enzyme activity, as well as anatomical stem structure and scanning stomata parameters of carnation plants.

Morphological parameters

SiO_2 NPs showed a positive effect on most morphological parameters of *Dianthus caryophyllus* L plant, especially with the spray application method

Table 2 Effect of silica Nanoparticles application on morphologecal and flowering paramaters of *Dianthus caryophyllus* L., plant during two seasons

Year		Silica NPs (ppm) 0	150 (spray)	300 (spray)	150 (drench)	300 (drench)	LSD
2021	Plant height (cm)	38.00^{d}	49.00^{b}	55.00^{a}	47.5^{b}	43.00^{c}	**3.73**
	Number of leaves	25.00^{b}	31.67^{a}	33.00^{a}	28.33^{b}	25.67^{b}	**5.88**
	Stem diameter (cm)	0.52^{c}	0.63^{a}	0.65^{a}	0.58^{b}	0.53^{c}	**0.04**
	Leaf area (cm^2)	8.33^{c}	11.0^{ab}	12.33^{a}	10.0^{b}	9.53^{bc}	**1.475**
	Fresh weight of shoot (g)	3.26^{e}	6.14^{b}	7.41^{a}	5.12^{c}	4.7^{d}	**0.25**
	Dry weight of shoot (g)	1.30^{e}	2.45^{b}	2.96^{a}	2.04^{c}	1.88^{d}	**0.10**
	Fresh weight of roots (g)	1.66^{e}	2.15^{b}	2.68^{a}	1.88^{c}	1.75^{d}	**0.04**
	Dry weight of roots (g)	0.59^{d}	0.79^{b}	0.96^{a}	0.67^{cd}	0.63^{c}	**0.070**
	Diameter of flowers (cm)	5.17^{d}	6.63^{b}	7.1^{a}	5.63^{c}	6.45^{b}	**0.34**
	Fresh weight of flowers (g)	2.24^{c}	2.69^{b}	3.54^{a}	2.37^{bc}	2.67^{b}	**0.39**
	Dry weight of flowers (g)	1.7^{d}	2.04^{b}	2.68^{a}	1.79^{cd}	1.98^{bc}	**0.19**
	Vase life (days)	8.83^{d}	12.17^{b}	13^{a}	10.5^{c}	10.67^{c}	**0.56**
2022	Plant height (cm)	35.0^{c}	47.0^{a}	51.0^{a}	46.0^{ab}	40.33^{bc}	**6.24**
	Number of leaves	23.33^{c}	29.67^{a}	31.0^{a}	27.0^{ab}	24.67^{bc}	**4.28**
	Stem diameter (cm)	0.381^{e}	0.54^{b}	0.595^{a}	$0.5.00^{c}$	0.435^{d}	**0.03**
	Leaf area (cm^2)	7.66^{d}	9.93^{ab}	10.60^{a}	9.33^{bc}	8.66^{c}	**0.952**
	Fresh weight of shoot (g)	3.02^{e}	5.41^{b}	6.93^{a}	4.65^{c}	4.10^{d}	**0.24**
	Dry weight of shoot (g)	1.21^{e}	2.15^{b}	2.77^{a}	1.95^{c}	1.64^{d}	**0.06**
	Fresh weight of roots (g)	1.33^{e}	2.05^{b}	2.38^{a}	1.72^{c}	1.57^{d}	**0.07**
	Dry weight of roots (g)	0.48^{e}	0.74^{b}	0.86^{a}	0.62^{c}	0.57^{d}	**0.03**
	Diameter of flowers	5.00^{d}	6.17^{b}	7.00^{a}	5.50^{c}	6.00^{b}	**0.90**
	Fresh weight of flowers (g)	1.95^{d}	2.59^{b}	2.92^{a}	2.27^{c}	2.57^{b}	**0.39**
	Dry weight of flowers (g)	1.49^{d}	1.97^{b}	2.21^{a}	1.72^{c}	1.93^{b}	**0.17**
	Vase life (days)	8.50^{d}	11.83^{a}	12.33^{a}	10.03^{c}	10.33^{b}	**0.60**

Means having the different letter(s) within the same column are significantly different among the treatments according to Duncan's multiple range tests at 5% level of probability with high concentrations of silica NPs (300 ppm) compared with the drench application and control (untreated SiO_2 NPs application) (Table 2). At the same time, the lowest values of morphological characteristics were found in untreated plants (control).

Flowering parameters

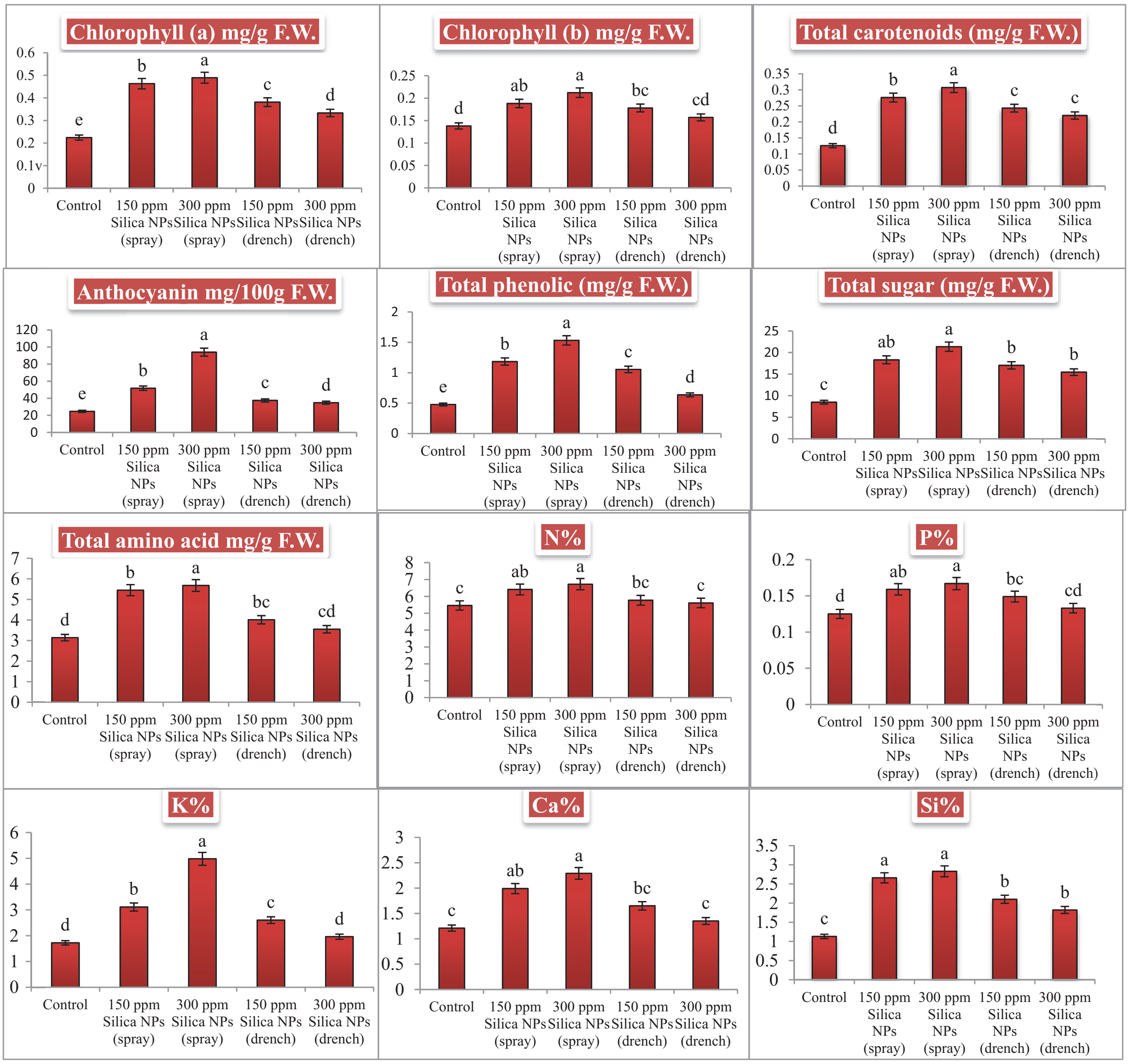
Generally, the foliar utilization showed a better effect on all carnation flower parameters (diameter of flower, fresh and dry weight of flowers, and vase life), especially at 300 ppm concentration, than different concentrations of drench application and control plants in both growing seasons Table 2. On the other hand, the lowest values of flower parameters were recorded in the nontreated control plants.

Bioactive chemical analysis

Photosynthetic pigments in leaves and anthocyanin content in petals of Dianthus caryophyllus L.

Chlorophyll a, b, total carotenoid, and anthocyanin content in treated plants with different levels of SiO_2 NPs showed positive effects. Furthermore, an apparent increase was noticed with foliar application of 300 ppm (0.48, 0.21, 0.31 mg/g F.W., and 94.9 mg/100 g F.W.) followed by foliar spray application of 150 ppm (0.46,

Figure 2



Effect of silica nanoparticles application on the chlorophyll a, b, total carotenoids, anthocyanin contents, total sugar, total phenolic, total amino acid, N%, P%, K%, Ca%, Si% of *Dianthus caryophyllus* L., plant, in the first season (2021).

0.19, 0.27 mg/g F.W. and 51.77 mg/100 g F.W.) when compared with soil drench and control in (Fig. 2).

Total phenol, total sugar and total amino acids (mg/g F. W.) content in shoot

Total phenol content, total sugar, and total free amino acids have been significantly affected by exposed SiO_2 NPs when compared with control; the highest value was obtained from plants treated with 300 ppm foliar spray application compared with other treatments (Fig. 2).

Macro-and micronutrient content in shoot

The high concentrations of SiO_2 NPs (300 ppm) in the foliar spray method modified the concentration of macronutrients in the shoot. Dependably, a concentration of 300 ppm SiO_2 NPs in foliar applications increased the content of N (3.49%), P (0.16%), K (4.98%), and Ca (2.29%) content. On the other hand, applying 300 or 150 ppm SiO_2 NPs via foliar spray increased Si content (2.83, 2.66%) in carnation plants compared with the control and other treatments (Fig. 2).

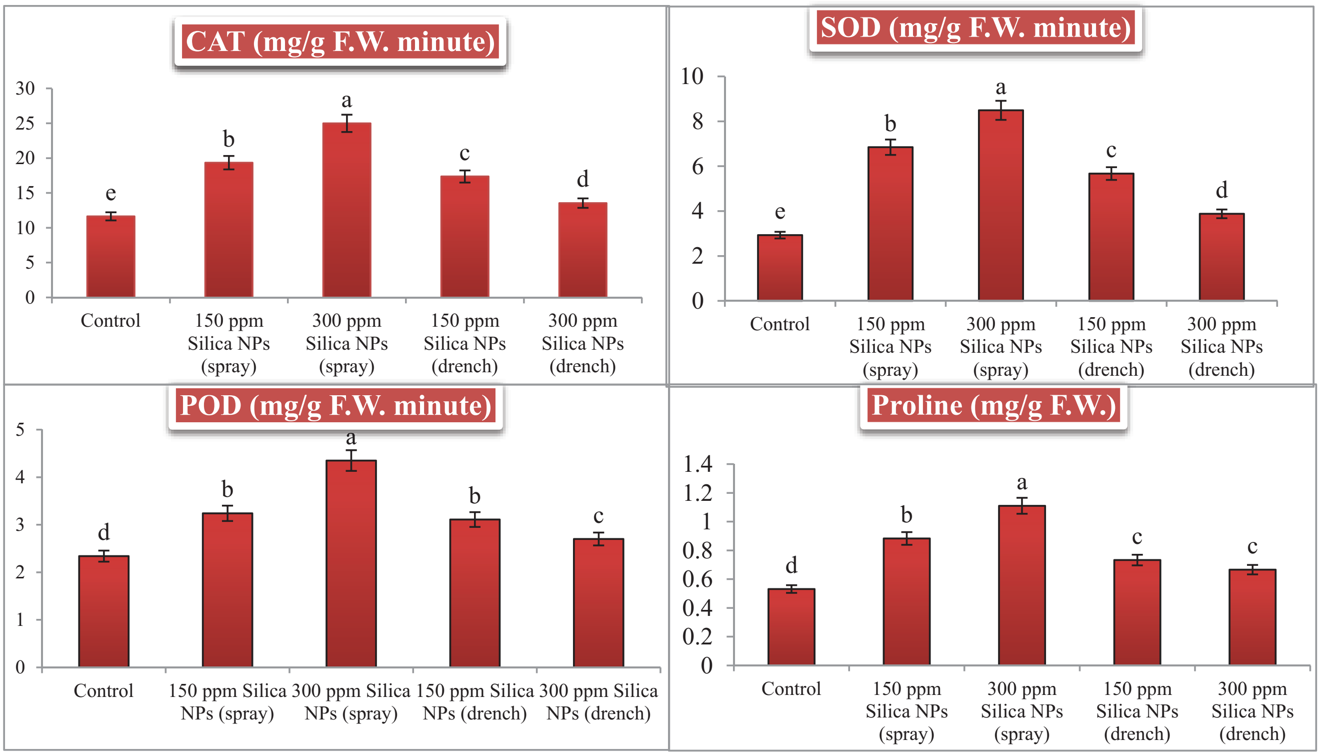
Antioxidant enzymes activities and proline content in leaves

Moreover, the utilization of SiO_2 NPs through the foliar and drench methods showed changes in activity of catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD). The data showed that foliar application was more effective than the control and drench methods. The maximum enzyme activity values were observed in treated plants with 300 ppm foliar application in all enzyme activities (24.99, 4.35, and 8.49 mg/g F.W. minute, in respect order). The proline content in the shoot gave a high value in the concentration of 300 ppm followed by 150 ppm (1.11, 0.83 mg/g F.W., in respect order) SiO_2 NPs foliar application, compared with the control Fig. 3.

Anatomical structure of stems

SiO_2 NPs treatments showed an enhancement in most stems anatomical parameters of carnation plants (Table 3 and Fig. 4), comparable to the control without any treatments. The anatomical characteristics of the stem of carnation include stem diameter, epidermis thickness, cortex thickness, phloem thickness, xylem thickness, and pith thickness (Fig. 4). The treatments with SiO_2 NPs caused an enhancement in stem diameter, cortex thickness, phloem thickness, xylem thickness and pith thickness than the control plants, the best results were recorded with SiO_2 NPs at 300 ppm as a foliar application method and 150 ppm as drench application method.

Figure 3

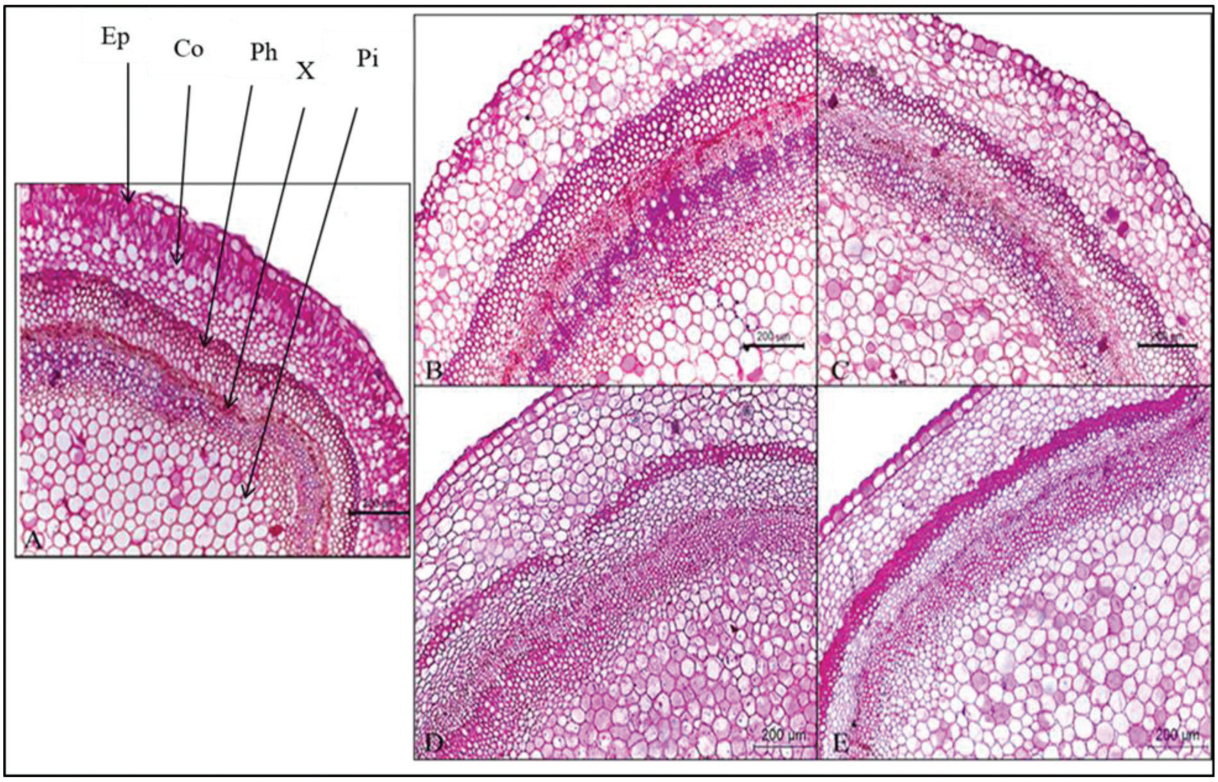


Effect of silica nanoparticles application on some enzyme activity (A–C) and proline (D) of *Dianthus caryophyllus* L., plant, in the first season (2021).

Table 3 Effect of silica nanoparticles application on stem anatomy measurements (μm) of *Dianthus caryophyllus* L., plant

Treatments	Stem diameter (μm)	Epidermis thickness (μm)	Cortex thickness (μm)	Phloem thickness (μm)	Xylem thickness (μm)	Pith thickness (μm)
Control	2756.63	44.82	237.45	107.24	150.43	1050.43
150 SiO_2 NPs (spray)	2901.61	47.27	147.07	152.71	133.96	2038.5
300 SiO_2 NPs (spray)	4306.52	43.23	229.8	182.54	185.19	3025.10
150 SiO_2 NPs (drench)	4187.68	44.13	267.62	161.22	164.18	2907.33
300 SiO_2 NPs (drench)	3670.11	54.14	233.98	111.99	233.98	2423.74

Figure 4



Effect of silica nanoparticles application on stem anatomy measurements (μm) of *Dianthus caryophyllus* L., plant. Control (A), plants treated with 150 ppm spray (B), plants treated with 300 ppm spray (C), plants treated with 150 ppm drench (D), and plants treated with 300 ppm drench(E). Ep, epidermis; Co, cortex; Ph, phloem; X, xylem; Pi, pith.

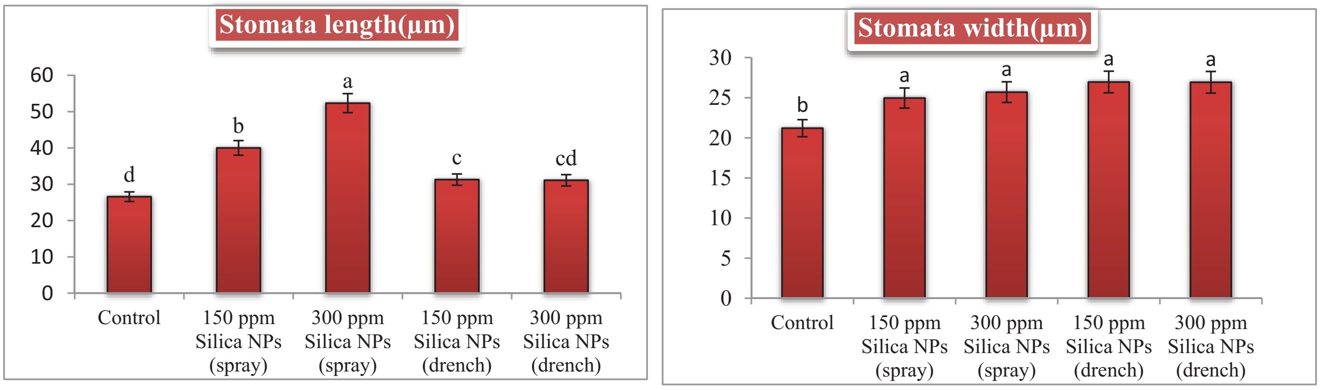
Scanning electron microscopy (SEM)

The SEM images demonstrated the impact of SiO_2 NPs concentrations and the methods on the stomata of the upper surface of the leaf. The findings of (Figs 5 and 6) showed that the characteristic of stomata length was significantly affected by 300 ppm SiO_2 NPs spray application, with the most significant value (52.33 μm). However, in the width of the stomata, SiO_2 NPs concentrations had no significant effect, with the highest value (26.96 μm) found when treated plants with 150 ppm SiO_2 NPs added drench.

Discussion

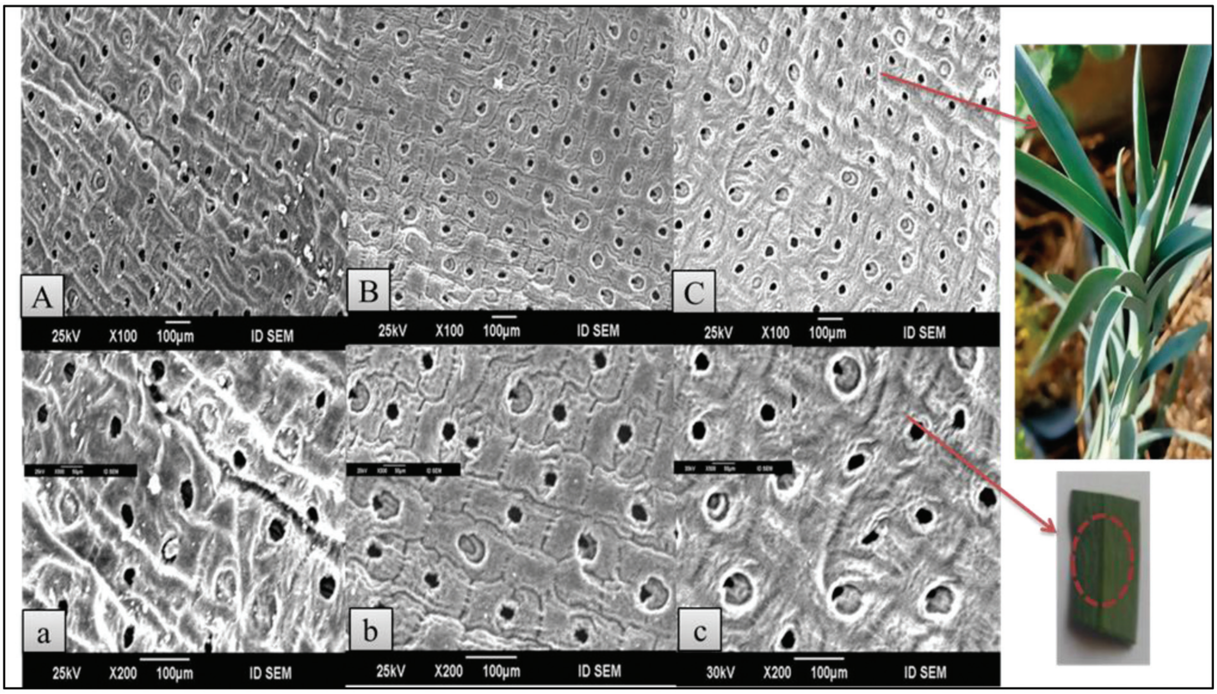
Recently, nanoparticle application has attracted the attention of the public and policy maker, particularly in the agriculture sector. The majority of these nanoparticles can be used into soil or foliar applications. Silicon is a valuable plant nutrient and has improved plant growth and production [3]. Si is significant in promoting plant resistance too many fungal and oomycete diseases due to increasing longevity vase life. Additionally, it stimulates plant yield, growth, and fruit physicochemical characteristics [4]. This research aimed to evaluate the effect of SiO_2 NPs in carnation to stimulate morphological parameters, flowering characteristics, antioxidant accumulation, and anatomical stem structure. These results are in agreement with Asgari and Diyanat [32], who demonstrated that applying silicon NPs (Si NPs) at 1000 mg/l treatments in *Rosa chinensis* improved growth traits and decreased

Figure 5



Effect of silica nanoparticles application on stomata measurements of *Dianthus caryophyllus* L., plant in the first season (2021).

Figure 6



Scanning electro-microscope micrograph of *Dianthus caryophyllus* L., at lower surface of leaf, showing the impact of some treatments of application of silica nanoparticles on stomata parameters. (A, a) control (without any treatments), (B, b) plants treated with 300 ppm silica nanoparticles spray, (C, c) plants treated with 300 ppm silica nanoparticles soil.

the negative effect of salinity stress. Karimian *et al.*, [33], who indicated that Si NPs spraying at 200 mg/l and 400 mg/l enhanced fresh leaf weight, root and bullet dry weight, and root valium in tuberose plants. Using Si NPs has positively increased the leaf area of carnation plants and their relative chlorophyll content. This may help to explain the significant impact of Si NPs on the growth and improvement of carnation plants, as their large leaves with high chlorophyll content have more excellent rates of photosynthesis process. Hence, better Si precipitation in leaf cells improves the orientation and position of the leaves, which enhances light absorption and increase photosynthesis rate [34]. Also, the application of Si NPs could raise the deposition of irregular crystal wax in the plant cortex which is related to water-use efficiency and water evaporation, thereby maintaining the chlorophyll content and enhancing the growth of plants [35,36].

For ornamental plants, flower characteristics are desirable parameters for attractive plants. Higher fresh and dry flower weights are crucial, particularly carnation. In the present study, all the flower parameters and vase life were significantly and positively affected by the use of SiO_2 NPs . This may be explained by the reliance on the amount of Si that accumulates in leaves after applying increasing concentrations of Si NPs through foliar and soil methods (300 ppm). Previous studies cited a release in flower production of Lilium [37] *Tagetes erecta* L. [38] *Rosa chinensis* [32] tuberose plants [33] due to increase contents of Si obtained in the leaves.

One of the well-known methods of foliar fertilization is silica spraying, which enhances the plant's physiological performance and nutrient balance to promote growth, productivity, and resistance and subsequently increase its yield [3]. Our findings reported that the chlorophyll rate and anthocyanin content improved with the application of SiO_2 NPs. In addition, Si NPs application increased the photosynthetic activity rate, making it easier for nutrients to be absorbed through the opening of the xylem [6]. In addition, the expression levels of the chlorophyll synthesis gene increased with applied Si NPs, which may the reason for the increased, content of chlorophyll a and b [39]. The accumulation of Si NPs in the leaves of plants is advantageous for maintaining leaves upright and stretching leaf surfaces to capture most sunlight, thus promoting photosynthesis [4]. Moreover, metal ions play a critical role in the stabilization of petal color in flowers by their effects on the acidity of the petal and the activity of different enzymes implicated in biosynthesis, accumulation and transportation of different pigments [40]. Anthocyanin and phenolic levels increased significantly after applying Si NPs [41]). Furthermore, our current research revealed that SiO_2 NPs enhanced the physico-chemical parameters. These results are in harmony with El-Shawa et al., [1], who indicated that treating philodendron plants with 60 mg/l Si NPs increases N, P, K%, catalase, polyphenol oxidase, and peroxidase compared with untreated plants. In addition, the antioxidant defense system is activated by nanoparticles, and the accumulation of enzymatic and nonenzymatic antioxidant molecules is enhanced [42,43]. The foliar application of SiO_2-NPs showed increased activity of CAT, POD, and SOD enzymes and proline content in both normal and stress conditions in hybrid rice [44]. One of the nanoparticle's critical effects is the modification of plant antioxidant system, which is tolerant to their ability to resist stress [45]. Furthermore, they additionally can change secondary metabolism and, consequently, the production of secondary metabolites such as flavonoids and phenols [46,47]. The mechanism of Si NPs induces phenols probably due to the insoluble Si NPs, which are accumulated in epidermis, that induce the enrichment of structural phenols in cells of epidermal by their premium high adsorption surface [48]. The reason for increased phenol compounds with Si NPs applied could be an electing pathway of phenol biosynthesis or enhancing activity of enzymes such as polyphenol oxidase, which catalyzed the oxidation of different phenolic compounds to quinones using oxygen as an electron acceptor [49]. According to the findings of prior studies, the reason for higher soluble sugar content may be partially attributable to improve photosynthesis, which encourages the synthesis of soluble sugars [39,50]. Additionally, SiO_2 NPs can alter nutrient uptake in plants, via various mechanisms, including the formatting of organic acids by the roots, which can eventually promote nutrient uptake [51]. In particular, citric, oxalic, and malic acids, create complexes with metals that impact the fixation, mobility, and availability of nutrients for plants [52].

Moreover, the anatomical parameters of stems, such as the stem diameter, epidermis thickness (μ), cortex thickness (μ), phloem thickness (μ), xylem thickness (μ), and pith thickness (μ), were enhanced due to the utilization of silica NPs (150 and 300 ppm) in most stem anatomical characteristics via two methods comparison to control. This supportive impact of this treatment may be due to SiO_2 NPs in stimulating plant height, the number of leaves/plant, fresh and dry weight of shoots, chlorophyll content consequently, and nutrient status improving the anatomical characteristics of carnation stems. These findings are in agreement with the results of [53,54]. Si treatments can improve photosynthesis by expanding the size of chloroplasts and increasing the number of grana [55].This information is provided by the findings obtained from scan observation in this investigation. Scan observations of stomata parameters revealed that spraying silica NPs on carnation leaves had a significant impact. Besides, Stomata number and size increased with Si treated, resulting in more CO_2 entering leaf tissue [55]. Consequently, improving photosynthetic and transpiration efficiency may be a reason for the increase in growth and biomass [56,57].

Conclusions

Using SiO_2-NPs in carnation production is a more positive alternative for improving morphological, practical flowering, vase life, antioxidant accumulation, and enzyme activity (CAT, SOD, and POD). In addition, it is significantly affecting the anatomical structure of the stem and improving stomata parameters using SEM. In this study, it was repeatedly observed that silica NPs applied topically to leaves were more effective than those applied topically to the drench in enhancing antioxidant systems and enzyme activity as well as extending the vase life of flowers, counting higher contents of N, P, K, Ca, and Si; counting more chlorophyll contents and anthocyanin; counting greater total phenols, sugars, amino acids; counting higher activities of CAT, SOD, POD, and proline content; and having improved anatomical structure and scanning stomata parameters. All of these significant effects may increase the quality of flowers. Furthermore, applying SiO_2 NPs in the production of flowers, such as carnation and other commercially important species, can be an exceptional alternative for enhancing the quality of morphological and flowering parameters and chemical analysis, particularly antioxidant and enzyme activity, as well as the longevity of their vase life.

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Nil.

Conflicts of interest

The authors declare there are no conflicts of interest.

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