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RESEARCH

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Evaluation of nano-silicon efficiency on compatible solutes and nutrient status of Damask rose affected by in vitro simulated drought stress

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Abstract

Background Drought stress is a critical environmental factor that disturbs plant performance. However, some non-essential elements such as silicon can improve water deficit tolerance by modulating photosynthesis assimilates and compatible solutes production. Therefore, the present work was conducted to modulate polyethylene glycol (PEG)-induced water deficiency under in vitro culture in Damask rose genotypes (Maragheh and Kashan) by nano-silicon (SiO_2-NPs) treatment. A completely randomized factorial experiment was used as three concentrations of SiO_2-NPs (0, 50, and 100 mg L^{-1}) and five concentrations of PEG (0, 25, 50, 75, and 100 g L^{-1}). Then, the comparative effects of water deficiency on vegetative traits, metabolites, and nutrients were studied.

Results The drought promoted a significant decrease in chlorophyll, fresh/dry weight, biomass, and an increase in electrolyte leakage. The amount of micro- and macronutrients were affected by drought stress and decreased in both genotypes. In contrast, the activity of polyphenol oxidase (PPO) and total phenolic compounds (TPC) along with biochemical traits was increased. Treatment with SiO_2-NPs improved the leaf area index (LAI), chlorophyll, and biomass under severe water deficiency. The concentration of compatible solutes such as carbohydrates, total flavonoid content (TFC), TPC, anthocyanin, and antioxidative capacity enhanced by the application of SiO_2-NPs by about twofolded. As well as an increase in PEG concentration, the absorption of nutritional elements such as P, K, Mn, Fe, Zn, and Cu was decreased. However, SiO_2-NPs application especially at 100 mg L^{-1} increased the amount of nutrient absorption.

Conclusions In general, the drought tolerance in Damask rose was associated mainly with its suitable manipulation of antioxidant production and orderly enhancement of nutrient adsorption, so that the effect of SiO_2-NPs in improving the qualitative and quantitative characteristics of 'Kashan' was more than that of 'Maragheh'. These results briefly highlight that the SiO_2-NPs may provide greater tolerance to drought stress in Damask rose.

Keywords *Rosa damascena*, Total phenolic compounds, Polyethylene glycol, Chlorophyll, Minerals

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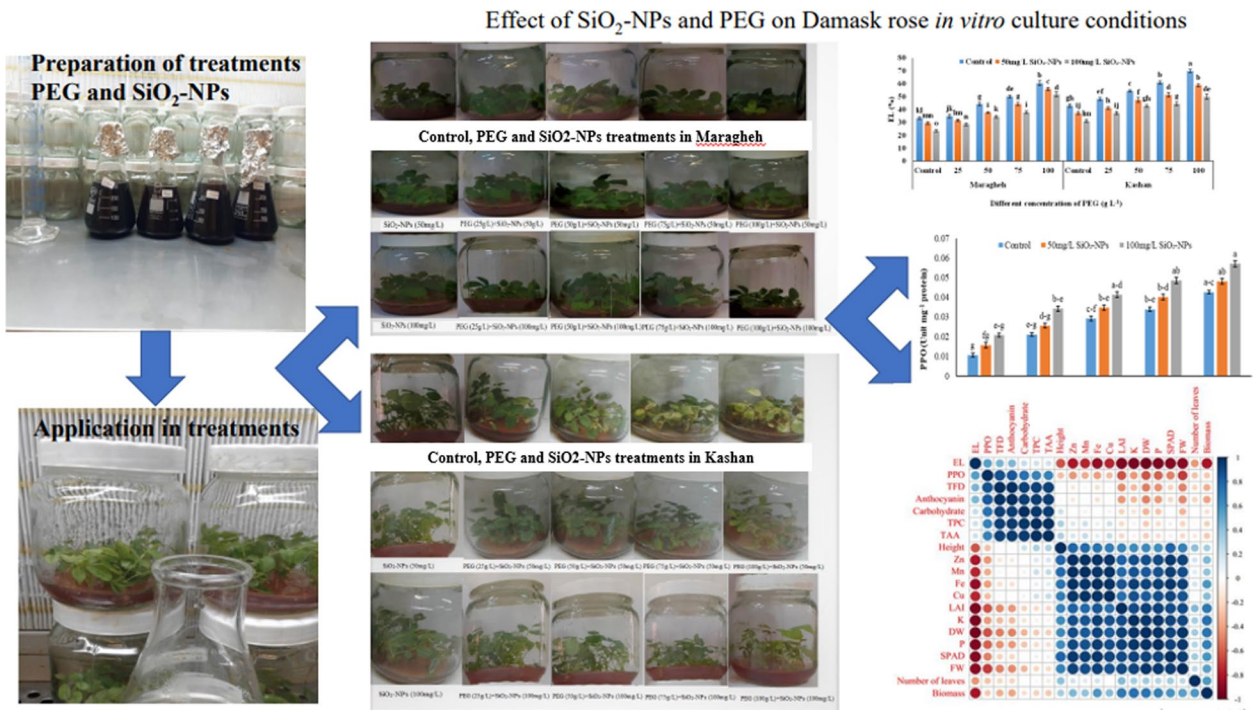
Graphical Abstract



Introduction

Rosa damascena Mill. is a perennial shrub related to the Rosaceae family used in the perfume, cosmetics, and food industries [1]. The main biologically active molecules isolated from various organs of *R. damascena* include flavonoids, glycosides (kaempferol, cyanidin 3,5, d-glycosides, and quercetin), gallic acid, terpenes, and anthocyanins. Damask rose leaves are sources of vitamins C, A, B, and K, pectin, tannins, and carotenoids [2]. *R. damascena* flowers have analgesic, anti-inflammatory, antibacterial, anti-depressant, and anti-viral effects, as well as a diuretic, and are used in traditional medicine as sedatives [2].

Damask rose essential oil has large amounts of alcoholic monoterpenes such as geraniol, citronellol, and phenylethanol, which are the main factors in evaluating the quality and also the odor of rose essential oils [3] which is different also between thorny genotypes than the others without thorn [4]. Increasing the demand for *R. damascena* essential oil requires extensive propagation of screened genotypes. This may be achieved by in vitro culture. The traditional methods of propagating Damask rose are cuttings and grafting. Some limitations of these traditional methods include seasonal dependence, high reproductive costs, laborious work, and time consumption [5].

In vitro culture techniques are useful for assessing resistance or adaptation to various stressors as extreme factors can be easily controlled [6]. The simplicity of such manipulations makes it possible to study large populations of plants and stress conditions on a small scale and in the least time. Simulation of water deficiency under in vitro culture by some materials such as PEG during the regeneration process is a good method to evaluate the effect of water deficit on morpho-physiological features [7]. PEG is an osmotic laxative that reduces the ambient water potential and has been used to mimic water deficiency without any toxicity in plants [8].

Agricultural practices, genetic factors, and environmental conditions affect crop quality [9]. Damask rose is mostly planted in several altitude regions of Iran, in which Isfahan, Fars, and Kerman have the highest area under cultivation and flower production [10].

Approximately 33% of the land area is exposed to water deficit, which poses a serious threat to plant growth and performance [11]. Water deficit stress causes different effects on the morpho-physiological responses of plants, such as changes in plant water use efficiency, lower growth rate, reduced stem length, leaf area, nutritional imbalance, and photosynthetic reactions [12]. Against oxidative stress due to water stress, antioxidative compounds including phenolics, flavonoids, and anthocyanins have a major effect in reducing the negative features

of water deficiency [13]. Phenolic substances act as reactive oxygen species scavengers which accumulated in plants exposed to extreme environmental factors [14]. Dissolved sugars in plants accumulate in response to water stress [15] which can be due to the decomposition of starch [16]. The enhancement in flavonoids and phenols content under severe drought stress is because of the accumulation of soluble sugars in plants, which is attributed to the reduced transport of carbohydrates under water deficiency [17].

It is believed that silicon (Si) is not an essential element for plant growth and development, but several studies demonstrated the benefits of Si application in reducing the harmful effect of abiotic and biotic stress in plants [18]. Previous research emphasized the positive effect of Si in increased tolerance of plants to abiotic stress, especially salt and water stresses [19]. Si may cause osmotic regulation and reduce oxidative injury in plants under stress [20]. Numerous mechanisms modulated in plant growth parameters improvement by Si under drought stress including activation of photosynthetic enzymes [21], activation of antioxidative enzymes, improvement of hydraulic conductivity [22], nutrient uptake [23], root growth and water use efficiency [24], and accumulation of organic osmolytes [25]. Previous studies have shown the positive effect of silicon on plants under hydroponic condition, as Si in nutrient solution cause tolerance against dehydration of explants by modulating in hydraulic relations [26].

Nanoparticles, due to their special characteristics consisting of size, surface charge, shape, and potential interaction with plants, reduce the effect of water stress [27]. With increasing interest in silicon nanoparticles, it has been found that SiO_2-NPs penetrate the roots through symplastic and apoplastic pathways [28]. Hamayun et al. [29] stated that the application of Si ameliorated the adverse effects of drought stress induced by PEG on plant growth attributes, such as stem length, root weight, and chlorophyll content.

To our knowledge, there is no research on the effect of nano-silicon (SiO_2-NPs) application in Damask rose in drought stress under in vitro conditions. Therefore, the goal of the present work was to study whether the application of SiO_2-NPs can reduce drought stress under in vitro culture caused by PEG, thus improving the growth of *R. damascena*.

Materials and methods

Collect plant material and set the experiment

One-year branches of two Damask rose genotypes of Maragheh and Kashan were collected from Maragheh (37.3892 N, 46.2534 E) and Kashan (33.9850 N, 51.4100°E) according to our previous studies [30]. For surface disinfection, the explants (cuttings) were first placed under running water for half an hour and then for 20 min in water and dishwashing liquid on a shaker. They were rinsed three times with ddH_2O and then immersed in 5% NaOCl for 15 min under a flow-box and after three rinses were immersed in 70% ethanol for 180 s. Finally, after washing with distilled water, the explants were ready for culture. The one node shoot explants were recut into 1.5–2 cm length, and they were placed on the MS medium culture. The MS free hormone media [31] were considered as the establishment initial which solidified with 7.5 g of agar. The pH value was adjusted to 5.7 before autoclaving at 121 °C, 150 kPa for 20 min. Five shoot nodes were cultured, in 150 ml culture vessels containing 30 ml of establishment medium as one replication, then kept at 25 ± 2 °C and 16 h-photoperiod (light intensity, 8.85 W/m^2) and 60–70% RH. Following explants were screened every day for fungal or bacterial contamination then any contaminated vessels were removed from the experiment collection. Shoots were repeatedly subcultured three times at a constant 3 week subculture interval. For the proliferation, the basic medium was the same as the MS medium establishment [31], except that instead of iron stock, 130 mg of the iron sequester and 332 mg of calcium chloride, as well as 0.36 mg L^{-1} BA and 0.03 mg L^{-1} IBA were added to the medium. After sterilization and transfer to the flow-box, 25 ml of medium was added to each culture vessel to be used for subculture. Finally, five explants were placed in 150 ml culture vessels containing the proliferation medium as one replication and keep in the growth chamber to be propagated, and for the next stages, small shoots propagated from these explants have been used. This project was arranged as a factorial experiment based on a completely randomized design with four replications.

Preparation of medium containing PEG and SiO_2-NPs treatment

PEG treatments were used to stimulate water deficiency. Therefore, PEG-6000 was purchased from Merc (Germany) and used at five levels of drought stress (0, 25, 50, 75, and 100 g L^{-1} with an osmotic pressure of 0, − 0.2, − 0.5, and − 0.9 MPa, respectively) as the first factor. The SiO_2-NPs (size < 50 nm) were bought from NANOSANY Corporation (Mashhad, Iran), prepared at three levels (0, 50, and 100 mg L^{-1}) and added to the MS medium in which the two genotypes (Maragheh and Kashan) were cultured as the second factor. After preparing the propagation medium, as mentioned above, the shoot explants were placed in jars containing the culture medium with the mentioned treatments under a flow-box. Therefore,

five shoot explants were placed in each culture vessel and kept in the growth chamber and after about 14 days were collected to the traits assessment.

Morpho-physiological traits

After the harvest of samples, morphological traits including shoot height, number of leaves, fresh (FW) and dry weight (DW) of leaves, and biomass percentage were measured using Eq. 1. The leaf area index (LAI) was determined using Image J software:

$$\text{Biomass (\%)} = \left[\left(\text{Dry weight plant}\right) / \left(\text{Fresh weight plant}\right)\right] \times 100 \quad (1)$$

Determination of leaf chlorophyll

The amount of leaf chlorophyll is expressed as chlorophyll index (SPAD readings) using a portable chlorophyll meter (Instruments SPAD-502, Osaka, Japan). For this purpose, three points of the fully expanded leaves were read in each replication and the average was calculated.

Electrolyte leakage (EL)

To study the percentage of the EL of shoots, the youngest fully developed leaves were separated from each shoot and placed in a glass tube containing 20 ml of ddH_2O and placed on a shaker for 24 h at room temperature, then centrifuged at 1000 rpm for 24 h. After 24 h, the electrical conductivity (EC) of each sample was measured using an EC meter (Jenway model, UK) and read as EC1. To measure the total leakage of electrolytes (EC2), the leaf samples were placed in an autoclave for 20 min at 120 °C, and after cooling the samples in the ambient temperature, their EC read as EC2. Then, the percentage of EL was evaluated according to the following formula and was recorded as a percentage [32]:

$$\text{EL (\%)} = (\text{EC1}/\text{EC2}) \times 100$$

Biochemical traits

Measurement of total soluble carbohydrates (TSC)

For the analysis of TSC, a mixture of 5 ml of 80% ethanol (*v*/*v*) and 0.1 g of leaf sample was prepared and centrifuged at 15,000 rpm for 15 min. Then, 3 ml of 0.2% anthrone reagent (0.5 g of anthrone in 250 ml of 72% sulfuric acid) was added to 100 ml of the ethanolic extract and then incubated in boiling water (95 °C) for 10 min [33] After cooling on ice bath, the sample absorbance was read spectrophotometrically (model: AA-6300, Shimadzu, Japan) at 620 nm. The TSC content was expressed in mg g^{-1} FW [34].

Total flavonoid content (TFC) measurement

For the estimation of TFC, the (Dewanto et al. [35] method was used. The extract (20 µl) was added to 75 µl of $NaNO_2$ solution (5%) and vortexed for 6 min, after adding 0.15 ml of $AlCl_3$ (10%). After 5 min, 0.5 ml of 1 M NaOH solution was added to the previous solution. The final volume reached 2.5 ml and was thoroughly mixed and the absorbance of the mixture was determined using a spectrophotometer at 510 nm. The TFC of *R. damascena* extracts was expressed as mg catechin per g of dry weight (mg CE g^{-1} DW).

Anthocyanin assay

To measurement of anthocyanin, 1 ml of the leaf extracts were mixed with 5 ml of 95% ethanol, 1.0 N HCl (85:15, *v*:*v*) for 4 h at 4 °C in a dark room [36]. The absorbance was read at 530 nm. The following formula was used to evaluate the anthocyanin content:

$$\text{Anthocyanin content} = (\text{absorbance at 530 nm} \times \text{volume of extraction solution} \times 100) / (\text{volume of sample (mL)} \times 98.2)$$

Total antioxidant activity (TAA)

TAA of *R. damascena* shoots was calculated by the DPPH method [37]. The extract was obtained from potassium phosphate buffer (100 mM) and added to 1 ml of 50 µM DPPH solution in methanol. The mixture was incubated in a dark room for 20 min. The reduction of DPPH absorbance at 515 nm was recorded using a spectrophotometer. DPPH radical inhibition activity or TAA was evaluated using the following equation:

$$\text{TAA\%} = [(\text{absorbance control} - \text{absorbance sample}) / (\text{absorbance control})] \times 100.$$

Total phenol content (TPC) measurement

TPC was calculated by the method of Singleton et al. [38]. The mixture was 200 µl of leaf extracts (1% HCl in methanol), 800 µl of methanol, 500 µl of Folin–Ciocalteu reagent (1: 1 with water), and 2500 µl of sodium carbonate solution (20%). After the vortex of the admixture, the tubes were incubated in the darkness at room temperature for 40 min. The absorbance at 725 nm was read using a spectrophotometer. TPC was expressed as mg gallic acid per g DW (mg GAE g^{-1} DW).

Polyphenol oxidase (PPO) enzyme

The activity of PPO was assayed with 4-methyl catechol as a substrate by the method of Zauberman et al. [39].

The fresh leaf samples (0.5 g) were extracted with 10 ml of 0.1 M sodium phosphate buffer (pH = 6.8) and 0.2 g of polyvinylpyrrolidone (PVP). After centrifugation at 19000 rpm for 20 min, the supernatant was collected as crude enzyme extract. The activity of PPO was measured using 1 ml of 0.1 M sodium phosphate buffer (pH 6.8), 0.5 ml of 100 mM l, 4-methyl catechol, and 0.5 ml of the extract. The increase in absorbance at 410 nm was automatically recorded using a spectrophotometer. The activity of PPO was expressed as μM ml^{-1} min^{-1} mg^{-1} protein or unit mg^{-1} protein.

Measurement of shoot mineral elements

To measure nutrients, shoots were placed in an oven at 65 °C for 24 h. After the shoots dried, the samples were powdered with an electric mill. After preparing the ash from the plant samples at 550 °C, the extract was extracted using 10 ml of 2 N hydrochloric acid and distilled water to a volume of 50 ml [40]. The content of P with molybdate vanadate reagent using a spectrophotometer at 450 nm, K content (with chlorosis solution 0.87 g L^{-1}) using the Flame photometer (model: PFP7, UK) and some micronutrients (Fe, Mn, Zn, and Cu) were read by dry digestion and combined with hydrochloric acid using the atomic absorption spectrometer.

Statistical analysis

This study was conducted as a factorial experiment based on a completely randomized design with four replications and five explants in each vessel culture. Data were statistically analyzed by MSTAT-C ver. 2.1 software and the means were compared using the *LSD* test and at 5% probability.

Results

Effect of SiO_2-NPs and PEG-induced water deficiency on morpho-physiological traits of Damask rose

According to Table 1, increasing in PEG level reduced explant shoot height in both genotypes by 12% and 35.9% in 'Maragheh' and 'Kashan', respectively. However, 'Maragheh' had the highest shoot height in controls treated with 100 mg L^{-1} SiO_2-NPs. Treatment with SiO_2-NPs under drought stress to some extent prevented height reduction and its effect was greater in 'Maragheh'. 'Kashan' had the lowest height at 75 and 100 g L^{-1} PEG without SiO_2-NPs treatment. The most leaf area index (LAI) was related to the 'Maragheh' at severe drought stress and 100 mg L^{-1} SiO_2-NPs, while 'Kashan' had the least LAI at severe drought stress without SiO_2-NPs treatment (Table 1). Both genotypes showed a decreasing trend in LAI as well as increasing concentration. However, the LAI of the genotypes under water deficit and well-watered conditions significantly increased with the supplementation of SiO_2-NPs (Table 1). In addition, treatment with SiO_2-NPs increased LAI in 'Kashan' more than in 'Maragheh'. Water deficiency caused to a reduction in shoot FW and DW by 42.5% and 66% in 'Maragheh' and 52.4% and 63.7% in 'Kashan', respectively. SiO_2-NPs improved shoot FW and DW of Damask explants under drought stress. Different concentrations of PEG on Damask rose biomass had a decreasing trend by 40.7% and 23.7% in 'Maragheh' and 'Kashan', respectively. Treatment with SiO_2-NPs improved biomass percentage up to 16% and 14% in Maragheh and Kashan genotypes, respectively. Both genotypes had the highest percentage of biomass in control plants treated with 100 mg L^{-1} SiO_2-NPs, while the lowest was related to 'Maragheh' under severe drought stress (Table 1).

EL percentage of both genotypes of Damask rose were reduced under drought stress up to 81% and 62%, respectively, in 'Maragheh' and 'Kashan' (Fig. 1). However, treatment with SiO_2-NPs reduced the content of EL by 200% and 160% in 'Maragheh' and 'Kashan', respectively. 'Maragheh' had the lowest EL at the control and was treated with 100 mg L^{-1} SiO_2-NPs.

Chlorophyll content showed a decreasing trend in both Damask rose genotypes as well as an increase in PEG concentration up to 30% and 41%, respectively, in 'Maragheh' and 'Kashan', although the total level of chlorophyll in 'Maragheh' was higher than 'Kashan'. Treatment of plants under water deficiency with 100 mg L^{-1} SiO_2-NPs caused to an increase in the level of leaf chlorophyll up to 17% and 30% in 'Maragheh' and 'Kashan', respectively (Fig. 2).

Effect of SiO_2-NPs and PEG-induced water deficiency on biochemical traits of Damask rose

According to Table 2, Damask rose TSC was increased during different levels of PEG levels by 4.9- and 1.7-fold in 'Maragheh' and 'Kashan', respectively. 'Maragheh' under severe water deficiency and treated with 100 mg L^{-1} SiO_2-NPs had the most TSC, while the control plants in 'Kashan' had the least amount of TSC. Similar results were observed in TFC and anthocyanin which the highest being observed in Maragheh genotype treated with 100 mg L^{-1} SiO_2-NPs under severe water deficiency, while the control explants in both genotypes had the least amount of TFC and anthocyanin. Both TFC and anthocyanin had an increasing trend with an increase in drought stress as TFC content in control explants of 'Maragheh' and 'Kashan' increased from 1.1 (mg CE g^{-1} FW) to 6.9 (mg CE g^{-1} FW) and 5.8, respectively. However, treatment with SiO_2-NPs caused more increase in stress and also control Damask explants in the same situations. SiO_2-NPs application from 0 to 100 m L^{-1} caused

Table 1 Effect of PEG and SiO_2-NPs on Height, Number of leaves and Leaf area index (LAI), Shoot FW and DW and Biomass of Maragheh and Kashan genotypes

Genotype Drought (PEG g L^{-1})	Treatment (SiO_2-NPs mg L^{-1})	Maragheh Height (mm)	Kashan Height (mm)	Maragheh Number of leaves	Kashan Number of leaves	Maragheh LAI (mm^2)	Kashan LAI (mm^2)
Control	0	34.0 ± 0.4ab	27.4 ± 0.6hi	13.8 ± 0.5f-i	15.5 ± 0.08cd	229.8 ± 0.6b-d	179.5 ± 1.7f-i
	50	33.4 ± 0.3bc	29.8 ± 0.2e-g	15.6 ± 0.1cd	17.2 ± 0.5b	256.1 ± 2.6b	205.6 ± 2.6d-g
	100	35.2 ± 0.7a	32.4 ± 0.9cd	16.4 ± 0.8bc	18.8 ± 0.5a	286 ± 1.2a	240.5 ± 1.7bc
	0	31.2 ± 0.2de	24.9 ± 0.6kl	12.8 ± 0.7j-m	13.9 ± 0.5f-h	206.7 ± 2.2d-f	160.7 ± 1.5i-l
25	50	29.2 ± 1.5fg	26.6 ± 0.2ij	14.4 ± 0.3e-g	14.7 ± 0.3d-f	218.6 ± 1c-e	171.9 ± 0.9h-j
	100	30.6 ± 1.2e	28.7 ± 0.1gh	15.1 ± 0.8de	16.7 ± 0.1b	227.5 ± 1.9cd	178.7 ± 3.1g-i
	0	28.9 ± 0.3g	21.39 ± 0.8n	11.7 ± 0.6no	12.9 ± 0.5i-l	125.5 ± 2m-q	140.7 ± 2.2k-o
50	50	34.2 ± 0.4ab	24.0 ± 0.4lm	12.9 ± 0.4i-l	13.8 ± 0.2f-i	195.3 ± 2.8e-h	152.7 ± 2i-m
	100	33.2 ± 0.6bc	26.0 ± 0.3jk	13.5 ± 0.4g-j	14.7 ± 0.2d-f	209.1 ± 1.1de	161.8 ± 2.1i-l
	0	28.9 ± 0.6g	17.7 ± 0.7q	11.2 ± 0.8op	10.7 ± 0.9p	155.9 ± 2i-l	123.1 ± 1.4n-q
75	50	30.3 ± 0.1ef	20.3 ± 0.6no	12.1 ± 0.2l-o	12.1 ± 0.4l-o	167 ± 2.2i-k	134.2 ± 0.9l-p
	100	30.7 ± 0.0e	23.1 ± 0.4m	13.3 ± 0.5h-j	13.2 ± 0.3h-k	179.4 ± 0.6f-i	144.3 ± 0.8j-n
	0	27.2 ± 1.5ij	17.5 ± 0.2q	10.6 ± 0.5p	9.6 ± 0.1q	113.1 ± 0.3o-q	0.8863 ± 0.3r
100	50	33.3 ± 0.5bc	18.7 ± 0.2pq	11.9 ± 0.5m-o	10.5 ± 0.2pq	146.7 ± 3.5j-n	107.9 ± 1.1pq
	100	33.1 ± 0.8bc	19.5 ± 0.2op	12.3 ± 0.2k-n	11.9 ± 0.06m-o	154.1 ± 2.1i-l	105.5 ± 2.5q
S. O. V							
Drought (D)		**	**	**	**	**	**
Treatment (T)		**	**	**	**	**	**
D × T		**	**	**	**	**	**
Genotype (G)		**	**	**	**	**	**
D × G		**	**	**	**	**	**
T × G		**	**	**	**	ns	ns
D × T × G		**	**	**	**	**	**
CV		2.96	2.96	4.36	4.36	10.09	10.09
Genotype Drought (PEG g L^{-1})	**Treatment (mg L^{-1} SiO_2-NPs)**	**Maragheh Shoot FW (g)**	**Kashan Shoot FW (g)**	**Maragheh Shoot DW (g)**	**Kashan Shoot DW (g)**	**Maragheh Biomass (%)**	**Kashan Biomass (%)**
Control	0	1.8 ± 0.01c	1.3 ± 0.06 h	0.63 ± 0.005c	0.40 ± 0.009kl	34.2 ± 0.06fg	29.2 ± 0.7m
	50	2.0 ± 0.01b	1.4 ± 0.01 g	0.73 ± 0.005b	0.49 ± 0.01g	36.3 ± 0.03b-d	33.6 ± 0.6f-h
	100	2.0 ± 0.007a	1.5 ± 0.007f	0.77 ± 0.01a	0.59 ± 0.003d	37.1 ± 0.6a-c	37.9 ± 0.6ab
	0	1.6 ± 0.01e	1.1 ± 0.03kl	0.51 ± 0.01f	0.35 ± 0.009m	31.5 ± 0.6i-l	31.2 ± 0.9j-l
25	50	1.7 ± 0.01d	1.2 ± 0.02j	0.58 ± 0.004d	0.44 ± 0.006i	33.1 ± 0.3g-i	36.0 ± 0.1c-e
	100	1.8 ± 0.006cd	1.2 ± 0.02ij	0.63 ± 0.002c	0.48 ± 0.005h	35.2 ± 0.04d-f	38.7 ± 0.1a
	0	1.2 ± 0.01i	0.88 ± 0.008p	0.41 ± 0.005jk	0.28 ± 0.004qr	31.9 ± 0.1i-k	31.6 ± 0.5i-l
50	50	1.3 ± 0.03h	0.95 ± 0.009o	0.48 ± 0.008gh	0.33 ± .003o	34.6 ± 0.5d-g	34.5 ± 0.7e-g
	100	1.4 ± 0.01g	1.0 ± 0.004n	0.56 ± 0.01e	0.38 ± 0.007l	37.8 ± 0.1ab	37.6 ± 0.5a-c
	0	1.1 ± 0.009l	0.76 ± 0.007r	0.29 ± 0.006p	0.20 ± 0.006tu	26.9 ± 0.4n	26.6 ± 1.8n
75	50	1.1 ± 0.009k	0.79 ± 0.02qr	0.35 ± 0.01mn	0.24 ± 0.006s	30.1 ± 0.4lm	30.3 ± 0.9k-m
	100	1.2 ± 0.01j	0.85 ± 0.01pq	0.41 ± 0.008j	0.29 ± 0.004pq	33.8 ± 2.3f-h	34.3 ± 0.3fg
	0	1.0 ± 0.02mn	0.65 ± 0.02s	0.21 ± 0.003t	0.14 ± 0.005v	20.3 ± 0.9p	22.3 ± 0.6o
100	50	1.0 ± 0.01n	0.70 ± 0.009s	0.27 ± 0.01r	0.19 ± 0.004u	26.6 ± 0.8n	27.4 ± 0.7n
	100	1.0 ± 0.01lm	0.83 ± 0.01q	0.33 ± 0.009no	0.27 ± 0.006r	30.9 ± 0.8 6j-l	32.5 ± 0.4h-j
S. O. V							
Drought (D)		**	**	**	**	**	**
Treatment (T)		**	**	**	**	**	**
D × T		**	**	**	**	**	**
Genotype (G)		**	**	**	**	ns	ns

Table 1 (continued)

Genotype Drought (PEG g L^{-1})	Treatment (mg L^{-1} SiO_2-NPs)	Maragheh Shoot FW (g)	Kashan Shoot FW (g)	Maragheh Shoot DW (g)	Kashan Shoot DW (g)	Maragheh Biomass (%)	Kashan Biomass (%)
D × G		**	**	**	**	**	**
T × G		ns	ns	ns	ns	**	**
D × T × G		**	**	**	**	**	**
CV		1.84	1.84	2.22	2.22	3.11	3.11

Different letters indicate significant differences in each trait according to the LSD test at $P < 0.05$. ns, * and ** indicate no significant difference, significant at a 5% probability level and significant at a 1% probability level, respectively. S. O. V. and CV refer to the source of variation and coefficient variation, respectively

more increase, more than two folded in 'Maragheh' which was a little bit more than 'Kashan'. A similar increase was evaluated in anthocyanin content, with more than twofolded increases in both genotypes as well as increases in drought stress and SiO_2-NPs level, so that by 15% and 24% enhancement in anthocyanin content were observed in 'Maragheh' and 'Kashan', respectively as illustrated in Fig. 3.

In addition, our results showed an increase in TAA of the explants extracts of both Damask rose genotypes with enhancement in PEG concentration by twofolded. Under severe drought stress (100 g L^{-1} PEG), treatment of Damask explants with 100 mg L^{-1} SiO_2-NPs increased TAA by 19% and 28% in 'Maragheh' and 'Kashan', respectively (Table 2).

TPC has heightened along with enhancement in the level of PEG in both Damask roses approximately by twofolded. Application of SiO_2-NPs under severe water deficiency caused to increase in TPC in 'Kashan' (38%) more than in 'Maragheh' (54%). However, the highest TPC was observed in 'Maragheh' treated with 100 mg L^{-1} SiO_2-NPs under severe drought stress (Fig. 4). The results of PPO activity assay also showed the same results as in TPC observations, the activity of PPO increased by fourfolded in both Damask roses, so that the 'Maragheh' had the highest PPO enzyme activity. In addition, the application of SiO_2-NPs led to an increase in enzyme activity, as well (Fig. 5).

Effect of SiO_2-NPs and PEG-induced water deficiency on nutrient minerals of Damask rose

According to the results of Table 3, the effect of PEG-induced water deficiency and SiO_2-NPs on nutritional elements of 'Maragheh' and 'Kashan' genotypes showed a significant difference ($P \leq 0.01$). Water deficiency caused a decrease in K and P content of Damask leaf by 56% and 52% in 'Maragheh' and 47% and 52% in Kashan,

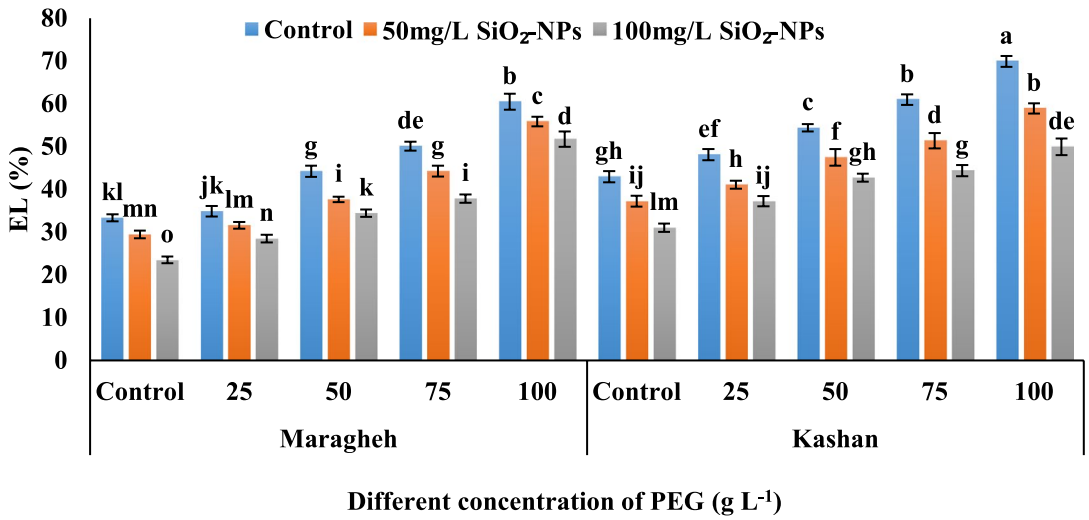


Fig. 1 Effect of SiO_2-NPs application under drought stress induced by PEG on leaf electrolyte leakage (EL) of two Damask genotypes. Different letters indicate significant differences according to the LSD test at $P < 0.05$

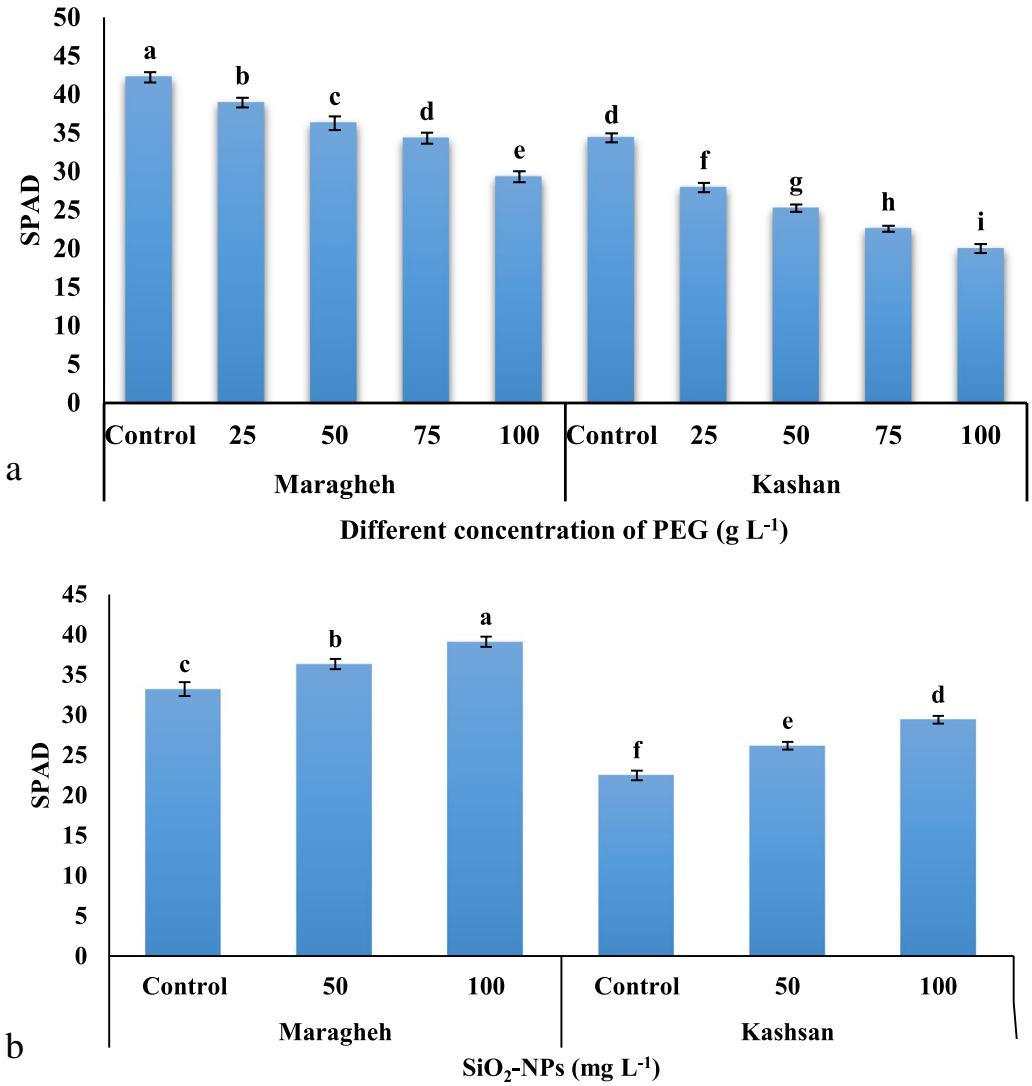


Fig. 2 Interaction between drought stress × two Damask genotypes on leaf chlorophyll index **a** and SiO_2-NPs × two Damask genotypes on chlorophyll index **b**. Different letters indicate significant differences according to the LSD test at $P < 0.05$

respectively. The highest leaf P and K contents were obtained in 'Maragheh' explants treated with 100 mg L^{-1} SiO_2-NPs and without water deficit. In contrast, 'Kashan' showed the least content of P and K in leaves at severe water deficiency and without SiO_2-NPs treatment. However, the explants supplemented with SiO_2-NPs improved the K and P absorption up to 44% and 30% in 'Maragheh' and 50% and 43% in 'Kashan'.

The effect of PEG-induced drought stress and SiO_2-NPs application had a significant difference in Zn, Mn, and Cu concentrations in Damask explants (Table 4) as along with increased PEG concentration, the amount of these elements was decreased in comparison with un-stress explants. Use of SiO_2-NPs caused an improvement in microelements such as Zn (75% vs 44%) and Mn (79% vs 45%) absorption in 'Kashan' more than 'Maragheh', although the effect of SiO_2-NPs on Cu (60% vs 56%) absorption was not so impressive. The Fe content showed a declining trend along with rising in the level of PEG up to 49% in 'Maragheh' and 51% in 'Kashan', although the initial content of Fe was more in 'Maragheh' compared to 'Kashan'. Treatment with SiO_2-NPs enhanced the Fe absorption up to 38% and 58% in 'Maragheh' and 'Kashan', respectively (Fig. 6).

Multivariate analysis of Damask Rose under normal and PEG treatments supplemented with SiO_2-NPs

Pearson's correlations of some growth parameters, biochemical traits, and nutrient content are presented in Fig. 7. The findings indicated that PPO,

Table 2 Effect of PEG and SiO_2-NPs on total carbohydrate content (TSC), Total Flavonoid content (TFC), Anthocyanin and TAA of Maragheh and Kashan genotypes

Genotype Drought (PEG g L^{-1})	Treatment (mg L^{-1} SiO_2-NPs)	Maragheh TSC (mg g^{-1} FW)	Kashan TSC (mg g^{-1} FW)	Maragheh TFC (mg CE g^{-1} FW)	Kashan TFC (mg CE g^{-1} FW)	Maragheh Anthocyanin (mg g^{-1} FW)	Kashan Anthocyanin (mg g^{-1} FW)	Maragheh TAA (%)	Kashan TAA (%)
Control	0	4.12 ± 0.1o	4.87 ± 0.2o	1.19 ± 0.1q	1.15 ± 0.1q	1.43 ± 0.09u	1.61 ± 0.1u	21.53 ± 1.8p	18.58 ± 0.7q
	50	5.90 ± 0.2n	6.43 ± 02n	2.54 ± 0.1o	2.14 ± 0.05p	2.55 ± 0.1s	2.27 ± 0.08t	30.03 ± 0.7n	22.53 ± 1p
	100	9.56 ± 0.4k	8.46 ± 0.2l	3.26 ± 0.1n	3.07 ± 0.1n	3.77 ± 0.1n	2.76 ± 0.1r	38.81 ± 0.1k	27.45 ± 0.6o
	0	9.92 ± 0.1k	7.29 ± 0.4m	3.68 ± 0.1m	2.64 ± 0.03o	3.36 ± 0.08op	3.03 ± 0.03q	38.35 ± 1.3kl	26.43 ± 0.3o
25	50	12.9 ± 0.5ij	9.96 ± 0.2k	4.19 ± 0.1jk	3.06 ± 0.1n	4.03 ± 0.06m	3.19 ± 0.02pq	42.87 ± 0.5j	29.95 ± 0.3n
	100	16.57 ± 0.4ef	13.6 ± 0.5hi	5.15 ± 0.1h	3.79 ± lm	4.75 ± 0.2j	3.45 ± 0.07o	48.89 ± 0.6g	33.97 ± 0.5m
	0	12.74 ± 0.3j	9.49 ± 0.2k	5.02 ± 0.07hi	4.02 ± 0.1kl	4.46 ± 0.06k	3.69 ± 0.01n	46.72 ± 0.9h	29.52 ± 0.5n
50	50	16.39 ± 0.2f	12.21 ± 0.3j	5.76 ± 0.07fg	4.30 ± 0.04j	5.05 ± 0.03hi	4.18 ± 0.1lm	51.14 ± 0.1f	32.92 ± 0.2m
	100	20.65 ± 0.3c	16.07 ± 0.3fg	6.72 ± 0.1d	4.85 ± 0.04i	6.03 ± 0.1e	4.80 ± 0.03j	58.02 ± 0.8d	39.34 ± 0.3k
	0	18.20 ± 0.3d	12.12 ± 0.2j	5.96 ± 0.3f	4.93 ± 0.1hi	6.16 ± 0.07e	4.35 ± 0.02kl	54.28 ± 0.8e	32.61 ± 0.4m
75	50	20.46 ± 0.4c	15.55 ± 0.7g	6.47 ± 0.09e	5.13 ± 0.03h	6.62 ± 0.05d	4.92 ± 0.04ij	58.32 ± 1.2d	37.1 ± 0.3l
	100	23.99 ± 0.4b	18.64 ± 0.4d	7.75 ± 0.2b	5.55 ± 0.01g	7.19 ± 0.05c	5.46 ± 0.07g	64.82 ± 0.5b	45.08 ± 0.1hi
	0	20.5 ± 0.6c	8.43 ± 0.2l	6.92 ± 0.06cd	5.80 ± 0.3f	7.11 ± 0.05c	5.20 ± 0.01h	60.95 ± 0.7c	38.86 ± 0.6k
100	50	24.42 ± 0.2b	13.85 ± 0.6h	7.61 ± 0.1b	6.32 ± 0.05e	7.48 ± 0.09b	5.67 ± 0.04f	66.09 ± 1.3b	43.52 ± 0.6ij
	100	28.49 ± 0.5a	17.34 ± 0.2e	8.64 ± 0.08a	7.15 ± 0.06c	8.21 ± 0.1a	6.48 ± 0.03d	72.82 ± 1.4a	49.79 ± 0.8fg
S.O.V									
Drought (D)		**	**	**	**	**	**	**	**
Treatment (T)		**	**	**	**	**	**	**	**
D × T		**	**	**	**	**	**	**	**
Genotype (G)		**	**	**	**	**	**	**	**
D × G		**	**	**	**	**	**	**	**
T × G		ns	ns	**	**	**	**	**	**
D × T × G		**	**	**	**	**	**	**	**
CV		3.49	3.49	3.09	3.09	2.53	2.53	2.40	2.40

TFD, anthocyanin, carbohydrate, TPC, and TAA positively correlated with each other, and also a significant positive was observed among height, LAI, DW, FW, SPAD, Zn, MN, Fe, Cu, K, and P content. On the other hand, EL negatively correlated with height, LAI, DW, FW, SPAD, Zn, MN, Fe, Cu, K, P content, number of leaves, and biomass. Finally, a positive correlation was observed between the number of leaves and biomass (Fig. 7a).

The principal component analysis (PCA) clarified that two PCA were contributing 86.1% of the total variation. The first PCA was the most effective by a variance of 56. 8% and the second PCA elucidated 27.3% of the total variance. Moreover, the biplot of traits indicated which traits were classified into three groups. The first group included PPO, TFD, anthocyanin, carbohydrates, TPC, TAA, and EL; the second group contained height, LAI, DW, FW, SPAD, Zn, Mn, Fe, Cu, K, and P content; and finally, the third group included a number of leaves and biomass (Fig. 7b).

Discussion

Drought stress, in addition to a reduction in plant growth and reproductivity, causes a change in some metabolic pathways which caused plant tolerance to stress. Drought tolerance depends on the reactions to continue primary metabolic processes and improved plant tolerance. Damask rose is also similar to other plants that reacted against to drought stress and coped to stress via changes in physiological characteristics and the content of absorption of elements. Our findings showed that along with increases in drought stress levels, the Damask rose biomass decreased as well as a reduction in LAI and plant length. These results were in line with Hessini et al. [41], who demonstrated decrease in FW and DW by approximately 29% under moderate (50% FC) water stress and 48% and 33% under severe (25% FC) water stress, respectively, relative to the well-watered *R. damascena*. The mechanism for Si-induced biomass increase could be attributed to the involvement of Si in cell wall deposition and nutrient absorption [42] as Hattori et al. [43]

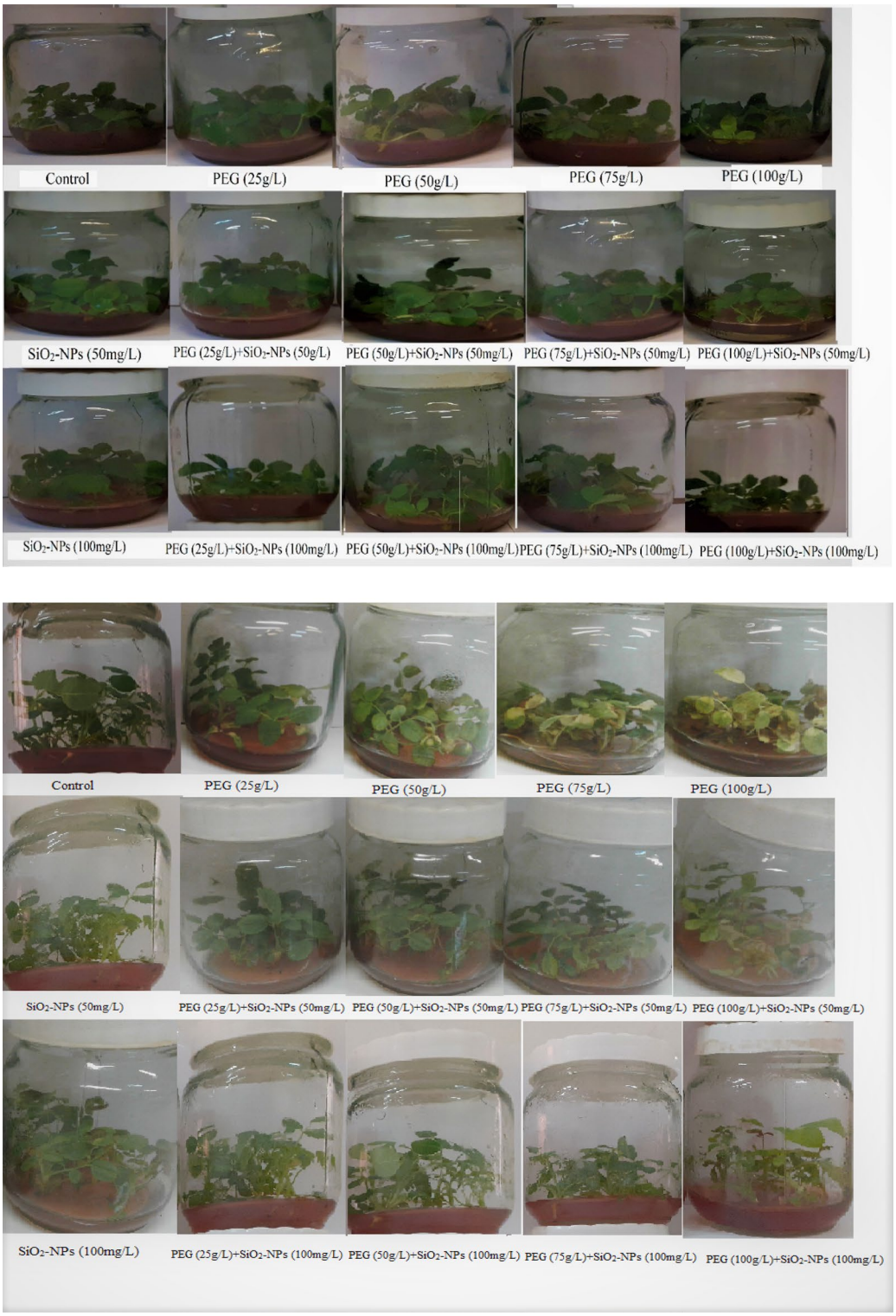


Fig. 3 Effect of SiO_2-NPs and PEG-induced water deficiency on morpho-physiological charactristics in leaves of Maragheh and Kashan genotypes in vitro culture conditions

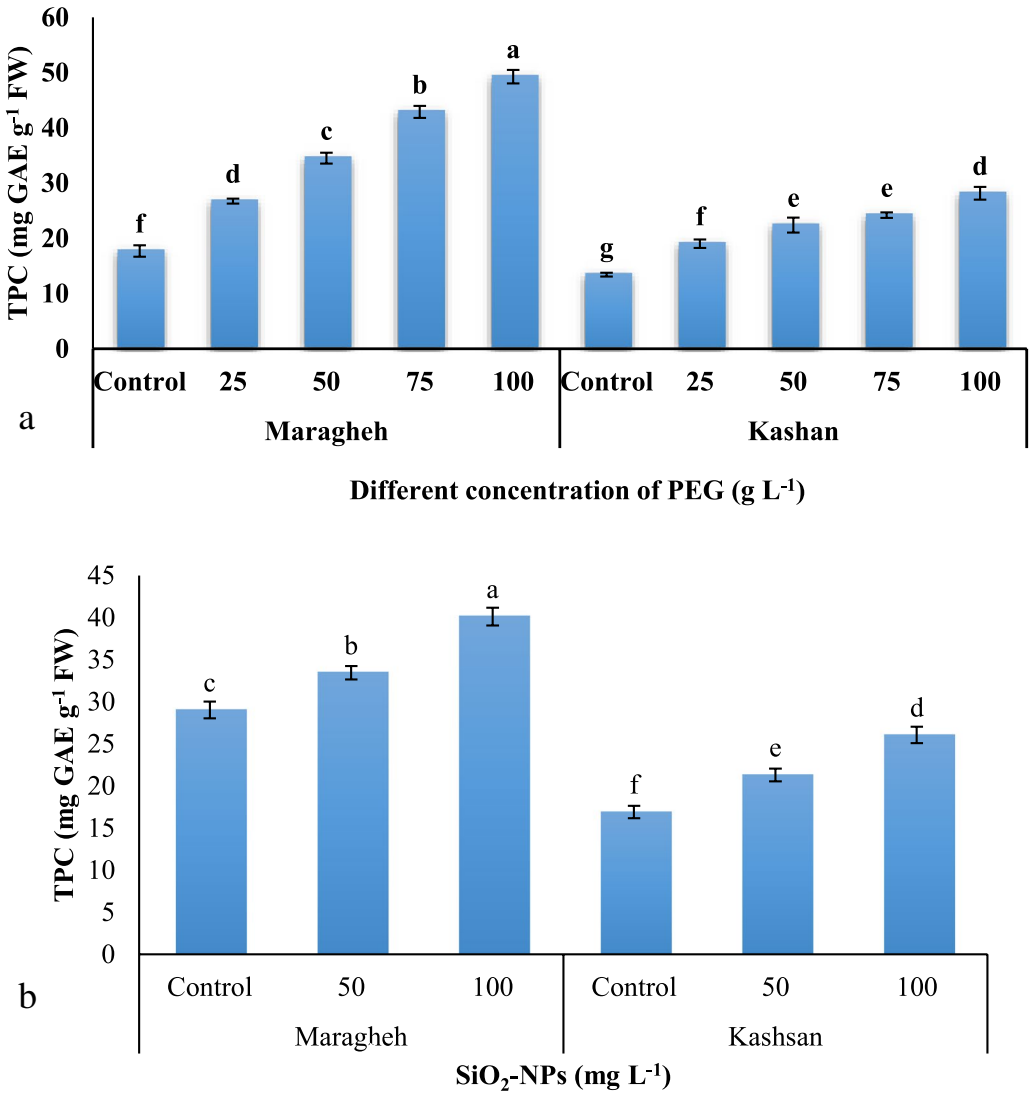


Fig. 4 Interaction between drought stress × two Damask genotypes on leaf total phenolic content **a** and SiO_2-NPs × two Damask genotypes on total phenolic content **b**. Different letters indicate significant differences according to the LSD test at $P < 0.05$

demonstrated that silicon-induced acceleration of biomass production in sorghum only when the plants were subjected to water deficit conditions. In fact, drought stress causes a decrease in cell enlargement and swelling, and as a result, growth decreases as demonstrated by reduced fresh/dry weight (Table 1). On the other hand, along with an increase in the severity of water deficiency, as leaf photosynthesis decreases, the carbohydrate needs for osmotic regulation in plants increase, and then, root growth is inevitably prevented [44].

The application of nano-silicon prevented EL (%) increase, as illustrated in Fig. 1. It is suggested that silicon is identified as an immobile element inside the plant, and as soon as it accumulates inside the cell, changed to a polymerized gel which is no longer usable for the plant. Therefore, it caused the cells to be strong and stable, thus reducing the amount of leakage of electrolytes in the plant [45]. It is demonstrated that Si is a mineral nutrient that caused to improve the water use efficiency of plants [46]. In addition, the positive effect of SiO_2-NPs on leaf chlorophyll content seems to be related to its role as a cofactor in pigments biosynthesis [47] and inhibition of the activity of chlorophyllase which becomes more active under extreme conditions [48]. Furthermore, silicon accumulates in the width of the leaf and increases the strength of the leaves which caused to increase in the concentration of chlorophyll in the leaf area. Silicon has also the potential to increase the photosynthesis rate

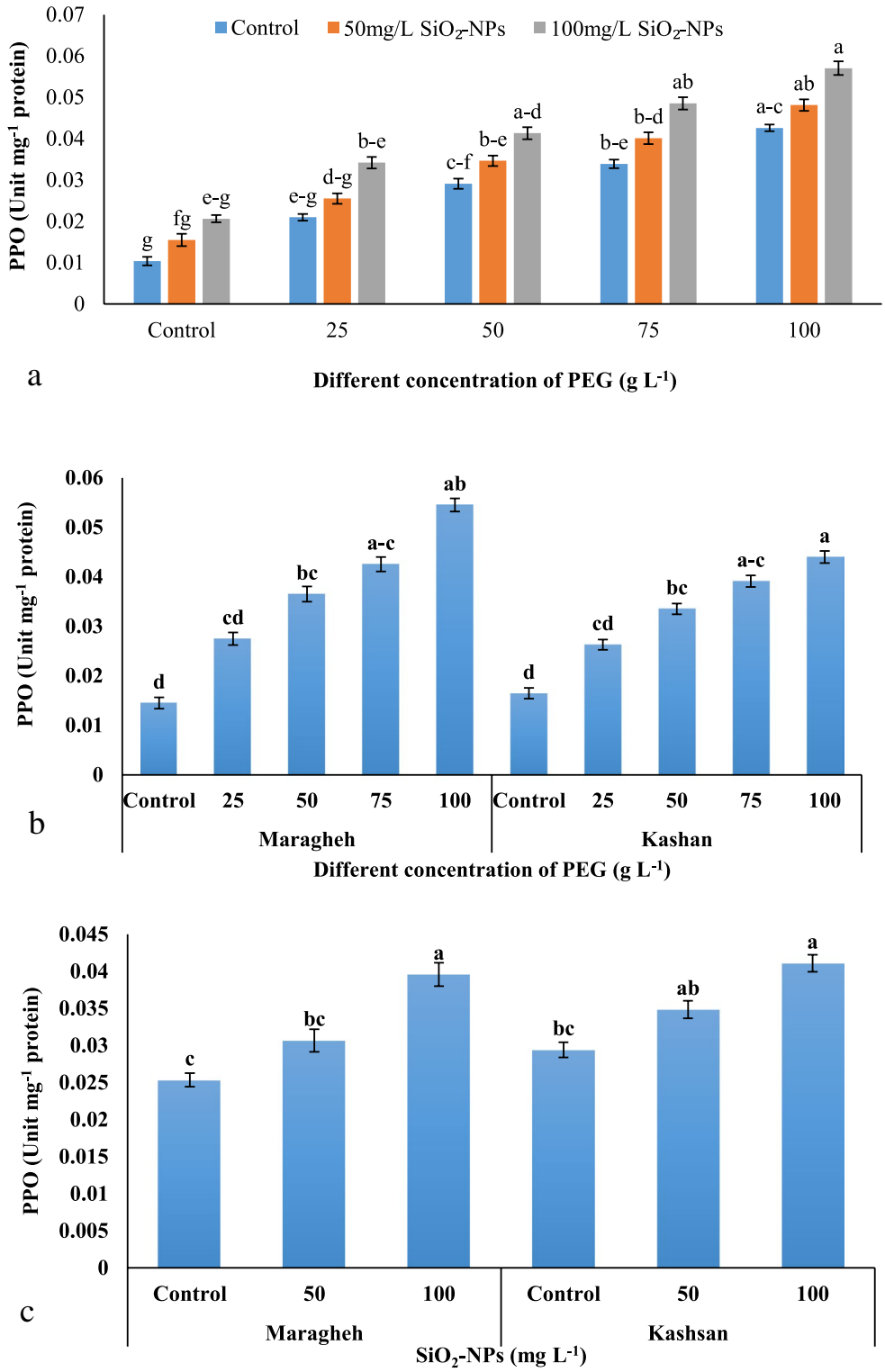


Fig. 5 Interaction between drought stress × SiO_2-NPs on leaf PPO activity **a**, drought stress × two Damask genotypes on PPO activity **b**, and SiO_2-NPs × two Damask genotypes on PPO activity **c**. Different letters indicate significant differences according to the LSD test at $P < 0.05$

Table 3 Effect of PEG and SiO_2-NPs on K and P of Maragheh and Kashan genotypes

Genotype Drought (PEG g L^{-1})	Treatment (mg L^{-1} SiO_2-NPs)	Maragheh K (mg g^{-1} DW)	Kashan K (mg g^{-1} DW)	Maragheh P (mg g^{-1} DW)	Kashan P (mg g^{-1} DW)
Control	0	15.91 ± 0.2c	9.87 ± 0.3h-j	4.69 ± 0.1d	3.65 ± 0.2hi
	50	18.97 ± 1b	13.66 ± 0.5d	5.52 ± 0.2b	3.97 ± 0.2g
	100	21.35 ± 0.7a	15.57 ± 0.9c	6.61 ± 0.2a	4.23 ± 0.07f
	0	12.50 ± 0.1ef	9.57 ± 0.3j	3.90 ± 0.1gh	3.13 ± 0.05kl
25	50	16.16 ± 0.4c	11.73 ± 0.4fg	4.52 ± 0.1de	3.44 ± 0.03ij
	100	18.87 ± 0.2b	13.89 ± 0.5d	5.09 ± 0.08c	3.77 ± 0.04gh
	0	10.47 ± 0.4h-j	7.67 ± 0.3lm	3.25 ± 0.1jk	2.58 ± 0.06n-p
50	50	13.06 ± 0.2de	9.77 ± 0.1ij	3.84 ± 0.1gh	2.90 ± 0.07lm
	100	15.65 ± 0.4c	11.83 ± 0.4fg	4.35 ± 0.08ef	3.23 ± 0.05jk
	0	8.44 ± 0.5kl	6.41 ± 0.4n	2.78 ± 0.07m-o	2.18 ± 0.06qr
75	50	10.97 ± 0.3gh	8.08 ± 0.3l	3.30 ± 0.08jk	2.56 ± 0.08op
	100	14.14 ± 0.3d	9.72 ± 0.2j	3.68 ± 0.07hi	2.82 ± 0.05mn
	0	6.94 ± 0.4mn	5.23 ± 0.2o	2.25 ± 0.1qr	1.74 ± 0.07s
100	50	9.38 ± 0.3jk	6.24 ± 1.3no	2.79 ± 0.07m-o	2.03 ± 0.05r
	100	11.93 ± 0.8fg	10.85 ± 0.8g-i	3.25 ± 0.01jk	2.38 ± 0.06pq
S. O. V					
Drought (D)		**	**	**	**
Treatment (T)		**	**	**	**
D × T		*	*	*	*
Genotype (G)		**	**	**	**
D × G		**	**	**	**
T × G		*	*	**	**
D × T × G		*	*	**	**
CV		5.67	5.67	4.34	4.34

Different letters indicate significant differences in each trait according to LSD test at $P < 0.05$. ns, * and ** indicate no significant difference, significant at 5% probability level and significant at 1% probability level, respectively. S. O. V. and CV refers to source of variation and coefficient variation, respectively

by stabilizing the chloroplast structure [45] and increasing the efficiency of photosystem II [49]. A reduction in the amount of chlorophyll with the increment along with an increase in drought severity is also reported by Hsu and Kao [50] which was in agreement with our findings in both genotypes. On the other hand, silicon caused to firmer xylem cell walls [51] which are responsible for water transportation into the plant [52]. Besides, the accumulation of silicon in the leaf, forms a layer double of silicon [53] and reduces transpiration. Recent reports showed the positive effects of bulk silica [54, 55] and nanoparticles of silicon [30] in photosynthesis parameters improvement of some plants under water deficiency.

Total carbohydrates are also a group of compatible osmolytes that accumulate under water-deficient conditions and act as an osmoprotectant. An increase in carbohydrates due to drought stress is related to osmotic regulation and turgor maintenance which is caused to stabilizing membranes and proteins [56]. In the present work, with the increase in water deficiency, the content of carbohydrates increased from 4.12 and 4.8 mg g^{-1}FW in control explants to 20.5 and 8.4 mg g^{-1} FW under 100 g L^{-1} PEG, respectively, in 'Maragheh' and 'Kashan'. In general, the increase of carbohydrates during stress may be caused by the breakdown of polysaccharides, such as starch, biosynthesis of sugars via non-photosynthetic pathways, the failure to convert these compounds into other products, the reduction of transfer from leaves to other organs, or the cessation of growth, which also increases carbohydrates content [57] which is the passive reaction to plant growth prevention under drought stress [58]. In the present study, total polyphenol content, total flavonoid content, total antioxidant capacity (DPPH), and anthocyanin were significantly increased with the increase in the PEG concentration. extreme conditions, such as drought stress, caused to increase in the anthocyanin pigments in leaves that have an antioxidative role in the protection of the photosynthetic system against light oxidation [59]. Results showed a synergistic effect between drought stress and SiO_2-NPs, as they strengthen each other's effect and caused increased levels of biochemical traits under severe water deficiency

Table 4 Effect of PEG and SiO_2-NPs on nutritional elements of Maragheh and Kashan genotypes

Genotype Drought (PEG g L^{-1})	Treatment (mg L^{-1} SiO_2-NPs)	Maragheh Zn (mg g^{-1} DW)	Kashan Zn (mg g^{-1} DW)	Maragheh Mn (mg g^{-1} DW)	Kashan Mn (mg g^{-1} DW)	Maragheh Cu (mg g^{-1} DW)	Kashan Cu (mg g^{-1} DW)
Control	0	1.774 ± 0.08c	0.862 ± 0.01hi	1.304 ± 0.04c	0.402 ± 0.03i	0.087 ± 0.06cd	0.021 ± 0.02j-n
	50	2.037 ± 0.06b	0.956 ± 0.02gh	1.545 ± 0.05b	0.645 ± 0.03g	0.122 ± 0.06b	0.034 ± 0.03h-k
	100	2.422 ± 0.05a	1.300 ± 0.02ef	1.803 ± 0.07a	0.849 ± 0.04f	0.153 ± 0.03a	0.047 ± 0.02gh
	0	1.565 ± 0.05d	0.533 ± 0.05j	1.001 ± 0.03e	0.283 ± 0.01jk	0.072 ± 0.04de	0.018 ± 0.01k-n
25	50	1.846 ± 0.07c	0.786 ± 0.07i	1.209 ± 0.04d	0.325 ± 0.01ij	0.095 ± 0.08c	0.027 ± 0.01i-m
	100	2.106 ± 0.04b	1.051 ± 0.06g	1.531 ± 0.1b	0.375 ± 0.03i	0.136 ± 0.08b	0.038 ± 0.02g-i
	0	1.236 ± 0.06f	0.357 ± 0.04kl	0.794 ± 0.05f	0.193 ± 0.07lm	0.065 ± 0.04ef	0.014 ± 0.04l-n
50	50	1.590 ± 0.07d	0.383 ± 0.07kl	1.050 ± 0.06e	0.233 ± 0.06kl	0.073 ± 0.08de	0.018 ± 0.01k-n
	100	1.836 ± 0.07c	0.428 ± 0.01k	1.324 ± 0.07c	0.264 ± 0.05j-l	0.093 ± 0.05c	0.029 ± 0.02i-l
	0	1.026 ± 0.03g	0.220 ± 0.01mn	0.634 ± 0.08g	0.143 ± 0.02mn	0.051 ± 0.05fg	0.010 ± 0.05n
75	50	1.223 ± 0.06f	0.288 ± 0.01lm	0.793 ± 0.07f	0.180 ± 0.04l-n	0.068 ± 0.03e	0.015 ± 0.07l-n
	100	1.549 ± 0.05d	0.356 ± 0.02kl	1.068 ± 0.08e	0.217 ± 0.03 k-m	0.090 ± 0.04c	0.021 ± 0.06j-n
	0	0.835 ± 0.05i	0.160 ± 0.05n	0.518 ± 0.02h	0.095 ± 0.05n	0.035 ± 0.04g-j	0.008 ± 0.03n
100	50	1.057 ± 0.04g	0.229 ± 0.06mn	0.823 ± 0.01f	0.134 ± 0.06mn	0.047 ± 0.02gh	0.011 ± 0.05mn
	100	1.345 ± 0.04e	0.316 ± 0.04lm	0.990 ± 0.04e	0.176 ± 0.04l-n	0.065 ± 0.03ef	0.018 ± 0.06k-n
S. O. V							
Drought (D)		**	**	**	**	**	**
Treatment (T)		**	**	**	**	**	**
D × T		**	**	**	**	**	**
Genotype (G)		**	**	**	**	**	**
D × G		**	**	**	**	**	**
T × G		**	**	**	**	**	**
D × T × G		**	**	**	**	**	**
CV		6.11	6.11	7.67	7.67	8.91	8.91

Different letters indicate significant differences in each trait according to LSD test at $P < 0.05$. ns, * and ** indicate no significant difference, significant at 5% probability level and significant at 1% probability level, respectively. S. O. V. and CV refers to source of variation and coefficient variation, respectively

and 100 mg L^{-1} SiO_2-NPs. As a matter of fact, Verma and Dubey [60] reported that silicon has a significant effect on the metabolism of soluble sugars and the partitioning of photosynthetic substances in growing plants increases it. Therefore, it assumed that silicon keeps the carbohydrate reserve of plants under stress, for metabolic processes and maintenance of basic metabolism. On the other hand, the research on PEG-induced water deficiency in wheat showed that the reason for the increase in the levels of phenolic compounds is the increase in the activity of the biosynthetic enzymes of phenols [61]. Phenolics accumulation during stress conditions can act as a sign/alarm and start a cascade of other reactions that ultimately lead to an increase in stress tolerance [62]. An increased DPPH scavenging activity during water deficit conditions was also observed in Salvia [63] and Fraxinus [64]. Phenolic substances are derivatives of the phenylpropanoid pathway which are a part of the non-enzymatic antioxidative defense. It seems that silicon may directly or indirectly induce the genes of the biosynthesis pathway of these compounds and thereby increase the plant's resistance to drought stress [65].

The nutrient element content of Damask rose explants was remarkably influenced by water deficiency. Totally, the concentration of measured elements including K, P, Cu, Zn, Fe, and Mn sharply reduced with the increment of water deficiency. Brown et al. [66] also showed the same results relying on the reduced levels of absorbed Fe under water deficit. Pei et al. [54] reported that Si decreased Mg, K, and Ca contents in wheat under water deficiency. The same results rely on the reduction in Zn, Mn, and Cu obtained by Sarker and Oba [67] and Gunes et al. [68]. It is believed that, besides the harmful effect of water deficiency on plant growth and productivity, problems with nutrient minerals can occur as a secondary effect, because it is dependent on the moisture in the soil to move through the soil matrix and be taken up by plants [69]. Under drought stress, roots are not able to absorb most of the nutrients from the rhizosphere because of the lack of root activity and also, slow ion diffusion and

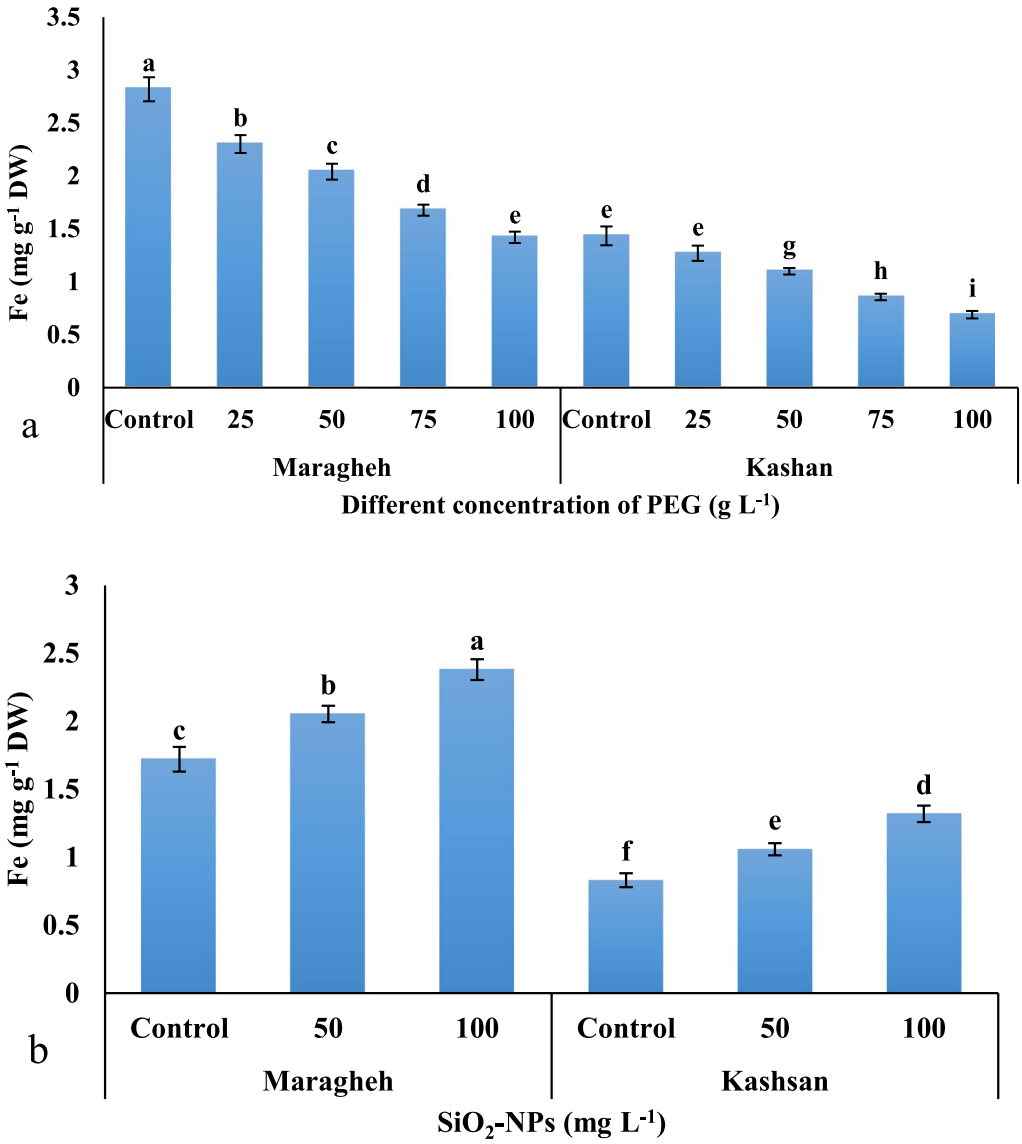


Fig. 6 Interaction between drought stress × two Damask genotypes on leaf Fe **a** and SiO_2-NPs × two Damask genotypes on Fe **b**. Different letters indicate significant differences according to the LSD test at $P < 0.05$

water movement rates [70] Furthermore, the mineralization process depends on microorganisms and enzyme activity, which may be influenced by drought. Therefore, water deficit causes low nutrient availability in the soil and lower nutrient transport in plants [71]. It seems that the severe decrease in root length under water deficiency is the most important reason for reducing the absorption of potassium (K) in the soil by the plant. Increasing the amount of K is an important indicator in tolerance to drought stress and it seems that treatment with SiO_2-NPs had the potential to increase the plant K in 'Maragheh' more than 'Kashan' (44% vs 30%), as shown in Table 3. Besides, Mahouachi [72] found reduced amounts of K in bananas under water deficiency. Similar findings were obtained by Restrepo-Diaz et al. [73] in the leaves of olive plants under water stress, regardless of nutritional status. By reducing the amount of soil water, the mobility of K is reduced, and consequently, the availability of K by plants root is also reduced [71]. It has been reported that the reason for leaf K reduction under water deficiency may be due to the movement of this element from the leaves to the roots, because K acts as an osmotic protector. Potassium has less solubility in arid conditions and as a result is less absorbed by the plant [74]. Phosphate (P) moves through diffusion in the soil so that under water deficiency, the radii of water-filled pores decrease,

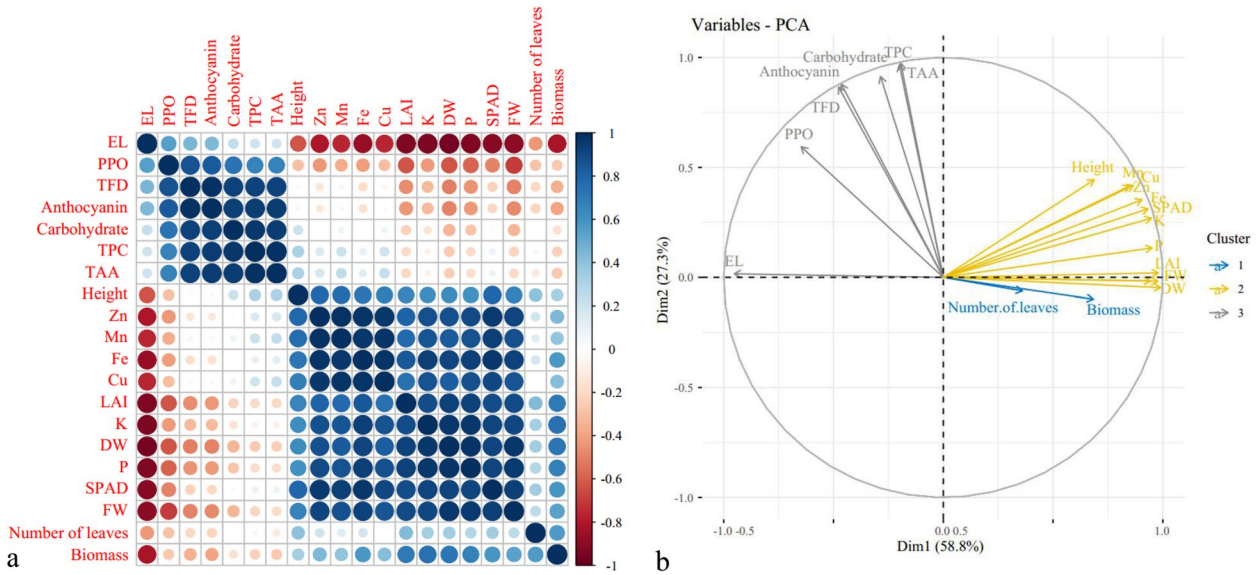


Fig. 7 Heat maps of Pearson correlation heat map **a** and loading biplot of the evaluated traits **b** of the growth parameters, biochemical and nutrient changes in Damask rose under PEG-induced osmotic stress treated with SiO_2-NPs. Heat maps representing electrolyte leakage (*EL*), polyphenol oxidase (*PPO*), total flavonoids content (*TFD*), Anthocaynin, total soluble carbohydrate, total phenolics content (*TPC*), height, leaf area index (*LAI*), leaf dry weight (*DW*), leaf fresh weight (*FW*), SPAD, number of leaves, biomass and some nutrient content such as Zn, Mn, Fe, Cu, K, P

tortuosity increases, and P mobility decreases [75]. Water deficit causes a reduction in P absorption and transport in plants. A decrease in available P forms and an increase in occluded P in the soil caused to reduce in P uptake and consequently induces lower foliar P content [76, 77]. Sardans and Peñuelas [77] demonstrated that a 22% reduction in soil moisture produced a 40% decrease in the accumulated aboveground P content in plants, primarily because there was a little increase in aerial biomass. Jin et al. [78] showed that water deficit caused to decrease in plant growth and development, and total P uptake. Despite 21 mg of absorbable P per kilogram of soil, which is more than plants need, immobilization of phosphorus in high acidity and its stabilization, especially in water deficiency conditions, is the major reason for the reduction of P accumulation in the leaf tissue [79].

Silicon increases root endodermal silicification and improve the water balance in cells [80]. Under stress conditions, the application of silicon offers beneficial effects for plant growth and development, promoting enhanced water uptake and alleviating oxidative damage [81]. It seems that the effect of SiO_2-NPs in microelements absorption especially in the Kashan genotype which has moderate tolerance to drought stress [30], is more drastic than that in 'Maragheh'. Several destinations are estimated for silicon once it has entered the plant symplast; In the roots, it is mostly found in endo- and exodermal tissues where it could be integrated into the cell wall by cross-linking with other wall components, such as hemicelluloses, pectins, and phenolic compounds [82]. In the shoots, high concentrations of silicic acid led to its autopolymerisation into silica [83]. Deposited silica can be found in the form of phytoliths which occur in a multitude of shoot tissues [84]. Alternatively, silica accumulates in or beneath the cuticle layer of the cell wall in epidermal cell layers and tissues that surround the vasculature [85]. In general, SiO_2-NPs efficiency seems to be more pronounced in 'Kashan' which is considered as a moderate tolerance to water deficiency [30]. In both genotypes exposed to drought stress, nano-silicon application increased chlorophyll, indicating the synthesis of new pigments, and maintenance of chlorophyll previously existing. Although, the exact mechanisms are still under debate but it seems that silicon can relieve drought by lowering root hydraulic conductance and reduction of water loss through transpiration, activation of antioxidant capacity and enhancement of minerals. However, the positive effects of silicon treatment in the plants are obvious not only under stress conditions but also have confirmed in stress-free conditions.

Conclusion

In general, the results demonstrated that silicon nanoparticles play a key role in maintaining critical physiological and biochemical functions as well as minerals adsorption in Damask rose under water deficiency. Silicon treatment

under water deficiency increased carbohydrates content compared to the lack of silicon application. It is concluded that the effect of SiO_2-NPs in Kashan was more drastic in increasing the antioxidant capacity and total phenolic compounds. In addition, the effect of SiO_2-NPs application in Kashan genotype was more efficient in microelements adsorption compared to Maragheh. In general, having more biomass and leaf area under drought probably makes 'Maragheh' more tolerant than 'Kashan' but the effect of SiO_2-NPs application in sensitive genotypes is more pronounced. Finally, further research should be conducted to understand the possible synergistic effect of SiO_2-NPs on Damask rose various physiological events such as biostimulation elucidating the up-regulation of gene expression, crosstalk amongst phytohormones that could be altered and enzyme activity.

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Declarations

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