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Original Article

Biochemical Changes of Coriander (*Coriandrum sativum* L.) Plants under Drought Stress and Foliar Application of Salicylic Acid and Silicon Nanoparticles

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ABSTRACT

There is an increasing interest to use nanoparticles (NPs) and growth regulators in mitigating deleterious effects of the drought stress. The present work was conducted to investigate the effect of the salicylic acid (SA) and silicon (Si)-NPs on physiological and biochemical attributes of coriander (*Coriandrum sativum* L.) plants expose to drought stress. A split-plot experiment was carried out with irrigation regimes (irrigation after 60, 90, and 120 mm evaporation from Class A pan) as main plot and foliar application of SA and Si-NPs as the subplots during 2019 and 2020. The results showed drought stress reduced chlorophyll (Chl) content, but enhanced total soluble sugar (TSS), superoxide dismutase (SOD) and peroxidase (POX) activities of coriander leaves. Increases in Chl content, TSS, and activity of antioxidant enzymes were observed when plants sprayed with SA and Si-NPs. Moderate drought stress (90 mm evaporation from Class A pan) along with Si-NPs significantly increased total phenolic content (TPC) and total flavonoid content (TFC), essential oil (EO) content, and EO yield. Foliar application of Si-NPs was more effective than SA to improve the antioxidant potential and EO yield of coriander plants when exposed to drought stress.

INTRODUCTION

Coriander (*Coriandrum sativum* L.) is an annual plant species of Apiaceae family, which is widely used due to its strong nutritional and medicinal values [1]. It originally belongs to the European-Mediterranean area, but recently it has been widely cultivated as a useful vegetable all over the world [2]. It can be used as vegetable and food spice due to its nutritional value. Moreover, coriander exerts various medicinal uses such as treatment of disorders in skin inflammation, digestive, respiratory and urinary systems [2,3]. In addition, it has essential oil (EO) in both leaves and seeds with different EO profile [1,4].

Drought, a main abiotic stress, affects physiological and biochemical processes of plants, especially the synthesis and accumulation of secondary metabolites [5]. Under deficit of water supply, chemical signals are transmitted from the roots to the leaf through xylem pathways, in which plants stimulate physiological changes such as stomatal closure, photosynthesis reduction, and enhancement of the antioxidant potential through biochemical pathways like antioxidant enzymes and phenolic content [6]. Secondary metabolites are the principal active compounds in medicinal plants, which were affected by drought stress [7]. Therefore, water deficit stress has a greater impact on medicinal plants. In fact, changes in essential oil (EO) yield and composition, phenol and flavonoid contents are the main biochemical response of medicinal plants under drought stress [7].

The use of plant hormones and metal nanoparticles (NPs) is a beneficial practice to improve plant growth and yield particularly at stress conditions. Salicylic acid (SA) is an important growth regulator with phenolic nature and participates in the regulation of the physiological processes in plants [8]. This growth regulator plays a key role in the defense response of plant cells to environmental changes [8,9]. Foliar spray of SA is a useful practice to reduce the harmful effects of abnormal plant

conditions [9]. In addition, silicon (Si), as the second abundant element in earth crust, has an important role on soil productivity [10]. According, positive effects of Si on plant growth and development under biotic and abiotic stress conditions have been well documented [5, 11]. Si improves plant growth by enhancing the resistance against toxicity of metals, water deficiency, inequalities in nutrient concentration, salinity, and radiation [12]. The positive effects of Si-NPs on physiological and biochemical attributes of plants in order to obtaining the better growth have been addressed in different plants [13,14]. Si-NPs due to their small size can penetrate into plant cells and scavenge reactive oxygen species (ROS) under stress conditions [15]. NPs have various advantages on the environment like mitigating of water contamination, sewage, air pollution, and greenhouse gases. However, NPs can impose a risk to the environment, humans and animals due to their mechanism of rapid movement and transport in the environment, facilitating the transfer of other toxic substances, microbial biotoxicity, biodegradation, and environmental accumulation [15].

There is an enhancing interest on nanotechnology for obtaining the improved products in medicinal plants. Nano-fertilizers due to their rapid uptake and positive effect on plants is widely used to replace synthetic materials. Several studies have addressed the effective role of SA [16-18], and Si [12,19,20] on alleviating drought stress. However, little is known about SA and Si-NPs in the regulation of drought effects in medicinal plants. Therefore, the aims of present study were to investigate the physiological and biochemical status of coriander plants under different irrigation regimes. These results provide an effective practice with SA and Si-NPs to cope with deleterious impacts of drought stress on coriander plants.

MATERIALS AND METHODS

Experimental Site and Plant Materials

The experiment was conducted in the research farm of Islamic Azad University, Shahre rey Branch, Tehran, Iran (1070 m asl, 35°36′44" N, 51°26′30" E) in 2019 and 2020. Table 1 shows the soil properties used in the study. The total annual precipitation was 216 mm in the first year and 214 mm in the second year. The mean annual temperature of first and second years were 16.7 and 16.9 °C, respectively.

The seeds of coriander were purchased from Pakan Bazr-e-Esfahan Company (Esfahan, Iran), and sown at 19 and 20 April. The area of each plot was 6 m^2. The distance between two lines and between two plants on lines was 30 cm and 20 cm, respectively. The distance between plots was 1 m.

Experimental Design and Treatments

The split plot experiment was carried out in a randomized complete block design (RCBD) with three replications in 2019 and 2020. Irrigation regimes as main plot were applied in three levels based on evaporation from Class A pan as irrigation after 60, 90, and 120 mm evaporation from Class A pan. The SA and Si-NPs were used as subplots in the experiment. They were purchased from Nano Pasargad Novin company, Tehran, Iran. The Si-NPs included the purity of 99%, particle size of 20–35 nm, and active level of 461 g/m^2. To homogenize and separate the particles, the NPs were ultra-sonicated for 30 min by using distilled water before application. Si-NPs was used as silicon dioxide (SiO_2, Sigma-Aldrich) at 1.5 mM and SA (Sigma-Aldrich) was also used at 1.5 mM as foliar application. Seed were cultivated in 19 and 20 April by hand. Weeds were controlled manually during the growing season.

Table 1 Soil analysis of experimental field

Depth (cm)	pH	EC (ds/m)	Na (meq/l)	P (mg/kg)	Organic carbon (%)	K (mg/kg)	NH_4 (mg/kg)	NO_3 (mg/kg)	Clay (%)	Silt (%)	Sand (%)	Soil Texture
0-15	7.84	1.03	6.36	10.46	1.03	598.8	5.95	14.63	31	49	20	Clay Loam
15-30	7.82	1.11	6.75	9.57	0.97	603.5	6.04	14.57	30	49	21	

Drought was applied after emerging 4 leaves, and during the growth period, plants were foliar-applied with a solution containing at two levels of SA (0 and 1.5 mM SA) and two levels of Si-NPs (0 and 1.5 mM Si-NPs) for three times (both side of leaves) at an interval of 15 days.At harvesting stage (4 months after sowing the seeds), the plants were divided in three groups of fresh, dry, and frozen samples.The frozen samples were kept at -80 °C using liquid nitrogen to biochemical assays.

Chlorophyll (Chl) Assay

The Chl content was extracted according to Arnon [21]. The 200 mg of fresh samples were homogenized in 8 ml 80% acetone. After that, the mixture was centrifuged at 4 °C for 15 min (3000 rpm). Supernatants were used to analyze Chl a and Chl b concentration. The 645 and 663 nm were applied at a spectrophotometer.

Determination of Total Soluble Sugar (TSS)

To measure TSS, 0.5 g of frozen leaf samples were crush with liquid nitrogen and grind with 5 mL of 95% ethanol to release sugar, then 5 mL of 70% ethanol was added in two times and centrifuged at 3500 rpm for 10 min and kept in the refrigerator for one week. After that, 0.1 mL of the stored stock was mixed with 3 mL antron (150 mg antron and 100 mL 72% sulfuric acid). The solution was placed in the boiling water bath at 90 °C for 10 min. The absorbance was measured at 625 nm using a UV-Vis spectrophotometer (Shimadzu, Tokyo, Japan) [22].

Determination of Total Phenolic Content (TPC)

Folin–Ciocalteu reagent was selected to measure leaf TPC spectrophotometrically [23]. 100 µl of the MeOH solution of the precisely measured weight of investigated plant 1–10 (2.54, 2.58, 2.25, 4.03, 4.80, 2.13, 4.62, 1.47, 1.58, 15.05 mg/mL respectively) were mixed with 0.75 mL of Folin–Ciocalteu reagent and allowed to stay at 22 ºC for 5 min. The mixture was supplied with 0.75 mL of $NaHCO_3$. Absorbance was measured at 725 nm by UV–VIS spectrophotometer (Varian Cary 50) after 90 min at 22 ºC. Standard curve was calibrated by Gallic acid (0–100 mg/mL; r > 0.99). The results were represented as mg Gallic acid (GA)/g Dry weight.

Determination of Total Flavonoid Content (TFC)

Leaf TFC were measured by aluminum chloride colorimetric method [24]. Briefly 0.5 mL of extract solution with 1.5 mL of 95% ethanol, 0.1 mL of aluminum chloride 10%, 0.1 mL of 1 M potassium acetate were mixed with 2.8 mL of distilled water. The mixture vortexed for 10 s and left to stand at 25 ºC for 30 min. The absorbance of the mixture was read at 415 nm. Quercetin concentrations (0 to 1200 µg/mL) were prepared and linear fit was used for calibration of the standard curve.

Enzyme Assay

To obtain enzyme extracts, 0.5 g of leaf samples was homogenized in a prechilled pestle and mortar with 5 mL of ice-cold 50 mM sodium phosphate buffer (pH 7.5) containing 1 mM phenylmethylsulfonyl fluoride (PMSF). The mixture was centrifuged at 4 °C for 15 min at 13000 rpm. The supernatant was used for enzyme assay as the extract.

Superoxide dismutase (SOD) activity was determined as described by Beyer and Fridovich (1987). The reaction mixture consisted of $1.17 \times 10{-}6$ M riboflavin, 0.1 M methionine, $2 \times 10{-}5$ M KCN and $5.6 \times 10{-}5$ M nitroblue tetrazolium salt (NBT), which was dissolved in 3 ml of 0.05 M sodium phosphate buffer (pH 7.8). 1 mL of enzyme extract was enriched with 3 ml of the reaction. Illumination was started to initiate the reaction at 30 °C for 60 min. The blanks were identical solutions that were kept under dark condition. The absorbance was determined at 560 nm with the spectrophotometer against the blank. SOD activity was calculated by using extinction coefficient of 0.036 m/M/ cm and expressed in U/mg protein. It was calculated as follow:

(OD Control –OD Sample) / OD Control

To measure peroxidase activity (POX), 1.2 g Tris-HCl buffer, 2 g ascorbic acid, 3.8 g borax, 40 g polyethylene glycol 2000, and 2 g EDTA Na_2 were placed in a container and diluted to 100 mL with distilled water. For the extraction of enzymatic extract, 1 g sample was ground in 4 mL extraction solution and kept at 4 °C for 24 h. Then, it centrifuged at 4000 g for 30 min. For measuring enzymatic activity, 2 mL 0.2 M acetate buffer, 0.4

mL 3 % hydrogen peroxide, and 0.2 mL benzidine were mixed in a test tube; 0.2 mL enzymatic extract was added to it, and spectrophotometry at λ =530 nm was used to measure its absorption after 1 min . POX activity was calculated extinction coefficient of 26.6 m/M/cm and expressed in U/mg protein [26].

Essential Oil (EO) Content and Yield

EO content was quantified based using the method described by the European Pharmacopoeia for oil production [27]. The aboveground plant parts (leaves and flowers) were dried at shade conditions for 7 days. The samples were grinded and 100 g were used to hydro-distillation for 3 h using a Clevenger-type apparatus. The oil samples were dehydrated by placing them in dark glass bottles containing anhydrous sodium sulfate. EO yield was determined as the amoun of EO extracted from total dry weight per pot.

Data Analysis

The SAS software package for Windows (SAS, version 9.3, SAS Institute, Cary, NC) was used for data analysis. The mean values were compared with Duncan's multiple range tests. The data were statistically analysed at 5% probability level ($P \leq 0.05$).

RESULTS AND DISCUSSION

Chlorophyll (Chl) Content

The amounts of Chl a and Chl b were significantly ($P \leq 0.05$) affected by drought, Si, and SA Drought stress (Table 2). Drought decreased Chl a and Chl b contents but Si-NPs increased them (Table 3). The highest Chl a was observed in plants under normal irrigation and Si-NPs to be 1.35 mg/g FW. In contrast, the lowest Chl a amount was obtained in plants upon severe stress without Si-NPs as 0.65 mg/g FW (Fig. 1a). Moreover, the interaction of SA and Si-NPs was significant on Chl a ($P \leq 0.05$). Compared to control, the interaction of SA and Si-NPs increased Chl a by 43% (Fig. 1b). like Chl a, Chl b increased with the simultaneous application of SA and Si. The maximum Chl b was obtained in plants sprayed with Si or the interaction of SA and Si-NPs to be 0.34 mg/g FW. Plants decrease leaf area and photosynthesis rate to cope with drought stress [7]. The decreased chlorophyll content under drought stress have been reported in corn [28] and *Salvia sinaloensis* [29]. In fact, the decline of Chl a and Chl b with progressing drought stress could be attributed to inhibition of cell elongation and expansion, reduced turgor pressure, alteration of energy from growth to synthesis of compatible solutes to maintain cell turgor, which result in reduced tissue water contents and trimming down the photo-assimilation and metabolites required for cell division [30]. The higher Chl a and Chl b of SA-treated plants may be related to the influence of SA on endogenous cytokinin contents. SA-treated plants synthesize more cytokinin which, in turn, enhance Chl differentiation and Chl biosynthesis, and prevent Chl degradation [30]. Foliar applied SA improves net photosynthesis; this may be attributed to the role of SA in improving the functional status of the photosynthetic mechanism of plants, either by mobilizing nitrate from internal tissues or by chlorophyll biosynthesis. The positive effects of SA can be attributed to higher CO_2 assimilation and photosynthetic rates and higher mineral absorption to improve plant yield [31]. The Si-NPs may improve the nutrients uptake by plants that affect Chl a and Chl b content. The Si-NPs can improve photosynthesis rate via uptake of Mg, P, K and S contents in stressed plants [32,33].

Total Soluble Sugar (TSS)

Drought, SA, and Si-NPs increased TSS of coriander leaves (Table 3). In addition, the interaction of drought and Si was significant on TSS, which its highest amount (138.7 mg/g) was recorded in plants exposed to severe drought stress and foliar applied Si-NPs. In non-Si treatments, severe and moderate drought stress increased TSS by 50 and 44% compared to the normal irrigation (Fig. 2a). Although there were no significant changes between the interactions of Si-NPs and SA, they showed the higher TSS compared to alone SA and control. In addition, SA also resulted in a noticeable increase in TSS (Fig. 2b). The increased TSS was the strategy of coriander to cope with the stressed conditions. TSS is an indicator to find the physiological changes upon environmental stresses [34]. In this regard, increased TSS under drought stress has been demonstrated in several studies [35, 36]. In contrast, a few works have shown that drought significantly decreases TSS in different tissues of plants [34].

Table 2 Analysis of variance for studied traits under drought, salicylic acid (Sa) and silicon nanoparticles (Si-NPs)

S.O.V	df	MS								
		Chl a	Chl b	TSS	SOD	POX	TPC	TFC	EO	EO yield
Year	1	5×10^{-4} ns	1.5×10^{-3} ns	177.3 ns	0.91*	0.01 ns	3.25 ns	4.16 ns	0.003 ns	2.5 ns
Year (rep)	4	2×10^{-3}ns	3.8×10^{-4} ns	13.76 ns	0.07	0.56	1.07 ns	2.34 ns	0.000 ns	2.1 ns
Drought	2	1.2**	9.6×10^{-2} **	10018 ns	47.9 ns	346 ns	154**	145 **	0.186**	1071**
Year*drought	2	5×10^{-4} ns	6.2×10^{-4} ns	17.5 ns	1.08 ns	0.00 ns	3.23 ns	13.2 ns	0.005**	5.3 ns
Year (rep*drought)	8	3×10^{-4} ns	3.8×10^{-4} ns	56.2*	0.06 ns	0.06	1.96 ns	1.09 ns	0.001 ns	5.6 ns
Si	1	1.10**	5.2×10^{-2}**	5530 **	5.95 *	22.11 ns	204 **	204**	0.030*	469**
SA	1	1×10^{-1} **	3.6×10^{-3}*	455 **	1.47 **	3.42 ns	118**	58.5**	0.038 *	176**
Year × Si	1	2×10^{-4} ns	6.1×10^{-4} ns	5.01 ns	0.13 ns	0.00 ns	0.66 ns	1.15 ns	0.003 ns	8.0 ns
Year × SA	1	4×10^{-4} ns	1.1×10^{-5} ns	115 ns	0.03 ns	0.00 ns	1.65 ns	10.3 ns	0.000 ns	3.5 ns
Drought × Si	2	5×10^{-1} **	8.4×10^{-4} ns	132*	0.10 ns	0.96 *	14.8*	20.2**	0.001 **	10.8 **
Drought × SA	2	4×10^{-3} ns	8.2×10^{-4} ns	9.85 ns	0.19 *	1.00 *	0.08 ns	0.44 ns	0.001 ns	3.9 ns
Si × SA	1	1×10^{-2} **	6.2×10^{-3} **	147*	0.00 ns	1.15 *	8.20 ns	0.42 ns	0.005*	14.3 *
Year × drought × Si	2	1×10^{-4} ns	1.1×10^{-3} ns	29.3 ns	1.30 ns	0.01 ns	3.74 ns	0.44 ns	0.002 ns	13.1 ns
Year × drought × SA	2	1×10^{-4} ns	1.8×10^{-4} ns	12.3 ns	0.20 ns	0.01 ns	2.19 ns	7.42 ns	0.002 ns	7.3 ns
Year × Si × SA	1	5×10^{-5} ns	3.1×10^{-5} ns	1.13 ns	0.00 ns	0.01 ns	0.96 ns	0.19 ns	0.002 ns	5.8 ns
Drought × Si ×SA	2	8×10^{-4} ns	4.7×10^{-4} ns	3.01 ns	0.02 ns	0.12 ns	0.03 ns	2.37 ns	0.001 ns	1.7 ns
Year × drought × Si × SA	2	1×10^{-4} ns	5.6×10^{-4} ns	23.63 ns	0.36 ns	0.01 ns	2.67 ns	0.39 ns	0.003 ns	19.5 ns
Error	36	4×10^{-2}	6×10^{-4}	26.5	0.06	0.23	3.6	1.3	0.0007	3.3
CV	-	7.1	8.1	4.4	6.6	6.2	4.9	7.4	8.1	9.4

*, **, and ns show significance at 5%, 1%, and not significant, respectively.

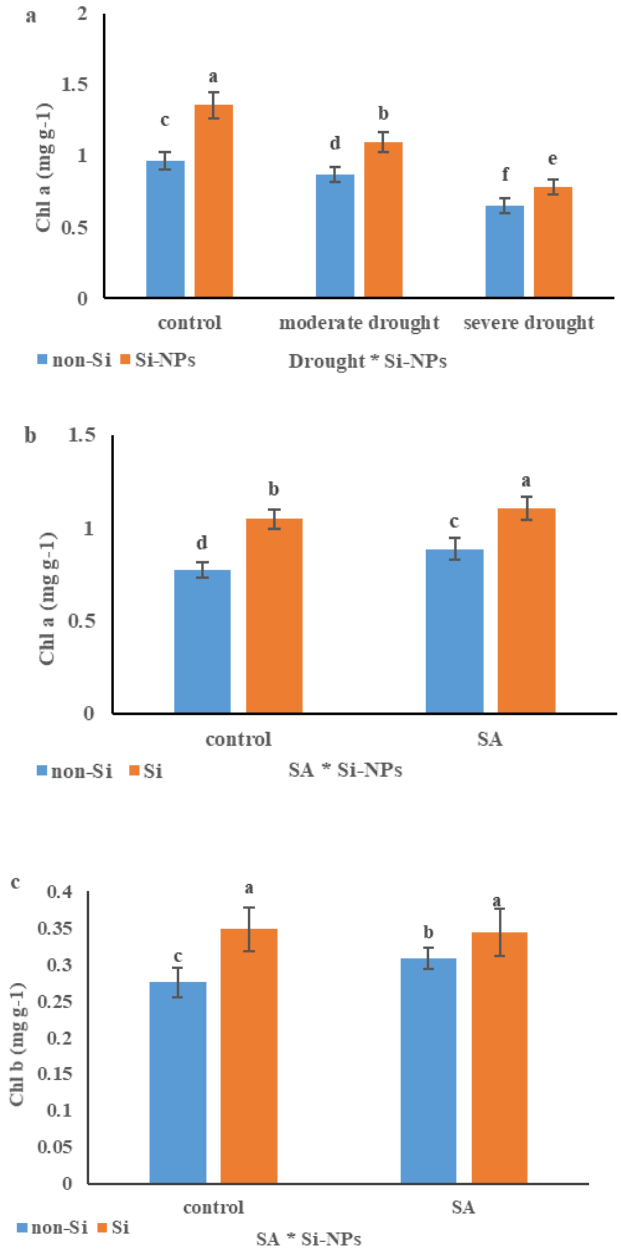

Fig. 1 Chlorophyll (Chl) content of coriander plants treated with salicylic acid, silicon nanoparticles under drought stress. Values are means ± standard deviation (SD) of three replications. Different letters show statistically significant differences among treatments at $P \leq 0.05$.

In this two-year study, moderate and severe drought stresses enhanced sugar accumulation in leaves of coriander plants.

Soluble sugar plays the vital role an osmoprotectant, regulating osmotic adjustment, scavenging toxic ROS, and providing membrane protection under biotic and abiotic stresses [36]. The accumulation of TSS is an effective strategy of plants to maintain water content and membrane stability of cells under water stress conditions [36].

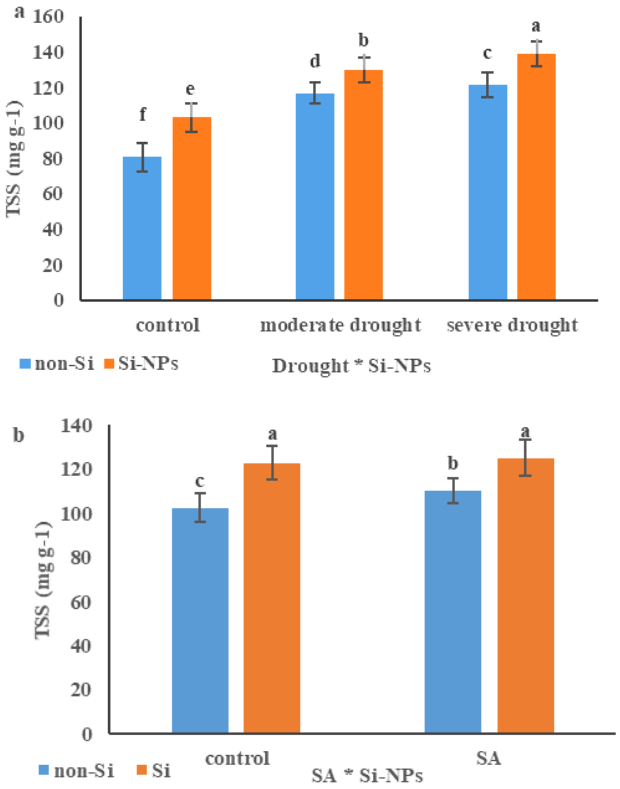

Fig. 2 Total soluble sugar (TSS) of coriander plants treated with salicylic acid, silicon nanoparticles under drought stress. Values are means ± standard deviation (SD) of three replications. Different letters show statistically significant differences among treatments at $P \leq 0.05$.

Total Phenolic Content (TPC) and Total Flavonoid Content (TFC)

The TPC and TFC possessed different responses to drought stress, which increased by moderate drought stress and then decreased under severe drought (Table 3). In addition, SA and Si-NPs increased TPC and TFC. The interaction of drought and Si-NPs significantly affected TPC and TFC, where the highest TPC (Fig. 3a) and TFC (Fig. 3b) were reported in plants experienced moderate drought along with Si-NPs. The change of TFC was greater than TPC, in which under normal irrigation, Si-NPs increased TFC by 25% compared to control. Phenolic compounds are effective in improving antioxidant capacity through scavenging ROS.

Table 3 Biochemical attributes of coriander plants under main effects of drought, salicylic acid and silicon nanoparticles

		Chl a	Ch b	TSS	TPC	TFC	SOD	POX	EO	EO yield
Drought	Control	1.16 a	0.38 a	92 c	37.9 b	17.1 a	2.2 c	4.3 c	0.29 b	19.4 b
	Moderate stress	0.98 b	0.31 b	123.5 b	41.2 a	17.2 a	3.9 b	6.8 b	0.45 a	26.1 a
	Severe stress	0.71 c	0.24 c	130 a	36.7 c	12.9 b	5.1 a	11.8 a	0.30 b	12.6 c
Si-NPs	Non-Si-NPs	0.82 b	0.29 b	106.5 b	37.0 b	14.1 b	3.4 b	7.1 b	0.32 a	16.1 a
	Si-NPs	1.07 a	0.34 a	124.1 a	40.4 a	17.4 a	4.1 a	8.2 a	0.36 b	21.9 b
SA	Non-SA	0.90 b	0.31 b	112.7 b	37.2 b	14.8 b	3.6 b	7.4 b	0.32 b	17.7 a
	SA	0.99 a	0.33 b	117.7 a	40.2 a	16.6 a	3.9 a	7.9 a	0.37 a	20.1 b

Units: Chlorophyll (Chl) and total soluble content (TSS) : mg/g, total phenolic content (TPC) : mg GA/g DW, total flavonoid content (TFC) : mg QE/g DW, superoxide dismutase (SOD) and oeroxidases (POX), U/mg protein, essential oil (EO): g 100/g, EO yield: Kg/ha

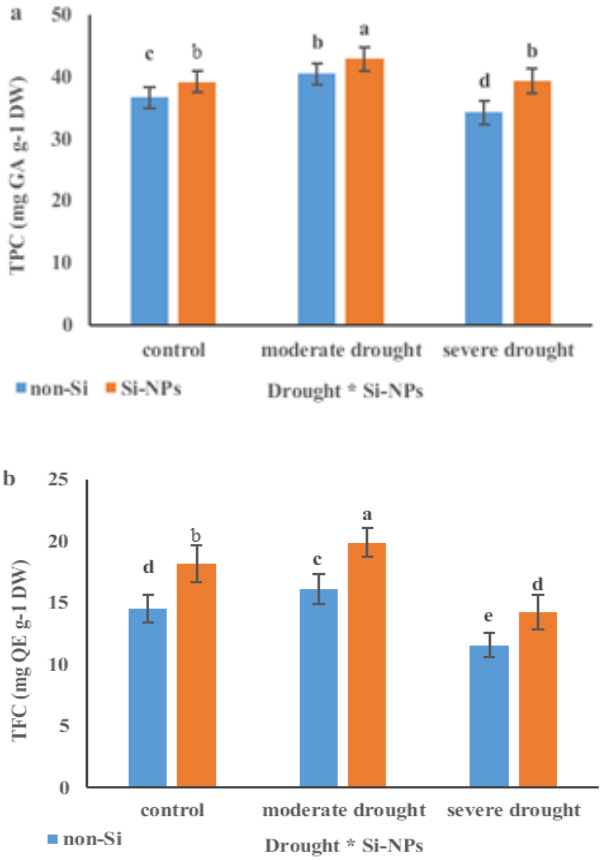

Fig. 3 Total phenolic content (TPC) and total flavonoid content (TFC) of coriander plants under silicon nanoparticles and drought stress. Values are means ± standard deviation (SD) of three replications. Different letters show statistically significant differences among treatments at $P \leq 0.05$.

The moderate stress along with SA and Si-NPs increased TPC and TFC upon moderate water stress, but it decreased in plants exposed to the severe drought. Similarly, Gharibi *et al*. [37] showed the increased TPC and TFC under moderate drought, while they remained unchanged upon severe stress conditions. Hence, it can be represented that severe drought stress might inhibit the synthesis of TPC and TFC [38]. In addition, SA and Si-NPs increased TPC and TFC of coriander plants, and in this regard, Nadeem *et al*. [38] showed increased TFC under SA. The accumulation of TPC and TFC under SA application in our experiment is related to high expression of genes and enzymes involved in biosynthesis of theses secondary metabolites. Si-NPs due to their role in improving the production of secondary metabolisms such as TPC and TFC can protect the stressful plants from the ROS. Similarly, a positive role of Si-NPs on polyphenols has been observed on coriander plants grown in lead (Pb)-spiked soil [11].

Antioxidant Enzymes

The SOD and POX activities were significantly ($P \leq 0.05$) affected by drought, SA and Si-NPs. Drought increased the activity of SOD and POX so that the maximum activity was obtained upon severe drought stress. In addition, SA and Si-NPS significantly improved the activity of antioxidant enzymes. The interaction of SA and drought stress was significant on SOD activity, where its highest amount was obtained under severe drought stress and foliar applied SA (Fig. 4a). Under Si-NPs, a 2.5-fold enhancement of POX activity was observed in plants exposed to severe drought stress compared with control (Fig. 4b).

In the interaction of SA and Si-NPs, the stimulations application of SA and Si-NPs increased POX activity by 22% in comparison to control (Fig. 4c).

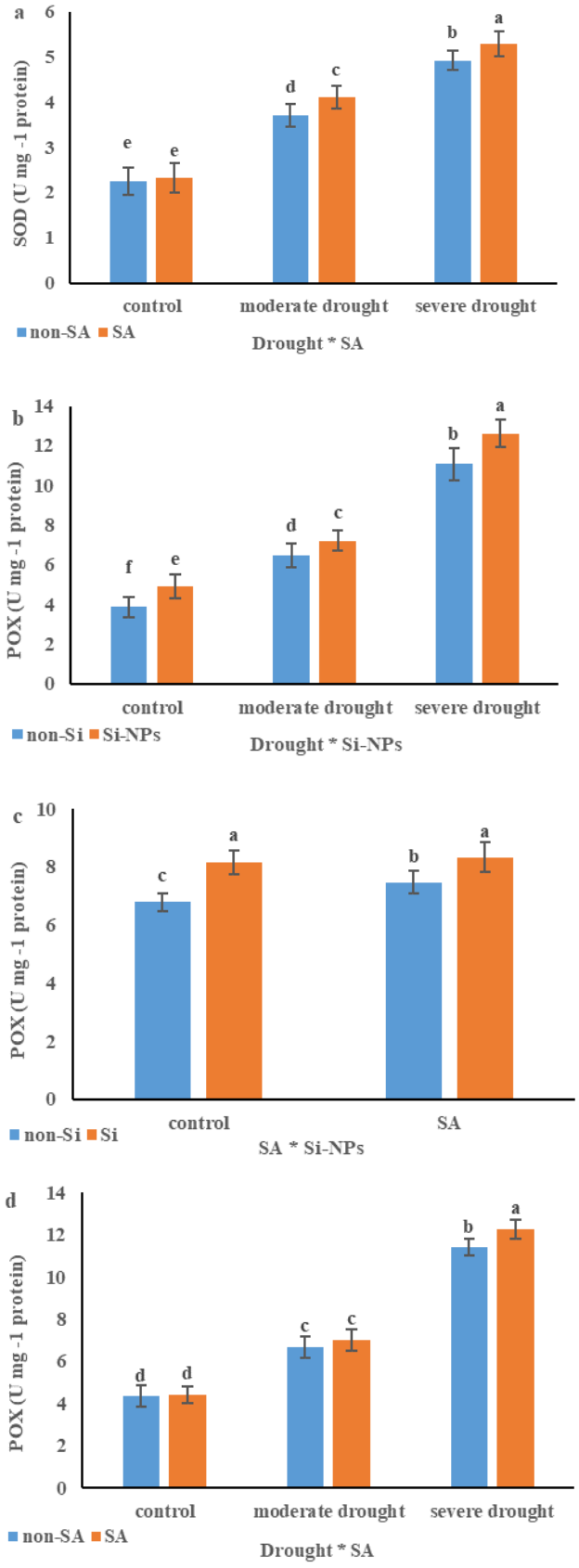

Fig. 4 Superoxide dismutase (SOD) and peroxidase (POX) activities of coriander plants treated with salicylic acid, silicon nanoparticles under drought stress. Values are means ± standard deviation (SD) of three replications. Different letters show statistically significant differences among treatments at $P \leq 0.05$.

In addition, the interaction of SA and drought significantly changed POX activity. The maximum POX activity was reported in plants under severe drought stress and foliar application of SA to be 12.2 U/mg protein (Fig. 4d).

Under drought stress, plants promote the expression of genes involved in SOD and POX to cope with the stress. The increased SOD and POX with SA application have been reported by Yüzbaşıoğlu and Dalyan [40] and Haydari *et al*. [41]. SA protects cells from various types of injury in cells by enhancing the expression of antioxidant enzymes involved in the defense system [39].

Essential Oil (EO) Content and EO Yield

The EO content increased with moderate drought but decreased with severe drought stress. The SA and Si-NPs increased EO content and yield; in this regard, moderate drought stress increased EO content by 47% under Si-NPs (Fig. 5a). Compared with control, SA separately increased EO content by 21%, while this enhancement was 29% with the interaction of SA and Si-NPs (Fig. 5b). Like EO percentage, EO yield reached the maximum amount in the interaction of moderate drought and Si-NPs to be 28.5 kg/ha (Fig. 5c). Moreover, plants sprayed with the interaction of SA and Si-NPs revealed the higher EO yield (23.1 kg/ha) reactive to when they were only treated by SA (18.8 kg/ha) (Fig. 5d). The moderate drought stress resulted in optimum EO percentage and yield of coriander leaves. However, severe drought stress had a negative impact on EO yield. Since EO yield is calculated by dry matter and EO percentage, the reduction of shoot biomass and EO percentage results in reduced EO yield [42]. The foliar applied SA was effective in improving EO content and yield when plants suffer drought stress [43]. The exogenous application of SA has been documented to increase EO in peppermint [44] and fennel [6] under drought actress. Moreover, exogenous application of SA may have a stimulatory effect on the expression of the key regulatory enzyme (limonene synthase) of the EO biosynthetic pathway which possibly increases the concentration and yield of EOs in coriander plants. The slight drought stress was effective to reach the optimum EO percentage and yield of aerial parts of coriander.

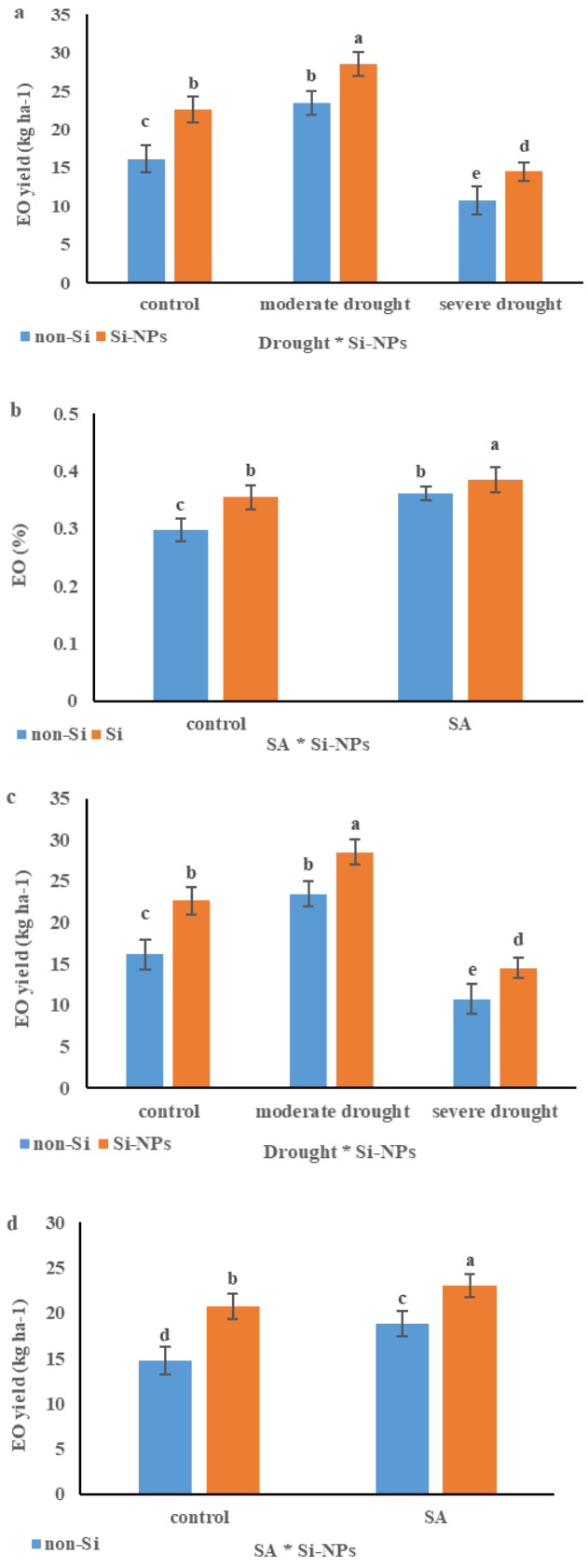

Fig. 5 Essential oil (EO) content and EO yield of coriander plants treated with salicylic acid, silicon nanoparticles under drought stress. Values are means ± standard deviation (SD) of three replications. Different letters show statistically significant differences among treatments at $P \leq 0.05$.

However, the adverse impact of severe drought stress on EO yield of coriander was addressed. Since EO yield is calculated by dry matter and EO percentage, the reduction of shoot biomass and EO percentage results in reduced EO yield [42]. SA and Si-NPs subsided the undesirable effects of severe drought stress and promoted EO yield. The enhanced EO amount under slight drought stress may be attributed to the decline in leaf surface and enhancement of oil gland number and density [45]. The abiotic stresses may affect EO production through changing the pathways of secondary metabolites production and their distribution [46]. This study demonstrated the improvement of EO yield by Si-NPs application. Si plays an important role in elicitor-accelerated secondary metabolite production by inducing several transcriptional modifications [46]. Si-NPs can enhance EO yield via improved cell development, ion uptake, and leaf oil gland density and size [47]. Si-NPs increased EO production, and probably could serve as an effective stimulant to increase the production of secondary metabolites [48].

CONCLUSION

Water stress is the main environmental concern with the challenge of finding beneficial methods for mitigating this stress. In the present study, we used SA and Si-NPs to alleviate the deleterious effect of drought on physio-chemical attributes and essential oil quality and quantity of coriander plants. Moderate drought stress with Si-NPs was the best treatment to reach the highest main secondary metabolites in coriander plants (i.e., TPC:42.8 mg GA/g DW, TFC: 19.9 mg QE/g DW, and EO content:0.46%). Severe drought stress was the destructive treatment on Chl content and EO yield of coriander. Therefore, optimum EOs in coriander plants can be obtained by changing the soil moisture as well as foliar application of SA and Si-NPs.

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