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RESEARCH ARTICLE

Foliar application of silicon nanoparticles affected the growth, vitamin C, flavonoid, and antioxidant enzyme activities of coriander (*Coriandrum sativum* L.) plants grown in lead (Pb)-spiked soil

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Abstract
Lead (Pb) is among the most abundant toxic trace elements which causes direct and indirect negative effects on humans, animals, and plants. Thus, there is a need to alleviate the Pb toxicity in plants for good quality food production especially from marginal soils. In this study, the effects of silicon nanoparticles (Si NPs) were investigated on coriander (*Coriandrum sativum* L.) biomass, vitamin C, flavonoid, antioxidant enzyme activities (i.e., catalase (CAT), peroxidase (POD), and super oxide dismutase (SOD)), malondialdehyde (MDA), and Pb concentration in plants subjected to different Pb concentrations. Treatments included four levels of Pb (0, 500, 1000, and 1500 mg/kg of soil), and two levels of Si NPs (0 and 1.5 mM) in all combinations. The Pb treatments alone decreased the plant biomass and vitamin C while increased the flavonoid, MDA, antioxidant enzyme activities, and Pb concentration in tissues depending upon the Pb treatments. The foliar-applied 1.5 mM Si NPs alleviated the adverse impacts of Pb on coriander plants which were due to the minimization of Pb concentration in plants and improvements in the plant defense system. Si NPs minimized accumulation of MDA in plant tissues and adjusted the activities of POD, CAT, and SOD in plants under Pb stress. Overall, Si NP foliar application might be a suitable approach in reducing the Pb concentrations in plants. However, field studies with various plant species and environmental conditions are required to highlight the role of Si NPs on the plant under toxic trace element stress.

Keywords Foliar application · Enzymatic antioxidant · Silicon · Heavy metals

Introduction

Lead (Pb) destructiveness in living organisms has been able to be a real concern, which is basically due to the use of Pb-contaminated soil everywhere throughout the world (Norton et al. 2014; Xie et al. 2017). Extreme Pb in soil has harmful impacts on soil microbial action and development of plants (Iqbal et al. 2015; Kushwaha et al. 2018). Pb impaired the plant growth of plants at morphological, physiological, and molecular levels (Kaur et al. 2015; Singh et al. 2016). Pb, a non-redox active element, may alter the redox homeostasis in plants via several indirect mechanisms such as replacement of essential elements from cellular biomolecules and variation in metal-related enzyme activities, which increased the production of reactive oxygen species (ROS) in plants (Chen et al. 2017; Shahid et al. 2014; Shu et al. 2012). Therefore, any disruption of redox homeostasis in plants may be the cause of oxidative burst in plants (Adrees et al. 2015a; Kaur et al. 2015). Thus, persistence of oxidative stress environment in plants may be due to physiological disorders in plants which ultimaltey the cause of cell death (Keunen et al. 2011; Adrees et al. 2015b). Pb may accumulate in soil mainly via anthropogenic activities such as use of sewage sludge, and waste water and subsequently enters to food crops mainly vegetables which is due to the cultivation of vegetables near highways and industrial regions. The higher Pb concentrations have been reported in the leafy vegetables than the other vegetables (Feleafel and Mirdad 2013; Rizwan et al. 2018).

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Nanoparticles (NPs) have been generally used to improve the human life in various fields (Karimi and Mohsenzadeh 2016; Rizwan et al. 2017a). The application of nanotechnology has been gaining greater attention in recent decades for remediation of contaminated agricultural soils and might be considered one of the important approaches aiming to use for the treatment of metal polluted soils (Ali et al. 2019; Hussain et al. 2019). Nanoparticles have unique characteristics such as high sorption capacity and large surface area which make these NPs different from their bulk materials. The NPs can pass through the plant cell walls and may enter into the plants or NPs may dissociate at the surface of plants and enter into the plants depending upon the conditions and NP types and sizes along with other factors (Rameshaiah et al. 2015; Rizwan et al. 2019). Various published studies demonstrated the potential efficiency of NPs in plants especially in cereals when they were simultaneously exposed to NPs and toxic trace elements (Hussain et al. 2018; Rizwan et al. 2016). Among the different NPs, the nanoparticles of silicon (Si NPs) can improve the photosynthesis and plant biomass under abiotic-stressed conditions (Hussain et al. 2019; Siddiqui et al. 2020). Although it was depicted Si can minimize the metal toxicity in plants, the easily bioavailable sources of Si are not explored at large scale (Adrees et al. 2015b). Thus, there is still a need to explore the bioavailable Si sources which can be easily used in agriculture (Keller et al. 2015; Rizwan et al. 2017b). Silicon can be used in NP form for agricultural purposes which can be considered a novel source of this element (Hussain et al. 2019). Due to wide attention in nanotechnology in recent years, Si NPs can increase biomass quantity and quality and decrease evaporation and transpiration in plants; also, it stimulates production of some antioxidant enzymes and reduces the susceptibility of crops to some fungal diseases, most projects respecting the use of Si NPs in soil conditions (Tripathi et al. 2015; Wang et al. 2015). Moreover, most of the studies have highlighted the effect of Si NPs on element uptake by rice (Cui et al. 2017; Wan et al. 2016), and wheat (Hussain et al. 2019), but less information is available in literature concerning the impacts of Si NPs on other important food crops such as coriander (*Coriandrum sativum* L.) plants. In addition, short-term studies were mainly conducted to highlight the impact of Si NPs in plants under stressful environments (Cui et al. 2017).

Coriander is one of the annual aromatic plants which belongs to *Apiaceae* family, known as herb and medicinal plants with special roles in human life. Coriander leaves are a good source of chemicals including vitamin C (160 mg per 100 g fresh weight), vitamin A (beta-carotene 12 mg per 100 g fresh weight), vitamin B12 (60 mg per 100 g), polyphenols, and essential oils (Prakash 1990). Coriander is used in the food industry, and as an essential oil in the pharmaceutical, cosmetic, and sanitary industries, and as fruit oil in the food and pharmaceutical industries (Sefidkon 1999). Considering that coriander is one of the most widely used vegetables and a demanded medicinal plant, its extensive cultivation in unfavorable conditions and the use of unconventional water for irrigation are unavoidable. Such situations have faced the plant to be exposed to the dangers of heavy elements, especially Pb. Since that, antioxidants are one of the important mechanisms of plant against toxic trace element stress; therefore, the present study was performed to explore the effects of Si NPs on enzymatic and non-enzymatic antioxidant and development of coriander under a soil condition with high Pb contents.

Materials and methods

Plant cultivation

In this experiment, air-dried soil (38° 25′ N, 48° 30′ E and 1500 m above the sea level) was spiked with a solution of either one of four amounts (0, 500, 1000, and 1500 mg/kg) of $PbCl_2$ and the soil was incubated under stable conditions (darkness, 40 °C, for 6 months in dry/wet cycle). The soil was sandy loam having pH of 7.3, 1.45% organic carbon, and EC of 2.0 dSm^{-1}. Then, 30 healthy and uniform seeds of selected coriander variety were planted and cultivated in each plastic box with 10 kg soil (40 cm × 25 cm × 20 cm). The seed was prepared from native cultivar from Nahavand, Iran, because the city is considered the biggest producers of coriander in the country. The pots were placed in a greenhouse and regularly irrigated, when necessary. The temperature in the greenhouse during the experiment was 25–32 °C. The Si NPs were of Sunny company, Iran, with the purity of 99%, particle size of 20–35 nm, and active level of 461 g/m^2. The weighed amount Si NPs was added in small quantity of deionized water and these NPs were dispersed with the help of ultra-sonication for about 30 min, and final volume was made for further use. During the cultivation period for 12 weeks, plants were foliar-applied with a solution containing either without or with 1.5 mM of Si NPs for three times (both side of leaves) at an interval of 2 weeks. After harvesting (4 months after seeds sowing), the plant samples were washed with the help of distilled water, and then, these samples were divided into two parts. One part of the samples was frozen by using liquid N_2 prior to biochemical and enzyme activity measurements while the subsample was dried at 80 °C in an oven for dry weight measurement. The samples were dried for about 48 h until constant dry weight was achieved. The samples were weighted and ground with a Retsch mixer mill and used for Pb measurements.

Vitamin C contents in shoots

For the measurement of vitamin C, coriander leaves were used according to the procedure of Omaye et al. (1979). For this purpose, 1 g of powdered samples was digested in 1 ml of trichloroacetic acid 10%, and for 20 min at 2100 rpm. Ten microliters were taken from the illuminating solution, and 1 ml of dihydrofenylhydrazine-copper sulfate-thiora 6-mM reagent was added and placed in a thermometer at 31 °C for 3 h. Then, 110 µl of 41% sulfuric acid were added to the samples and the absorption of samples and standard was taken at 120 nm wavelength by a 6705-genius spectrophotometer. Vitamin C content was calculated based on the standard curve of milligrams of ascorbic acid per 100 g of weight.

Flavonoid content

Flavonoid contents were measured by the method of Beketov et al. (2005). In brief, 0.2 ml of extract was mixed with 4.5 ml ethanol 90%, 0.2 ml of aluminum chloride (2%), and 0.1 ml acetic acid (33%), and then, the mixture was placed in dark for 30 min. After this, the absorbance was measured at 414 nm with a spectrophotometer (Model: 6850, Jenway, UK).

Activities of antioxidant enzymes and MDA level

Activity of glutathione peroxidase (POD) was assessed according to the protocol of Polle et al. (1994). In brief, 3 ml of the sample includes 100 mM buffer solution of potassium phosphate (pH = 7.0), 20 mM guaiacol, 10 mM H_2O_2, and 50 ml of an enzyme extract. The absorbance was recorded by guaiacol oxidation at 470 nm for 3 min. Finally, the POD activities were assessed according to coefficient of 2.8 mM^{-1} cm^{-1} and denoted as µMol/g FW min.

Measurement of SOD activity was performed in a 1.5-ml mixture comprised of 50 mM phosphate buffer (pH = 7.0), 0.1 mM EDTA, 13 mM methionine, nitrotetrazolium (NBT), riboflavin, and 10 µL sample. 560-nm wavelength was used for the measurement of absorbance by a spectrophotometer (Giannopolitis and Ries 1977).

The catalase (CAT) activity was assessed according to the procedure of Chance and Maehly (1955) with little modifications. The reaction mixture for CAT (3 ml) was comprised of enzyme extract (0.1 ml), phosphate buffer (50 mM at pH 7.0), and 15 Mm H_2O_2. The reaction was started by using enzyme extract. The variation in the absorbance of the reaction mixture was recorded at 240 nm after every 20 s. One unit of the CAT activity was comprised of the change in absorbance of 0.01 unit min^{-1}. This enzyme activity was measured by measuring the oxidation of ascorbate by a spectrophotometer at 290 nm for 1 min. The reaction solution contained a 25 mM phosphate buffer, 0.1 EDTA, 1.0 mM H_2O_2, 0.25 mM ascorbate peroxidase, and enzyme extract.

The determination of malondialdehyde (MDA) level was performed by the protocol of Heath and Packer (1968). In brief, 0.2 g of fresh samples were weighed and homogenated in water with 0.5 ml of 0.1% trichloroacetic acid (TCA), followed by centrifugation at 5,000 rpm for 5 min. The reaction mixture was consisted of 1 ml of supernatant, 4 ml of 20% trichloroacetic acid solution comprised of 0.5% thiobarbituric acid (TBA). The resultant solution was heated at 95 °C for 30 min. Then, it was immediately put in ice and centrifuged at 5,000 rpm for 10 min. The intensity of light absorption was noted at 523 nm by a spectrophotometer. The amount of enzyme activity was calculated in 1 min/ml of protein. An enzyme activity unit was a small amount of NBT from the enzyme, which caused 50% reduction in inhibition at 560 nm.

Concentration of Pb

To determine Pb concentrations in roots and shoots of coriander plants, samples were kept in 80 °C oven and then were ground with pestle and mortar. In this step, the sample was digested and heat. Pb was analyzed using an atomic absorption spectrophotometer (GTALLO, model Varian, Model Spectra AA 200, USA).

Statistical analysis

All data obtained were analyzed with a two-way ANOVA with a statistical program (SAS 9.4, SAS institute, USA). Means were separated by the Duncan test and p values less than 0.05 were considered statistically significant.

Results

According to our results, the effect of Pb and Si and interaction effect of Si NPs and Pb have significant effect on fresh and dry biomass, photosynthesis pigment, and antioxidant enzyme, proline, carbohydrate, MAD, and Pb concentration.

Effect of NPs on biomass

The results showed that Pb concentration and Si NP treatments had a significant effect on the biomass of coriander. Plants grown in contaminated soil, especially in high concentrations of Pb (1500 mg/kg), had dramatically lower biomass, almost 60% compared with the control plant. Si NPs have positive effect on biomass especially under Pb stress. Foliar application of Si NPs has beneficial effect on fresh biomass, and the highest value was 70% more than the control, and it obtained in the treatment of 0 mg/kg Pb in the soil combined with 1.5 mM Si foliar application (0.70 g) (Fig. 1). The lowest plant biomass was found in the plant treated by 1500 mg/kg Pb in the soil without any Si NPs application, and it was 56% lower than the control.

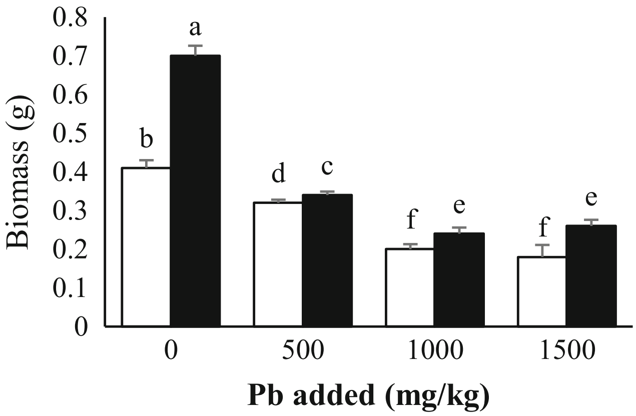


Fig. 1 Interaction of Si NPs and Pb biomass in coriander plants. Treatments included Pb (0, 500, 1000, and 1500 mg/kg) and Si-NPs (– Si (white) and + Si (black)) represent foliar application with 0 or 1.5 mM Si NPs. Bars are means of four plants per replicates. Bars with different letters differ significantly from each other at $p < 0.05$ as determined by LSD test

Flavonoid, vitamin C, and anthocyanin content

The data related to flavonoid contents were reported in Fig. 2. The results revealed that the Pb stress increased this trait compared with the control plants, almost 33% in plant treated 1500 mg/kg. The Si NPs increased the flavonoid content by 13, 10, 8, and 2% in 0, 500, 1000, and 1500 mg/kg treatment compared with these Pb treatments without NPs, respectively. Vitamin C in coriander plant was also affected by Pb concentrations, and it was observed by 15 % destruction in 1500 mg/kg compared with control plant. Although Si NPs increased this treated, but it was not significant in most of the treatments (Fig. 2b). The results regarding anthocyanin content in coriander were reported in Fig. 2c. The Pb caused a significant increase in anthocyanin until 500 mg/kg which was almost 93% compared with control, and after that, 1000 and 1500 mg/kg treatment showed a decreasing trend compared with 500 mg/kg. The Si NPs have not influenced on anthocyanin content in coriander plants under Pb stress.

Activities of antioxidant enzymes

In this study, antioxidant enzyme, POD, CAT, and SOD activities were also measured. The results indicated that Pb stress affected all enzyme activities either alone or under Si NPs application. POD activity significantly increased by Pb level until 1500 mg/kg (Fig. 3a). Si NPs statically diminished POD activity up to 9, 26, 5, and 47% under 0, 500, 1000, and 1500 mg/kg Pb stress conditions, respectively. Nevertheless, Pb and Si NPs interaction in 500 and 1000 mg/kg did not show a significant effect.

CAT activity increased until 500 mg/kg of Pb, while decreased in higher Pb concentration (Fig. 3b). Si NPs decreased the CAT activity under 0, 500, and 1000 mg/kg Pb by 24, 37, and 75%; however, Si NP exposure increased enzyme activity almost 124% at Pb concentration of 1500 mg/kg By increasing in Pb concentration, SOD activity increased significantly but not dramatically, particularly when Pb was present, and Si NPs applied enzyme activity almost was 237, 57, and 15% at 0, 500, and 1000 mg/kg Pb respectively.

Malondialdehyde content

Malondialdehyde content dramatically increased by Pb concentration, as it increased until 1000 mg/kg of Pb, but after that decreased. The interaction effect between Si NPs and Pb for this parameter was significant. Foliar application of Si NPs decreased the MDA content (Fig. 3c), but at the highest concentration of Pb, there is no significant effect between with or without Si application.

Pb concentration

Figure 4 shows that the Pb concentration was higher in root than shoot. Si NPs effectively decreased the Pb concentration in roots by 22, 11, and 10%, respectively compared with related control. Also, Pb concentration decreased in shoots by 2, 5, and 21%, respectively in 500, 1000, and 1500 mg/kg Pb.

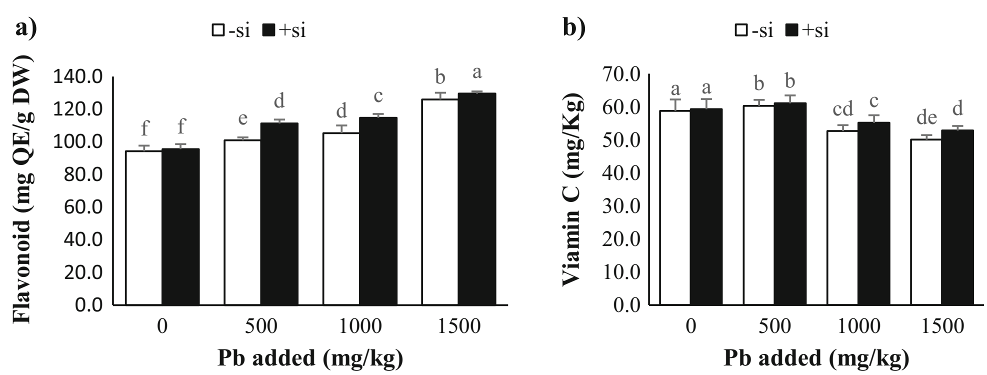
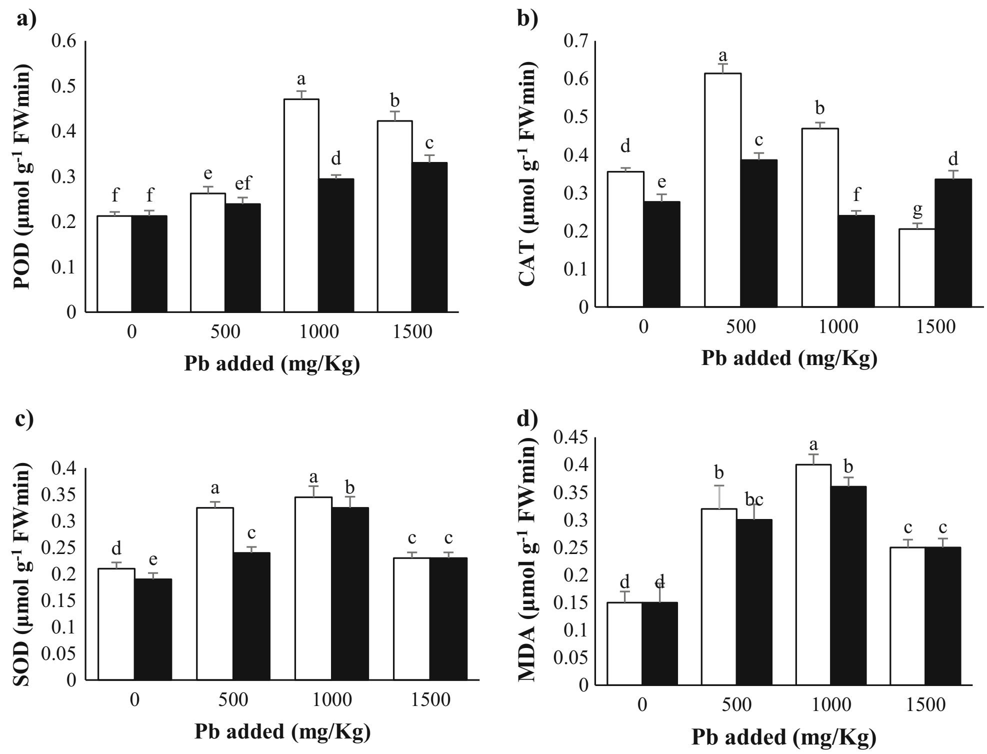


Fig. 2 Interaction of Si NPs and Pb biomass on **a** flavonoid, **b** vitamin C in coriander plants. Treatments included Pb (0, 500, 1000, and 1500 mg/kg) and Si-NPs (– Si (white) and + Si (black)) represent foliar application with 0 or 1.5 mM Si NPs. Bars are means of four plants per replicates. Bars with different letters differ significantly from each other at $p < 0.05$ as determined by LSD test

Fig. 3 Interaction of Si NPs and Pb biomass on **a** POD, **b** CAT, **c** SOD, and **d** MDA in coriander plants. Treatments included Pb (0, 500, 1000, and 1500 mg/kg) and Si-NPs (– Si (white) and + Si (black)) represent foliar application with 0 or 1.5 mM Si NPs. Bars are means of four plants per replicates. Bars with different letters differ significantly from each other at $p < 0.05$ as determined by LSD test



Discussion

The Pb is one of the non-essential elements for crops but is accumulating in the soils due to human activities which is serious thread to agriculture (Parys et al. 2014; Silva et al. 2017; Rizwan et al. 2018). In general, Pb exists in various forms in the soil including free metal ions or complexes with organic and inorganic materials. Pb toxicity is related to many factors including concentration, species chemical form (Kroukamp et al. 2016). Our results indicated that Pb had adverse effects on plant biomass dramatically (Fig. 1). It is clear that both biomass and photosynthesis are related to each other while heavy metal stress decreased the photosynthesis and cell division (Dallas and Ho 2005; Keller et al. 2015) by altering the performance of Calvin cycle enzymes and the electron transport chain and also damaged the stomata cells (Souza et al. 2005) and thus greatly reduce the biomass. Additionally, declining in biomass due to Pb stress has been revealed in *Brassica napus* (Shakoor et al. 2014), and water hyacinths (Malar et al. 2016) and coriander (Fatemi et al. 2020a, b). In this study, Si NPs helped the plants to alleviate the negative effect of Pb (Fig. 1). A similar improvement in plant biomass was reported in many studies under the application of Si NPs and metal stress (Asgari et al. 2018; Tripathi et al. 2015; Hussain et al. 2019). Plant biomass seems to be affected positively by Si NPs which might be due to its placement in the leaf bundle which would affect the structure of chloroplasts and leaf yield at the unit level and thus increase the plant's ability to use light. Some researchers also noted this increase in biomass as the effect of Si on improving the

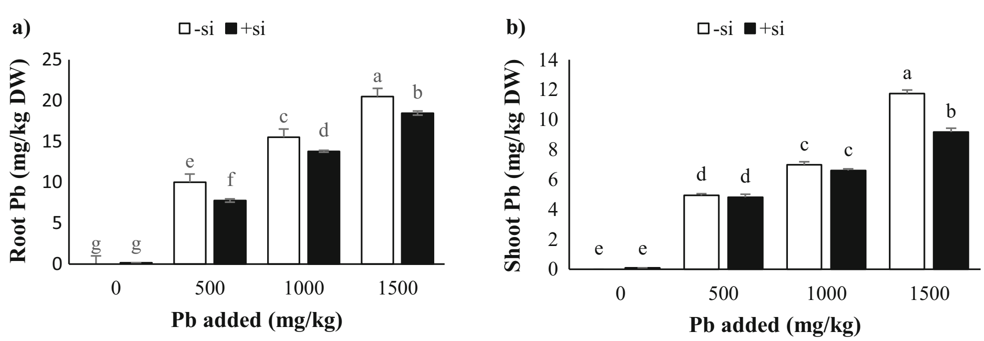


Fig. 4 Interaction of Si NPs and Pb biomass on **a** Pb concentration in root, **b** Pb concentration in shoot in coriander plants. Treatments included Pb (0, 500, 1000, and 1500 mg/kg) and Si-NPs (– Si (white) and + Si (black)) represent foliar application with 0 or 1.5 mM Si NPs. Bars are means of four plants per replicates. Bars with different letters differ significantly from each other at $p < 0.05$ as determined by LSD test

efficiency of photosystems II (Torabi et al. 2013; Adrees er al. 2015b). Some studies demonstrated the recovering of plant biomass by using Si NPs under stressed conditions (Asgari et al. 2018; Wang et al. 2015; Rizwan et al. 2019). Si NPs may enhance the growth of metal-stressed plants by improving the nutritional status, photosynthesis, and morphology and physiology of crops (Hussain et al. 2019; Keller et al. 2015).

The MDA content increased in the studied Pb-stressed plants, which is sign of peroxidation of lipids via Pb toxicity for coriander plants, and our results further suggest that Si NPs alleviated the oxidative stress (Fig. 3). Si NPs have beneficial effect in plants via improving enzymatic and non-enzymatic antioxidant and decreasing MDA. Similar results have been shown in cucumber plant under Mn stress (Mishra et al. 2006), cotton plant under Pb stress (Bharwana et al. 2013) and also spinach, barley, and tomato (Zhang and Selim 2008). Reddy et al. (2005) conducted that one of the important damaging of Pb is the ROS production in plants. ROS destroys plasma membrane via different mechanisms such as composition alteration of lipids in membrane, combination with thiols in membrane, and destruction of transporter in membrane. Previous studies indicated that Pb stress increased the oxidative stress in numerous plant species under various experimental conditions (Hattab et al. 2016; Rizwan et al. 2018). The results demonstrated that Si NPs enhanced the antioxidant system which may protect the plants under Pb stress. Similarly, Si supply minimized the H_2O_2 and MDA contents in different plant species (spinach, rice, and wheat) under various metal toxicities (Chalmardi et al. 2014; Gunes et al. 2007; Song et al. 2011; Tripathi et al. 2013).

Antioxidants are one of the important and critical mechanisms in plants under abiotic stress; there are two kinds of important antioxidants such as enzymatic and non-enzymatic (Gill et al. 2015; Suzuki et al. 2012). Changing of the antioxidants during Pb-stressed condition along with Si NPs has been rarely reported especially in leafy plants like coriander. According to our result, vitamin C was greatly affected by Pb stress in coriander plants (Fig. 2) and Pb stress decreased vitamin C in plants dramatically (Leiva-Brondo et al. 2012; Rizwan et al. 2018). Vitamin C mainly functions in plants as an antioxidant and cofactor in many redox reactions. In addition, vitamin C can control cell differentiation along with other functions (Fenech et al. 2019). The vitamin C is strongly altered by stressful conditions. For human health, vitamin C is involved in many biochemical processes, and thus, the absorption of this vitamin is required for better growth (Wohlrab et al. 2017), but for this case probably, Pb deactivate enzyme involved in vitamin C production. Our findings have shown that flavonoids, one of the important phenolic compounds, increased by increasing the Pb levels (Fig. 2). Phenolic compound is important antioxidant under stressful condition that this compound is produced by shikimic acid or phenyl propanoid pathways (Ren and Sun 2014). Phenolic compounds may act as antioxidants as the hydroxyl groups can donate hydrogen and can react with ROS in the termination reaction, which ultimately breaks the cycle of producing new radicals. The exogenous exposure of Si NPs further improved the production of flavonoid in Pb-stressed coriander plants which may enhance the tolerance against metal stress.

According to our results, antioxidant enzyme activities varied under Pb stress or Pb + Si NPs (Fig. 3). The alteration in enzyme activities due to the Pb stress is the typical response of the plants under stressed conditions (Rizwan et al. 2018). It plays a crucial role in preventing damage to the protein and membrane of the cell during the early stages of stress. By persistence of the stress and increase of the peroxide accumulation, cells would be damaged, and death may occur (Ibrahim and Bafeel 2011). Some studies highlighted that the high activities of enzymes are required for tolerance of plants to heavy metal exposure such as Pb (Li et al. 2012; Semane et al. 2007). Wang et al. (2010) stated that reducing germination of the seeds and decreasing seedling growth in Pb-contaminated soils was due to increased cell peroxidation and increased activity of enzymes such as SOD and POD, to reduce the harmful effects of hydrogen peroxide. Si NP foliar application decreased POD and SOD activities under all Pb treatments, and also, CAT activity decreased. This might be due to the removal of ROS in a non-enzymatic way by enhancing the activities of non-enzymatic antioxidants (Adrees et al. 2015a) or due to the enhancement of other antioxidant enzyme activities (Liu et al. 2013). Increasing antioxidant enzyme activities was also confirmed in other studies for many plants like the following: cotton, soybean, and ramie (Farooq et al. 2013; Miao et al. 2010; Tang et al. 2015). Plants suffer from oxidative stress when they are grown under stressful environmental conditions (Adrees et al. 2015b; Ali et al. 2015; Habibi 2015; Noman et al. 2015). It is indicated that Si supply may overcome the oxidative stress in plants by improving antioxidants that scavenge ROS in plants. This Si NP-mediated reduced ROS may reduce the injuries to cell membranes (Alzahrani et al. 2018)

Similarly, in our result, the growth of coriander was decreased under Pb toxicity, and this reduction was concentration-dependent. Pb is mainly entered the path of apoplastic or calcium ion channel to the root. Higher accumulation of Pb in root compared than shoot is also confirmed by other studies (Hou et al. 2014; Malar et al. 2016). Indeed, it is a defense mechanism by plant that accumulate Pb in root (Soares et al. 2016; Rizwan et al. 2018) and it depends on genotypic and environmental variations (Lal 2010). The accumulation of Pb in seedlings depends on its concentration in the culture medium. Also, the Pb accumulated in root part was more than leaves in coriender plants (Fig. 4); this is in agreement with other studies (Malar et al. 2016; Rizwan et al. 2018). Our results showed a decreasing in Pb absorption by plants with 1.5 mM Si NP foliar application in both root and leaf. The studies conducted that the Si coprecipitation with heavy metals in apoplast may decline the absorption of these metals, and then, adverse effects would be ameliorated (Iwasaki et al. 2002; Keller et al. 2015; Shi et al. 2018). Declining metal accumulation by plants via Si NPs was also confirmed by other studies (Ali et al. 2019; Fatemi et al. 2020a). This reduction in Pb uptake by coriander under Si NPs might be due to several mechanisms. For example, Si can trigger root exudates those can chelate with metals and decrease their uptake by plants (Kidd et al. 2001; Adrees et al. 2015b). Furthermore, Si may decrease free metals ions in plants (Iwasaki et al. 2002; Rogalla and Römheld 2002), and Si may reduce cell wall porosity (da Cunha and do Nascimento 2009). Overall, Si NP foliar spray might be helpful to reduce the adverse effects of Pb in coriander and probably in other plants.

Conclusions

Our results indicated that Si NPs have beneficial effect on plants especially under Pb stress. The obtained results suggested that the effect of Pb stress on the biomass and enzymatic parameters of the plant was varied with the levels of Pb applied. The alteration in activities of POD and CAT enzymes of leaves showed the effects of Pb toxicity and the production of free oxygen radicals. Si NPs minimized these toxic effects of Pb in plants by altering the physiological and metabolic processes of coriander plants. It seems enzymatic antioxidant affected more than non-enzymatic by Pb stress and Si NP applicant. It can be concluded that spraying with Si NPs could be used as a ration to reduce the harmful effects of Pb stress on coriander plants. Si NPs can adjust antioxidant enzyme activities and minimize the oxidative stress in plants. The most important mechanism of Si NPs is the reduction of the Pb concentration in plants and its transfer from roots to aerial parts of the plants.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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