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Research article

Silicon nanoparticles enhanced the growth and reduced the cadmium accumulation in grains of wheat (*Triticum aestivum* L.)

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ABSTRACT

The application of silicon (Si) under heavy metal stress is well known, but the use of Si nanoparticles (NPs) under metal stress in not well documented. Thus, the experiments were performed to investigate the impacts of soil and foliar applied Si NPs on wheat (*Triticum aestivum* L.) growth and cadmium (Cd) accumulation in grains under Cd toxicity. The plants were grown under natural environmental conditions and were harvested after physiological maturity (124 days after sowing). The results demonstrated that Si NPs significantly improved, relative to the control, the dry biomass of shoots, roots, spikes and grains by 24–69%, 14–59%, 34–87%, and 31–96% in foliar spray and by 10–51%, 11–49%, 25–69%, and 27–74% in soil applied Si NPs, respectively. The Si NPs enhanced the leaf gas exchange attributes and chlorophyll *a and b* concentrations, whereas diminished the oxidative stress in leaves which was indicated by the reduced electrolyte leakage and enhancement in superoxide dismutase and peroxidase activities in leaf under Si NPs treatments over the control. When compared with the control, the foliar spray of Si NPs reduced the Cd contents in shoots, roots, and grains by 16–58%, 19–64%, and 20–82%, respectively, whereas soil applied Si NPs reduced the Cd concentrations in shoots, roots, and grains by 11–53%, 10–59%, and 22–83%, respectively. In comparison with the control, Si concentrations significantly ($p \le 0.05$) increased in the shoots and roots in both foliar and soil supplementation of Si NPs. Our results suggested that Si NPs could improve the yield of wheat and more importantly, reduce the Cd concentrations in the grains. Thus, the use of Si NPs might be a feasible approach in controlling Cd entry into the human body *via* crops.

1. Introduction

Cadmium (Cd) is a toxic trace element which is accumulating in the agricultural soils mainly due to anthropogenic sources such as sewage sludge, industrial effluents, mining and the application of phosphorus (P) fertilizers (Rizwan et al., 2016a; Abbas et al., 2017; Tabelin et al., 2018). Due to higher solubility and mobility of Cd, The Cd is non-essential element for crops as well as all living organisms (Adrees et al., 2015; Yu et al., 2017). Cadmium induces the oxidative stress in many plant species by reactive oxygen species (ROS) production and inhibiting the activities of antioxidant enzymes which is the cause of lower biomass of plants (Alyemeni et al., 2018; Guo et al., 2018; Loix et al., 2018; Rizwan et al., 2018). Cadmium can be transferred from soil to plants and thus inhibit the photosynthesis and deteriorate the food quality (Rehman et al., 2017; Hussain et al., 2018). In this way, Cd enters into the food chain and thus shows a big threat to human health (Alkharashi et al., 2018; Ali et al., 2019). Therefore, there is an urgent need to eliminate the uptake of Cd in the edible portions of the food crops.

Considerable efforts have been done to check the Cd accumulation in food plants (Hussain et al., 2018; Rizwan et al., 2018; Rehman et al., 2018), and exogenous supplementation of silicon (Si) is one of the feasible techniques in this regard. Silicon is among the abundant elements present in the earth's crust, and it exists in various forms such as

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potassium silicate, calcium silicate, rock dust, and fine silica particles in Si-accumulator crops (Keller et al., 2015; Rao et al., 2018). Various reports have shown that Si can diminish the Cd in crops (Rizwan et al., 2016b; Chen et al., 2018; Pereira et al., 2018). In stressed conditions, Si is considered one of the beneficial elements for plants (Haddad et al., 2018). It has been depicted that Si may diminish the Cd stress in crops (Greger et al., 2016). Moreover, it has been considered that Si application reduced the Cd uptake in crops, while increased the yield and quality (Alzahrani et al., 2018). Although Si has the ability to reduce the metal accumulation in plants, there is a lack of bioavailable sources of Si for the application in agricultural soils (Rizwan et al., 2012).

In the recent past, the nanotechnology has gained considerable attention due to its wider use in various environmental and agricultural challenges like the sustainable use of resources, resource and energy constraints, urbanization, accumulation and runoff of fertilizers and pesticides (Liu and Lal, 2015; Iavicoli et al., 2017; Rizwan et al., 2017). Nanotechnology is an emerging tool to improve the plant vigor and nutritional value under stressful environment. Nanotechnology has been receiving attraction for the betterment of the agricultural production (Jain et al., 2018; Saxena et al., 2018). The nanoparticles (NPs) may suppress the diseases, reduce nutrient losses, improve the crop yield, help in seed germination, seedling vigor and photosynthesis in plants (Khan et al., 2017; Rizwan et al., 2017). The NPs provide the innovative solutions to remediate and protect the soil and water, thus boosting the global food quality and production (Iavicoli et al., 2017). Hence, the supply of NPs might be a practical approach to reduce the stress of Cd and its entry into the food crops (Mohamed et al., 2017; Hussain et al., 2018). Among the various NPs, the Si NPs have the ability to enhance the photosynthesis and plant biomass under stressful environment (Siddiqui et al., 2014; Ashkavand et al., 2015; Hussain et al., 2019). It has been depicted that Si NPs has eliminated the chromium (Cr) stress in seedlings of *Pisum sativum* (Tripathi et al., 2015), and these NPs have a protective role for plants against various environmental stresses including the heavy metals stress (Tripathi et al., 2017; Yu et al., 2018; Rizwan et al., 2019). The most studies regarding the application of Si NPs have been conducted on soil spiked with metals (Tripathi et al., 2015; Wang et al., 2015; Cui et al., 2017), but less is known regarding their impact on metal uptake by the plant in aged contaminated soils. Furthermore, most of the studies have shown the efficiency of Si NPs on metal uptake by rice (Wang et al., 2015, 2016; Cui et al., 2017; Chen et al., 2018), but less is known regarding the impacts of Si NPs on other food crops such as wheat. In addition, the short-term studies have been performed to explore the role of Si NPs on metal uptake by crops (Cui et al., 2017; Mousavi et al., 2018).

Wheat is an important staple crop which is being produced about 650 million tons annually in all over the world (FAO, 2012). Various reports have shown the Cd stress in the wheat plants (Rizwan et al., 2016b; Hussain et al., 2018; Shi et al., 2018). To fulfill the food demands of ever-increasing world population, wheat is being cultivated on contaminated soils without showing Cd toxicity in plants (Rehman et al., 2015). Therefore, minimization of Cd in the edible portions of the crops including wheat, is a major concern particularly when these food crops are cultivated in Cd-contaminated soils. In the current study, effect of foliar and in soil amendment of Si NPs was observed on growth and yield, chlorophyll contents and Cd accumulation in wheat cultivated on soil contaminated with Cd.

2. Materials and methods

2.1. Materials

The soil was collected from an arable field which is located in Multan, Pakistan. The selected field was irrigated mainly by using raw effluent to grow the crops since last 30 years which resulted the accumulation of non-essential metals in the soil mainly Cd. A random method of soil sampling was used to collect the soil from the field by

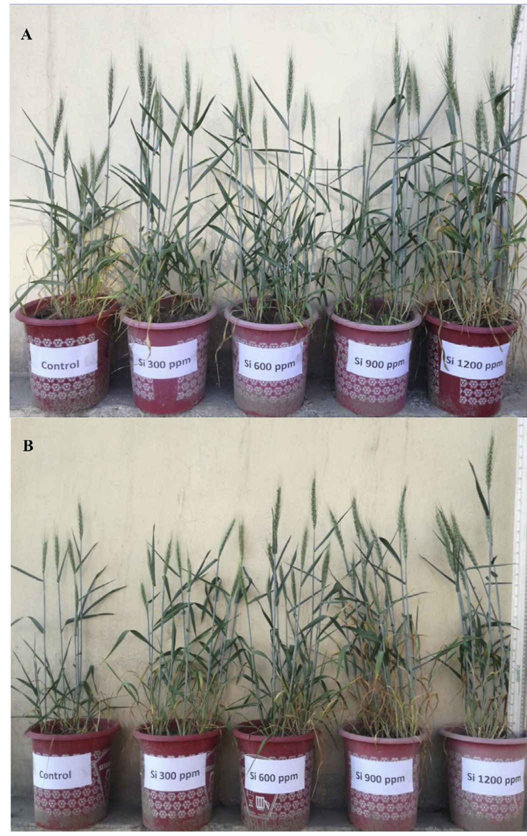

Fig. 1. Pictorial view of wheat plants after 80 days of growth in the pots. (a), and (b) represent the foliar and soil application of increasing concentrations of SiO_2 NPs, respectively.

using sharp stainless-steel blade at a depth of 0–20 cm. After collecting the soil, the samples were pooled, mixed thoroughly, and any roots or other parts of plants were removed. Thereafter, soil was dried without contacting direct sunlight and sieved by using 2.0 mm sieve. Soil was characterized for numerous properties by using established procedures such as soil texture was determined by using hydrometer meter (Bouyoucos, 1962), EC and pH was recorded by using EC and pH meters after taking soil to water ratio of 1:2.5 and horizontal shaking for two hours. Soil bioavailable metals were estimated after extracting the soil with AB-DTPA solution (Soltanpour, 1985). Total metals in the initial soil were estimated by using the procedure of Amacher (1996). In brief, 1.0 g soil was taken in 10 mL of concentrated HNO_3 and the mixture was heated after about 24 h at 200 °C, cooled, then 1.0 mL of HNO_3 and 4 mL of $HClO_4$ were added. Thereafter, heating was given to the solution until fumes appeared and then HCl was added and the solution was heated again at 70 °C for 1 h and specified volume was made by using 1% HCl and then filtered the sample for further analysis. Soil organic matter and $CaCO_3$ contents were determined by using calcimeter (Moodie et al., 1959) and the method described by Walkley and Black (1934), respectively. Soluble ions, sodium adsorption ratio and EC were determined by using methods finalized by US Salinity Lab. Staff (1954) or page et al. (1982). The detailed description of the soil properties has been given in Hussain et al. (2018). Briefly, soil was sandy loam with the proportions of the sand, silt and clay of 78%, 12%, 10%, respectively. Furthermore, the EC, pH, organic matter, $CaCO_3$ and CEC of the soil were 2.11 dS m^{-1}, 7.85, 0.92%, 1.71%, 3.86 $cmol_c$ kg^{-1}, respectively. The total concentrations of Cd, Pb, and Zn were 7.38, 45.76, and 41.15 mg/kg, while AB-DTPA extractable Cd concentration was 0.93 mg/kg. The Si NPs were of Alfa Aesar with crystalline structure, purity of 98%, size of ≤50 nm and surface area of 70–100 m^2/g.

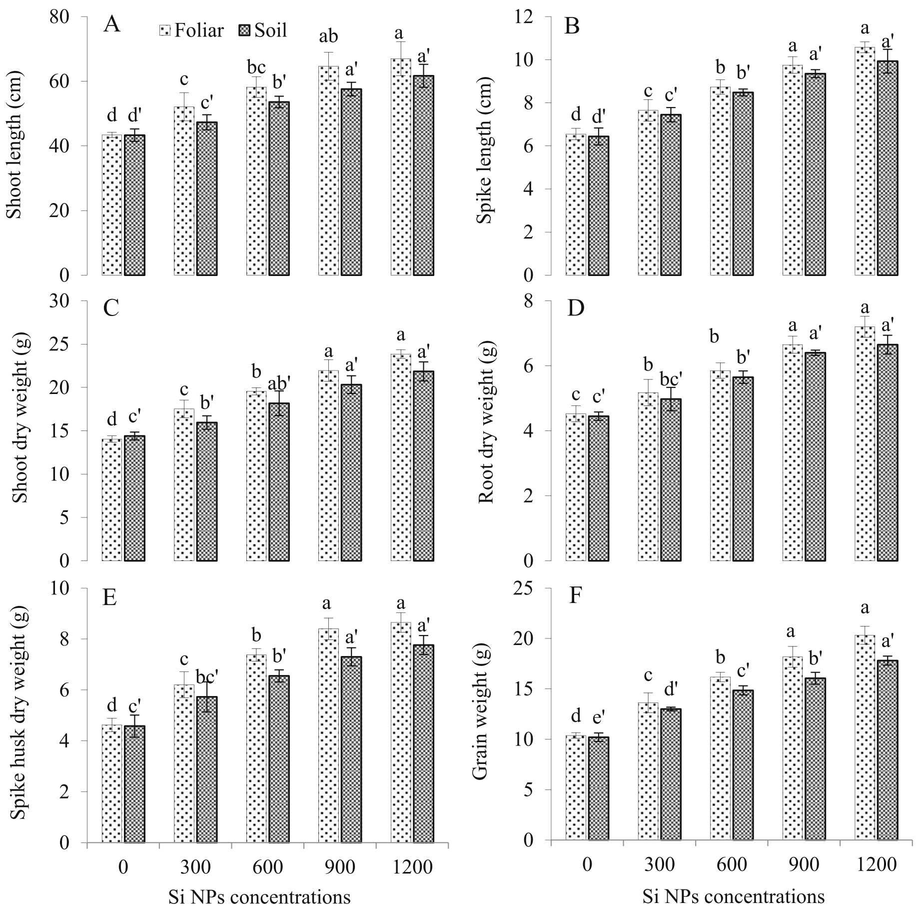

Fig. 2. The Si NPs effect on the shoot length (A), spikes length (B), shoot dry weight (C), roots dry weight (D), spike husk dry weight (E) and the grains dry weight (F) of wheat grown in soil contaminated with cadmium. The values reported are means of 4 replicates. Letters on bars showed the significant difference between given treatments at $P < 0.05$.

2.2. Experimental design

The wheat seeds were surface sterilized for 2 min by sodium hypochlorite and washed with distilled water. In total, 5.0 kg of the soil was used per pot. The pots were separated into two sets and half set of pots was amended with different Si NPs doses (0, 300, 600, 900 and 1200 mg/kg) by thoroughly mixing in the soil and the remaining half pots were used for the foliar application of the same Si NPs levels. Eight seeds of wheat (cv. Lasani-2008) were sown per pot and thinned to five plants per pot after fifteen days of sowing. The study was performed under natural environmental conditions containing four replicates in completely randomized design as described previously (Hussain et al., 2018). In order to homogenize and separate the particles, the NPs were ultra-sonicated for 30 min by using distilled water before application. The 1st foliar spray of NPs was done just after the thinning while the 2nd, 3rd, and 4th spray was applied on 4th, 6th and 8th week of sowing, respectively. At the times of foliar spray, the neighboring plants and the pots were covered in order to avoid the direct entry of NPs into the soil. At the same time, distilled water was sprayed on controlled plants. Total two litters of volume for each treatment was used during 4 foliar sprays. Pots were fertilized by NPK of 120, 50 and 25 kg ha^{-1} respectively, as urea for N, diammonium phosphate for P and the potassium sulfate for K. Approximately, 70% of soil moisture contents were maintained in each pot during entire experimental period.

2.3. Plant harvesting and data collection

After 124 days, at full maturity, the plants were harvested and roots, shoots, and grains were separated from each other. At the time of harvesting, the length of shoot and spike was recorded with stainless-steel meter scale. To remove metals from roots surface, the plants roots were washed by using 0.1 M HCl for two minutes and washed with distilled H_2O and all the plant tissues were dried at 70 °C for about 72 h. Thereafter, dry biomasses were noted and all samples were ground to small size and used for the measurement of Cd and Si.

2.4. Chlorophyll determination and gas exchange parameters

The concentrations of chlorophylls were determined with 85% acetone (v/v) at 4 °C, after 80 days of sowing in the pots. Thereafter, spectrophotometer was employed to measure the photosynthetic pigments at specific wavelengths and chlorophyll concentrations were measured by using coefficient given by Lichtenthaler (1987). During sunny days, after 80 days of sowing, stomata conductance, photosynthetic rate and the transpiration rate were recorded with the help of Infra-Red Gas Analyzer.

2.5. Determination of the activities of SOD, POD and electrolyte leakage

For the determination of above parameters in leaves of wheat, the sampling of leaves was done after 80 days of sowing. For EL, the EC_1 and EC_2 of the leaf samples were recorded by given procedure of Dionisio-Sese and Tobita (1998). In brief, small pieces of leaves were made and placed vertically into tubes with distilled water and heated the samples at 32 °C for a time period of two hours and EC_1 was noted and then the same samples were heated at 121 °C for twenty minutes and final EC_2 was noted. Finally, the value for EL was recorded by the use of following equation:

$$EL = (EC_1/EC_2) \times 100 \quad (1)$$

While leaf SOD and POD activities were measured by grinding the samples in the liquid N_2, then standardized by phosphate buffer (0.5 M) at 7.8 pH through procedure of Zhang (1992).

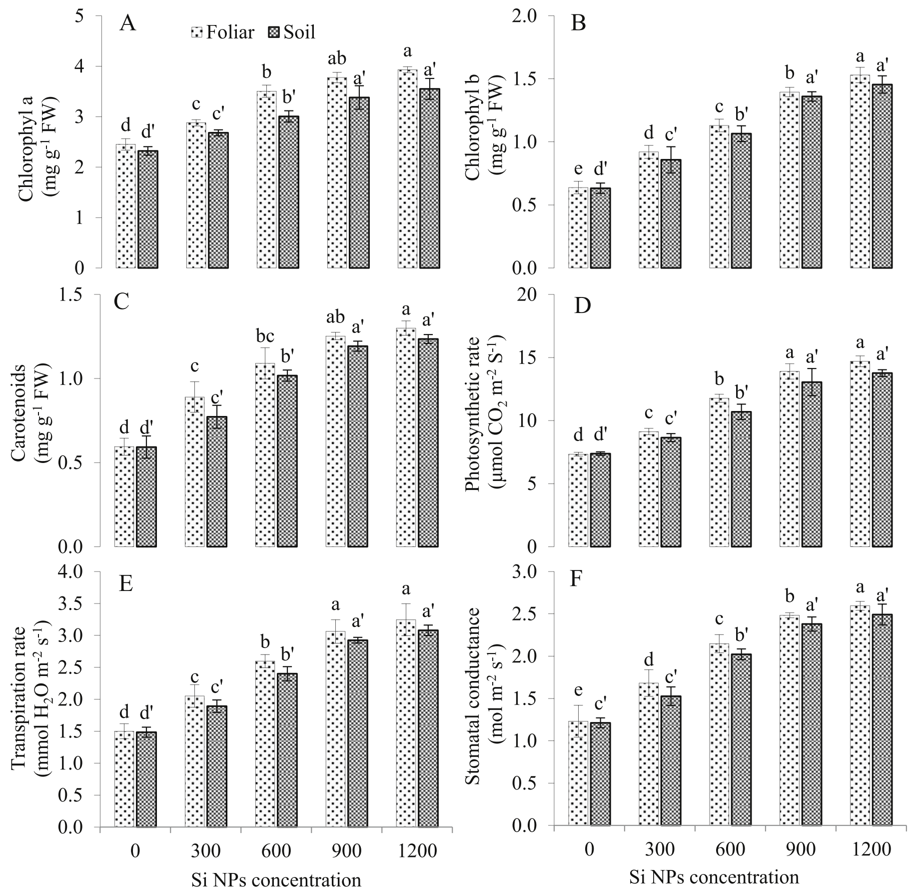

Fig. 3. The Si NPs effect upon the chlorophyll a (A), chlorophyll b (B), carotenoid (C), photosynthetic rate (D), transpiration rate (E) and stomata conductance (F) of wheat grown on soil contaminated with cadmium. The values reported are means of 4 replicates. Letters on bars showed the significant difference between given treatments at $P < 0.05$.

2.6. Cd and Si concentrations in plants and soil analysis

A hot plate was used to heat the plant samples for digestion by taking 0.5 g of each sample in 1:3 ratio of $HClO_4$-HNO_3 as described previously (Rehman et al., 2015). After digestion, the specied volume of each digested sample was made by using distilled water and atomic absorption spectrophotometer was used for the measurement of Cd. The shoot and root were extracted by using Tiron (4,5-dihydroxy-1,3-benzene-disulfonic acid disodium salt) for the determination of Si concentrations as given by Guntzer et al. (2010). The soil samples collected after the wheat harvesting were analyzed for pH and bioavailable Cd as reported in section 2.1.

2.7. Statistical analysis

For data analysis, one-way ANOVA was used with 5% probability level by the use of IBM SPSS Statistical software, version 21.0. By Tukey's HSD post hoc test, the multiple comparison for means was done.

3. Results

3.1. Plants biomass and photosynthesis

In order to see the Si NPs effect on the growth of Cd-stressed wheat, the plant growth related attributes were measured at different time periods during the experiment. The Fig. 1 depicted that the shoot length of wheat positively influenced with increasing NPs doses either in the soil or foliar spray. The findings for the shoot and spike lengths and roots, shoot, spike husks and grain dry weights are given in Fig. 2. The spike and shoot lengths significantly increased by foliar spray and soil doses of supplemented Si NPs. The plant growth attributes and dry weight linearly increased with the doses of supplemented Si NPs. The shoot length increased by 9, 24, 33 and 42% in soil application and increased by 20, 34, 49 and 54% in a foliar application of the 300, 600, 900 and 1200 mg/L Si NPs treatments, respectively, as compared with control. At a maximum rate of NPs, the spike length was enhanced by 54 and 61% in soil and foliar treatment, respectively, over the respective treatments without amendments. At the maximum foliar spray of Si NPs (1200 mg/L), the dry biomass of roots, shoots, spikes, and grains were enhanced by 59, 69, 87 and 96%, respectively, when compared with the control. At soil amendment of 900 mg/kg Si NPs, the shoot, roots, spike, and the grains dry weights were increased by 43, 26, 45 and 57%, respectively, as compared with respective control.

The carotenoid and the chlorophyll concentrations were increased with the application of Si NPs than that of control (Fig. 3). At the highest treatment of NPs, the highest concentrations of carotenoids and chlorophyll concentrations were observed in leaves while the lowest concentrations were observed in the control without amendments. At the maximum rate of NPs, the chlorophyll *a* content increased by 53 and 60%, while chlorophyll *b* contents enhanced by 130 and 140% than respective controls in the soil and foliar applied NPs respectively. Whereas, at a maximum rate of NPs, the photosynthetic rate increased by 86 and 100%, transpiration rate increased by 107 and 116% and stomatal conductance increased by 105 and 110% than respective control, in soil and foliar applied NPs, respectively.

3.2. Leaf EL, SOD and POD contents

To explore the impact of Si NPs on oxidative stress in leaves of wheat under Cd stress, EL, SOD, and POD activities were measured in leaf (Fig. 4). The highest value for EL was noticed in the control leaves, whereas the lowest value of EL was found in the leaves amended with the highest dose of NPs irrespective of the application method. The EL

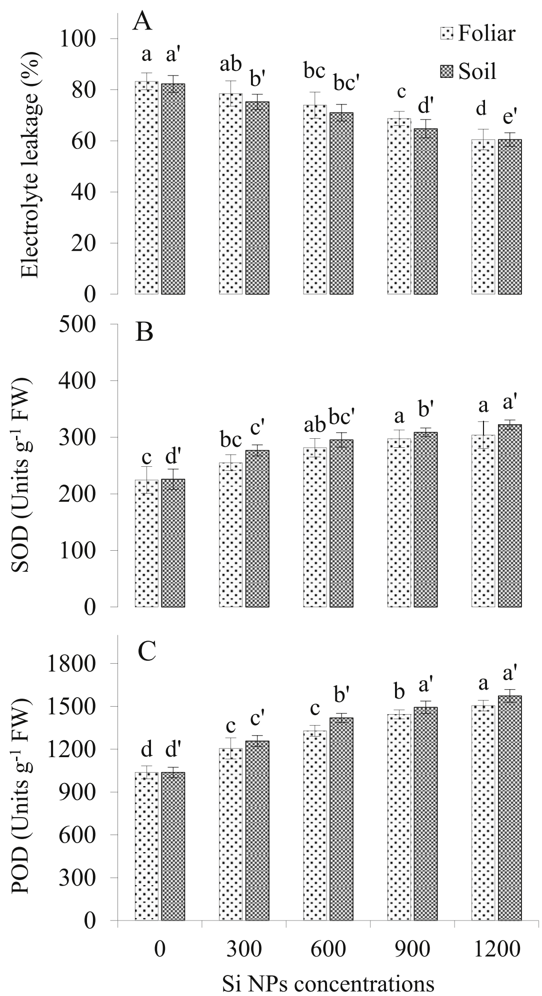

Fig. 4. The SiO_2 NPs effect upon the electrolyte leakage (A), superoxide dismutase (B) and the peroxidase (C) activities in wheat leaf grown on soil contaminated with cadmium. The values show four replicates means along with the standard deviation. The values reported are means of 4 replicates. Letters on bars showed the significant difference between given treatments at $P < 0.05$.

concentrations reduced by 27 and 26% in the foliar and soil application of 1200 mg/L of NPs, respectively, when compared with the control. The changes in antioxidant enzymes like SOD, and POD activity in leaves with Si NPs under Cd-stress has been demonstrated in Fig. 4. Both foliar and soil applications of Si NPs enhanced the leaf SOD, and POD activities when compared with the control. At the highest rate of NPs applied, the SOD activity enhanced by 35, and 42%, whereas POD activity improved by 45, and 51% in foliar and soil amendment of NPs, respectively, over the respective control treatments.

3.3. Cadmium and Si concentrations in wheat tissues

To observe the impact of Si NPs on the accumulation of Cd and Si by wheat, the accumulation of Cd and Si in different parts of wheat was investigated and the results are reported in the Fig. 5.

The Cd concentration decreased in the shoot, root, and grains of wheat with the increasing doses of Si NPs either foliar spray or soil application when compared with the control. When compared with the control, the Cd level in shoots diminished by 29, 45, 54, and 65% and in roots decreased by 19, 41, 52, and 64% and decreased in the grains by 20, 52, 75, and 82% with the foliar application of 300, 600, 900, and 1200 mg/L Si NPs, respectively. Furthermore, in comparison with the control, the Cd level in shoots diminished by 32, 46, 53, and 64% and in roots decreased by 10, 33, 47, and 59% and decreased by 22, 63, 80, and 83% in the grains with the foliar application of 300, 600, 900, and 1200 mg/kg Si NPs, respectively. The Cd shoot to root ratio decreased with the increase in Si NPs treatments (Fig. 5d). A significant decrease in Cd shoot to root ratio was observed in the lowest rate of NPs applied over the control.

Exogenous supplementation of Si NPs significantly enhanced the Si concentrations in tissues of wheat (shoots and roots) and the increasing trend was further enhanced with the increasing doses of Si NPs (Fig. 5e and f). The Si concentration in shoot increased by 54, 82, 118, and 144% and in roots increased by 53, 66, 95, and 128% when the plants were treated with 300, 600, 900, and 1200 mg/L foliar Si NPs, respectively. The Si concentration in shoot increased by 60, 89, 127, and 153% and in roots increased by 80, 102, 127, and 172% when the plants were treated with 300, 600, 900, and 1200 mg/kg soil Si NPs, respectively.

3.4. Soil pH and bioavailable Cd

The both soil and foliar amendment of Si NPs did not significantly affect the soil pH (Table 1). The soil pH was lower over the control with the application 300 and 600 mg/kg NP either soil or foliar supplementation, whereas the higher rate of NPs slightly enhanced the soil pH over the control. The increasing doses of NPs supplementation linearly decreased the AB-DTPA extractable concentration of Cd in the soil (Table 1). The AB-DTPA extractable Cd concentration was slightly lower in the soil applied NPs treatments than respective foliar application of NPs. There was a significant ($P < 0.05$) reduction in soil Cd in the highest rate of NPs applied in comparison with the control treatments irrespective of application methods.

4. Discussion

In the present study, the Si NPs significantly enhanced the biomass of Cd-stressed wheat (Figs. 1 and 2) confirming a potential of Si NPs in reducing metal stress in plants. This increase in plant biomass is may be ascribed to the beneficial effect of Si NPs under abiotic stresses (Tripathi et al., 2016; Wang et al., 2016). A similar improvement in plant biomass due to Si NPs was demonstrated in many studies (Wang et al., 2015; Merwad et al., 2018; Asgari et al., 2018). The Si NPs enhanced the plant biomass under stress, which may be the result of plant nutritional status under metal stress (Wang et al., 2015, 2016). The Si alleviated the Cd stress by increasing K^+ contents in wheat plants under Cd stress (Alzahrani et al., 2018), and this result is similar to Xu et al. (2015). The Si NPs improved the uptake of Mg, P, K and S contents in plants under stressful environment (Chen et al., 2018; Asgari et al., 2018). The Si has the efficiency to improve the minerals nutrition by alleviating the Cd toxicity in rice plants (Farooq et al., 2016). After the Si translocation from roots to shoots, the Si is accumulated in the leaf apoplast as polymer and acts as a barrier which provides protection to plants against various stresses (Silva et al., 2017). Silicon prevents the cell membrane deterioration and improves the plant growth and productivity by alleviating stress (Merwad et al., 2018). Protein synthesis is an important step for plant growth and Si application improved the protein concentration in fenugreek (Nazaralian et al., 2017). In our study, the improvement in wheat biomass under the simultaneous application of Cd and Si NPs might be attributed to the decrease in Cd concentrations in wheat tissues (Fig. 5), which resulted in the enhancement of plant photosynthesis (Fig. 3) and ultimately improved the growth and vigor of wheat (Figs. 1 and 2).

The measurement of photosynthetic pigments acts as an indicator of trace element stress in crops (Rizwan et al., 2016b; Hussain et al., 2018). The Si NPs increased the photosynthesis of Cd-stressed wheat (Fig. 3). The Si NPs induced improvement in the photosynthesis is also one of the possible reasons for higher biomass under Cd stress (Fig. 2). The increase in photosynthesis might be ascribed to the lower oxidative stress in plants and provision of nutrients (Wang et al., 2015; Tripathi

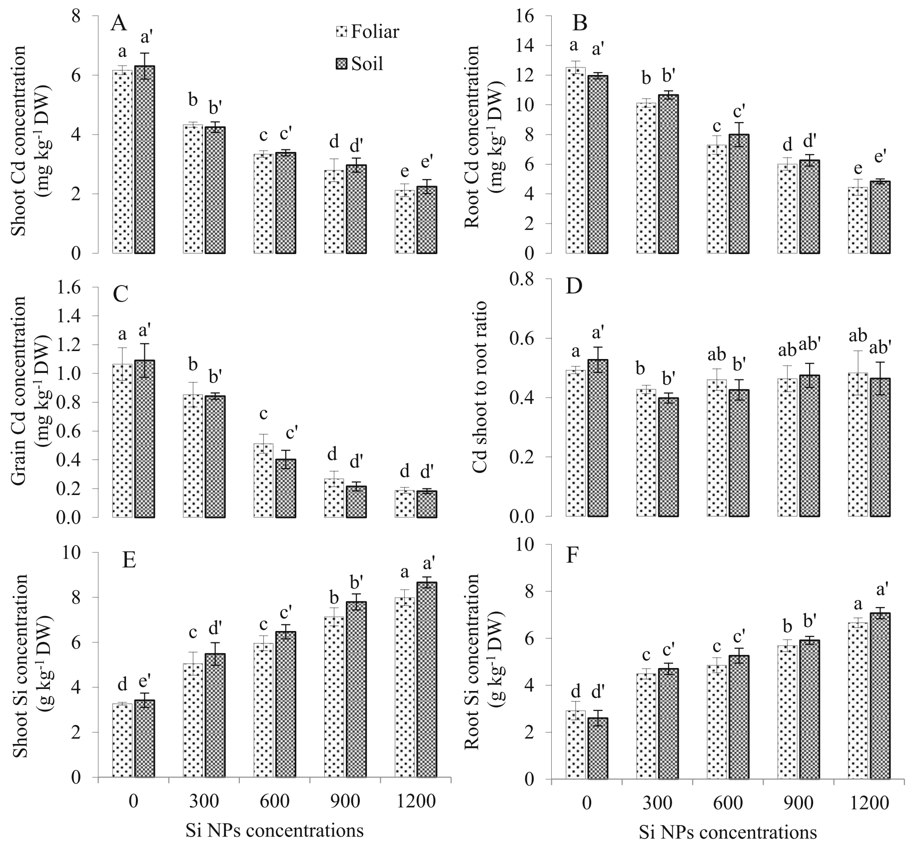

Fig. 5. The Si NPs effect on the shoot Cd concentration (A), root Cd concentration (B), grain Cd concentration (C), Cd shoot to root ratio (D), shoot Si concentrations (E), and root Si concentrations (F) of wheat grown in soil contaminated with Cd. The values reported are means of 4 replicates. Letters on bars showed the significant difference between given treatments at $P < 0.05$.

Table 1
Bioavailable Cd and post-harvest soil pH. The values show four replicates mean.

NPs Treatment	0	300	600	900	1200
AB-DTPA extractable Cd (mg kg^{-1})					
Foliar	0.87 ± 0.05^{a}	0.81 ± 0.04^{a}	0.80 ± 0.03 ^{ab}	0.79 ± 0.03 ^{ab}	0.74 ± 0.02 ^{b}
Soil	0.86 ± 0.03^{a}	0.80 ± 0.02^{a}	0.79 ± 0.01 ^{ab}	0.77 ± 0.02 ^{ab}	0.73 ± 0.03 ^{b}
pH					
Foliar	7.91 ± 0.04^{a}	7.84 ± 0.04^{a}	7.87 ± 0.05^{a}	7.95 ± 0.03^{a}	7.83 ± 0.04^{a}
Soil	7.97 ± 0.05^{a}	7.87 ± 0.06^{a}	7.86 ± 0.10^{a}	7.98 ± 0.13^{a}	7.98 ± 0.17^{a}

et al., 2016; Asgari et al., 2018; Hussain et al., 2019) as these are required for photosynthesis and Cd stress caused the oxidative stress and impairment in plant nutrients (Rizwan et al., 2016a; Shi et al., 2018). Silicon is actively involved in improving the light use efficiency of the crops (Adrees et al., 2015; Gao et al., 2018) which might be the reason of substantial improvement in chlorophyll contents in wheat.

Cadmium stress induced the oxidative injury by stimulating ROS generation in plants (Loix et al., 2018). Electrolyte leakage contents were reduced by the Si NPs application and the decreasing tendency was higher with the increasing level of NPs (Fig. 4a). Silicon decreased the EL contents by maintaining the cell membrane integrity under Cd toxicity (Coskun et al., 2016; Alzahrani et al., 2018). The Si NPs foliar application might have supported the membrane stability in Cd-stressed rice (Wang et al., 2015). In order to cope with oxidative and various other stresses, the plants have well developed self-defensive mechanism comprising of antioxidant enzymes along with other mechanisms (Terzi et al., 2018). The Si NPs significantly increased the SOD and POD activities in leaves as compared to the control (Fig. 4b and c). The higher production of antioxidants by the application of Si NPs has been reported in pea seedlings under Cr stress (Tripathi et al., 2015), maize hybrids under arsenic (As) stress (Tripathi et al., 2016) and in rice seedlings under Cd stress (Wang et al., 2015). However, the response of Si NPs on the activities of antioxidant enzymes is complex and varied with the type of the metal stress, plant species, growth stages, method of Si NPs application, and duration of the exposure (Tripathi et al., 2015, 2016; Wang et al., 2015). The lower antioxidant enzyme activities without Si NPs might be due to the increased stress in plants as was depicted by the increase in EL in the shoots (Fig. 4a). The higher production of antioxidant enzymes under Cd and Si NPs might be due to the improvement in the tolerance of the wheat plants to Cd stress.

The supplementation of Si NPs significantly reduced the Cd concentration and its translocation towards aerial parts and grains of wheat (Fig. 5). Numerous studies demonstrated that Si NPs reduced the toxic metal concentrations in a variety of crops under diverse growth conditions (Tripathi et al., 2015, 2016; Wang et al., 2015). Wang et al. (2016) highlighted that foliar application of Si NPs were more effective in decreasing Cd concentrations in grains of wheat than other metals. Rachises are plant organs which connects the stem with grains and Cd accumulated first in rachises and then translocate to grains (Liu et al., 2017). The foliar supply of nano-Si significantly affected the Cd contents in rachises at anthesis stage in rice plants (Chen et al., 2018). Soil application of Si may reduce the Cd accumulation by plants through reducing Cd bioavailable concentrations (Rizwan et al., 2012). However, this mechanism is not true for foliar application of Si NPs and in foliar spray the increase in plant biomass may dilute the metal concentration in plants which is named as so called 'dilution effect' (Adrees et al., 2015). The lower grain Cd concentrations by the Si NPs application might be due to the co-precipitation of metals with Si in metabolically less active parts of plants (Keller et al., 2015). The Si may increase the binding of Cd to the cell walls and enhanced the Cd compartmentation into the vacuoles (Adrees et al., 2015) which restrict metal translocation to grains.

The Si concentration in the shoot and roots was increased with Si NPs (Fig. 5e and f). These results are similar to the previous studies indicated that Si NPs application increased the Si concentrations in plants (Nazaralian et al., 2017; Hussain et al., 2019). The contents of Si in plant leaves and root increased with increasing Si NPs levels in the growing medium (Asgari et al., 2018). From the absorbed concentration of Si by plant roots, the higher Si is translocated to shoot and this translocation may be supported by xylem with water flow (Adrees et al., 2015; Rizwan et al., 2015). This showed that the increased concentration of Si in plants resulted in decreased uptake and translocation of Cd and more investigations are needed to find out new insights through which uptake and the translocation of Cd or other metals is affected by Si NPs in plants. It is highlighted that Si can improve the plant tolerance to Cd toxicity (Adrees et al., 2015). However, the availability of Si fertilizers for field applications is problematic due to the low solubility of Si sources in the soils (Rizwan et al., 2012). Our results indicated that foliar Si NPs equally improved the growth of wheat than that of soil amendments. But the quantity applied in the foliar spray was lower than the soil amendments. Recently, it has been reported that split application of Si was effective in reducing the Cd concentration in cereals (Rehman et al., 2019). Thus, foliar split application of Si NPs might have a promising role in the production of wheat or other crops. However, little is known about the quantity and application methods of Si NPs and the mechanisms of Si NPs in the resistance of plants to abiotic stress, which needs further detailed studies under diverse environmental conditions.

5. Conclusion

The findings of the current study depicted that Si NPs can inhibit the Cd concentrations in grains and other parts of wheat grown in Cd-contaminated agricultural soil. Both soil amendment and foliar supplementation of Si NPs inhibited the Cd translocation from roots to shoot. Nano-Si can effetely improve the growth of wheat as well as photosynthesis and reduced the oxidative stress in plants. High levels of Si NPs were more effective in inhibiting Cd concentrations in wheat grains than lower doses applied. Nano-Si diminished the bioavailable Cd in the soil after harvesting the plants. Therefore, Si NPs has the potential for reducing Cd concentration in plants and could be developed as a fertilizer for controlling metal accumulation in grain crops. However, further detailed studies are needed under various climatic conditions by using various crops before final decision regarding the use of Si NPs for crops mainly to reduce metal uptake by plants.

Authors' contributions

S.A, M.R, M.Z.R, and B.Y, conceived the idea and designed the experiment. A.H, and M.R performed the experiment. B.A, M.R, LW and S.A, analyzed the data. M.R, S.A. MNA, PA and A.H. wrote the manuscript. M.R, S.A. MNA, PA and A.H revised the manuscript. All authors read and approved the final draft.

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