

Mitigating cadmium (Cd) toxicity and enhancing growth, yield, and antioxidant defence of wheat (*Triticum aestivum* L.) through silicon fertilizers

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Abstract

Cadmium (Cd) stress in agricultural soils poses a significant threat to wheat production, food safety, and human health. Wheat productivity is severely hampered by Cd toxicity; however, to overcome this problem silicon (Si) fertilization has emerged as a promising strategy to mitigate heavy metal toxicity in plants; in this study, we compare the efficacy of natural and synthetic Si fertilization sources in modulating wheat growth, Cd accumulation, and antioxidant responses under Cd-contaminated soil. The Si was used as Ca silicate at 75 kg ha⁻¹ (synthetic Si source), and the rice husk at 150 kg ha⁻¹ (natural Si source) with and without humic acid (10 mg kg⁻¹ of soil) in comparison to control (Cd stress). Both Si sources were found to significantly boost the growth and yield attributes of wheat, while Cd stress significantly increased the electrolyte leakage that triggered oxidative stress. However, both Si sources decrease the oxidative stress and increase the superoxide dismutase and peroxidase activities. Si fertilization also inhibited the uptake of Cd from roots and its translocation to shoots and grains of wheat plant. In comparison, the synthetic Si fertilization was more effective than natural Si fertilization as it produced highest increase in plant height (21.40%), grain yield (25.21%), and reduced Cd concentration in root (42.60%) and shoot (59.71%) than control (Cd stress). Conclusively, Si fertilization (preferably Ca silicate at 75 kg ha⁻¹) alleviates the opposing impact of Cd on wheat growth by strengthening the antioxidant defense system, decreasing the Cd uptake and its translocation to humans.

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Keywords: antioxidant activities; Cd toxicity; food safety; heavy metals; Si fertilization

Introduction

Heavy metal pollution is increasing rapidly due to urbanization, industrialization, unreasonable use of pesticides, fertilizers, and untreated wastewater, which cause many environmental problems (Saxena, 2025). Metal toxicity is hard to eradicate since it is non-degradable, which persists in the soil for a longer period than other biosphere components (Mao *et al.*, 2019). Moreover, heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) can also accumulate in the atmosphere, posing serious threats to plants, animals, and humans (Aziz *et al.*, 2021). The increasing Cd stress has become a global challenge, as its concentration in several food crops has exceeded safe tolerance limits in recent decades (El Rasafi *et al.*, 2022). Naturally, Cd uptake by plants when grown in Cd-polluted soils, which resulted in retardation of plant growth, inhibition of photosynthesis, destruction of the antioxidative system, and unbalancing of the nutriment, and could lead to a harmful effect on the animal and human health, when it enters the food chain (Lux *et al.*, 2011; Hussain *et al.*, 2021). In the world, the average concentration of Cd in polluted soil is 20-800 mg kg⁻¹ whereas in normal soil it is 0.06 mg kg⁻¹ and this difference causes Cd to enter the food chain and can have adverse effects on human health (Rigby and Smith, 2020).

To overcome the harmful impacts of Cd toxicity, researchers have been using various strategies, however, the most sustainable, eco-friendly, and acceptable remedy is to provide plants with a substrate of quasi-essential elements (Xuebin *et al.*, 2020). Silicon (Si) may serve as a more effective means to reduce heavy metals accumulation in plants. As a valuable element, Si plays an indispensable role in the expansion and growth of numerous crops (Keeping, 2017). Elsokkary (2018) reported that Si is also important for many higher plants, moreover, Si shows effective role in mitigating both biotic and abiotic stresses (Zhao *et al.*, 2017; Dong *et al.*, 2019). As, Si has been reported as a non-corrosive element (Xuebin *et al.*, 2020) thus, Si, regarded as a high-quality fertilizer, can be used for eco-friendly enhancement of agriculture. Previous investigations indicated that exogenous application of Si significantly diminishes metal toxicity by restricting Cd uptake and transport in Chinese cabbage (Silva *et al.*, 2017), wheat (Rizwan *et al.*, 2016), and peanut (Silva *et al.*, 2017). Studies have demonstrated that in wheat, Si alleviates Cd toxicity and lowers its accumulation. Moreover, it was also found that application of calcium silicate markedly reduced the Cd concentration in rice grain and straw (Javed *et al.*, 2020).

Wheat (*Triticum aestivum* L.) is the most widely produced cereal crop, providing 20% of the daily protein requirements for 4.5 billion people worldwide (Flister and Galushko, 2016). It is the second most important food crop in the developing world, after rice. Wheat production in Pakistan has remained stagnant or declined in recent years, which can be attributed in part to the current adverse crop growing circumstances (Waseem *et al.*, 2014). The wheat crop can adapt to a variety of environmental conditions, although significant grain yield loss has been documented in heavy metals pollution, predominantly Cd-contaminated soils (Rady *et al.*, 2015). The majority of crop producing areas are under heavy metals stress due to industrialization, human interference, along other agricultural practices, which are presently becoming a worldwide significant danger (Zabin *et al.*, 2015).

As heavy metals contamination (particularly Cd), poses a critical threat to wheat productivity and food safety. Si supplementation has been reported to alleviate metal-induced stress. Therefore, the present study aims to evaluate the impact of two Si fertilizer sources on wheat growth, Cd accumulation, and antioxidant activities in Cd-contaminated fields, with the ultimate goal of identifying effective Si management strategies to enhance crop resilience and food safety in heavy metal-polluted soil.

Materials and Methods

Study site, growth conditions, and raw effluents

The study was carried out during the winter season of 2021-22 in farmer fields at Malik Zarai Farm in the Industrial Area of Faisalabad, Pakistan. Contamination of the soil could originate from multiple sources, among them fertilizers, irrigation water, and emissions from neighboring industries and urban centers. Moreover, three chemical production plants situated about 5 kilometers from the study site may act as pollution sources. Since 2014, the soils have been receiving municipal and industrial sewage sludge for a period of at least eight years. In a wastewater, Cd concentrations ranged from 0.10-0.12 mg L⁻¹. However, the Cd concentration in the soil was measured between 0.6 and 0.8 mg kg⁻¹. Table 1 presents the physiochemical characterization of the soil. Standard procedures were used to measure several soil physiochemical properties. The experimental soils were noted to be pH 5.58, EC 786 μ S cm⁻¹, contain 29.17 mg kg⁻¹ dissolved organic C, exhibit a C:N ratio of 38.66, and consist of sandy clay loam. Figure 1, portrayed the daily maximum or minimum temperatures values with the rainfall profiles recorded over the course of the trial. Across the wheat growing season, precipitation amounted to 97.04 mm.

Table 1. Fundamental properties of cadmium (Cd) contaminated field

Characteristics	Values
Soil texture class	Sandy clay loam
Sand (%)	45
Silt (%)	26
Clay (%)	28
EC (μ S cm ⁻¹)	786 \pm 5.58
Soil pH	5.58 \pm 0.12
Dissolved organic C (mg kg ⁻¹)	29.17 \pm 2.95
Water holding capacity (g g ⁻¹)	0.23 \pm 0.06
C:N ratio	38.66 \pm 0.35
Available P (mg kg ⁻¹)	3.80 \pm 0.80
Available N (mg kg ⁻¹)	24 \pm 1.04
Available K (mg kg ⁻¹)	124.24 \pm 3.25
Total cadmium (Cd) (mg kg ⁻¹)	0.6-0.8 \pm 0.02

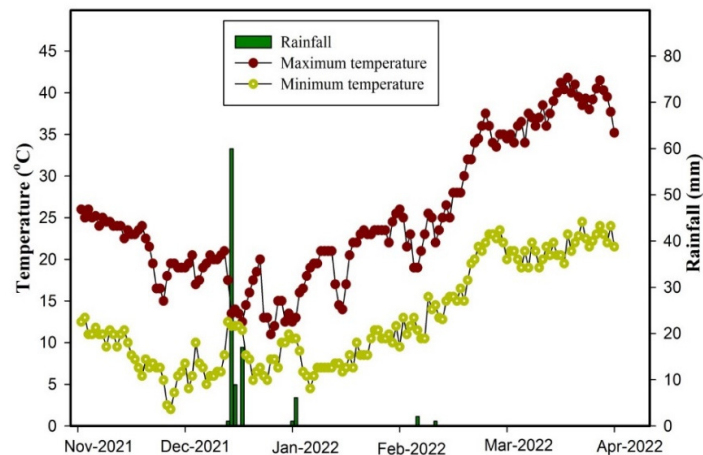


Figure 1. Climatic conditions of the experimental area during the wheat crop growing season from 2021-2022

The reported climatic data were taken from a weather station: 416300, latitude: 31.43, longitude: 73.1 and altitude: 184

Experimental design and treatments

The field trial was carried out using a randomized complete block design (RCBD) with four replications. Accordingly, the experiment involved five treatments: T₁: control (only Cd stressed soil), T₂: T₁ + Si as Ca silicate at 75 kg ha⁻¹, T₃: T₁ + Si as the treated burnt rice husk at 150 kg ha⁻¹, T₄: T₁ + humic acid (10 mg kg⁻¹ of soil) + Si as Ca silicate at 75 kg ha⁻¹, and T₅: T₁ + humic acid (10 mg kg⁻¹ of soil) + Si as the treated burnt rice husk at 150 kg ha⁻¹. The Ca silicate used in the study comprised of 80% Si in the form of SiO₂, 12% CaO, 2% MgO and 6% other trace minerals without Cd. The burnt rice husk had 75% Si (as SiO₂), pH of 7.8 and were prepared by controlled pyrolysis at 600 °C for 60 minutes under the conditions of limited oxygen. The material was crushed and sieved (below 2 mm) and stored in airtight containers until used.

Application procedure and crop management

Seeds of wheat variety 'Faisalabad-2008' were procured from the Ayub Agricultural Research Institute (AARI), Faisalabad, Pakistan. The natural form of Si fertilizer utilized in the field was burnt rice husk; the synthetic counterpart was Ca silicate. Before preparing the seedbed, delineate the plots and remove debris. The Ca Silicate, burnt rice husk and humic acid weight for each plot based on chosen rate and mix thoroughly with the soil. Broadcast evenly across the plot and incorporate into the top 15-20 cm using rotavator. Moisten the soil to field capacity and incubate for 7-14 days before sowing to allow equilibration and initial reactions between amendment and soil. Seeds at a rate of 100 kg ha⁻¹ were used at a distance of 22.5 cm between rows. The experimental plots measured an area of 5 × 2 m². Each plot received equal amounts of basal fertilizer applied as 25 kg ha⁻¹ nitrogen as urea (46% as N), 50 kg ha⁻¹ phosphorus as single super-phosphate (18% as P₂O₅) and 30 kg ha⁻¹ potassium as sulphate of potash (50% as K₂O) at planting time and two further doses of 25 kg ha⁻¹ nitrogen as urea were applied at the start and end of tillering stages. Sowing was conducted on 24 November 2021, and the crop was harvested on 22 April 2022. Post and pre-emergence herbicides were utilized for weed control, with insects kept in check through proven best management practices for wheat. However, the irrigation was applied only when the crop needed.

Measurement of growth and yield attributes

Wheat was harvested when fully mature, and the grains were detached. First, the samples were air-dried and later subjected to 72 h of oven drying at 65 + 5 °C. Afterward, they were ground using a grinding mill. Agronomic parameters e.g., plant height (cm), spike length (cm), number of grains spike⁻¹, 1000-grain weight (g) and grain yield (kg ha⁻¹) were measured using standardized procedures. After 65 days of germination, total chlorophyll content was assessed between 9:00 and 10:00 am using a chlorophyll meter (SPAD-502 Konika Minolta Sensing, Inc., Japan).

Estimation of Si contents in plant tissue

Si contents in wheat plant tissue were measured by using Tiron extraction methods (Guntzer *et al.*, 2010). For this, 50 mg of each plant sample (roots and shoots) was mixed with 30 mL of 0.1 M tiron, [4,5-dihydroxy-1,3-benzene-disulfonic acid disodium salt, (OH)₂C₆H₂(SO₃Na)₂], buffered at a pH of 10.5. The polypropylene tubes were subsequently put in at 85 °C water bath and shaken horizontally for two hours with the lids loosely covered in an attempt to prevent loss of water through evaporation. After cooling the tubes, 10 ml of the mixture was pipetted into 40 mL vials that were previously labeled, and 10 ml of 30% H₂O₂ was added in order to remove the Tiron. The fresh solution also became colorless after shaking the solution, once again in a water bath, at 85 °C, approximately for 30 minutes. After the solution was filtered at 0.2 μm, its Si concentration was measured via inductively coupled plasma optical emission spectroscopy (Jobin-Yvon, Ultima-C).

Estimation of Cd contents in plant tissue

To determine the levels of Cd, 0.25 g of finely ground plant materials (root, shoot and grain) was digested in 4 mL of concentrated 70% HNO₃ (Fluka, Buchs, Switzerland) in a mineralization block that was heated to 95 °C for six hours. The material was then filtered through a Whatman cellulose nitrate membrane 0.2 µm in size (Keller *et al.*, 2003). The Cd contents of the plant digests and extracts were determined via an atomic absorption spectrophotometer.

Estimation of electrolyte leakage (%)

The Dionisio-Sese and Tobita (1998) technique was used to measure the electrolyte leakage. Following a 21-day treatment period, the leaves that had fully developed at the top were divided into 5-mm-long pieces and placed in test tubes containing 8 ml of deionized and sanitized water. After the tubes were processed for two hours at 32 °C in a water bath incubator, the initial medium (EC₁) electrical conductivity was measured. Following a 20-minute autoclaving period at 121 °C to eliminate all electrolytes, the samples were cooled to 25 °C. The electrical conductivity (EC₂) was subsequently measured again and computed via the following formula:

$$EL = \left(\frac{EC_1}{EC_2} \right) \times 100$$

Antioxidant enzymes activities

The leaf samples were crushed in a pestle and mortar in a phosphate buffer solution (pH 7.8, 0.01 M) and centrifuged at 13,000 × g within 10 min. Following centrifugation, the supernatant was tested on the presence of antioxidant enzymes by following the procedure. Superoxide dismutase (SOD) activity was assessed in a reaction solution with 20 µM of riboflavin, 130 mM of methionine, 75 µM of NBT, 100 µM of EDTA-NA2, and enzyme extract. The absorbance was recorded at 560 nm using the method mentioned by Zhang *et al.* (2008). Peroxidase (POD) activity was measured by the procedure outlined by Chance and Maehly (1955). The 25 uL enzyme extract was combined with 1% guaiacol (v/v) and 10 mM H₂O₂ in 50 mM Tris buffer (pH 7.0) to make a total volume of 750 uL. Differing absorption values related to guaiacol oxidation ($\epsilon = 25.5 \text{ mM}^{-1} \text{ cm}^{-1}$) were recorded at 470 nm.

Statistical analysis

The data collection was analyzed statistically with the help of Statistix 10.1. Analysis of variance was used to determine the effects of Si on the growth, yield and Cd uptake of wheat. The HSD test of 0.05 was done to compare the mean values (Steel *et al.*, 1997; Naz *et al.*, 2022). The graphical demonstration of the data was done using the Sigmaplot 12.5 Software.

Results*Growth and yield attributes*

Growth and yield attributes of wheat were significantly affected by Cd stress and Si fertilization (Figure 2 A-E). Compared to T₁ (Cd stress), all Si based treatments significantly boosted the wheat productivity by reducing the Cd toxicity. Taller plants (85.57 cm) and the highest spike length (13.34 cm) were observed with T₄, followed by T₂. However, the lowest plant height and spike length were observed under T₁ (control). Plant height and spike length were respectively 21.40% and 31.18% larger with T₄ than those of the T₁. A significant improvement in the number of grains spike⁻¹ (82), 1000-grain weight (34.04 g), and grain yield (2840.8 kg ha⁻¹) were also recorded under T₄, followed by T₂ and T₅. A significant increase of 21.44% in 1000-grain weight and 25.21% in grain yield was recorded under T₄ compared with T₁. The total chlorophyll content in wheat

plants significantly improved with both natural and synthetic Si fertilizers compared to the control (T_1); however, the effect of synthetic Si fertilizer was more effective (Figure 2 F). Among all treatments, T_4 had maximum total chlorophyll contents (1.875 mg g^{-1}), followed by T_2 (1.827 mg g^{-1}) and T_5 (1.725 mg g^{-1}), respectively. However, the lowest value of total chlorophyll contents (1.440 mg g^{-1}) was under T_1 (Cd stress). A significant increase of 23.20% was recorded in total chlorophyll contents under T_4 compared with T_1 . However, it was noted that synthetic Si fertilization was more effective than a natural Si fertilization source.

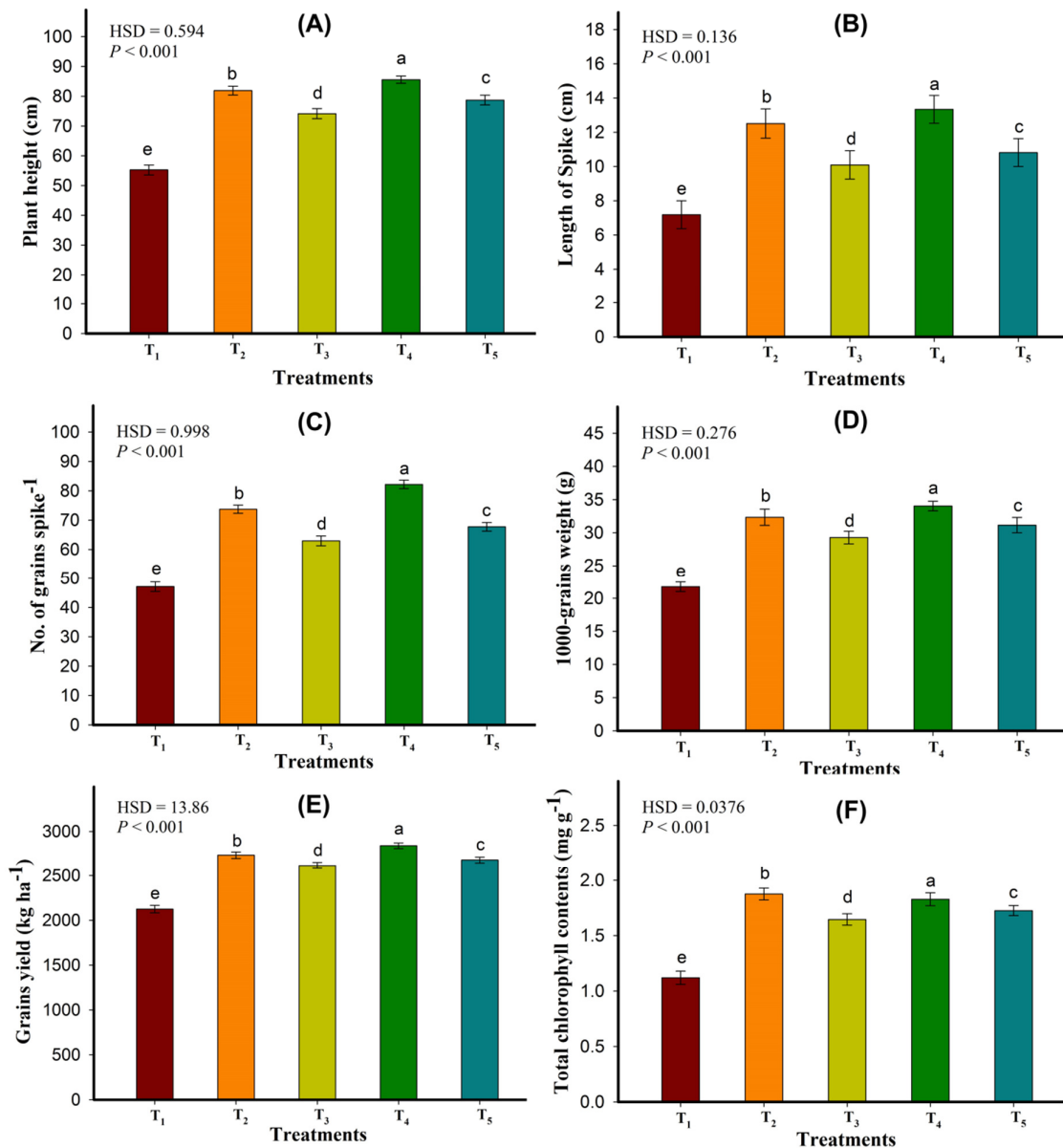


Figure 2. Effect of synthetic and natural Si fertilization sources on growth and yield traits of wheat (A) Plant height, (B) Length of spike, (C) Number of grains spike⁻¹, (D) 1000-grain weight, (E) Grain yield (F) Total chlorophyll contents under Cd stress

Four biological replicates were used, and the data represent the mean \pm SE ($n = 3$). Different letters indicate significant differences at the 0.05 level. T_1 : Control (Cd stress), T_2 : T_1 + Si as Ca silicate at 75 kg ha^{-1} , T_3 : T_1 + Si burnt with rice husk at 150 kg ha^{-1} , T_4 : T_1 + humic acid (10 mg kg^{-1} of soil) + Si as Ca silicate at 75 kg ha^{-1} , T_5 : T_1 + humic acid (10 mg kg^{-1} of soil) + Si burnt with rice husk at 150 kg ha^{-1}

Si uptake and metal distribution in plant parts

Si concentrations in the plant shoots and roots were significantly enhanced with Si fertilization (Figure 3 A-B). For instance, the Si concentration in shoot ($6.83 \text{ g kg}^{-1} \text{ DW}$) and root ($7.26 \text{ g kg}^{-1} \text{ DW}$) of wheat plant was observed highest with T_4 , followed by T_2 and T_5 . Notably, T_4 increased Si concentrations in the shoot and root by 67.64% and 63.60%, respectively, compared with T_1 . An increased concentration of Cd was recorded in the root, shoot, and grains of wheat under T_1 (Figure 3 C-E). However, both natural and synthetic Si fertilization sources (T_2 to T_5), inhibited the Cd uptake from the root and its transfer to aerial parts of the plants (shoot and grains). Results showed that among all treatments, T_4 responds better and recorded the least Cd concentration in root ($6.44 \text{ mg kg}^{-1} \text{ DW}$), shoot ($2.73 \text{ mg kg}^{-1} \text{ DW}$), and grain ($0.013 \text{ mg kg}^{-1} \text{ DW}$). Notably, a significant reduction of 42.60% and 59.71% in Cd concentration of root and shoot was observed under T_4 as compared to T_1 .

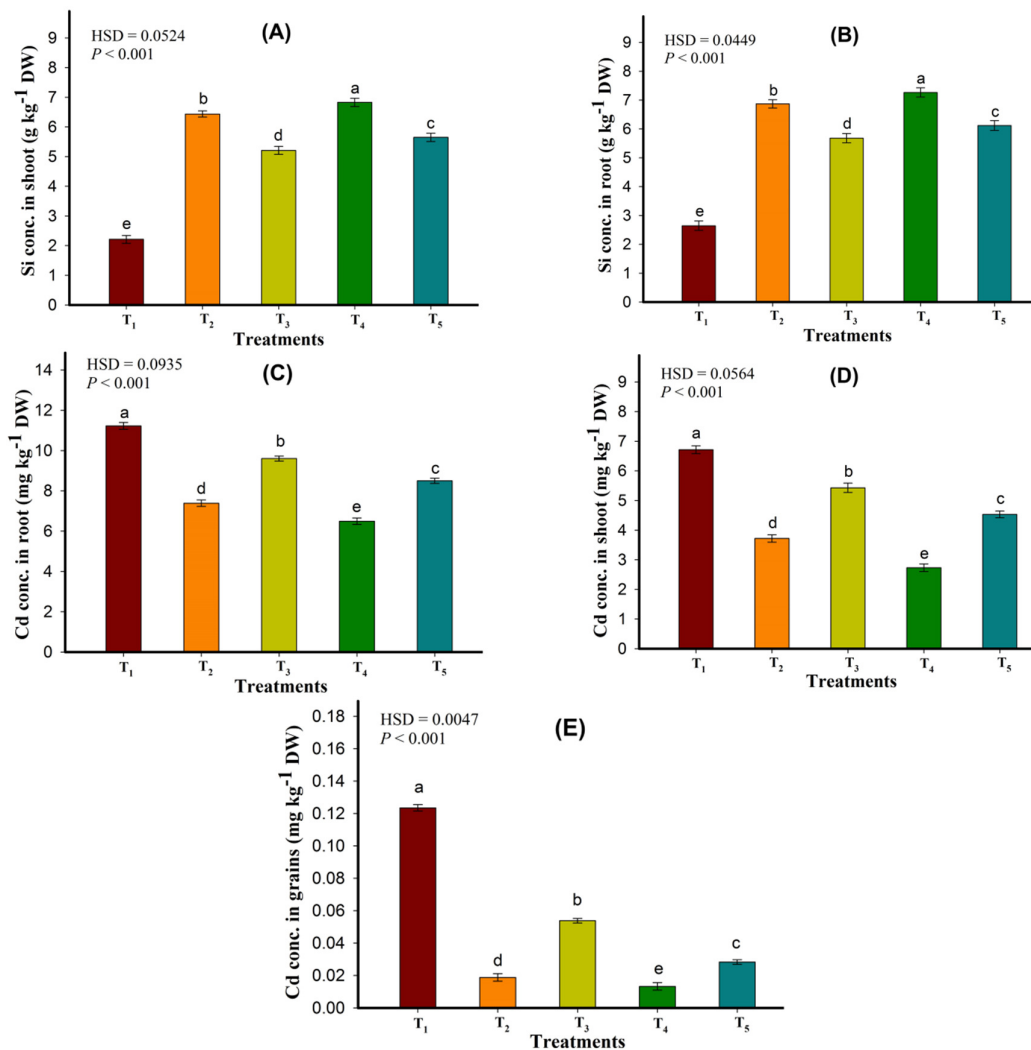


Figure 3. Effect of synthetic and natural Si fertilization sources on wheat (A) Si concentration in shoots, (B) Si concentration in roots, (C) Cd concentration in root, (D) Cd concentration in shoot and (E) Cd concentration in grain under Cd stress

Four biological replicates were used, and the data represent the mean \pm SE ($n = 3$). Different letters indicate significant differences at the 0.05 level. T_1 : Control (Cd stress), T_2 : T_1 + Si as Ca silicate at 75 kg ha^{-1} , T_3 : T_1 + Si burnt with rice husk at 150 kg ha^{-1} , T_4 : T_1 + humic acid (10 mg kg^{-1} of soil) + Si as Ca silicate at 75 kg ha^{-1} , T_5 : T_1 + humic acid (10 mg kg^{-1} of soil) + Si burnt with rice husk at 150 kg ha^{-1}

Electrolyte leakage and antioxidant activities

Application of both Si fertilization sources to Cd contaminated soil reduced the electrolyte leakage (%) in wheat significantly ($P \leq 0.05$), as demonstrated in Figure 4 A-C. T_1 produced the highest electrolyte leakage (68.12%), followed by T_3 (54.12%). Conversely, T_4 had the lowest electrolyte leakage (33.13%) in the wheat plant. In case of antioxidant activities, the Si fertilization sources showed statistically significant results for Superoxide dismutase (SOD) and Peroxidase (POD) activities of the wheat plant. The tolerance to Cd stress was enhanced by the Si fertilization. In comparison with Cd stressed control (T_1), the highest SOD (285.25 Units g^{-1} FW) and POD (1377.8 Units g^{-1} FW) activity was measured with T_4 , followed by T_2 . Notably, SOD and POD activities under T_4 increased by 39.83% and 38.46%, respectively, relative to T_1 .

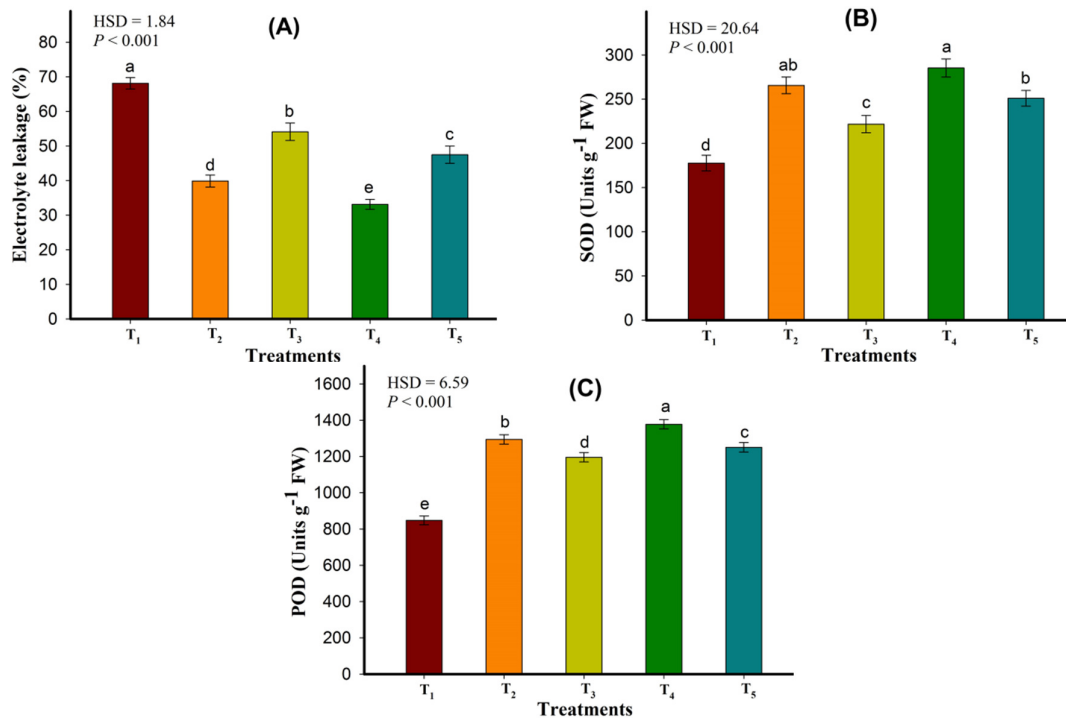


Figure 4. Effect of synthetic and natural Si fertilization sources on wheat (A) electrolyte leakage (B) Superoxide dismutase (SOD) and (C) Peroxidase (POD) under Cd stress

Four biological replicates were used, and the data represent the mean \pm SE ($n = 3$). Different letters indicate significant differences at the 0.05 level. T_1 : Control (Cd stress), T_2 : T_1 + Si as Ca silicate at 75 $kg\ ha^{-1}$, T_3 : T_1 + Si burnt with rice husk at 150 $kg\ ha^{-1}$, T_4 : T_1 + humic acid (10 $mg\ kg^{-1}$ of soil) + Si as Ca silicate at 75 $kg\ ha^{-1}$, T_5 : T_1 + humic acid (10 $mg\ kg^{-1}$ of soil) + Si burnt with rice husk at 150 $kg\ ha^{-1}$

Correlation analysis of morphological, physiological, and biochemical parameters under Cd stress

Correlation analysis revealed strong and significant relationships among the evaluated morphological, physiological, and biochemical parameters under Cd stress and Si treatments (Figure 5). Plant growth traits; including plant height (PH), length of spike (LOS), number of grains per spike (NGPS), 1000-grain weight (KGW), grain yield (GY), and total chlorophyll content (TCC); showed strong positive correlations with Si accumulation in both shoot (SiS) and root (SiR). Conversely, these growth traits exhibited significant negative correlations with Cd accumulation in shoot (CdS), grain (CdG), and root (CdR), indicating that higher Cd uptake adversely affects plant performance. Antioxidant enzyme activities, including superoxide dismutase (SOD) and peroxidase (POD), were positively associated with growth parameters and Si content but negatively correlated with Cd concentration. Electrolyte leakage (EL) showed strong negative correlations with Si-related traits and positive correlations with Cd related traits, suggesting increased membrane damage under elevated

Cd stress. Overall, the correlation matrix demonstrates that Si application mitigates Cd toxicity by enhancing growth, reducing Cd uptake, and improving antioxidant defense.

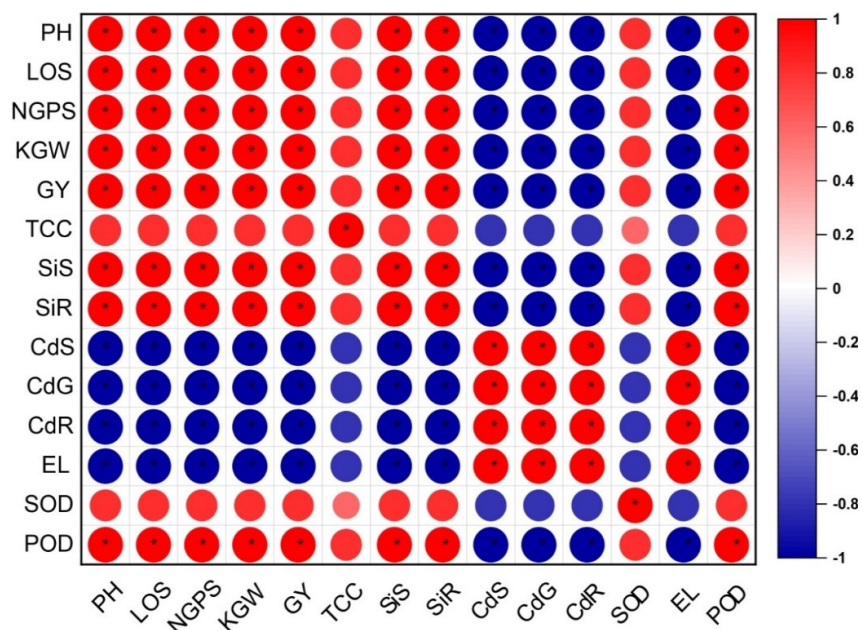


Figure 5. Correlation matrix showing the relationships among agronomic traits (PH, LOS, NGPS, KGW, GY), chlorophyll content (TCC), Si accumulation (SiS, SiR), Cd accumulation (CdS, CdG, CdR), electrolyte leakage (EL), and antioxidant enzyme activities (SOD, POD)

Positive correlations are shown in red and negative correlations in blue, with color intensity and circle size proportional to the correlation coefficient. Asterisks (*) indicate statistically significant correlations ($p < 0.05$)

Discussion

Plants are exposed to various environmental stresses, and among these environmental challenges, cadmium (Cd) stress has become one of the most critical due to its pronounced adverse effects on plant growth and productivity (El Rasafi *et al.*, 2022). Plant toxicity to Cd has increasingly emerged as a significant hindrance not only to the growth of plants but also that of the human body since human nutrition is directly or indirectly linked to plants (Chmielowska-Bąk *et al.*, 2017). The Cd contamination of soil causes direct venality of the roots of the plants, slows down the nutrient absorption, and reduces the relative growth rate, causing yellowing of the leaves and eventually lowers the final output of the crops (Li *et al.*, 2025).

The present research revealed that Cd stress adversely affected growth and yield attributes of wheat. However, the natural and synthetic forms of silicon (Si) fertilization increased the height and spike length of wheat by reducing the Cd toxicity. This may be attributed to the fact that Cd inhibits the activity of nitrate reductase enzyme and reduces the intake of nitrogen by plants, which affects the metabolism of plants. Further, Cd reduced zinc assimilation in plants that also harms cells and reduces photosynthesis levels by destroying chloroplasts and chlorosis (Awan, 2017). In previous studies, the experimental results suggested that in plants that grow in Cd polluted soil, improving shoot growth through expanding nitrogen intake, root nitrate transporter gene expression, root oxidative stress induced by ROS, and crop photosynthetic performance is enabled by the use of Si (Haddad *et al.*, 2018; Nasar *et al.*, 2021). There have been positive reports of enhanced plant height and shoot length consequentially on Cd and lead (Pb) contaminated soils following Si application on melon, lettuce, strawberries and cucumber (Artyszak, 2018). In spite of these advantages, Si does not have

absolute ability to alleviate of Cd toxicity. The high levels of Cd may still cause severe growth inhibition, oxidative damage and genotoxicity that cannot be completely overcome by Si application (Çatav *et al.*, 2020).

The positive response in the levels of yield attributes (Number of grains spike⁻¹, 1000-grains weight, and grain yield) of wheat with Si fertilization under Cd toxicity may be explained by the positive aspect of the photosynthetic activity and availability of nutrients as a result of Si fertilization. The raised 1000-grains weight upon the use of Si may come together with improved photosynthetic capacity and sustained photosynthate translocation. That has led to improved carbohydrate assimilation and to the number of consumed filled grains, and this leads to an improvement in grain yield. Naeem *et al.* (2015) have also indicated that Si significantly promoted the yield of wheat grain in the soil treated with calcium silicate at 150 mg kg⁻¹ compared to control under Cd stress. There is a possibility that Si application enhanced the grain yield of plants subjected to stress of heavy metals due to their influence on the uptake and translocation of numerous mineral components, which are required to conduct important vegetative activities (Rahman *et al.*, 2020). The current study concluded that applied Si had a positive influence on the yield quality of wheat and its associated attributes, which correlates with the results of Lavinsky *et al.* (2016), stating that Si can significantly contribute to the increase in the grains panicle⁻¹ yield in rice. In the present study, the use of both sources of Si as fertilizers increased the chlorophyll concentration of wheat plants under the influence of Cd toxicity. One of the possible reasons why wheat plants showed increased chlorophyll content under Cd toxicity is the ability of Si fertilization, which enhanced the photosynthesis of the plants. The improvement in photosynthesis might be attributed to decreased oxidative stress in plants and the supply of nutrients (Asgari *et al.*, 2018; Hussain *et al.*, 2019) that are the central components required in the process of photosynthesis, and Cd stress created the oxidative pressure that led to the ruin of the plant nutrients (Shi *et al.*, 2018). Also, Si plays an active role in boosting crop light use efficiency (which massively boosts the chlorophyll levels of wheat) (Gao *et al.*, 2018). Researchers have already found that heavy metal concentrations significantly inhibited the formation of chlorophyll (Yang *et al.*, 2020). As it was reported by Song *et al.* (2019), at the concentrations of Cd at 10 and 20 mg kg⁻¹ no significant changes in the contents of chlorophyll were observed, but at the Cd concentrations of 50-100 mg kg⁻¹ the reduction in the contents of chlorophyll in wheat was 9.0 to 20.4%.

With the Si fertilization, it was observed that the level of Si increased in the shoot and root of the wheat plant when subjected to Cd toxicity. Most likely, the Si reduces the adverse impacts of Cd on wheat plants, and the influence was based on the increased contents of Si taken up by root structures, which were further translocated to shoot parts that could have been facilitated via xylem water transportation (Rizwan *et al.*, 2015). These observations are in line with the results made on the prior research that Si supplementation in the form of NPs increased the Si deposition in wheat and fenugreek (Nazaralian *et al.*, 2017; Hussain *et al.*, 2019). As the concentration of Si in growing media increased, there was an improvement in terms of the quantity of Si both in plant roots and in plant leaves (Asgari *et al.*, 2018). The process of fertilization has also been found to upregulate the plant tolerance to Cd toxicity (Adrees *et al.*, 2015).

The Si supplement, whether synthetic or natural, drastically reduced the Cd root uptake as well as its transportation to the aerial wheat parts and grain under Cd stress, which is possibly because Si enhances the Cd binding to cell walls or even in the internalization of Cd to the vacuoles, thus reducing the metal movement to the grains (Adrees *et al.*, 2015). This proves that the reduction in the uptake and movement of Cd to the wheat aerial part was a result of an increased amount of Si in the plant. Several studies demonstrated that Si can reduce the levels of hazardous metals in a variety of crops grown under different conditions (Tripathi *et al.*, 2015; Wang *et al.*, 2015). Wang *et al.* (2016) claimed that application of Si was a more effective method of reducing Cd concentration in wheat grains relative to the other metals. The components of the plants connecting the stem and the grains are called rachises, where the Cd and other grains are collected in rachises first and then translocated to the grains (Liu *et al.*, 2017). A significant influence of the Si application on the Cd contents in rachises of rice was observed at the anthesis stage (Chen *et al.*, 2018). The application of Si is

likely to reduce the quantities of Cd in crops by decreasing the bioavailable levels of Cd (Rizwan *et al.*, 2012). Metabolically, fewer active parts of the plants could be subjected to a lower amount of co-precipitation of metals with Si fertilization, which could decrease the Cd concentrations in grain (Keller *et al.*, 2015). On the same note, Shi *et al.* (2005) stipulated that Si treatment alleviated the mobilization of Cd from the root into the shoot in rice plants by 33%. It was also shown that Cd was deposited mostly in endodermis and epidermis, but the former was highly deposited in comparison to the latter. The decrease in Cd translocation may be connected with the deposition of Si in the endodermis. The study of Vaculik *et al.* (2012) revealed that Si reduced the factor translocating Cd roots to shoots at high Cd concentration (0.05 mol L^{-1}). A study by Naeem *et al.* (2015) suggested that Cd accumulation in the roots and subsequent reduction of its translocation to the shoots and grains was induced by the application of Si on wheat plants. Further, although Si lowers the bioavailability and build-up of Cd, its efficacy depends on the particular environmental and genetic conditions, the type and amount of Si applied (Huang *et al.*, 2024). Thus, though the strategy of Si fertilization can be used as a promising effort to overcome Cd toxicity in wheat, its limitations should be recognized, especially in environmental condition variations and the necessity to use optimal Si levels in order to gain significant protective benefits (Amirjani, 2012).

Heavy metal stress caused oxidative damage in plants by increasing ROS production (Mansoor *et al.*, 2023). In current study, the electrolyte leakage (EL) percentage was reduced by both Si fertilization sources, however, the reducing tendency was higher by using the synthetic Si fertilization source. Si decreased the EL levels by maintaining the consistency of the cell membrane through the toxicity of Cd (Alzahrani *et al.*, 2018). It is possible that Si treatment assisted the Cd stressed in rice plant by maintaining its membrane integrity (Wang *et al.*, 2015). The plants developed a self-defense mechanism that comprises antioxidant enzymes and other mechanisms to counteract oxidative stress (Terzi *et al.*, 2018). The implications of Cd toxicity in this study were the significant reduction in the levels of Superoxide dismutase (SOD) and Peroxidase (POD) activities in the wheat plant. This reduced activity of the enzyme could be due to the direct influence of the heavy metals on the proteins, leading to inhibition of enzyme production and crippling of the functionality of the enzymes, as suggested by Sharma and Dietz (2009). POD and SOD activity was heavily increased due to Si fertilization. The results indicated that Si significantly up-regulated antioxidant enzymes that enhance the disappearance of H_2O_2 and degradation of the ROS that were induced by Cd stress. Other past studies have also been proven that in rice (Tang *et al.*, 2015) and Chinese cabbage (Wu *et al.*, 2017), Cd toxicity was alleviated by supplementing with Si. Nonetheless, the results presented by Wang *et al.* (2015) revealed that POD activity in the shoots was enhanced following the application of Si in comparison with Cd treatment alone. The improvement of the activities of antioxidant enzymes in the presence of Si could be attributed by higher stress in the plants as indicated by the increased EL in shoot of wheat plant. Wheat plants have the capacity to survive heavy metal stress may be due to the higher production of antioxidant enzymes under Si fertilization. According to study conducted on rice seedlings (Wang *et al.*, 2015), pea (Tripathi *et al.*, 2015), and maize hybrids (Tripathi *et al.*, 2016) under Cd stress, the application of Si NPs boosted antioxidant production.

Current study reveals that Si fertilization, especially Ca silicate with humic acid, is important in alleviating Cd toxicity and enhancing wheat growth. These findings suggest the possibilities of applying Si fertilization in the context of regular nutrient management programs in industrial pollution-prone areas to minimize the accumulation of Cd in edible plant parts and increase food safety. In agricultural practice, the results validate the use of synthetic Si fertilizers as a viable and affordable approach to enhancing crop tolerance, as well as the productivity of crops under heavy-metal stress. Future investigations must address the long-term field tests of Si sources in higher Cd level soil, cropping systems, the economic viability of Si supplementation to farmers, and mechanistic research to gain a deeper insight into Si-Cd interactions at molecular/cellular level. Furthermore, the investigation of the application of Si in combination with other organic or biological amendments can further expand its use on the sustainable management of polluted agricultural soils.

Conclusions

The current research established the effectiveness of silicon (Si) fertilization in alleviating the impact of cadmium (Cd) toxicity on wheat growing on contaminated soils. However, Si fertilization, particularly as calcium silicate, boosted the plant growth and yield while decreasing Cd uptake and translocation to aerial tissues. Improved physiological health, reflected by higher chlorophyll levels and a strengthened antioxidant system, contributed to better stress tolerance. Correlation analysis revealed strong positive relationships between Si accumulation and key growth and physiological traits, while Cd accumulation showed significant negative correlations, indicating its adverse effects on plant performance. Conclusively, Si application offers a practical, sustainable approach to mitigate Cd accumulation in wheat and support safer food production on polluted agricultural lands.

Authors' Contributions

Conceptualization: MKS, MAT, ZAS; Writing - original draft: MKS, AMAS; Supervision: MAT; Formal analysis: AMAS; Methodology: MAT, ZAS; Data Curation: MKS; Writing - review & editing: MM, BAB, AG, HW; Visualization: AG, HW.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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