

Alleviation of Pb toxicity in wheat (*Triticum aestivum* L.) through silicon supplementation

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ABSTRACT

Lead (Pb), like other heavy metals, exerts highly toxic direct and indirect effects on plants, animals, and humans. This hydroponic study investigated the alleviating effects and beneficial role of exogenous silicon (Si) application in Pb-stressed wheat plants (BARI-27). Growth and physiological parameters including chlorophyll content, photosynthesis, morphological traits, Pb uptake and accumulation, lipid peroxidation (LPO), hydrogen peroxide (H₂O₂) content, electrolyte leakage, cell death, soluble protein, glutathione, cysteine, and non-enzymatic antioxidant activities were evaluated. In this study plants were harvested after five days of treatment for physiological and biochemical analyses. Pb stress severely inhibited root and shoot growth, whereas Si supplementation markedly restored plant growth under Pb stress. Si application significantly reduced Pb uptake, electrolyte leakage, H₂O₂ accumulation, LPO content and cell death, while enhancing soluble protein content, Si accumulation, glutathione and cysteine in Pb-stressed wheat plants compared with Pb treatment alone. Overall, Si supplementation protected plant tissues from oxidative membrane damage under Pb stress, thereby alleviating Pb toxicity and improving wheat growth and physiological performance. These findings suggest that Si plays a significant role in mitigating Pb-induced morphological and physiological damage in wheat plants.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and serves as a major source of calories and protein for the human population (Shewry & Hey, 2015). However, wheat productivity is increasingly threatened by environmental contaminants, particularly heavy metals. Among these, lead (Pb) is considered one of the most toxic metals due to its high persistence in soil and its detrimental effects on plant growth, crop productivity, and food safety (Gupta et al., 2024). Pb contamination in agricultural soils mainly originates from industrial activities, mining,

sewage sludge, pesticides, and atmospheric deposition (Wan et al., 2024). Excess Pb accumulation in plants disrupts physiological and biochemical processes, including photosynthesis, nutrient uptake, membrane stability, and antioxidant metabolism, ultimately resulting in growth inhibition and oxidative damage (Mohamed et al., 2025). Pb toxicity induces excessive production of reactive oxygen species (ROS), such as hydrogen peroxide, which causes lipid peroxidation, electrolyte leakage, cellular damage, and impaired metabolic activities in plants. Although several remediation strategies have been proposed to reduce heavy



metal toxicity, many conventional approaches are expensive, labor-intensive, and environmentally unsustainable.

In recent years, silicon (Si) supplementation has gained considerable attention as an eco-friendly and cost-effective approach for enhancing plant tolerance to abiotic stresses, including heavy metal toxicity (Bhat et al., 2019). Si is known to improve plant growth and stress resilience by regulating metal uptake, strengthening cell walls, maintaining membrane integrity, enhancing antioxidant defense systems, and reducing oxidative stress in plants exposed to toxic metals (Liang et al., 2007).

Although the beneficial role of Si has been extensively studied in several crops, information regarding its protective effects against Pb toxicity in wheat remains limited. Therefore, the present hydroponic study was conducted to investigate the role of exogenous Si application in alleviating Pb-induced stress in wheat plants. Growth performance, chlorophyll content, Pb accumulation, oxidative stress markers, membrane damage, and non-enzymatic antioxidant responses were evaluated to better understand the physiological and biochemical mechanisms underlying Si-mediated Pb tolerance in wheat. The findings of this study may contribute to the development of sustainable strategies for improving wheat production under Pb-contaminated conditions.

Materials and methods

Plant Materials, growth conditions, and treatments

Seeds of wheat cultivar BARI-27 were surface sterilized and germinated under control conditions. Uniform seedlings were transferred to a hydroponic system containing basal nutrient solution and grown under controlled environmental conditions. The experiment consisted of four treatments with three replications: control (nutrient solution without Pb or Si), Pb treatment (100 μ M Pb), Pb + Si treatment (100 μ M Pb + 1 mM Si), and Si treatment alone (1 mM Si). Plants were maintained for five days after treatment

application before harvesting for physiological, biochemical, and elemental analyses.

Growth measurements and Pb determination

Root and shoot growth parameters were recorded after harvest. For Pb determination, roots and shoots were washed sequentially with CaSO₄ and deionized water and oven-dried at 90 °C for 4 days. Dried samples were digested in 3 mL HNO₃ at 75 °C for 10 min. After cooling, 1 mL H₂O₂ was added, and the mixture was further heated at 109 °C for 15 min. Pb concentration was determined using flame atomic absorption spectroscopy (AAS) equipped with an ASC-6100 auto sampler and air-acetylene atomization system (Shimadzu AA-6800). Standard calibration curves were prepared using Pb standard solutions.

Measurement of electrolyte leakage

Electrolyte leakage (EL) was measured to assess membrane permeability (Lutts et al., 1996). Plant tissue segments (1 cm) were washed thoroughly and incubated in 20 mL deionized water at room temperature (25 °C) on a shaker (100 rpm) for 2 h. Electrical conductivity of the bathing solution was then measured using a conductivity meter.

Determination of soluble protein

Total soluble protein was extracted from root and shoot tissues using ice-cold extraction buffer containing 50 mM Tris-HCl (pH 7.5), 2 mM EDTA, and 0.04% 2-mercaptoethanol. Homogenized samples were centrifuged at 12,000 rpm for 5 min, and the supernatant was mixed with Coomassie Brilliant Blue G-250 reagent. Absorbance was recorded at 595 nm, and protein concentration was calculated using bovine serum albumin (BSA) as the standard (Guy et al., 1992).

Determination of oxidative stress markers and cell death

H₂O₂ content was determined following Velikova et al. Fresh tissues (150 mg) were homogenized in 0.1% trichloroacetic acid (TCA) and centrifuged at 10,000 \times g for 20 min at 4 °C. The reaction mixture containing tissue extract, potassium phosphate buffer (pH 7.0), and KI solution was incubated, and absorbance was

measured at 390 nm (Ghafoor et al., 2019). Lipid peroxidation was estimated as thiobarbituric acid reactive substances (Fraga et al., 1988). Fresh tissues (200 mg) were homogenized in 0.25% thiobarbituric acid prepared in 10% TCA, heated at 95 °C for 1 h, rapidly cooled, and centrifuged. Absorbance was measured at 532 and 660 nm, and TBARS content was expressed as nmol g⁻¹ fresh weight using an extinction coefficient of 155 mM⁻¹ cm⁻¹.

Cell death was determined using the Evans blue staining assay. Treated cells were incubated with 0.25% Evans blue solution, washed thoroughly, homogenized in 1% SDS solution, and centrifuged. Absorbance of the supernatant was recorded at 600 nm, and cell death was quantified using a standard curve (Zhao et al., 2005).

Determination of glutathione and cysteine

Glutathione (GSH) and cysteine contents were determined following extraction with 5% sulfosalicylic acid. Fresh tissues were homogenized and centrifuged at 12,000 × g for 10 min. The supernatant was neutralized with sodium citrate before preparation of the reaction mixture containing EDTA, DTNB, potassium phosphate buffer, and sample extract. Absorbance was measured at 412 nm, and concentrations of GSH and cysteine were calculated using standard calibration curves.

Statistical analysis

All the data were statistically analyzed using one-way ANOVA at a significance level of $P \leq 0.05$ with SPSS 16.0 software for Windows. One-way ANOVA calculated of means, standard deviation was performed followed by Duncan's Multiple Range Test (DMRT) and post hoc test using SPSS Statistics 16.0 Software. Further, the graphical presentation was prepared using Graph Pad Prism 6. Different letters on the histograms indicate that the means were statistically different at $P \leq 0.05$ level. Data presented are from four treatments with three replicates as described above.

Results

Effect of Si on growth and chlorophyll pigments

After five days of Pb treatment, significant changes in plant growth were observed. The effects of exogenous silicon (Si) on wheat growth under Pb stress, particularly in terms of root length, root dry weight, shoot height and shoot dry weight (Fig. 1A and Table 1). Pb stress significantly reduced both root and shoot features compared with the untreated control plants (Table 1-2). However, Si supplementation in combination with Pb significantly improved shoot height and shoot dry weight relative to Pb-stressed plants. In contrast, Si treatment alone showed growth characteristics similar to those of the control plants (Table 1-2).

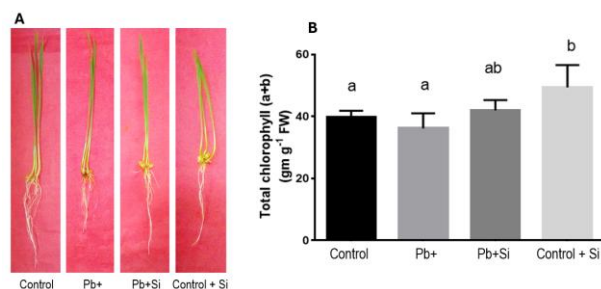


Fig. 1. Effect of Si application on plant phenotype (A) and total chlorophyll content in the leaves (B) of wheat seedlings under Pb stress. Data are presented as mean \pm SD. Different lowercase letters above the bars indicate significant differences among treatments according to Duncan's multiple range test (DMRT) at $P < 0.05$.

Table 1. Root features (root length and root dry weight) of young seedlings after cultivation for 5 days in nutrient medium with Pb and Si. Different letters in each column indicate significant differences between mean \pm SD of treatments ($n = 3$) at a $P < 0.05$ significance level.

Treatments details	Root length (cm)	Root dry Weight (mg)
Control	2.933 \pm 0.929 ^b	0.014 \pm 0.002 ^b
Pb	1.767 \pm 0.252 ^a	0.006 \pm 0.001 ^a
Pb + Si	2.767 \pm 0.252 ^b	0.015 \pm 0.006 ^b
Control + Si	3.133 \pm 0.153 ^b	0.012 \pm 0.001 ^b

Pb treatment did not cause significant changes in total chlorophyll content in the leaves compared

with the control plants. Similarly, the combined application of Pb and Si caused only slight changes in total chlorophyll content. However, Si supplementation alone increased total chlorophyll content compared with Pb-stressed plants. Overall, Si applied solely to control plants showed a significant increase in total chlorophyll content in wheat compared to control and Pb-treated plants (Fig. 1B).

Effect of Si on Pb and Si accumulation

The concentrations of Pb and Si in roots and shoots of wheat plants under different treatments are presented in Figure 3.3. Pb stress significantly increased Pb accumulation in both roots and shoots compared with the control plants (Fig. 2A). The highest Pb concentration was observed in Pb-treated plants, particularly in roots, indicating greater Pb retention in belowground tissues. However, Si supplementation in combination with Pb markedly reduced Pb accumulation in both roots and shoots relative to Pb-stressed plants. In contrast, plants treated with Si alone showed Pb concentrations comparable to the control plants (Fig. 1A).

Table 2. Shoot features (shoot height and shoot dry Weight) of young seedlings after cultivation for 5 days in nutrient medium with or without Pb and Si. Different letters in each column indicate significant differences between mean \pm SD of treatments ($n = 3$) at a $P < 0.05$ significance level.

Treatments details	Shoot height (cm)	Shoot dry weight (mg)
Control	11.2 \pm 1.539 ^b	0.025 \pm 0.004 ^b
Pb	7.167 \pm 0.764 ^a	0.010 \pm 0.002 ^a
Pb + Si	9.933 \pm 0.702 ^b	0.024 \pm 0.004 ^b
Control + Si	10.567 \pm 1.266 ^b	0.022 \pm 0.003 ^b

Furthermore, Si concentration in roots and shoots was significantly influenced by Si supplementation (Fig. 1B). Application of Si, either alone or in combination with Pb, significantly increased Si accumulation in roots compared with control and Pb-treated plants. A similar trend was observed in shoots, where the

highest Si concentration was detected in plants receiving Si alone, followed by the Pb+Si treatment. Pb stress alone did not significantly affect Si concentration compared with the control plants (Fig. 1B).

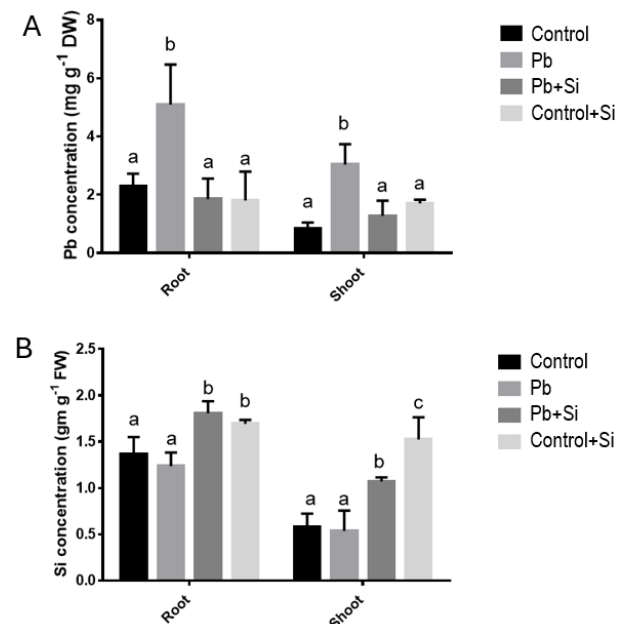


Fig. 2. Effect of Si on Pb (A) and Si (B) concentrations in roots and shoots of wheat plants under Pb stress. Data are presented as mean \pm SD. Different lowercase letters above the bars indicate significant differences among treatments according to Duncan's multiple range test (DMRT) at $P < 0.05$.

Effect of S on membrane stability and protein content

Electrolyte leakage and total soluble protein content in wheat plants were significantly affected by Pb stress and Si supplementation (Fig. 3A). Pb treatment markedly increased electrolyte leakage in both roots and shoots compared with control plants, indicating membrane damage under Pb toxicity. However, Si application in combination with Pb reduced electrolyte leakage relative to Pb-stressed plants and restored the values close to those of the control plants (Fig. 3A). Pb stress also significantly reduced total soluble protein content in both roots and shoots compared with the control treatment (Fig. 3B). In contrast, Si supplementation under Pb stress significantly

increased protein accumulation compared with Pb-treated plants. Application of Si alone showed protein contents comparable to or slightly higher than the control plants (Fig. 3B).

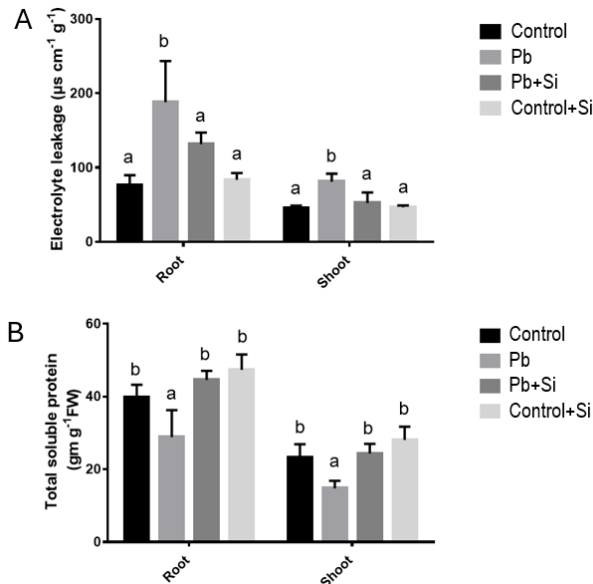


Fig. 3. Effect of Si application on electrolyte leakage (A) and total soluble protein content (B) in wheat plants under Pb stress. Data are presented as mean \pm SD. Different lowercase letters above the bars indicate significant differences among treatments according to Duncan's multiple range test (DMRT) at $P < 0.05$. FW = fresh weight.

Si alleviates Pb-induced oxidative damage in wheat plants

Pb toxicity markedly increased oxidative stress in both roots and shoots of wheat plants, as evidenced by elevated H_2O_2 accumulation and lipid peroxidation (Fig. 4A). In roots, Pb treatment significantly increased H_2O_2 content compared with the control plants. A similar increasing trend was observed in shoots, where Pb-stressed plants showed the highest H_2O_2 accumulation among all treatments (Fig. 4A). However, exogenous Si supplementation under Pb stress significantly reduced H_2O_2 levels in both roots and shoots compared with Pb treatment alone, indicating the protective role of Si against Pb-induced oxidative damage. Control plants supplemented with Si alone exhibited H_2O_2 levels comparable to the untreated control (Fig. 4A).

Furthermore, lipid peroxidation, measured as lipid peroxide content, also significantly increased under Pb stress in both roots and shoots compared with the control plants (Fig. 4B). The highest lipid peroxide accumulation was observed in Pb-treated roots, indicating severe membrane damage under Pb toxicity. In contrast, combined application of Pb and Si significantly lowered lipid peroxide content in both tissues compared with Pb treatment alone. Si supplementation without Pb stress maintained lipid peroxide levels similar to the control treatment (Fig. 4B).

Cell death percentage was also markedly elevated in response to Pb toxicity in both roots and shoots (Fig. 4C). Pb-treated plants exhibited the highest cell death, particularly in roots. Exogenous Si application significantly alleviated Pb-induced cell death in both tissues, resulting in substantially lower values than Pb treatment alone. No significant differences in cell death were observed between control and Control+Si treatments (Fig. 4C).

Si changes non-enzymatic antioxidants under Pb stress

Pb stress in combination with Si application significantly influenced the accumulation of non-enzymatic antioxidants in wheat roots and shoots (Fig. 5A). Glutathione content significantly increased in roots under Pb+Si treatment compared with the control and Pb-treated plants, whereas no significant differences were observed among treatments in shoots (Fig. 5A). Similarly, cysteine accumulation markedly increased in roots following Pb+Si treatment, showing significantly higher values than all other treatments (Fig. 5B). In contrast, cysteine content in shoots remained statistically unchanged among treatments. These results indicate that Si supplementation enhances non-enzymatic antioxidant metabolism, particularly in roots, to alleviate Pb-induced oxidative stress in wheat plants (Fig. 5B).

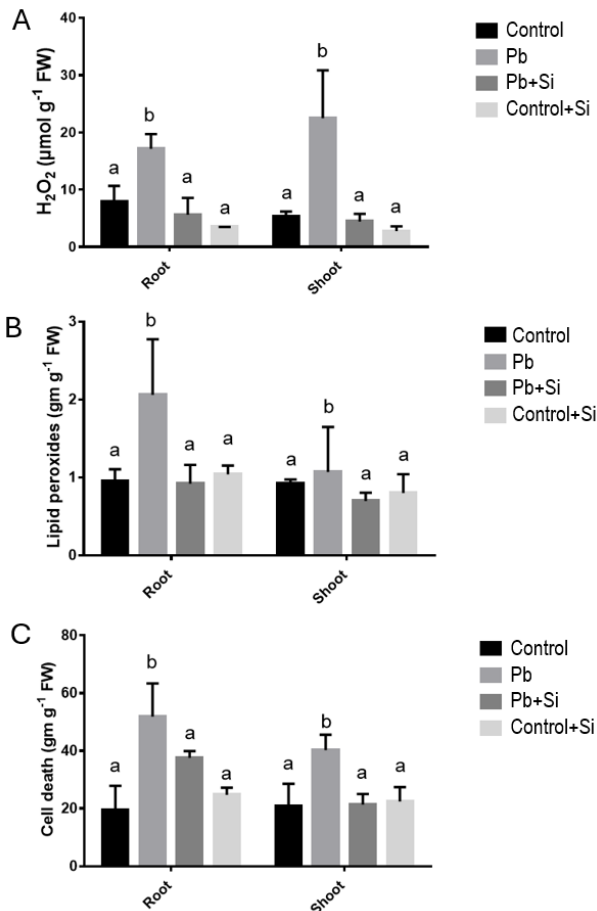


Fig. 4. Effect of exogenous Si on oxidative stress markers in wheat plants exposed to Pb toxicity. (A) H₂O₂ content, (B) lipid peroxidation and (C) cell death (%) in roots and shoots under different treatments: Control, Pb, Pb+Si, and Control+Si. Data represent mean ± SD (n = 3). Different letters above the bars indicate significant differences among treatments at *P* < 0.05 according to DMRT.

Discussion

The present study demonstrated that Pb toxicity severely impaired growth, physiological performance, and cellular stability in wheat plants, whereas exogenous Si application effectively alleviated Pb-induced damage. Pb stress significantly reduced shoot height, root length, and tissue biomass, indicating disruption of normal plant growth and metabolic activities. Heavy metals are known to inhibit cell division, root elongation, nutrient uptake, and biomass accumulation through oxidative and metabolic

disturbances (Ali et al., 2014; Singh et al., 2016). The reduction in growth observed in this study may therefore be associated with Pb-induced impairment of cellular processes and nutrient transport. In contrast, Si supplementation improved root and shoot growth under Pb stress, suggesting that Si enhanced plant tolerance against Pb toxicity. Similar beneficial effects of Si on plant growth under heavy metal stress have been reported in wheat, maize, rice, and barley (Liang et al., 2005; Rizwan et al., 2012; Vaculík et al., 2009).

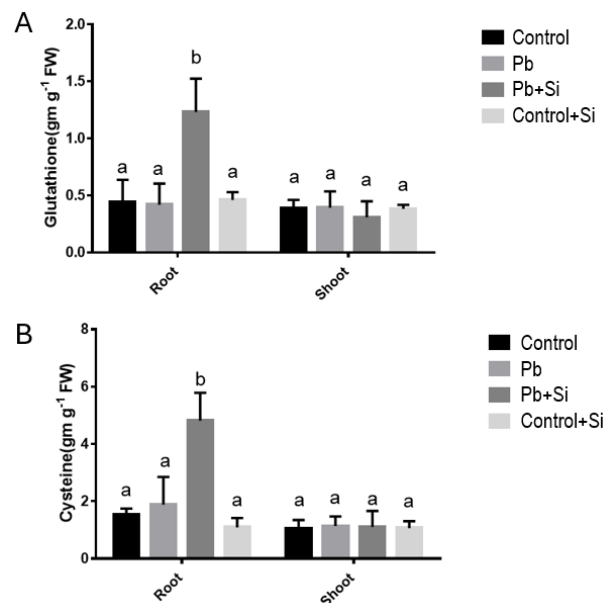


Fig. 5. Effect of exogenous Si application on non-enzymatic antioxidants in wheat plants exposed to Pb toxicity. (A) Glutathione and (B) cysteine contents in roots and shoots under different treatments: Control, Pb, Pb+Si, and Control+Si. Data represent mean ± SD (n = 3). Different letters above the bars indicate significant differences among treatments at *P* < 0.05 according to DMRT.

Pb toxicity also negatively affected photosynthetic performance. Heavy metals commonly disrupt chloroplast ultrastructure, chlorophyll biosynthesis, and photosynthetic electron transport, ultimately reducing photosynthetic efficiency (Ouzounidou et al., 1997; Sandalio et al., 2001). In the present study, Si application improved chlorophyll content and photosynthetic performance under Pb stress,



indicating that Si protected the photosynthetic machinery from oxidative injury. Similar observations have been reported in maize, cucumber, and rice under different abiotic stresses, where Si maintained chlorophyll pigments and improved photosynthesis (Feng et al., 2010; Kaya et al., 2009; Nwugo & Huerta, 2008). Improved photosynthesis in Si-treated plants may explain the enhanced biomass accumulation and growth observed under Pb stress.

Pb accumulation in plant tissues is one of the major causes of heavy metal toxicity. Increased Pb concentration in roots and shoots may interfere with nutrient homeostasis and induce severe physiological damage. In this study, Si supplementation reduced the toxic effects of Pb, possibly through decreased Pb uptake and restricted translocation from roots to shoots. Previous studies demonstrated that Si could immobilize heavy metals in root tissues or cell walls, thereby reducing their mobility and toxicity (Guo et al., 2005; Li et al., 2009). Silicon deposition in plant tissues may also act as a physical barrier limiting metal transport into metabolically active cells. Such mechanisms may explain the improved growth and physiological responses observed in Si-treated wheat plants under Pb stress.

Oxidative stress is one of the primary consequences of heavy metal toxicity. Pb-treated plants in the present study exhibited increased H_2O_2 accumulation, lipid peroxidation, electrolyte leakage, and cell death, indicating severe oxidative damage and membrane instability. Excessive reactive oxygen species (ROS) production under heavy metal stress damages lipids, proteins, nucleic acids, and cellular membranes (McCord, 2000). However, Si supplementation significantly reduced H_2O_2 accumulation, lipid peroxidation, electrolyte leakage, and cell death in both roots and shoots, suggesting that Si improved membrane stability and reduced ROS-mediated cellular injury. Similar protective effects of Si against oxidative stress have been reported under Cd, As, salinity,

drought, and UV stress conditions (Bharwana et al., 2013; Gong et al., 2005; Shen et al., 2010).

The alleviation of oxidative stress by Si may be associated with improved antioxidant defense systems. In the present study, glutathione and cysteine contents significantly increased in roots under Pb+Si treatment. Glutathione is an essential non-enzymatic antioxidant involved in ROS detoxification and metal chelation, whereas cysteine acts as a precursor for glutathione and phytochelatin synthesis. Enhanced accumulation of these metabolites suggests that Si strengthened antioxidant metabolism and detoxification pathways under Pb stress. Similar findings have been reported where Si stimulated antioxidant defense systems and maintained physiological stability under abiotic stress conditions (Pei et al., 2010; Saqib et al., 2008). Since roots are the primary site of Pb exposure, enhanced antioxidant responses in roots may help restrict Pb-induced oxidative damage before systemic transport to shoots occurs.

Pb stress also reduced soluble protein content in both roots and shoots, indicating disruption of protein synthesis and enhanced oxidative degradation of proteins. Silicon supplementation restored soluble protein levels, suggesting improved metabolic integrity and reduced oxidative injury. Previous studies similarly reported that Si improves protein stability and cellular metabolism under environmental stresses through reduction of ROS accumulation and protection of enzymatic functions (Gong et al., 2005).

Conclusion

Overall, the findings of the present study suggest that Si alleviates Pb toxicity in wheat plants through multiple physiological and biochemical mechanisms, including improved growth and biomass production, maintenance of photosynthetic pigments, reduced oxidative damage, enhanced membrane stability, and activation of non-enzymatic antioxidant defenses. The protective effects of Si were particularly evident under Pb stress conditions, indicating its role as an effective stress-



mitigating element. These findings support the potential application of Si in improving crop tolerance and productivity in Pb-contaminated environments. Further molecular and field-level studies are required to better understand Si-mediated heavy metal detoxification mechanisms and their practical agricultural applications.

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Conflict of interest

The authors declare they have no conflicts of interest.

Author contributions

O.D. conceived, conducted the experiments, analyzed the data and prepared the draft manuscript. M.S.P. interpreted the results and revised the final manuscript.

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