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Silicon and Strigolecton Application Alleviates the Adversities of Cadmium Toxicity in Maize by Modulating Morpho-Physiological and Antioxidants Defense Mechanisms

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Abstract: Cadmium (Cd) toxicity is a serious threat to agronomic crop productivity worldwide. It raises severe concerns about the food and nutrient security required to meet the demands of a rapidly growing population, while also creating grave challenges for agriculture. Silicon (Si) and strigolecton (SL) are reported to impart multiple benefits to plants exposed to abiotic stress. Therefore, the current experiment was performed to evaluate the effects of silicon (4.0 mM) and strigolecton (20 µM) on the amelioration of cadmium (25 mg kg^{-1} soil) stress in maize seedlings via intervention in morphological attributes, photosynthetic pigments, enzymatic antioxidant mechanisms, and osmolyte accumulation. The results indicated that morphological attributes and photosynthetic pigments were significantly reduced in Cd-exposed seedlings. However, foliar application of Si and SL, both individually and in combination, significantly improved the growth attributes and photosynthetic pigments of maize seedlings under both control and Cd-stress conditions. Exposure of maize seedlings to Cd stress increased H_2O_2 levels, malondialdehyde content, and electrolyte leakage and reduced cell membrane stability. These effects were significantly negated by Si and SL supplementation, both individually and in combination. Moreover, enzymatic antioxidants, including catalase, superoxide dismutase, peroxidase, and ascorbate peroxidase, were activated after Cd stress, but their activity was further increased with foliar application of Si or SL. In Cd-contaminated seedlings, the combined application of Si and SL enhanced soluble proline, sugars, and total phenolic contents as compared to the control treatment. Furthermore, Si and SL applications increased Si accumulation in Cd-exposed seedlings and decreased Cd uptake. It was concluded that the combined application of Si and SL improved Cd tolerance in maize seedlings by modulating morpho-physiological attributes, photosynthetic pigments, and osmolytes accumulation, and by supporting the antioxidant defense system. The findings of this study suggest that Si and SL could be safe and effective strategies for reducing Cd toxicity in maize seedlings.

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1. Introduction

Heavy metal toxicity has emerged as a severe environmental problem worldwide. The most challenging and severe soil contaminants are heavy metals, which are toxic to plants and harmful to people when ingested in agricultural products [1,2]. Cadmium (Cd), a heavy metal with particularly high toxicity that can harm a plant's capacity to grow and develop normally, is one of the most hazardous metals [3]. Cd, which is known to be harmful, induces phytotoxicity, water solubility, and membrane-bound organelle toxicity, and elevates the relative mobility rate. Moreover, Cd is not a pre-requisite element for plant growth and development, and excess Cd is dangerous for the plant's organs [4]. Iron transporters actively transport Cd in plants, as do xylem and phloem, while ionic transcription rates passively transport it [5]. Hence, the accumulation of Cd disrupts morphological and metabolic processes in plants, resulting in calcium, magnesium, and iron deficiency in plants [6]. Moreover, Cd toxicity harms plant cells, specifically mitochondria, cell nuclei, and chloroplasts, eventually reducing the amount of chlorophyll [7,8] in the cell. Reactive oxygen species (ROS) are affected by Cd toxicity as it triggers the lipid peroxidation reaction [9]. The malondialdehyde (MDA) level builds up much more quickly because of lipid peroxidation [4,10]. The generation of ROS activates the endogenous antioxidant defense system, which helps plants detoxify and reduce damaging effects. Superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxide (APX) are three primary antioxidant enzymes distinguished by their ability to convert hydrogen peroxide (H_2O_2) and superoxide (O^{-2}) to alleviate plant toxicity and decrease the concentrations of H_2O_2 and MDA [11,12].

Maize (*Zea mays* L.) is a cereal crop grown worldwide and a significant source of feed and industrial resources. Due to their transport and accumulation in cereal grains, heavy metal contamination, especially Cd, has a negative impact on human health [13]. Similarly, the Cd accumulation in the plants affects metabolic processes and physiological functions because of nutrient uptake imbalances, which prevent energy production [14]. Consequently, reducing the amount of Cd in food crops is important to prevent its spread through the food chain. As mono-silicic acid, silicon (Si) is the second-most prevalent metalloid and a crucial chemical component of plant biology [15]. It benefits plants and strengthens their structural integrity when subjected to environmental stresses, like drought, temperature variations, salt, heavy metals, drought, and freezing [5,16]. Batool et al. [12] proposed that Si application improves plant responses to metal toxicity with positive results. Silicon (Si) should be used in bio-available forms to combat abiotic stresses due to its limited plant accessibility in Cd-contaminated soils [17].

An effective method to prevent Cd uptake in plant organs and lower the amount of Cd in Cd-contaminated soil is the appropriate application of Si fertilizers [18]. While some publications stated that applying Si to plants will boost their yield, growth, and Cd buildup in their shoots, on the other hand, others have deflated these claims [19,20]. In comparison with control plants, the application of Si-boosted CAT and GPx activity in wheat plants that had been exposed to Cd [21]. Shi et al. [22] reported that boosting antioxidant activities, especially those involved in eliminating H_2O_2, can lower the production of ROS in crops under biotic stress. Exogenous Si treatment decreased Cd absorption and transport among plant organs in crops like maize [18], wheat [23] and rice [24,25] according to various studies.

Strigolactones (SLs) are a new class of plant hormones that play an important role in protecting plants against abiotic stress. This hormone may significantly modulate the harmful effects of abiotic stresses [26,27]. There are various approaches that can be used to reduce Cd toxicity; however, the process of Cd toxicity reduction in plants through

exogenous phytohormone application is significant [28]. Tai et al. [29] claimed that, by raising the concentration of photosynthetic pigments and decreasing Cd absorption, SL treatment mitigated the effects of Cd toxicity in switchgrass. However, more SL, which was connected to the competition between Cd and other elements, caused Fe and Zn levels to rise [29]. The application of SL improved the photosynthetic capability of plant leaves by improving chlorophyll content and reducing Cd-induced oxidative stress by increasing antioxidant enzyme activities. SL application regulated the antioxidant enzyme system for redox homeostasis, protected the chloroplasts and pigments that ultimately increased photosynthetic performance, and reduced Cd-induced damage in *A. annua* [30]. Maize is well known for its nutritive value, which has suffered due to the injudicious use of fertilizers, causing Cd toxicity. Inclusion of Cd in the food chain is equally harmful to humans and livestock. The reported literature presents the individual role of Si and SL in the alleviation of heavy metals in different crop species, but there are few studies that have investigated the combined application of Si and SL for heavy metal toxicity. Therefore, we hypothesized that a formulation which simultaneously applied Si and SL could alleviate cadmium (Cd) toxicity in maize. The primary aim of this study was to explore the physiological and biochemical mechanisms underlying maize's tolerance to Cd toxicity.

2. Materials and Methods

2.1. Experimental Conditions

A pot experiment was conducted in a greenhouse at the College of Agriculture, University of Layyah Pakistan, during the spring season 2022, to assess the efficacy of sole and combined foliar applications of silicon (Si) and strigolactone (SL) in ameliorating the negative effects of cadmium toxicity in maize crop seedlings. Five uniformly sized healthy seeds of maize hybrid NK-6654 were sown in each pot. Maize seeds were obtained from Syngenta Pakistan Limited. Earthen pots (16 cm diameter and 45 cm height) and were filled with 15 kg of sandy loam soil. At the time of sowing, to improve growth and development of crops, 80, 60, and 50 mg of N (in the form of urea), P_2O_5, and K_2O kg^{-1}, respectively, were mixed in the soil.

2.2. Experimental Treatments and Design

There were two main factors in the experiment: (i) Levels of Cd viz 0 mg Cd kg^{-1} soil (no-stress) and 25 mg Cd kg^{-1} soil (Cd-stress) and (ii) foliar application of Si and SL concentration (control Ck, 4.0 mM Si, 20 µM SL, and 4.0 mM Si + 20 µm SL). A factorial arrangement with completely randomized design (CRD) and five replications was used. Depending on the treatment, Si and SL were used separately and in combination. Cadmium stress was induced by skipping the soil with laboratory-quality cadmium chloride ($CdCl_2$). For the 15 days after sowing, Si in the form of sodium silicate ($NaSiO_3$) and strigolactone analog GR24 (obtained from Sigma-Aldrich Crop St. Louis, MO, USA) were applied to the respective treatments. Tween-20 (0.05%) was used as the surfactant. Both Si and SL were applied twice to achieve the maximum absorption by the leaves.

2.3. Morphological Traits

After one week of silicon (Si) and strigolactone (SL) application to the leaves, measurements were taken and root-shoot characteristics were measured). Maize seedlings, along with the soil from the pots, were carefully uprooted. The roots were carefully washed with distilled water to remove soil particles. Then, roots and shoots were separated from the joint. After recording the length and fresh biomass data, the samples were oven dried at 75 °C until constant weight for dry biomass was achieved.

2.4. Photosynthetic Pigments

To estimate the chlorophyll (a, b) and total chlorophyll contents, the method by Takaichi et al. [31] was used, while carotenoid contents were analyzed following the

Arnon [32] procedure. Fresh leaf material (0.1 g) from maize seedlings was homogenized in acetone (80%). The absorption of the samples was measured using a spectrophotometer at three different wavelengths: 645, 663, and 480 nm. Total photosynthetic pigments were then determined using the formula by Yoshida [33].

2.5. Determination of Oxidative Stress Indicators

Maize leaf samples were prepared to assess the oxidative stress indicators. Malondialdehyde (MDA) content was measured using the method by Heath and Packer [34]. For this method, leaf tissue (0.5 g) was ground in 0.1% (w/v) TCA (0.1 mL). Samples were centrifuged after homogenization with 1.5 mL of 20% TCA containing 0.5% TBA mixed in 0.5 mL of supernatant. The mixture was then placed in a water bath at 95 °C for fifteen minutes, and the concentration of MDA was determined at 532 nm. To determine the concentration of hydrogen peroxide (H_2O_2), the absorbance was measured at 390 nm following the procedure by Velikova et al. [35]. The electrolyte leakage was measured using the method described by Agarie et al. [36]. The membrane stability index (MSI) was calculated using the following formula: MSI (%) = $(1 - [C_1/C_2]) \times 100$, as described by Premachandra et al. [37].

2.6. Determination of Enzymatic Antioxidants Activities

Giannopolitis and Ries [38] described a method for determining SOD activity. A combined 0.1 mL of EDTA (3 mM), 0.1 mL of sodium carbonate (1.5 M), 0.1 mL of NBT (2.25 mM), 1.5 mL of phosphate buffer (100 mM), 1.0 mL of distilled water, 0.2 mL of L-methionine (200 mM), and 0.1 mL of enzyme extract were mixed to make a total volume of 3 mL. The reaction was initiated by adding 0.1 mL of riboflavin (60 µM), and the absorbance was measured at 560 nm using a spectrophotometer. For POD activity measurements, the method described by Chance and Maehly [39] was used. Activity was determined in a 3 mL reaction solution consist of phosphate buffer 50 mM (pH 7.0), 20 mM guaiacol, H_2O_2 40 mM, and 0.1 mL of enzyme extract. Absorbance measurements at 470 nm per 20 s were used to assess the increase in absorbance. To determine catalase activity, the method described by Chance and Maehly [39] was utilized. This measurement involved a 3 mL reaction solution consisting of a 50 mM phosphate buffer with a pH of 7.0, containing 5.9 mM H_2O_2, and 0.1 mL of enzyme extract. Every 20 s, a decrease in absorbance at 240 nm was measured to determine catalase activity. To measure APX activity, we applied the method described by Nakano and Asada [40]. Absorbance measurements by a spectrophotometer were made every 20 s for two minutes at 290 nm with an APX reaction mixture consisting of 1 mL of 50 mM phosphate buffer with a pH of 7.5, 0.5 mg ascorbate, 0.1 mg H_2O_2, and 0.1 mg enzyme extract. EU mg 1 protein has been used to show the activity of APX. At 25 °C, one unit of APX activity was defined as the amount of enzyme required to decompose 1.0 mol of substrate.

2.7. Osmolytes Determination

Using 0.5 g of fresh maize leaves, free proline and total soluble protein content were determined. A pre-chilled mortar and pestle with a pH buffer of 7 was used to crush the sample. A mixture of various phosphates, including cocktail protease inhibitors, was then added to a saline buffer containing 2 mM KH_2PO_4, 2.7 mM KCl,10 mM Na_2HPO_4, 1.37 mM NaCl, and 1 L of di-ionized water. HCl was used to maintain the pH stability of the buffer; it was autoclaved, then centrifuged at a rate of 12,000× g for around five minutes. In order to determine the concentration of a soluble protein, the samples were analyzed. The total amount was determined using the Bradford [41] protocol. Standard curves were built using BSA (bovine serum albumin) dilutions of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 g L^{-1}. The DI water and 400 mL dye stock were added to the incubated tubes to vortex them. In order to quantify the absorption, absorption measurements were made using a UV 4000 UVVIS spectrophotometer. Simaei et al. [42] (2011) procedure was used to measure the proline concentration. A total of 10 mL of sulpho-salicylic acid which

had w/v 3% was used to homogenize fresh leaf samples. The obtained filtrate was saved in test tubes for color development. The filtrate was mixed with 2.5% of ninhydrine and glacial acetic acid. After this, it was heated to 100 °C for 60 min in a water bath and the reaction was stimulated. After the test tubes were removed from the water bath, a solvent called toluene was added to help separate the chromophores. To determine total soluble sugars content, fresh leaf tissue having a weight of 0.2 g was homogenized in 5 mL of 80% aqueous ethanol. The centrifugation of resulting homogenate was complete at 3500× *g* for 10 min. The 100 mL of sample extract and 3 mL of anthrone reagent were combined before being heated at 95 °C for ten minutes in the water bath. Following the procedure outlined by Yemm and Willis [43], a spectrophotometer was used to measure the absorbance at 625 nm, once cooled. The Julkenen-Titto [44] procedure was used to calculate total phenolic contents of fresh leaf samples. Simply, 1 mL of acetone (80%) was used to homogenize fresh leaf tissue that had a weight of 0.2 g, which was then centrifuged for 15 min at 12,000 rpm. After that, a test tube containing 100 L of the supernatant, 2.5 mL of 20% Na_2CO_3, and 0.5 mL of Folin Ciocalteu's phenol reagent were combined and shaken. Distilled water was added to achieve the final volume of 5 mL. At 750 nm, the absorbance was measured after 20 min.

2.8. Determination of the Cd and Si Contents

A 0.1 g sample of maize root and shoot was taken and placed in a test tube containing a 3:1 mixture of HNO_3 and H_2SO_4. The test tube was then heated for 2 to 3 h on a hot plate. The temperature of the hot plate was gradually increased until it reached 200 °C. The mixture was returned to the test tubes after it had been heated. The test tubes were then filled with 0.5 mL of $HClO_4$ and heated until the solution became discolored. Next, the test tubes were removed from the hot plate and allowed to cool. Distilled water was added to the solution until it reached a final volume of 50 mL. The content of Cd was then determined using Wolf's [45] method and an atomic absorption spectrophotometer (Hitachi, Z-2000, Tokyo, Japan) to analyze samples of roots and shoots from maize. The determination of the silicon content in maize samples was completed using 0.1 g of dry sample. The maize sample was mixed with a combination of 1 mL of 40% hydrofluoric acid, 7 mL of HNO_3 (70%), and 2 mL of 30% H_2O_2 and then digested for 10 min using a microwave digestion system. After digestion, the samples were diluted with a 4% boric acid solution to a final volume of 50 mL. The Si concentration in the digested solution was determined as follows: 0.5 mL of dissolved aliquot was transferred to plastic centrifuge tube. Then, the tube was filled with 0.5 mL of ammonium molybdate (10%), 3.75 mL of HCl (0.2 N), and 0.5 mL of amino naphtholsulphonic acid. Furthermore, 0.5 mL of tartaric acid 20% was added to the mixture, which was then filled with distilled water to a volume of 12.5 mL. Using a UV visible spectrophotometer, the density of the solution was recorded at 390 nm. After allowing the mixture to stand for 1 h to complete the reaction. To calibrate the Si measurement, a Merck Certipur® Si standard solution (1000 mg L^{-1}) was used to prepare standards of Si with concentrations of 0, 0.2, 0.4, 0.8, and 1.2 ppm. The same procedure described by Ma et al. [46] was used to take these measurements.

2.9. Statistical Analysis

The data were analyzed using Statistix 8.1 software (Analytical Software, Statistix; Tallahassee, FL, USA, 1985–2003) with analysis of variance (ANOVA) methods. Tukey's test was used to establish mean distinctions at a 5% probability level. A Sigma plot was used to create a graphical representation of the data.

3. Results

3.1. Morphological Attributes

Results of this study revealed that the morphological attributes of maize seedlings were significantly reduced when exposed to cadmium stress. However, foliar application of Si and SL, alone or in combination, had a significant impact on morphological attributes of

maize seedlings under both non-stress and Cd-stress conditions (Figure 1). Under the non-stress condition, sole application of Si improved the shoot length, shoot fresh weight, shoot dry weight, root length, root fresh weight, root dry weight, and leaf area by 5.49%, 6.91%, 5.37%, 5.11%, 6.60%, 12.78%, and 15.50%, respectively, as compared to control treatment. Sole application of SL improved the shoot length by 14.71%, shoot fresh weight by 12.69%, shoot dry weight by 15.52%, root length by 9.44%, root fresh weight by 17.56%, root dry weight by 15.65%, and leaf area by 19.29% under the non-stress condition. Application Si + SL enhanced the growth of shoot length, shoot fresh weight, shoot dry weight, root length, root fresh weight, root dry weight and leaf area by 17.82%, 16.63%, 21.13%, 12.92%, 25.274%, 26.730%, and 22.06%, respectively, under the non-stress condition. Application of Si alone increased the shoot length by 11.93%, shoot fresh weight by 10.53%, shoot dry weight by 8.03%, root length by 7.32%, root fresh weight by 22%, root dry weight by 15.04%, and leaf area by 10.72% under the Cd-stress condition (Figures 1 and 2). Sole SL application enhanced the growth of shoot length by 20.50%, shoot fresh weight by 16.41%, shoot dry weight by 13.82%, root length by 20.32%, root fresh weight by 28.44%, root dry weight by 27.38%, and leaf area by 16.56% under the Cd-stress condition. Combination application of Si and SL showed the greatest increase in growth under the Cd-stress condition, with shoot length, shoot fresh weight, shoot dry weight, root length, root fresh weight, root dry weight and leaf area increasing by 23.71%, 18.26%, 19.50%, 24.30%, 39.12%, 39.23%, and 19.30%, respectively. Moreover, when Si and SL were applied together, there was a significant enhancement in growth parameters as compared to sole application of Si and SL.

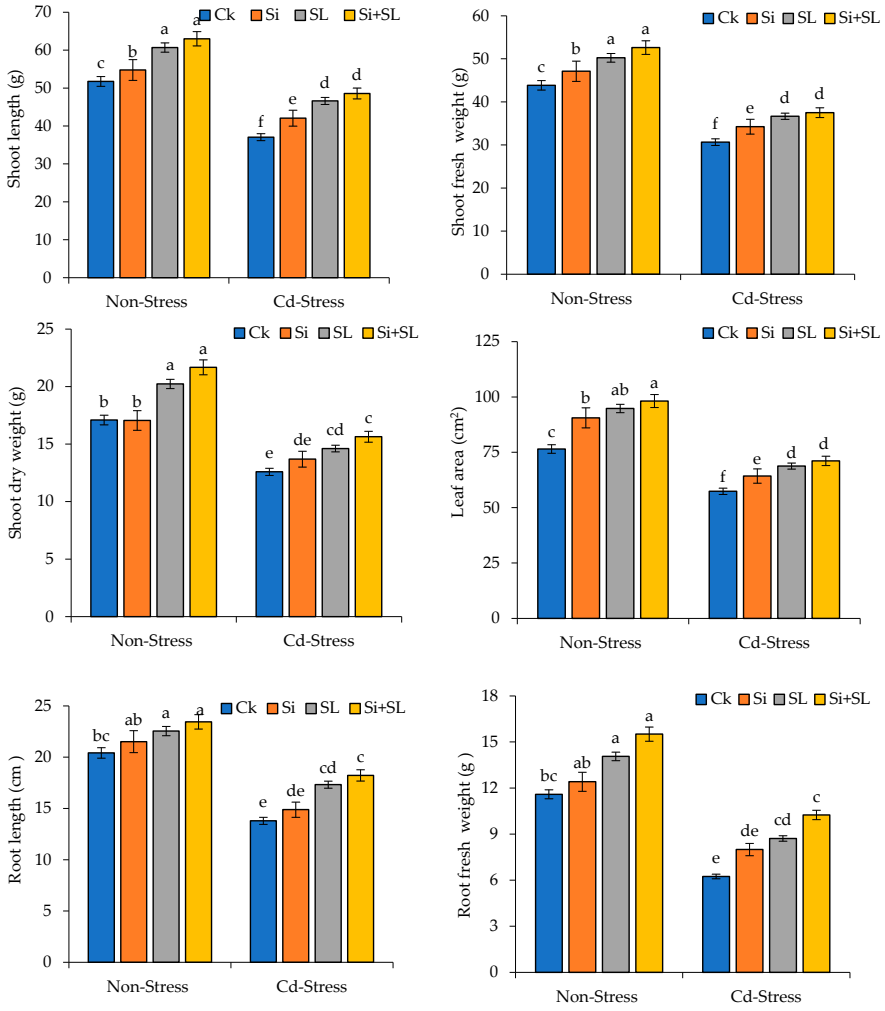

Figure 1. Influence of foliar application of silicon and strigolecton on shoot length (**a**), shoot fresh weight (**b**), shoot dry weight (**c**), leaf area (**d**), root length (**e**), and root fresh weight (**f**) of maize seedlings grown

under cadmium toxicity. Different letters above the bar indicate significance difference among the treatments.

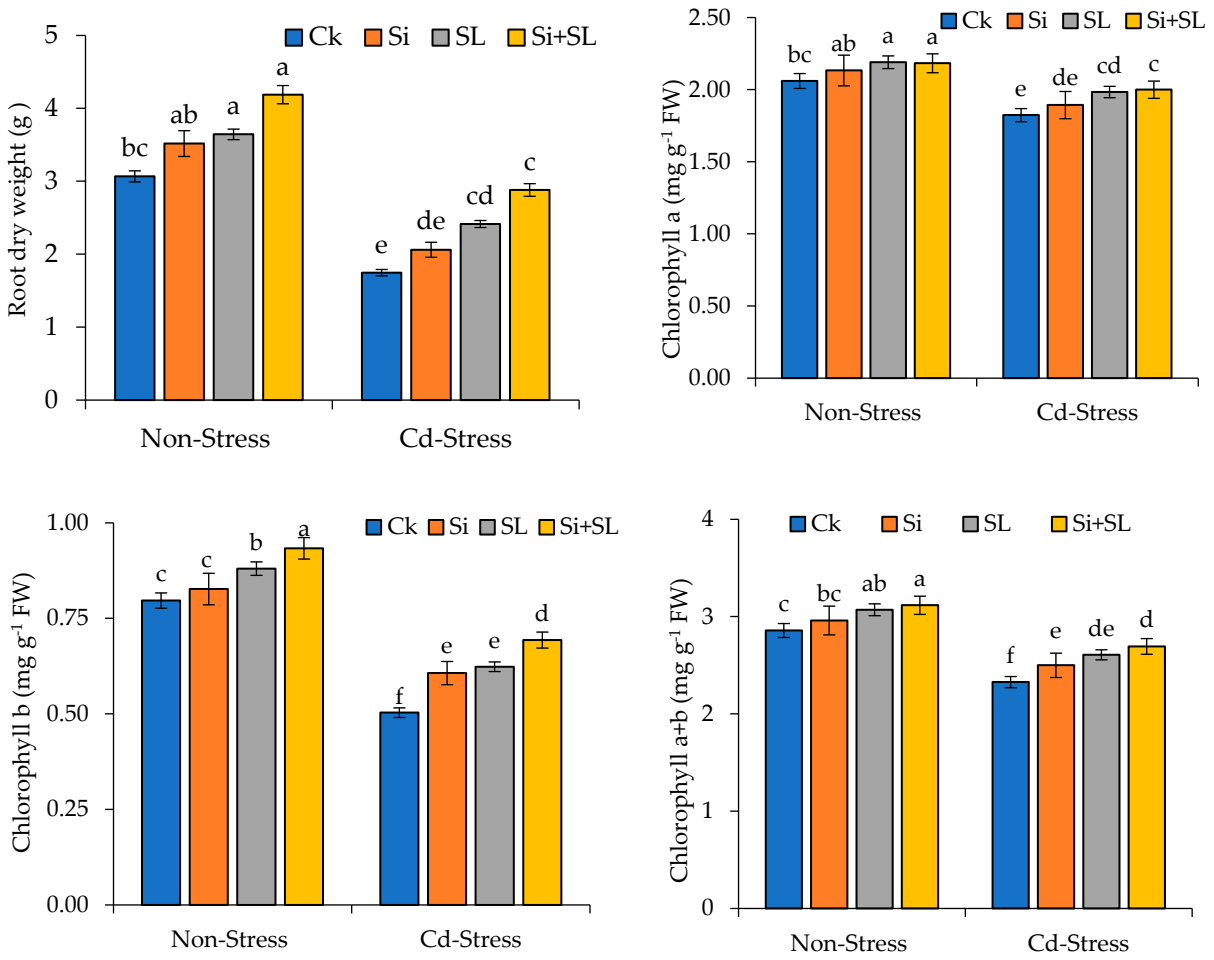

Figure 2. Influences of foliar application of silicon and strigolecton on root dry weight (**a**), chlorophyll a (**b**), chlorophyll b (**c**), and chlorophyll a+b (**d**) of maize seedlings grown under cadmium toxicity. Different letters above the bar indicate significance difference among the treatments.

3.2. Photosynthetic Pigments

In the absence of cadmium stress, application of Si, SL, and the two in combination, increased the levels of various photosynthetic pigments in maize seedlings, including chl a, chl b, chl a+b, and carotenoid. Sole application of Si increased the levels of chl a, chl b, chl a+b, and carotenoid by 3.28%, 3.614%, 3.378%, and 10.526%, respectively, under the non-stress condition. Sole SL application enhanced the levels of chl a by 5.93%, chl b by 9.09%, chl a+b by 6.84%, and carotenoid by 15% under the non-stress condition. Combined application of Si and SL increased the level of chl a, chl b, chl a+b, and carotenoid by 5.50%, 13.97%, 8.33%, and 16.04%, respectively, under the non-stress condition. However, when cadmium stress was applied, the levels of these pigments decreased significantly. Applying Si, SL, and their combination to maize seedlings under cadmium stress also increased the levels of these pigments. Application of Si alone increased the levels of chl a by 3.70%, chl b by 18.03%, chl a+b by 6.8%, and carotenoid by 12.5% under the Cd-stress condition (Figure 2). Sole SL application enhanced the levels of chl a by 8.08%, chl b by 19.35%, chl a+b by 10.72%, and carotenoid by 24.32% under the Cd-stress condition. Si and SL combination showed the greatest increase in the level of chl a, chl b, chl a+b, and carotenoid, by 9%, 27.53%, 13.38%, and 30%, respectively, under the Cd-stress condition The combined application of Si and SL yielded more significant results compared to the sole application of Si and SL.

3.3. Oxidative Stress Indicators

Application of Si and SL significantly reduced the H_2O_2, MDA, and electrolytic leakage and enhanced cell membrane stability of maize seedlings under Cd toxicity. Application of Si, SL, and Si + SL decreased H_2O_2, MDA, and electrolytes leakage and improved the cell membrane stability in both the Cd-stress and non-stress conditions, but the major and clear results were seen under the Cd-stress condition. Sole application of Si decreased the H_2O_2, MDA, and electrolytic leakage and increased cell membrane stability by 13.34%, 29.40%, 10.02%, and 2.81%, respectively, under the non-stress condition, and by 6.692%, 8.15%, 9.082%, and 11.489% under the Cd-stress condition (Figure 3). Sole application of SL also reduced the H_2O_2 by 39.31%, MDA by 31.35%, and electrolyte leakage by 8.97% and improved cell membrane stability by 12.83% in Cd toxicity. Under the Cd-stress condition, sole application of SL also reduced the H_2O_2, MDA, electrolytic leakage and increased cell membrane stability by 30.24%, 24.437%, 36.308%, and 17.283%, respectively. The combined treatment of Si and SL significantly decreased the H_2O_2, MDA, and electrolytic leakage and increased cell membrane stability by 53.87%, 43.02%, 57.49%, and 19.803%, respectively, under the Cd-stress condition.

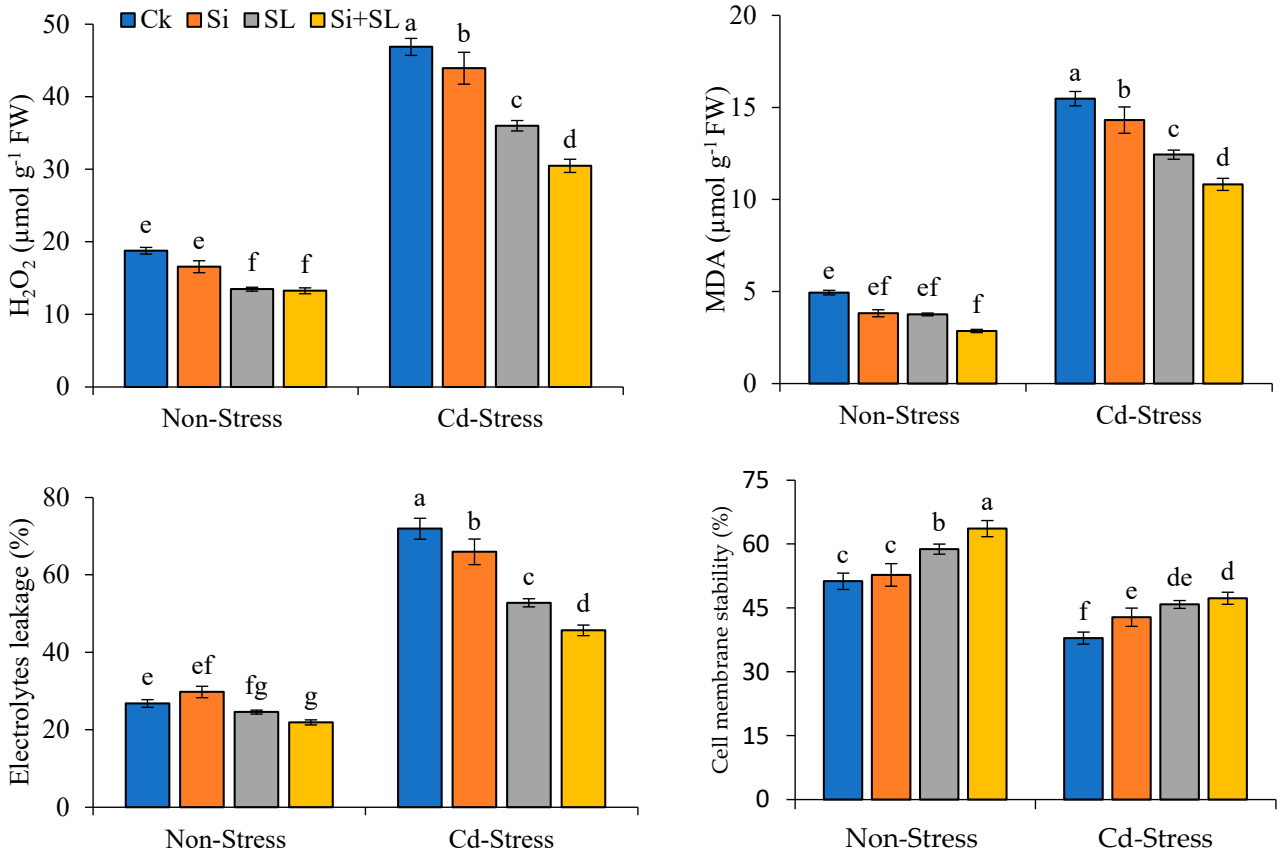

Figure 3. Influence of foliar application of silicon and strigolecton on oxidative stress indicators of maize seedlings grown under cadmium toxicity. Different letters above the bar indicate significance difference among the treatments.

3.4. Enzymatic Antioxidants Activities

The activity of antioxidant enzymes in plants was significantly affected by cadmium stress. The application of Si and SL alone, as well as their combination, had a significant impact on enzymatic antioxidant activity. Foliar application of Si, SL, and their combination to maize seedlings exposed to Cd stress increased the activities of enzymatic antioxidant enzymes. Application of Si alone increased the activity of SOD by 15.22%, CAT by 12.59%, POD by 19.75%, and ascorbate peroxidase by 9.58% under the Cd-stress condition. Sole SL application enhanced the activity of SOD, CAT, POD, and ascorbate peroxidase activity

by 20.86%, 21.13%, 33.56%, and 6.20%, respectively, under Cd-stress (Figure 4). Si and SL combination showed the greatest increase in the activity of SOD, CAT, POD, and ascorbate peroxidase activity under the Cd-stress condition by 24.41%, 26.93%, 41.78%, and 25.49%, respectively. The combined application of Si and SL showed more significant results compared to either the sole application of Si or SL.

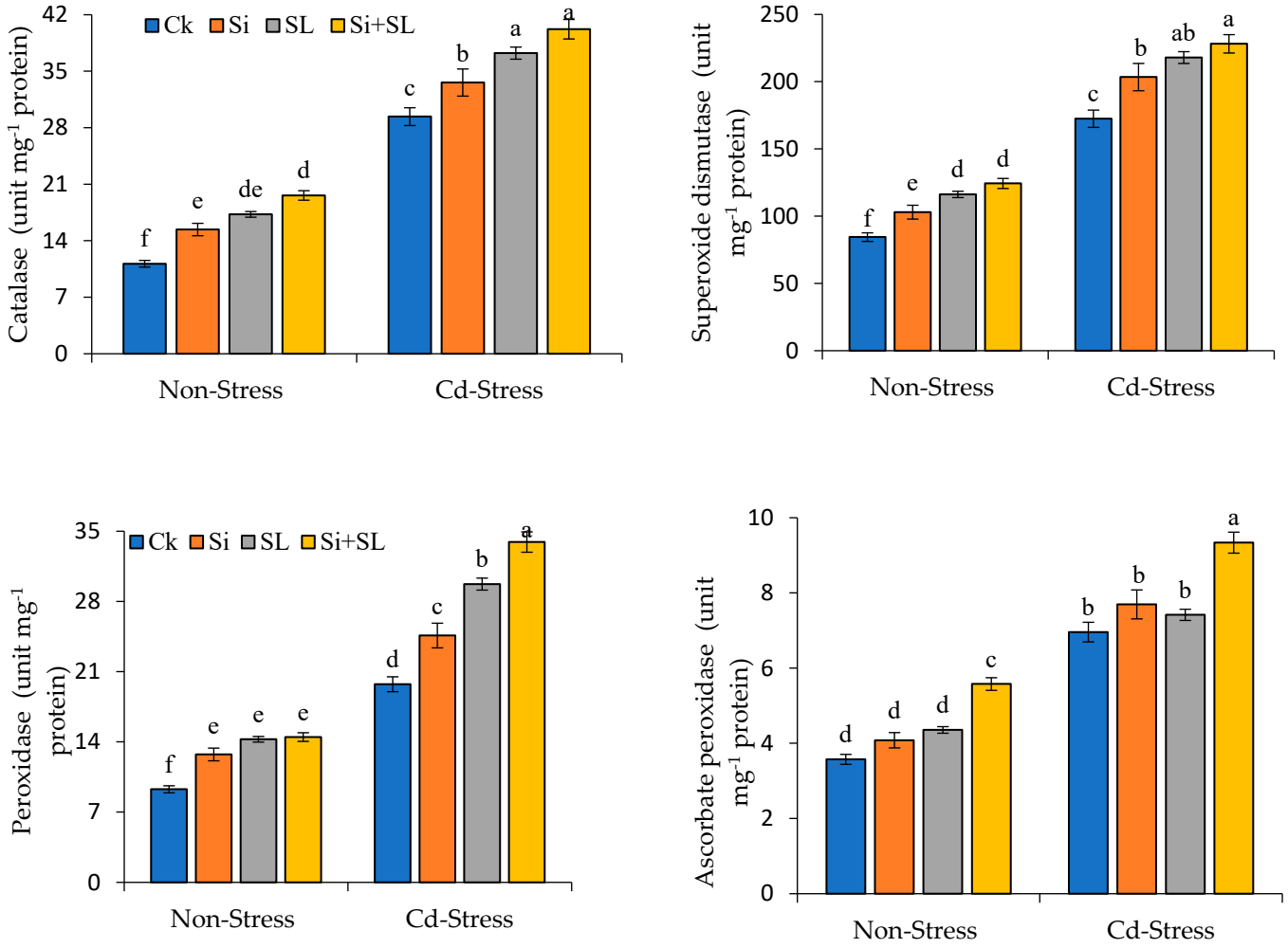

Figure 4. Influence of foliar application of silicon and strigolecton on antioxidants of maize seedlings grown under cadmium toxicity. Different letters above the bar indicate significance difference among the treatments.

3.5. Concentration of Osmo-Protectants

The number of osmo-protectants in maize seedlings was significantly affected by cadmium stress. The application of Si and SL alone, as well as their combination, had a significant impact on the levels of osmo-protectants in plants. However, when cadmium stress was applied, the levels of these osmo-protectants decreased significantly. Applying Si, SL, and their combination to maize plants under cadmium stress also increased the levels of these osmo-protectants. Application of Si alone increased the proline by 15.70%, soluble protein by 16.95%, total soluble sugar by 8.07%, and total phenolic contents by 30.51% under the Cd-stress condition. Sole SL application enhanced the amounts of proline by 23.53%, soluble protein by 30.94%, total soluble sugar by 13.11%, and total phenolic contents by 37.47% under the Cd-stress condition (Figure 5). Si and SL combination showed the greatest increase in growth of proline, shoot fresh weight, total soluble sugar, and total phenolic contents, by 31.35%, 36.41%, 17.12%, and 48.45%, respectively, under the Cd-stress condition. Furthermore, when Si and SL were combined, the level of osmo-protectants increased significantly more than when Si and SL were used alone.

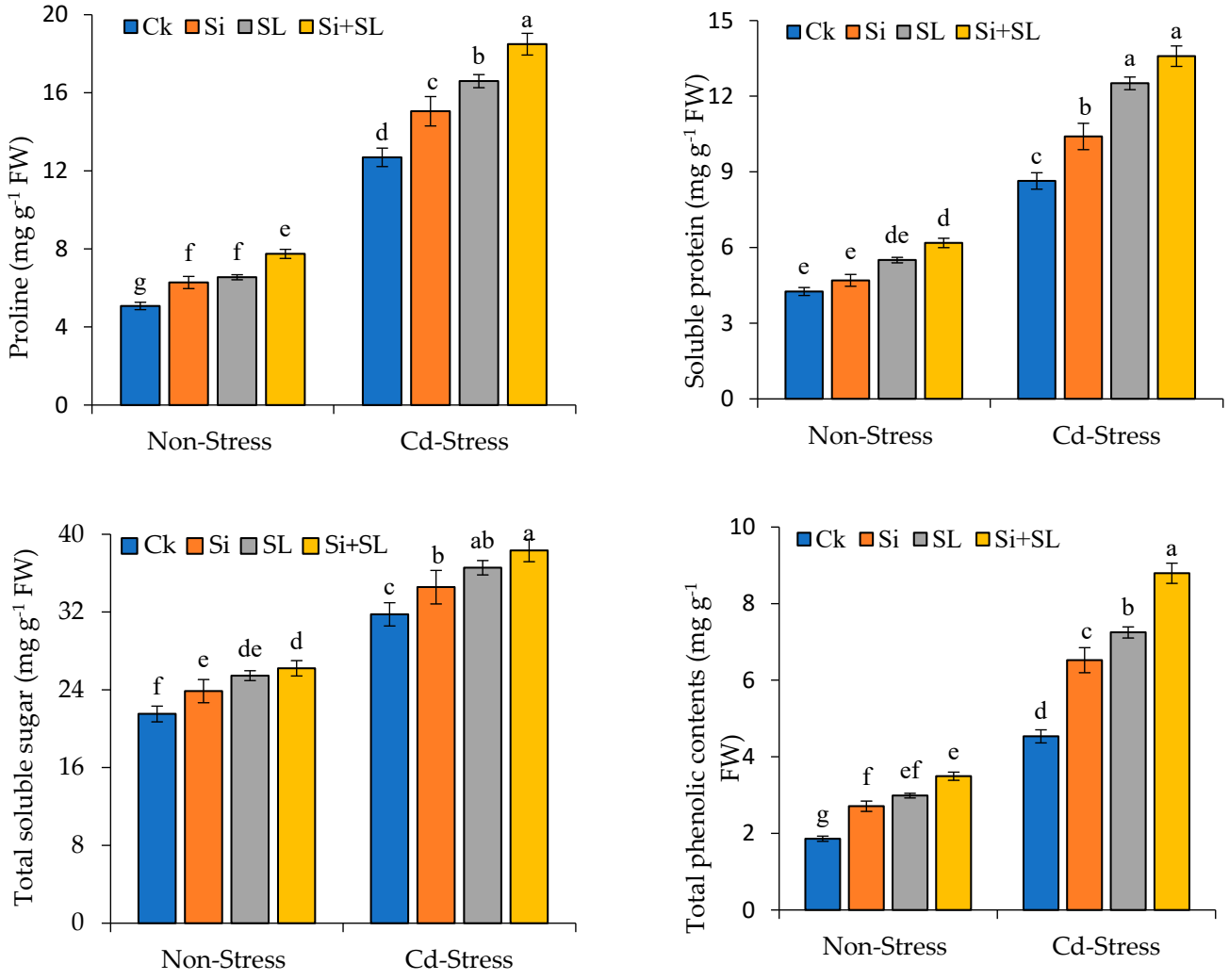

Figure 5. Influence of foliar application of silicon and strigolecton on osmolytes of maize seedlings grown under cadmium toxicity. Different letters above the bar indicate significance difference among the treatments.

3.6. Concentration of Cadmium and Silicon in Maize Seedlings

The application of Si and SL significantly influenced the concentration of Cd and Si in the shoots and roots of maize seedlings. The application of Si, SL, and Si + SL decreased the Cd contents in both shoots and roots in both Cd-stress and non-stress conditions, but the most significant and clear results were recorded under the Cd-stress condition. Sole application of Si declined the shoot Cd contents by 23.09% and root Cd contents by 29.48% under the Cd-stress condition. Sole application of SL also reduced the shoot Cd contents by 44.19% and root Cd contents by 45.65% in the presence of Cd stress. The combined treatment of Si and SL significantly decreased the shoot Cd contents and root Cd contents by 102.41% and 82.67%, respectively, under the Cd-stress condition (Figure 6). Applications of Si alone increased the shoot Si contents and root Si contents by 89.59% and 80%, respectively, under the Cd-stress condition. Sole foliar application of SL increased the shoot Si contents by 56.03 and decreased the root Si contents by 29.51% under the Cd-stress condition. Under the Cd-stress condition, the combined application of Si and SL enhanced the shoot and root Si contents by 89.66% and 83.10%, respectively.

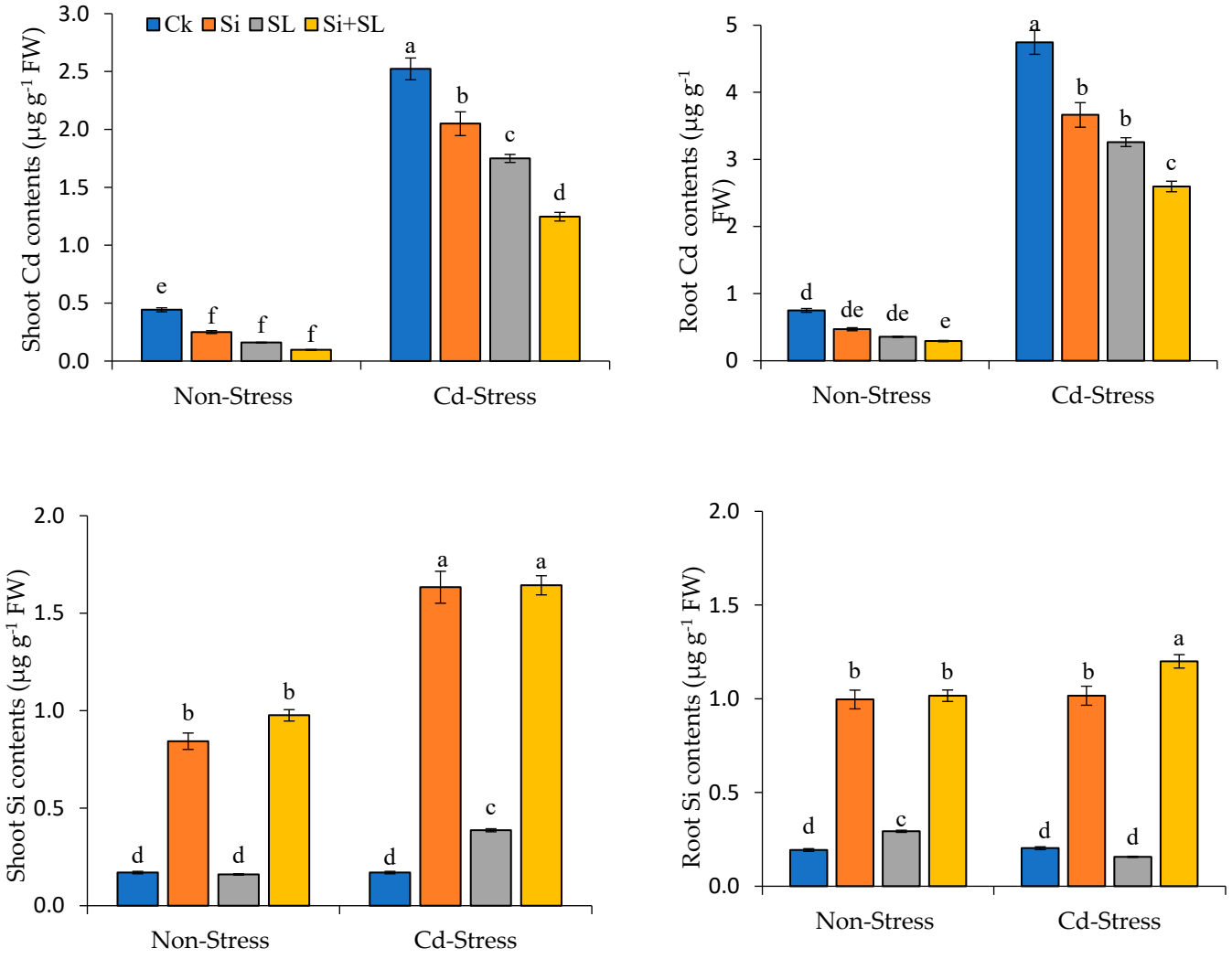

Figure 6. Influence of foliar application of silicon and strigolecton on Cd and Si contents of maize seedlings grown under cadmium toxicity. Different letters above the bar indicate significance difference among the treatments.

4. Discussion

Cadmium toxicity in plants and its mitigation through the use of mineral nutrients and plant hormones is a topic of great interest for researchers due to its wide-ranging applications. Silicon, already established as a beneficial and quasi-essential plant nutrient, forms a favorable combination for alleviating cadmium stress in maize plants when combined with a plant hormone. The morphological features of Cd-stressed plants improved as a result of sole Si and SL application; however, the overall synergistic response of both the nutrient and the plant hormone was far superior to their individual application. This might be attributed to their individual plant-growth-favoring properties, which become more prominent and beneficial in supporting the plant's existence and sustainability under stressed conditions. A serious reduction in growth parameters of Cd-stressed maize plants has been observed in terms of leaf necrosis, root browning, and growth restriction, as supported by Azzi et al. [47], Benavides et al. [48], and Hatamian et al. [49]. Excessive Cd disturbs moisture and nutrient uptake balance, thus interrupting the basic physiological processes of photosynthesis and transpiration [50,51]. It also results in a negative trend in Chlorophyll a, b, a+b and carotenoid contents [10,52]. Cd stress is an inducer of oxidative stress, as evidenced by an increase in H_2O_2 contents, MDA contents, and electrolyte leakage and an improvement in membrane stability. As plants have an innate ability to counteract such ROS species, which are produced as a result of stressed conditions, there is a rise in

SOD, CAT, POD, and APX enzymatic activities. The defense mechanisms of stressed plants are also supported by the osmo-protectants (proline, total protein, total soluble sugars, and total phenolics), which are helpful in balancing the water potential of the plant cells to counteract physiological drought conditions.

The unfavorable conditions of cadmium toxicity can impose severe checks on plant growth [53]. The prime action of cadmium toxicity is to limit the root development, which is ultimately the base for above-ground plant parts [54]. A check on root development is directly linked to nutrient absorption and its distribution through xylem and phloem. Moreover, as Cd can cause nutrient imbalances even at a low concentration and hampers the availability of Mg and Fe [48], it also causes a disturbance in chlorophyll contents, resulting in less photo assimilation rates in stressed plants [55]. However, silicon has established a role in protecting the photosynthetic process during stressed conditions [16]. The same response was noted when silicon was applied to Cd-stressed maize plants, as supported by the findings of Batool et al. [12]. Si supports cell division, chlorophyll contents, nutrient balance, reducing excessive transpiration loss, root development, and organic acid production [12]. These favorable features of Si application in nutrient-based stressed conditions increased the sustainability of plants. Si protects the stressed plants by activating the plant's defense mechanism to counteract the ROS (reactive oxygen species) activity, which is a consequence of stress. The ROS activities potentially cause damage at the cell level, denaturing its membranes and genetic material. Plants counteract these effects by using a specialized defense mechanism involving enzymes (SOD, CAT, POD, APX, etc.) and non-enzymes (ascorbic acid, phenols, etc.) that convert the ROSs into otherwise non-damaging molecules, like water and oxygen [56,57]. This defense mechanism activates whenever a plant experiences stress (biotic or abiotic); however, hastening the activation of this mechanism increases the plant's chances of survival. Si is reported to strengthen the plant's defense mechanism [58,59], and the current study also favors the previous findings. The contribution of Si in activating the plant's defense mechanism might be related to increasing the effectiveness of various ROS-scavenging metabolic pathways [12], resulting in improving membrane stability as evidenced by low electrolyte leakage and decreased MDA and H_2O_2 contents. These findings are also supported by Haider et al. [60]. The application of Si in Cd-stressed plants is also found to limit the Cd contents in plant body. In the current work, Si has restricted the Cd in roots and limited its distribution in above-ground plant parts, as indicated by lower Cd contents in shoots compared to roots.

The SL has the potential to improve root elongation [29] and, thus, supports plant growth during unfavorable conditions. The combination of both Si and SL strengthened the growth response of maize plants under Cd stress. SL is particularly related to root hair elongation, thus increasing the absorption area for water and nutrients [61] and restriction of Cd contents [29]. This trait is quite supportive under stressed conditions, as was found in current study. The improvement of root morphology through an increase in cell division rate by Si and root elongation by SL can be attributed to improved overall plant morphology when Si and SL are applied together. As SL is reported to increase nutrient absorption and Si is known for keeping absorption of nutrients balanced, their simultaneous application regulated the chlorophyll contents and its components under the Cd-stress condition. The role of SL in maintenance of chlorophyll contents is also confirmed by the findings of Min et al. [62] regarding grapes under drought stress. The conservation of photosynthetic pigments is also directly linked to photo assimilation rate; thus, the photosynthesis rate of SL-treated plants is found to be improved. The defense mechanism of stressed plants was found to be more efficient in terms of antioxidant enzymes and osmo-protectant (proline, total soluble sugars, soluble protein, and total phenolics) accumulation when Cd-stressed plants experienced SL and Si + SL (with Si + SL being more pronounced). These findings are also supported by Qiu et al. [63] and Mostafa et al. [64]. As reported by Mostafa et al. [64], SL biosynthesis in response to heavy metal stress stimulates the antioxidant system at the cell level and the sequestration of arsenic in vacuole. This stress-related response from SL can also account for improvement of antioxidant efficiency in Cd-stressed maize

plants and osmolyte accumulation, resulting in enhanced plant performance. The collective application of Si and SL acted synergistically and improved the Si contents of both shoots and roots in Cd-stressed plants. The sole application of SL, however, caused a higher Si content in the shoots. This finding is supported by the role of SL in balancing the nutrient uptake of stressed plants.

5. Conclusions

In conclusion, it has been determined that the combined application of Si and SL effectively supports maize plants under cadmium (Cd) stress conditions. This combined application synergistically mitigates the adverse effects of Cd toxicity. Si and SL alleviate Cd toxicity by improving plant morphology and photosynthetic pigments, reducing oxidative stress indicators, enhancing antioxidant defense enzymes, and elevating osmo-protectants. These positive outcomes collectively contribute to the enhanced survival of maize plants under stress conditions. Although the combined application of Si and SL improved maize growth and development under Cd toxicity, more field trials are required before making any commercial recommendation.

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References

1. Ahmad, S.; Mfarrej, M.F.B.; El-Esawi, M.A.; Waseem, M.; Alatawi, A.; Nafees, M.; Saleem, M.H.; Rizwan, M.; Yasmeen, T.; Anayat, A.; et al. Chromium-resistant Staphylococcus aureus alleviates chromium toxicity by developing synergistic relationships with zinc oxide nanoparticles in wheat. *Ecotoxicol. Environ. Saf.* **2022**, *230*, 113142. [CrossRef]
2. Naveed, M.; Mustafa, A.; Majeed, S.; Naseem, Z.; Saeed, Q.; Khan, A.; Nawaz, A.; Baig, K.S.; Chen, J.T. Enhancing Cadmium Tolerance and Pea Plant Health through Enterobacter sp. MN17 Inoculation Together with Biochar and Gravel Sand. *Plants* **2020**, *9*, 530. [CrossRef] [PubMed]
3. Imran, M.; Hussain, S.; Rana, M.S.; Saleem, M.H.; Rasul, F.; Ali, K.H.; Potcho, M.P.; Pan, S.; Duan, M.; Tang, X. Molybdenum improves 2-acetyl-1-pyrroline, grain quality traits and yield attributes in fragrant rice through efficient nitrogen assimilation under cadmium toxicity. *Ecotoxicol. Environ. Saf.* **2021**, *211*, 111911. [CrossRef] [PubMed]
4. Waheed, A.; Haxim, Y.; Islam, W.; Ahmad, M.; Ali, S.; Wen, X.; Khan, K.A.; Ghramh, H.A.; Zhang, Z.; Zhang, D. Impact of Cadmium Stress on Growth and Physio-Biochemical Attributes of *Eruca sativa* Mill. *Plants* **2022**, *11*, 2981. [CrossRef] [PubMed]
5. Amirahmadi, E.; Ghorbani, M.; Moudrý, J. Effects of Zeolite on Aggregation, Nutrient Availability, and Growth Characteristics of Corn (*Zea mays* L.) in Cadmium-Contaminated Soils. *Water Air Soil Pollut.* **2022**, *233*, 436. [CrossRef]
6. Javed, M.T.; Saleem, M.H.; Aslam, S.; Rehman, M.; Iqbal, N.; Begum, R.; Ali, S.; Alsahli, A.A.; Alyemeni, M.N.; Wijaya, L. Elucidating silicon-mediated distinct morpho-physio-biochemical attributes and organic acid exudation patterns of cadmium stressed Ajwain (*Trachyspermum ammi* L.). *Plant Physiol. Biochem.* **2020**, *157*, 23–37. [CrossRef] [PubMed]
7. Zhu, H.; Su, J.; Yang, F.; Wu, Y.; Ye, J.; Huang, K.; Yang, Y. Effect of lossy thin-walled cylindrical food containers on microwave heating performance. *J. Food Eng.* **2023**, *337*, 111232. [CrossRef]
8. Alam, P.; Kaur Kohli, S.; Al Balawi, T.; Altalayan, F.H.; Alam, P.; Ashraf, M.; Bhardwaj, R.; Ahmad, P. Foliar Application of 24-Epibrassinolide Improves Growth, Ascorbate-Glutathione Cycle, and Glyoxalase System in Brown Mustard (*Brassica juncea* (L.) Czern.) under Cadmium Toxicity. *Plants* **2020**, *9*, 1487. [CrossRef]

9. Haider, F.U.; Liqun, C.; Coulter, J.A.; Cheema, S.A.; Wu, J.; Zhang, R.; Wenjun, M.; Farooq, M. Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicol. Environ. Saf.* **2021**, *211*, 111887. [CrossRef]
10. Saleem, M.H.; Parveen, A.; Khan, S.U.; Hussain, I.; Wang, X.; Alshaya, H.; El-Sheikh, M.A.; Ali, S. Silicon Fertigation Regimes Attenuate Cadmium Toxicity and Phytoremediation Potential in Two Maize (*Zea mays* L.) Cultivars by Minimizing Its Uptake and Oxidative Stress. *Sustainability* **2022**, *14*, 1462. [CrossRef]
11. Hussain, S.; Irfan, M.; Sattar, A.; Hussain, S.; Ullah, S.; Abbas, T.; Ur-Rehman, H.; Nawaz, F.; Al-Hashimi, A.; Elshikh, M.S.; et al. Alleviation of Cadmium Stress in Wheat through the Combined Application of Boron and Biochar via Regulating Morpho-Physiological and Antioxidant Defense Mechanisms. *Agronomy* **2022**, *12*, 434. [CrossRef]
12. Batool, T.; Javied, S.; Ashraf, K.; Sultan, K.; Zaman, Q.U.; Haider, F.U. Alleviation of Cadmium Stress by Silicon Supplementation in Peas by the Modulation of Morpho-physio-biochemical Variables and Health Risk Assessment. *Life* **2022**, *12*, 1479. [CrossRef] [PubMed]
13. Mei, S.; Lin, K.; Williams, D.V.; Liu, Y.; Dai, H.; Cao, F. Cadmium Accumulation in Cereal Crops and Tobacco: A Review. *Agronomy* **2022**, *12*, 1952. [CrossRef]
14. Zhao, H.; Guan, J.; Liang, Q.; Zhang, X.; Hu, H.; Zhang, J. Effects of cadmium stress on growth and physiological characteristics of sassafras seedlings. *Sci. Rep.* **2021**, *11*, 9913. [CrossRef] [PubMed]
15. Heile, A.O.; Zaman, Q.U.; Aslam, Z.; Hussain, A.; Aslam, M.; Saleem, M.H.; Abualreesh, M.H.; Alatawi, A.; Ali, S. Alleviation of Cadmium Phytotoxicity Using Silicon Fertilization in Wheat by Altering Antioxidant Metabolism and Osmotic Adjustment. *Sustainability* **2021**, *13*, 11317. [CrossRef]
16. Bhardwaj, S.; Kapoor, D. Fascinating regulatory mechanism of silicon for alleviating drought stress in plants. *Plant Physiol. Biochem.* **2021**, *166*, 1044–1053. [CrossRef]
17. Bhat, J.A.; Shivaraj, S.M.; Singh, P.; Navadagi, D.B.; Tripathi, D.K.; Dash, P.K.; Solanke, A.U.; Sonah, H.; Deshmukh, R. Role of Silicon in Mitigation of Heavy Metal Stresses in Crop Plants. *Plants* **2019**, *8*, 71. [CrossRef]
18. Liu, X.; Yin, L.; Deng, X.; Gong, D.; Du, S.; Wang, S.; Zhang, Z. Combined application of silicon and nitric oxide jointly alleviated cadmium accumulation and toxicity in maize. *J. Hazard. Mater.* **2020**, *395*, 122679. [CrossRef]
19. Lu, L.; Zhai, X.; Li, X.; Wang, S.; Zhang, L.; Wang, L.; Wang, F. Met1-specific motifs conserved in OTUB subfamily of green plants enable rice OTUB1 to hydrolyze Met1 ubiquitin chains. *Nat. Commun.* **2022**, *13*, 4672. [CrossRef] [PubMed]
20. Coskun, D.; Deshmukh, R.; Sonah, H.; Menzies, J.G.; Reynolds, O.; Ma, J.F.; Kronzucker, H.J.; Belanger, R.R. The controversies of silicon's role in plant biology. *New Phytol.* **2019**, *221*, 67–85. [CrossRef]
21. Hussain, I.; Ashraf, M.A.; Rasheed, R.; Asghar, A.; Sajid, M.A.; Iqbal, M. Exogenous application of silicon at the boot stage decreases accumulation of cadmium in wheat (*Triticum aestivum* L.) grains. *Braz. J. Bot.* **2015**, *38*, 223–234. [CrossRef]
22. Shi, G.R.; Zhang, Z.; Liu, C.F. Silicon influences cadmium translocation by altering sub-cellular distribution and chemical forms of cadmium in peanut roots. *Arch. Agron. Soil Sci.* **2017**, *63*, 117–123. [CrossRef]
23. Wu, J.; Mock, H.P.; Giehl, R.F.H.; Pitann, B.; Muhling, K.H. Silicon decreases cadmium concentrations by modulating root endodermal suberin development in wheat plants. *J. Hazard. Mater.* **2019**, *364*, 581–590. [CrossRef] [PubMed]
24. Zhao, Y.; Liu, M.; Guo, L.; Yang, D.; He, N.; Ying, B.; Wang, Y. Influence of silicon on cadmium availability and cadmium uptake by rice in acid and alkaline paddy soils. *J. Soils Sediments* **2020**, *20*, 2343–2353. [CrossRef]
25. Zaman, Q.U.; Rashid, M.; Nawaz, R.; Hussain, A.; Ashraf, K.; Latif, M.; Heile, A.O.; Mehmood, F.; Salahuddin, S.; Chen, Y. Silicon Fertilization: A Step towards Cadmium-Free Fragrant Rice. *Plants* **2021**, *10*, 2440. [CrossRef]
26. Xiong, H.; Lu, D.; Li, Z.; Wu, J.; Ning, X.; Lin, W.; Bai, Z.; Zheng, C.; Sun, Y.; Chi, W.; et al. The DELLA-ABI4-HY5 module integrates light and gibberellin signals to regulate hypocotyl elongation. *Plant Commun.* **2023**, *31*, 100597. [CrossRef]
27. Sattar, A.; Ul-Allah, S.; Ijaz, M.; Sher, A.; Butt, M.; Abbas, T.; Irfan, M.; Fatima, T.; Alfarraj, S.; Alharbi, S.A. Exogenous application of strigolactone alleviates drought stress in maize seedlings by regulating the physiological and antioxidants defense mechanisms. *Cereal Res. Commun.* **2022**, *50*, 263–272. [CrossRef]
28. Wang, L.; Li, X.; Gao, F.; Liu, Y.; Lang, S.; Wang, C.; Zhang, D. Effect of ultrasound combined with exogenous GABA treatment on polyphenolic metabolites and antioxidant activity of mung bean during germination. *Ultrason. Sonochem.* **2023**, *94*, 106311. [CrossRef]
29. Tai, Z.; Yin, X.; Fang, Z.; Shi, G.; Lou, L.; Cai, Q. Exogenous GR24 Alleviates Cadmium Toxicity by Reducing Cadmium Uptake in Switchgrass (*Panicum virgatum*) Seedlings. *Int. J. Environ. Res. Public Health* **2017**, *14*, 852. [CrossRef]
30. Wani, K.I.; Naeem, M.; Khan, M.M.A.; Aftab, T. Insights into strigolactone (GR24) mediated regulation of cadmium-induced changes and ROS metabolism in Artemisia annua. *J. Hazard. Mater.* **2023**, *448*, 130899. [CrossRef]
31. Takaichi, S.; Tsuji, K.; Matsuura, K.; Shimada, K. A monocyclic carotenoid glucoside ester is a major carotenoid in the green filamentous bacterium *Chloroflexus aurantiacus*. *Plant Cell Physiol.* **1995**, *36*, 773–778. [CrossRef]
32. Arnon, D.I. Copper enzymes in isolated chloroplasts. Polyphenoloxidase in Beta vulgaris. *Plant Physiol.* **1949**, *24*, 1–15. [CrossRef]
33. Yoshida, S.; Forno, D.A.; Cock, J.H.; Gomez, K.A. *Laboratory Manual for Physiological Studies of Rice*; IRRI: Los Banos, Philippines, 1976.
34. Heath, R.L.; Packer, L. Photoperoxidation in isolated chloroplast I. Kinetics and stoichiometry of fatty acid peroxidation. *Arch. Biochem. Biophys.* **1968**, *125*, 189–198. [CrossRef]

35. Velikova, V.; Yordanov, I.; Edreva, A. Oxidative stress and some antioxidant systems in acid rain treated bean plants. Protective role of exogenous polyamines. *Plant Sci.* **2000**, *151*, 59–66. [CrossRef]
36. Agarie, S.; Hanaoka, N.; Kubota, F.; Agata, W.; Kaufman, P.B. Measurement of cell membrane stability evaluated by electrolyte leakage as a drought and heat tolerance test in rice (*Oryza sativa* L.). *J. Fac. Agric. Kyushu Univ.* **1995**, *40*, 233–240. [CrossRef]
37. Premachandra, G.S.; Saneoka, H.; Ogata, S. Cell membrane stability, an indicator of drought tolerance, as affected by applied nitrogen in soybean. *J. Agric. Sci.* **1990**, *115*, 63–66. [CrossRef]
38. Giannopolitis, C.N.; Ries, S.K. Superoxide Dismutases: I. Occurrence in Higher Plants. *Plant Physiol.* **1977**, *59*, 309–314. [CrossRef] [PubMed]
39. Chance, B.; Maehly, A.C. Assay of Catalase and Peroxidase. In *Methods of Enzymology*; Colowick, S.P., Kaplan, N.O., Eds.; Academic Press: New York, NY, USA, 1955.
40. Nakano, Y.; Asada, K. Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplast. *Plant Cell Physiol.* **1981**, *22*, 67–80.
41. Bradford, M. A rapid and sensitive method for the quantities of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal. Biochem.* **1976**, *72*, 248–254. [CrossRef] [PubMed]
42. Simaei, M.; Khavarinejada, R.A.; Saadatmanda, S.; Bernardb, F.; Fahimia, H. Interactive effects of salicylic acid and nitric oxide on soybean plants under NaCl salinity. *Russ. J. Plant Physiol.* **2011**, *58*, 783–790. [CrossRef]
43. Yemm, E.W.; Willis, A.J. The estimation of carbohydrates in plant extracts by anthrone. *Biochem. J.* **1954**, *57*, 508–514. [CrossRef]
44. Julkunen-Titto, R. Phenolic constituents in the leaves of northern willows: Methods for the analysis of certain phenolics. *J. Agric. Food Chem.* **1985**, *33*, 213–217. [CrossRef]
45. Wolf, B. A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. *Commun. Soil Sci. Plant Anal.* **1982**, *13*, 1035–1059. [CrossRef]
46. Ma, J.F.; Tamai, K.; Ichii, M.; Wu, K. A rice mutant defective in active Si uptake. *Plant Physiol.* **2002**, *130*, 2111–2117. [CrossRef]
47. Azzi, V.S.; Kanso, A.; Kobeissi, A.; Kazpard, V.; Lartiges, B.; El Samrani, A. Effect of Cadmium on *Lactuca sativa* Grown in Hydroponic Culture Enriched with Phosphate Fertilizer. *J. Environ. Prot.* **2015**, *6*, 1337. [CrossRef]
48. Benavides, M.P.; Gallego, S.M.; Tomaro, M.L. Cadmium toxicity in plants. *Braz. J. Plant Physiol.* **2005**, *17*, 21–34. [CrossRef]
49. Hatamian, M.; Nejad, A.R.; Kafi, M.; Souri, M.K.; Shahbazi, K. Interaction of lead and cadmium on growth and leaf morphophysiological characteristics of European hackberry (*Celtis australis*) seedlings. *Chem. Biol. Technol. Agric.* **2020**, *7*, 9. [CrossRef]
50. López-Millán, A.F.; Sagardoy, R.; Solanas, M.; Abadía, A.; Abadía, J. Cadmium toxicity in tomato (*Lycopersicon esculentum*) plants grown in hydroponics. *J. Environ. Exp. Bot.* **2009**, *65*, 376–385. [CrossRef]
51. Mobin, M.; Khan, N.A. Photosynthetic activity, pigment composition and antioxidative response of two mustard (*Brassica juncea*) cultivars differing in photosynthetic capacity subjected to cadmium stress. *J. Plant Physiol.* **2007**, *164*, 601–610. [CrossRef]
52. Huang, W.; Wang, X.; Xia, J.; Li, Y.; Zhang, L.; Feng, H.; Zhang, X. Flexible sensing enabled agri-food cold chain quality control: A review of mechanism analysis, emerging applications, and system integration. *Trends Food Sci. Technol.* **2023**, *133*, 189–204. [CrossRef]
53. Abbas, T.; Fan, R.; Hussain, S.; Sattar, A.; Khalid, S.; Butt, M.; Shahzad, U.; Atif, H.M.; Batool, M.; Ullah, S.; et al. Protective effect of jasmonic acid and potassium against cadmium stress in peas (*Pisum sativum* L.). *Saudi J. Biol. Sci.* **2022**, *29*, 2626–2633. [CrossRef]
54. Andresen, E.; Küpper, H. Cadmium toxicity in plants. In *Cadmium: From Toxicity to Essentiality*; Sigel, A., Sigel, H., Sige, R.K.O., Eds.; Springer: Dordrecht, The Netherlands, 2013; pp. 395–413.
55. Alcantara, E.; Romera, F.J.; Cafiete, M.; De La Guardia, M.D. Effects of heavy metals on both induction and function of root Fe(III) reductase in Fe-deficient cucumber (*Cucumis sativus* L.) plants. *J. Exp. Bot.* **1994**, *45*, 1893–1898. [CrossRef]
56. Zhang, Q.; Cheng, Z.; Wang, Y.; Fu, L. Dietary protein-phenolic interactions: Characterization, biochemical-physiological consequences, and potential food applications. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 3589–3615. [CrossRef]
57. Sen, A. Oxidative stress studies in plant tissue culture. In *Antioxidant Enzyme*; ElMissiry, M.A., Ed.; INTECH: London, UK, 2012; pp. 59–88.
58. Gheshlaghpour, J.; Asghari, B.; Khademian, R.; Sedaghati, B. Silicon alleviates cadmium stress in basil (*Ocimum basilicum* L.) through alteration of phytochemical and physiological characteristics. *Ind. Crops Prod.* **2021**, *163*, 113338. [CrossRef]
59. Khaliq, A.; Ali, S.; Hameed, A.; Farooq, M.A.; Farid, M.; Shakoor, M.B.; Mahmood, K.; Ishaque, W.; Rizwan, M. Silicon alleviates nickel toxicity in cotton seedlings through enhancing growth, photosynthesis and suppressing Ni uptake and oxidative stress. *Arch. Agron. Soil Sci.* **2016**, *62*, 633–647. [CrossRef]
60. Haider, F.U.; Farooq, M.; Naveed, M.; Cheema, S.A.; Ain, U.-N.; Salim, M.A.; Liqun, C.; Mustafa, A. Influence of biochar and microorganism co-application on the remediation and maize growth in cadmium-contaminated soil. *Front. Plant Sci.* **2022**, *13*, 983830. [CrossRef] [PubMed]
61. Kapulnik, Y.; Resnick, N.; Mayzlish-Gati, E.; Kaplan, Y.; Wininger, S.; Hershenhorn, J.; Koltai, H. Strigolactones interact with ethylene and auxin in regulating root-hair elongation in *Arabidopsis*. *J. Exp. Bot.* **2011**, *62*, 2915–2924. [CrossRef] [PubMed]
62. Min, Z.; Li, R.; Chen, L.; Zhang, Y.; Li, Z.; Liu, M.; Ju, Y.; Fang, Y. Alleviation of drought stress in grapevine by foliar-applied strigolactones. *Plant Physiol. Biochem.* **2018**, *135*, 11037. [CrossRef] [PubMed]

63. Qiu, C.-W.; Zhang, C.; Wang, N.-H.; Mao, W.; Wu, F. Strigolactone GR24 improves cadmium tolerance by regulating cadmium uptake, nitric oxide signaling and antioxidant metabolism in barley (*Hordeum vulgare* L.). *Environ. Pollut.* **2021**, *273*, 116486. [CrossRef] [PubMed]
64. Mostofa, M.G.; Ha, C.V.; Rahman, M.M.; Nguyen, K.H.; Keya, S.S.; Watanabe, Y.; Itouga, M.; Hashem, A.; Abd_Allah, E.F.; Fujita, M.; et al. Strigolactones modulate cellular antioxidant defense mechanisms to mitigate arsenate toxicity in rice shoots. *Antioxidants* **2021**, *10*, 1815. [CrossRef]

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