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Alleviating Cd Stress in Sunflower (*Helianthus annuus*) through the Sodium Silicate Application

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Abstract: Sunflower has substantial potential for the remediation of heavy metals in soil, but its efficiency in Cd-contaminated soil is limited, with high concentrations of Cd causing stress in plants. Exogenous Si enhances plant tolerance to heavy metals, but the mechanism for enhancing the tolerance of oil sunflower under Cd stress is not known. In potting experiments, sunflowers were grown in soil with a Cd concentration of 11.8 mg/kg soil (the maximum value in the Zhundong coal mining area of Xinjiang) and five Si treatment levels (0, 50, 250, 500, and 1500 mg/kg soil). Exogenous Si improved sunflower development, gas exchange characteristics, and antioxidant enzyme activities in sunflower compared with the Cd-only control; exogenous Si application increased Cd concentrations in sunflower roots, stems, and leaves, and Cd was mainly concentrated in sunflower roots. Sunflower biomass increased by 13.83–114.18%, and gas exchange parameters increased by 16.95–36.03%, 30.06–66.82%, and 9.77–14.71%, respectively, as compared to the control. With the increase in sodium silicate concentrations, sunflower antioxidant enzyme activities increased by 8.81–150.28%, 91.35–351.55%, and 35.11–54.69%, respectively, and MDA content decreased by 3.34–25.14% as compared to Si0. Moreover, exogenous Si increased Cd uptake and minimized Cd stress in sunflowers at the seedling and blooming stages, and it potentially facilitated the phytoremediation of Cd-contaminated soils through enriched plants such as sunflower, as well as contributing to the achievement of sustainable development of the soil environment.

Keywords: Cd-contaminated soil; sodium silicate; sunflower; gas exchange characteristics; antioxidant enzymes; phytoremediation; sustainability

Citation: Wu, H.; Wang, X.; Gao, H.; Chen, J.; Zhang, T. Alleviating Cd Stress in Sunflower *(Helianthus annuus)* through the Sodium Silicate Application. *Sustainability* **2024**, *16*, 2037. https://doi.org/10.3390/su16052037

Academic Editor: Georgios Koubouris

Received: 23 January 2024
Revised: 27 February 2024
Accepted: 28 February 2024
Published: 29 February 2024

1. Introduction

Cd is a highly environmentally toxic heavy metal and is widely present in the soil [1]. Cd pollution in soil mainly originates from human activities (e.g., sewage irrigation, agricultural production, metal smelting, factory emissions) and natural sources (e.g., atmospheric deposition, rock weathering, volcanic eruptions) [2,3]. Soil contaminated with heavy metals threatens human health because the contaminants can transfer to other environmental media [4,5]. The Zhundong coal mining area in the Xinjiang region has been polluted by heavy metals to hazardous levels. Studies show that the Cd soil content in the Zhundong coal mining area exceeds the national soil environmental quality class II standard, posing a high ecological risk [6]. Likewise, Cd contamination in the Zhundong mining area has also been found to negatively affect human health through diet. Cd has a cumulative effect on human health in the body. The consumption of Cd-containing foods can lead to kidney dysfunction, osteoporosis, and cancer [7]. Consequently, there is a need to find methods that can minimize heavy metals in the soil of the Zhundong coal mining area. Phytoremediation uses plants to sequester heavy metal pollutants from contaminated soils and is highly effective and more environmentally friendly than physical and chemical remediation techniques [8]. These characteristics have attracted considerable attention to phytoremediation in recent decades. Among phytoremediation techniques, phytoextraction is the most useful for removing heavy metals and metalloids from contaminated soil, sediments, and water [9]. However, this remediation technique has limitations, such as the slow growth rate and low biomass of plants, which result in the poor transfer of metals from the root system of plants to the aboveground parts, restraining the extraction of heavy metals by plants [10]. Therefore, the adoption of biomass-rich, fast-growing, and metal-enriched plants to improve soil remediation efficiency has received widespread attention.

Sunflower (*Helianthus annuus*) is an annual herbaceous plant that is a high-biomass, fast-growing annual herb, and it is widely planted in the Xinjiang region [11]. Sunflower, an enriched plant (e.g., Cd), is highly resistant to heavy metals and can effectively absorb them from the soil [12,13]. Merima et al. [14] revealed that the highest concentration of Cd was found in sunflower leaves, followed by roots, and the lowest in stems and seeds, both under low- and high-Cd-concentration treatments. Furthermore, Khalid et al. [15] stated that sunflower had the highest root bioaccumulation, at a Cd concentration of 20 mg/kg soil, and that Cd TF increased with increasing Cd content. Therefore, sunflowers are suitable for efficient phytoremediation. Cd is a mobile element readily absorbed by plant roots and accumulated aboveground [16,17]. Even at low levels in plants, Cd can impair the metabolism, leading to toxicity and even death [18,19]. Although sunflower is an enriched plant, it can be negatively affected by high levels of Cd. Thus, for effective remediation, it is important to search for a substance that can effectively alleviate Cd stress in sunflowers.

Generally, Si is not a necessary ingredient for plants but has beneficial impacts on plant and crop growth [20]. Si has been shown to mitigate the toxicity of many heavy metals in plants [21,22]. It can mitigate a variety of biotic (e.g., microbes, pests, and diseases) and abiotic (e.g., heavy metals, salinity, heat, cold, and drought) stresses in plants [23,24]. Si exerts its benefits in plants primarily via Si-transporter proteins. Rice Lsi1, together with exocytotic Si-transporter proteins, acts on Si transport between plastids and plant cells [25]. The mechanisms by which Si reduces the toxicity of heavy metals to plants are mainly that Si reduces metal activity by increasing ionic strength or pH, the release of metal–phenol complexes from Si-mediated phenolic compounds, and the co-precipitation of metals and Si in the growth medium [26]. In recent years, there has been extensive research on how Si improves plant tolerance to heavy metals. Previous studies have shown that supplementation with 1 mM Si significantly reduced the aboveground accumulation of AS in rice [27–29]. He et al. [30] observed that exogenous silica nanoparticles reduced Cd concentrations in barley leaves. Wu et al. [31,32] noted that Si supply significantly reduced Cd concentrations in wheat roots and aboveground. In addition, the addition of 400 mg/kg of Si reduced Cd concentrations in maize roots and aboveground [33]. Other studies have also reported that the Cd concentration in the xylem sap of cabbage treated with Si was significantly reduced [34]. Meanwhile, Wu et al. [35] found that Si application reduced Cd uptake by cucumber roots. Nevertheless, studies on the relieving of Cd stress in plants using sodium silicate have mainly focused on graminaceous plants (high-silica plants), such as rice (*Oryza sativa* L.) [27–29], barley (*Hordeum vulgare* L.) [30], wheat (*Triticum aestivum* L.) [31,32], and maize (*Zea mays* L.) [33], or non-accumulating plants, such as Chinese cabbage (*Brassica campestris* L. ssp. *chinensis* var. *utilis*) [34] and cucumbers (*Cucumis sativus* L.) [35]. Sunflowers are both enriched and meso-silicon; however, the mechanism by which Si alleviates Cd toxicity in metal-enriched plants remains unknown.

From a practical view, conducting studies on mitigating Cd toxicity to enhance phytoremediation efficiency, as well as promoting sustainable soil development, is crucial. Unfortunately, studies on the enhancement of Si tolerance in sunflowers remain limited. Thus, we used potting experiments to investigate the effects of five concentrations of Si on sunflowers under heavy metal stress. The aims of the study were to (1) explore the physiological changes in growth, photosynthesis, chlorophyll content, and antioxidant enzymes in sunflowers under Cd stress by adding different levels of Si to the soil at different growth stages, and (2) to examine the possible mechanisms of Cd detoxification in sunflowers at different reproductive periods after Si application.

2. Materials and Methods

2.1. Material and Conditions

Potting experiments were conducted on the rooftop of the second floor of the College of Ecology and Environment of Xinjiang University from 19 April to 6 July 2023. The rooftop was ventilated on all sides, and its center was exposed to the sun. Oil sunflower dwarf big-head DR667 was purchased from the Pearl Flower Market in Urumqi, Xinjiang, China, and grown in pots 30 cm in diameter and 24 cm in height, with a capacity of 6 kg of soil. Potting soil was collected from a depth of 0–20 cm in the forest near the teaching building of Xinjiang University and air-dried in the shade through a 10 mesh sieve. The soil texture was loamy, and its basic physical and chemical properties are listed in Table 1.

Table 1. Physical and chemical properties of the test soil.

Soil Characteristics	Value	Soil Characteristics	Value
Total Cd content ($mg \cdot kg^{-1}$)	0.29	Quick-acting phosphorus content ($mg \cdot kg^{-1}$)	58.88
Effective Cd content ($mg \cdot kg^{-1}$)	0.02	Quick-acting potassium content ($mg \cdot kg^{-1}$)	489.48
pH	7.89	Organic matter content ($g \cdot kg^{-1}$)	13.74
Alkaline nitrogen content ($mg \cdot kg^{-1}$)	43.43		

Following the nutrient requirements for potted crops [12], a base fertilizer consisting of urea, potassium dihydrogen phosphate, and potassium chloride was added to each pot. After one week, soil samples were mixed with a solution containing 11.8 mg/kg $CdCl_2$. The sunflowers were sown on 19 April 2023, and silicon treatments were carried out after interplanting after 15 days of growth: Si0, Si50, Si250, Si500, and Si1500 corresponded to the amounts of Si added (as SiO_2), namely 0, 50, 250, 500, and 1500 mg per kg of soil. Sodium silicate was added in the form of a solution [36–38]. The experiment used a completely randomized design, with nine replicates for each treatment. Sunflowers were watered with pure water (no Cd^{2+}) during the growing period, and watering was rationed according to the soil moisture, maintaining the soil water content at 30% of the maximum field water-holding capacity. Plants were grown to the seedling stage (21 June) and blooming stage (21 July). Three random plant samples were collected from each treatment. The collected fresh leaves were immediately stored in a refrigerator at −20 °C for subsequent growth and physiological and biochemical characterization at different growth periods. After sampling, the phytoremediated plants are gathered and burned or gasified into biogas for use as a gaseous fuel, which is fully utilized after the remediation of soil heavy metals [39].

2.2. The Estimation of Plant Growth and Biomass

Three pots per treatment were selected for harvest at both the seedling and blooming stages. All parts of the collected sunflowers were cleaned with tap water and rinsed thrice with purified water. Excess water was gently removed with filter paper, and plants were separated into roots, stems, and leaves to measure fresh weight. Plant height, stem thickness, number of branches, and number of leaves were recorded. Subsequently, roots, stems, and leaves were placed into paper envelopes and put into the oven, where they were killed at 105 °C for 30 min and then dried at 80 °C until a constant weight was achieved. The weight of the dried samples was measured on a ten-thousandths scale to ensure accuracy.

2.3. Quantification of Cd in Plants

Dried samples from each part of the sunflower were ground and sieved through a 0.149 mm mesh sieve. The sieved sunflower parts were removed and cooled after digestion with aqua regio-perchloric acid. The inner wall of the vessel was rinsed with plain water and filtered through quantitative filter paper into volumetric flasks. The Cd content in the sunflower roots, stems, and leaves was measured using an atomic absorption spectrophotometer (21504337) (Agilent AA240, Santa Clara, CA, USA).

$$\text{Cd accumulation} = \text{Cd content of aboveground parts (underground)} \times \text{dry weight of aboveground parts (underground)}$$

2.4. The Estimation of Chlorophyll Content and Photosynthetic Parameters

The photosynthetic characteristics of sunflower leaves were measured on the rooftop of the second floor of the College of Ecology and Environment from 10:00 a.m. to 12:00 p.m. using a portable photosynthesis meter (FS-3080D Plus, Shijiazhuang, China). Chlorophyll content was quantified using a chlorophyll content test kit (Beijing Boxbio Science & Technology Co., Ltd., Beijing, China).

2.5. Analysis of Antioxidant Enzymes and Malondialdehyde

Superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and malondialdehyde (MDA) were detected by the superoxide dismutase assay kit (Beijing Boxbio Science & Technology Co., Ltd.), POD assay kit (Beijing Boxbio Science & Technology Co., Ltd.), CAT assay kit (Beijing Boxbio Science & Technology Co., Ltd.), and malondialdehyde content assay kit (Beijing Boxbio Science & Technology Co., Ltd.), respectively.

2.6. Data Analysis

All experimental data were expressed as the mean $\pm$ standard deviation of three replicates and were statistically analyzed and plotted using Excel 2010, SPSS 26.0, and Origin 2022. One-way analysis of variance (ANOVA) and Duncan's multiple extreme variance tests were performed at a probability level of 0.05. To establish the statistical significance of the means between different reproductive periods (seedling and blooming), *t*-tests were performed at $p \leq 0.05$.

3. Results and Discussion

3.1. Impact of Sodium Silicate on Growth Characteristics of Sunflower under Cd Stress

Cd accumulation in the soil is a serious environmental problem. Heavy metal accumulation in fields of crops such as sunflowers not only affects their growth but also threatens human health. Research has said that Si promotes plant development [40]. In addition, because Si-rich ingredients such as fly ash and iron slag [41] are abundant, inexpensive, and easily accessible, the use of Si is promising. New Si fertilizers, such as nanosilicon fertilizers [42], are being developed. Nevertheless, few studies have investigated how Si mitigates Cd toxicity in sunflowers, enriched plants, and mesosilicate plants. As shown in Table 2, with an increasing gradient of Si, the plant height of each treatment showed an increasing trend, increasing by 1.40–8.17 units compared to the control Si0. The increase reached a significant level ($p < 0.05$) for the Si500 and Si1500 treatments during the seedling stage and the Si250, Si500, and Si1500 treatments during the blooming stage of the sunflower. In contrast to the sunflower plant height at the seedling stage, there was a tendency for plant height to increase with longer reproductive periods (seedling stage to blooming stage), with an increase of 21.37–25.13 units across treatments, with all five gradients of Si differing significantly ($p < 0.05$) for sunflower plant height at the blooming stage. With an increase in the Si gradient, the stem thickness of sunflowers in all treatments showed an increasing trend, increasing by 0.03–0.29 units, and the Si250, Si500, and Si1500 treatments in both periods reached significant levels ($p < 0.05$); stem thickness showed an increasing trend, 0.18–0.35 units larger in all treatments than in the seedling stage, and all five gradients of Si at the blooming stage differed significantly ($p < 0.05$). With an increasing

Si gradient, the Si1500 treatment at the seedling stage and the Si500 and Si1500 treatments at the blooming stage of the sunflowers significantly increased by 26.13–58.13% ($p < 0.05$), and the other Si treatments were nonsignificant compared with the leaf area of the control Si0. There was an overall trend of elevation in the treatments with prolonged fertility, with significant differences ($p < 0.05$) at the blooming stage compared with the seedling stage. There was no significant difference in the number of branches and number of leaf blades of the sunflowers compared with those of the control Si0; with the prolongation of the fertility period, there was an increasing trend in the number of branches and number of leaf blades in all treatments, and they were significantly larger by 20.69–63.83% and 20.31–56.60%, respectively, at the blooming stage than at the seedling stage. Our results indicated that Si application ameliorated the deleterious effects of Cd stress on sunflower growth during both reproductive periods (Table 2), which supports the results in the literature [43,44]. In this study, sunflowers treated with sodium silicate exhibited better growth than those treated with Cd alone, and the extent of growth became more pronounced as the concentration of sodium silicate increased. With the growth of sunflowers, growth indices such as plant height, stem thickness, and leaf area gradually increased, and the increase in sodium silicate concentration promoted the growth of sunflowers to a greater extent, especially with the Si250, Si500, and Si1500 treatments. These results demonstrate that the application of Si to Cd-contaminated soil significantly reduced the negative effects of Cd on sunflower growth and mitigated the stress of Cd on the plant.

Table 2. Impact of various levels of sodium silicate on growth parameters of sunflower under Cd stress.

Growth Period	Cd (mg/kg DW Soil)	Si (mg/kg DW Soil)	Plant Height (cm)	Stem Thickness (mm)	Leaf Blade Area (cm^2)	Number of Branches (One)	Number of Leaf Blades (Pieces)
Seedling	11.80	0	19.17 ± 0.60 cB	0.37 ± 0.06 cB	12.44 ± 2.91 bB	17.67 ± 1.15 abB	20.33 ± 2.52 abB
	11.80	50	20.57 ± 2.86 bcB	0.49 ± 0.05 bB	13.13 ± 2.60 bB	15.67 ± 1.15 bB	17.67 ± 1.53 bB
	11.80	250	21.73 ± 1.72 bcB	0.46 ± 0.04 bB	14.57 ± 3.24 abB	16.00 ± 1.73 bB	18.00 ± 1.73 bB
	11.80	500	23.63 ± 0.71 abB	0.60 ± 0.05 aB	18.02 ± 3.32 abB	16.67 ± 1.15 bB	19.00 ± 1.00 abB
	11.80	1500	25.93 ± 2.79 aB	0.66 ± 0.02 aB	19.68 ± 2.34 aB	19.33 ± 0.58 aB	21.33 ± 0.58 aB
Blooming	11.80	0	40.53 ± 4.01 cA	0.72 ± 0.03 cA	20.24 ± 1.05 bA	25.33 ± 1.53 aA	26.67 ± 1.53 aA
	11.80	50	42.40 ± 1.45 bcA	0.75 ± 0.05 bcA	24.22 ± 4.14 abA	25.67 ± 3.21 aA	27.67 ± 2.52 aA
	11.80	250	46.87 ± 3.33 abA	0.81 ± 0.01 abA	24.32 ± 3.41 abA	23.67 ± 2.08 aA	25.33 ± 1.53 aA
	11.80	500	46.27 ± 3.44 abA	0.80 ± 0.05 abA	25.53 ± 1.60 aA	25.67 ± 3.06 aA	28.33 ± 2.52 aA
	11.80	1500	48.70 ± 0.85 aA	0.84 ± 0.06 aA	28.68 ± 1.96 aA	23.33 ± 1.53 aA	25.67 ± 1.15 aA

Note: Data are means ± SD of three replicates. Small characters (e.g., a, b, c) represent significant ($p < 0.05$) differences between Si levels during the same growth period; uppercase characters (e.g., A, B) represent significant ($p < 0.05$) differences between growth periods for the same Si level.

3.2. Impact of Sodium Silicate on the Biomass of Sunflower under Cd Stress

As shown in Figure 1, the fresh and dry weights of each part of the sunflower changed with the concentration of sodium silicate and the growth of the sunflower. Figures 1a and 2b show pictures of sunflowers at the seedling and blooming stages. As shown in Figure 1c,e, compared with the control Si0 treatment, after all other treatments, the fresh weight of roots, fresh weight of the aboveground parts, and fresh weight of the whole plant of the sunflower showed an increasing trend, which increased by 0.02–4.28, 0.08–7.99, and 0.90–12.27 units, respectively; the seedling and blooming Si1500 treatments of the root fresh weight significantly increased by 100% and 22.89%, respectively; and the aboveground parts fresh weight and whole-plant fresh weight of Si1500 at the seedling stage, and the Si250, Si500, and Si1500 treatments at the blooming stage, were significantly increased by 91.36%, 13.32–16.92%, 94.27%, and 10.13–18.37% ($p < 0.05$). With the prolongation of the fertility period, the fresh weights of the root, aboveground parts, and whole plant exhibited an upward trend, which was significantly higher at the blooming stage than at the seedling stage by 69.03–176.78%, 155.85–438.61%, 126.51%, 126.51%, respectively ($p < 0.05$). As shown in Figure 1d,e, the aboveground dry weight and whole-plant dry weight of the sunflower, and the root dry weight, aboveground dry weight, and whole-plant dry weight of the sunflower, increased in the Si50-Si1500 treatment compared with the Si0 treatment, and the root dry weight at the seedling and blooming stage was significantly increased by 29.64–101.11% in the Si1500 treatment, and the aboveground parts dry weight and whole-plant dry weight of the Si1500 treatment at the seedling stage and the Si500 treatment at the blooming stage significantly increased by 13.83–114.18% and 14.58–111.47%, respectively ($p < 0.05$); weight tended to increase with the prolongation of the sunflower fertility period and was significantly higher at the blooming stage than at the seedling stage by 58.13–190.81%, 170.04–471.00%, and 147.93–412.46%, respectively ($p < 0.05$). In this study, the existence of Si mitigated Cd toxicity by increasing cosmetic growth indices (e.g., the plant height, stem thickness, and leaf area of sunflower plants) and biomass indicators (e.g., the fresh and dry weights of roots and aboveground parts; Figure 1). Vieira-Filho et al. [45] drew similar conclusions: the supply of Si improved plant tolerance to Cu stress and had a beneficial impact on photosynthetic parameters and antioxidant enzyme activities in Tanzanian guinea grass. However, Bokor [46] investigated the impact of Si on maize seedlings at higher Zn concentrations and did not observe any beneficial effect of Si on maize seedlings subjected to Zn toxicity. The biomass of the sunflowers gradually increased with their growth, and the increase in sodium silicate concentration promoted an increase in sunflower biomass to a greater extent, especially with the Si500 and Si1500 treatments.

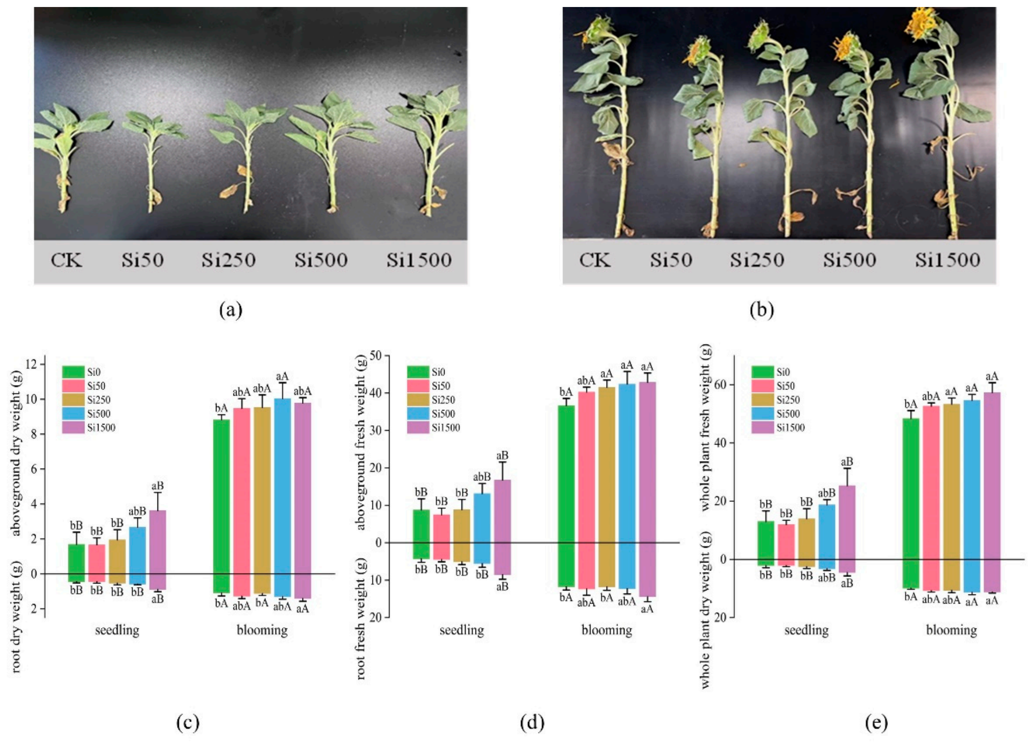

Figure 1. Impact of sodium silicate on the biomass of sunflowers at different reproductive stages. (**a**) Sunflowers grown under each treatment at the seedling stage; (**b**) sunflowers grown under each treatment at the blooming stage; (**c**) root dry weight, aboveground dry weight; (**d**) root fresh weight, aboveground fresh weight; (**e**) whole-plant fresh weight, whole-plant dry weight. Small characters a and b in the graphs represent significant ($p < 0.05$) differences between different Si levels under the same growth period; uppercase characters A and B represent significant ($p < 0.05$) differences between different growth periods under the same Si level.

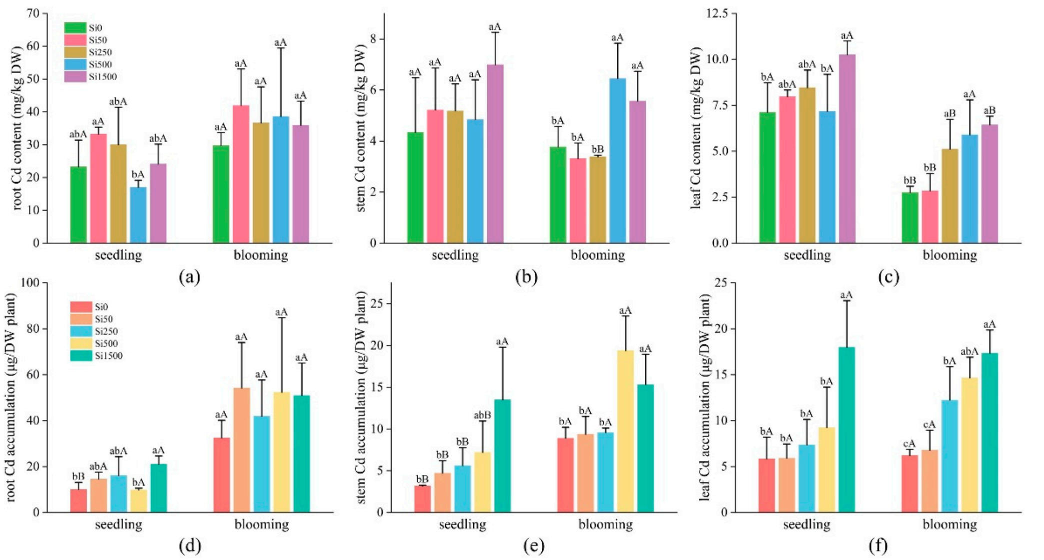

Figure 2. Impact of sodium silicate on Cd content and Cd accumulation in various parts of sunflower at different fertility stages. (**a**) Root Cd content, (**b**) stem Cd content, (**c**) leaf Cd content, (**d**) root Cd accumulation, (**e**) stem Cd accumulation, (**f**) leaf Cd accumulation. Small characters a, b, and c in the graphs represent significant ($p < 0.05$) differences between different Si levels under the same growth period; uppercase characters A and B represent significant ($p < 0.05$) differences between different growth periods under the same Si level.

3.3. Impact of Sodium Silicate on Cd Uptake and Enrichment Characteristics of Sunflower under Cd Stress

As illustrated in Figure 2a, with an increase in Si concentration, the root Cd content of each treatment showed an increasing trend, which increased by 0.82–12.17 units compared with the control Si0 and did not reach the significant level in all treatments at the seedling and blooming stages of sunflowers ($p > 0.05$). Compared with the Cd content of sunflower roots at the seedling stage, the Cd content of roots tended to increase with the fertility period, increasing by 6.45–21.60 units across treatments, with nonsignificant ($p > 0.05$) differences between fertility periods. As shown in Figure 2b, the Cd content of sunflower stems tended to increase with the increasing Si gradient, increasing by 0.50–2.68 units in all treatments and reaching significant levels ($p < 0.05$) in the Si500 and Si1500 treatments at the blooming stage. Cd content in the stems of all treatments showed a decreasing trend of 0.57–1.90 units compared with the seedling stage, and the difference between the two periods under the Si250 treatment was significant ($p < 0.05$). As shown in Figure 2c, the sunflower leaf Cd content, compared with that of the control Si0 and Si1500 treatments at the seedling stage and the Si250, Si500, and Si1500 treatments at the blooming stage, significantly increased by 44.23–133.37%, ($p < 0.05$), and the other Si treatments were nonsignificant. With the prolongation of the fertility period, there was an overall decreasing trend, with significant ($p < 0.05$) differences in the Si0, Si50, Si250, and Si1500 treatments at the blooming stage compared with the seedling stage. These results demonstrate that, with the growth of the sunflowers, the Cd content of the sunflower roots increased; the Cd content of stems and leaves gradually decreased; and the Cd content in the roots, stems, and leaves of the sunflowers increased with increasing sodium silicate concentrations, especially in the Si500 and Si1500 treatments. Sunflower, an enriched plant, is characterized by the transfer of heavy metals to the aboveground parts for accumulation [47]. However, the Cd level in sunflower roots was higher than that of the aboveground parts in all treatments (Figure 2), and it was not clear whether the heavy metals were transferred from the roots to the aboveground parts after Si addition. The results suggest that the application of Si in Cd-polluted soil significantly increased Cd uptake in all parts of the sunflower during the seedling and blooming periods, and with the prolongation of the fertility period, Cd uptake in sunflowers was mainly concentrated in the roots.

As shown in Figure 2d, root Cd accumulation in all treatments showed an increasing trend, compared with the control Si0 (i.e., increased by 4.45–21.70 units), and the Si1500 treatment at the seedling stage significantly increased by 108.60% ($p < 0.05$). With the extension of fertility compared with the seedling stage, root Cd accumulation in all treatments showed an increasing trend, by 141.98–272.84%, and the difference was significant ($p < 0.05$) only for the Si0 treatment. As shown in Figure 2e, with the increase in the Si gradient, the stem Cd accumulation of sunflower in each treatment showed an increasing trend, by 0.49–10.51 units, and reached a significant level in the seedling Si1500 and blooming Si500 and Si1500 treatments ($p < 0.05$); compared with the seedling stage, the stem Cd accumulation of each treatment showed an upward trend, increasing by 13.45–179.21%, and the differences between the two periods under the Si0, Si50, Si250, and Si500 treatments were significant ($p < 0.05$). As shown in Figure 2f, for Cd accumulation in sunflower leaves, the Si1500 treatment at the seedling stage and the Si250, Si500, and Si1500 treatments at the blooming stage significantly increased by 0.06–12.14 units ($p < 0.05$), compared with the control Si0, and the other Si treatments were nonsignificant; with the prolongation of the fertility period, there was an overall trend of elevation across treatments, and the difference between treatments was nonsignificant ($p > 0.05$) between the two periods compared with the seedling stage. Despite the better growth parameters of sunflowers treated with sodium silicate than with the control treatment of Cd, the Cd content in the underground and aboveground parts of plants treated with sodium silicate increased with the concentration of sodium silicate (Figure 2). This finding supports findings in the literature [48,49] that Si traps Cd and prevents its uptake by plant cells, mainly by combining with the cell wall. In addition, Cd is trapped in the rhizosphere through vesicles, reducing the translocation of Cd to the aboveground. Various effects of Si on plant growth parameters, and a reduction or increase in Cd uptake and accumulation by plants after Si addition treatments, have been observed in various plant soil tests [30,49,50]. These results suggest that the different results of Si on the uptake and accumulation of Cd in plants could correlate with the species of the plant, as well as the concentration of soil factors (cadmium and silicon). In our trial, Cd concentration and accumulation in sunflower tissues increased after sodium silicate application (Figure 2). These results and the improved growth of sunflowers under Cd-stressed conditions after Si application are critical for optimal phytoremediation performance [51]. Thus, a supply of Si that promotes plant growth would help sunflowers remediate Cd-contaminated soils. The aforementioned results indicate that Cd accumulation in sunflower roots, stems, and leaves increased with the growth of sunflowers and with an increase in sodium silicate concentration, especially with the Si1500 treatment. The results revealed that Si significantly increased the accumulation of Cd in all parts of the sunflower plant at the seedling and blooming stages and continued to increase with the prolongation of the reproductive period.

3.4. Effect of Sodium Silicate on Photosynthesis of Sunflower under Cd Stress

As shown in Figure 3a–c, there were no significant differences ($p > 0.05$) in chlorophyll a, chlorophyll b, and total chlorophyll contents among treatments with an increasing Si concentration. With prolonged fertility, the chlorophyll a and total chlorophyll contents of sunflower showed a tendency to increase, and chlorophyll a and total chlorophyll contents at the blooming stage were significantly higher than those of the seedling stage by 133.81–201.46% and 51.47–99.97% ($p < 0.05$), and the chlorophyll b content of sunflower showed a decreasing trend. The chlorophyll b content at the blooming stage decreased by 13.24–20.89% compared with the seedling stage, and the differences between the reproductive periods were nonsignificant ($p > 0.05$). Thus, the use of sodium silicate had little effect on the chlorophyll content of sunflowers, but chlorophyll increased with the prolongation of the reproductive period.

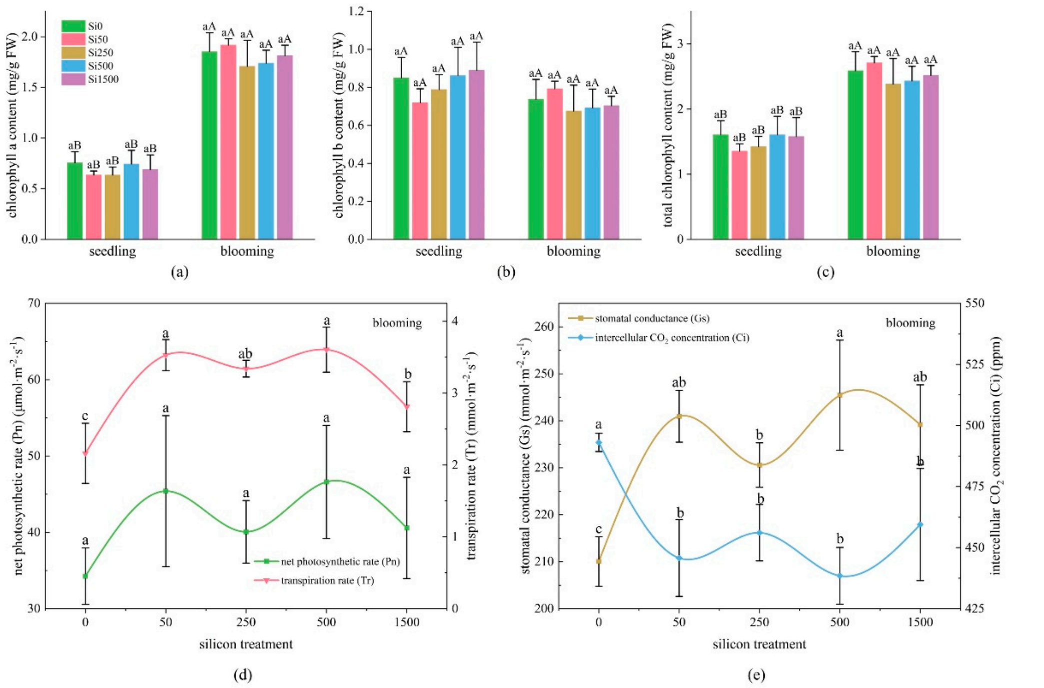

Figure 3. Effect of sodium silicate on chlorophyll content and gas exchange parameters of sunflowers at different reproductive stages. (**a**) Chlorophyll a content, (**b**) chlorophyll b content, (**c**) total chlorophyll content, (**d**) net photosynthetic rate (Pn) and transpiration rate (Tr), (**e**) stomatal conductance (Gs) and intercellular CO_2 concentration (Ci). Small characters a, b, and c represent significant ($p < 0.05$) differences among different Si levels under the same growth period; uppercase characters A and B represent significant differences ($p < 0.05$) between different growth periods at the same Si level.

As shown in Figure 3d, the net photosynthetic rate (Pn) of sunflower leaves at the blooming stage showed a trend of increasing and then decreasing slightly with an increasing Si concentration, increasing by 16.95–36.03% compared with the Si0 control, but the differences among the five treatments of Si were nonsignificant ($p > 0.05$). The transpiration rate (Tr) of sunflower leaves showed a trend of increasing and then decreasing slightly with an increasing Si concentration, increasing by 30.06–66.82% compared with the Si0 treatment, with significant ($p < 0.05$) differences between the Si50, Si250, Si500, and Si1500 treatments at the blooming stage. In relation to stomatal conductance (Gs) (Figure 3e), the Si50-Si500 treatments during blooming significantly increased the Gs of sunflowers by 9.77–14.71% ($p < 0.05$), respectively. With an increase in Si concentration, the intercellular carbon dioxide concentration (Ci) of sunflower leaves showed a slight decreasing and then increasing trend, which was opposite to the trend of Pn, Tr, and Gs. Sodium silicate was reduced by 6.81–11.07% for each treatment compared with the Si0 treatment, with significant differences between treatments ($p < 0.05$). The use of sodium silicate not only promoted sunflower growth but also reduced the toxic actions of Cd in sunflowers at the seedling and blooming stages, which were more pronounced in sunflowers treated with a sodium silicate concentration of 500 mg/kg and at the blooming stage (Figure 3). This discovery was also bolstered by the Si-induced improvements in photochemical parameters (Figure 3). In our study, there were no significant differences in chlorophyll a, chlorophyll b, or total chlorophyll content between the different growth periods of sunflowers and those of the Cd-only control (Figure 3); that is, the application of Si did not reduce the negative effect of Cd on chlorophyll. This finding contrasts with those of Attia and Farooq et al. [52,53]: exogenously applied Si enhanced the gas exchange characteristics (Pn, Gs, Tr, and water use efficiency), chlorophyll content, and carotenoid properties of cotton and marigold. However, in this study, the gas exchange parameters revealed a significant improvement in the photosynthesis of sunflowers under Cd stress because of proper Si supply. Cd stress damages the photosynthetic organs of plants, reduces Gs, severely affects photosynthesis, decreases Pn and Tr, changes the synthesis of sugars and sugar glycols, and ultimately damages plant growth [54]. Compared with the Cd-only control, the appropriate Si supply resulted in a significant increase in Pn, Tr, and Gs and a significant decrease in Ci in sunflowers under Cd stress (Figure 3). Researches have suggested that Si reduces the adverse effects of Cd on the photosynthetic machinery of plants, mainly by limiting Cd transport from the roots to the aboveground [55]. Moreover, Si can enhance aboveground internode elongation by increasing cell division and expansion [56], which may be one reason why plants improve their growth properties under stress. Furthermore, the improved gas exchange after Si application may also contribute to the improved growth properties of sunflowers under stress and non-stress situations. Therefore, the results obtained so far may mean that Si application diminishes the toxicity of Cd in photosynthesis and restores the activity of sunflower plants by protecting guard cell regulators, the integrity of chloroplast ultrastructure and bursa-like membranes, and by promoting Calvin cycle enzyme activity. With the growth of sunflower, its leaf Pn, Tr, and Gs showed a trend of increasing and then decreasing, and the intercellular carbon dioxide concentration Ci showed a trend of decreasing and then increasing, which indicated that the optimum concentration of sodium silicate for each photosynthetic parameter of sunflower was 500 mg/kg. During the blooming period, sodium silicate improved the photosynthetic parameters of sunflowers.

3.5. Impact of Sodium Silicate on Antioxidant Enzyme Activities of Sunflower under Cd Stress

As shown in Figure 4a, the SOD activity of sunflower leaves increased with an increasing Si concentration in all treatments, increasing by 8.81–150.28% compared with the Si0 control, and the differences were significant between the Si50, Si500, and Si1500 treatments at the seedling stage and the Si250 treatment at the blooming stage compared with the control; with the extension of the reproductive period, SOD activity showed an increasing trend, and the SOD activity at the blooming stage increased by 16.84–85.69% compared with that at the seedling stage, in which the differences between the Si0 and Si250 treatments were significant ($p < 0.05$). As shown in Figure 4b, the POD activity of sunflower leaves showed an increasing trend with an increasing Si concentration, increasing by 91.35–351.55% compared with the Si0 treatment, and the differences were significant ($p < 0.05$) between the Si1500 treatment at the seedling stage and the Si50, Si250, and Si1500 treatments at the blooming stage. With the prolongation of the reproductive period, POD activity tended to increase. The POD activity at the blooming stage increased by 39.27–761.11% compared with that at the seedling stage, in which the differences were significant ($p < 0.05$) between the Si0, Si50, and Si500 treatments. CAT activity analysis (Figure 4c) demonstrated that the Si250-Si1500 treatments at the seedling stage and the Si500 treatments at the blooming stage increased sunflower leaf CAT activity by 35.11–54.69% and 38.53%, respectively ($p < 0.05$), and CAT activity significantly ($p < 0.05$) decreased when the prolongation of the reproductive period decreased by 1.65–30.64% ($p < 0.05$). As shown in Figure 4d, sodium silicate significantly reduced leaf malondialdehyde content ($p < 0.05$) in each treatment, and compared with the Si0 treatment, sodium silicate in all treatments reduced by 3.34–25.14% ($p < 0.05$), of which the Si50-Si1500 treatments in the seedling stage and Si1500 treatment in the blooming stage were significantly different, and the malondialdehyde content of sunflower leaves showed a decreasing trend with the prolongation of the fertility period and was significantly reduced by 15.86% ($p < 0.05$) in the Si500 treatment at the blooming stage. The mechanisms of alleviating heavy metal toxicity in plants are categorized into internal and external mechanisms [57]. The Cd concentration in the roots and aboveground (stems and leaves) of sunflowers increased significantly after Si treatment (Figure 2), and sunflower growth improved (Table 2, Figure 1), indicating that the mitigating effect of Si may be due to the internal mechanism of stimulating enzymatic and non-enzymatic antioxidants to reduce membrane lipid peroxidation in sunflowers after the application of Si. Under Cd stress, Si application stimulates enzymatic and non-enzymatic antioxidants to reduce membrane lipid peroxidation [58–60]. High levels of Si activate physical and biochemical defense mechanisms in plant tissues and boost plant stress tolerance [61,62]. Oxidative stress is a key manifestation of biotic and abiotic stress. Cd disrupts the equation between the production and removal of reactive oxygen species (ROS), causing oxidative damage in plants and the inhibition of plant growth and development [42]. Huang [63] demonstrated that the use of sodium silicate alleviated oxidative stress under Cd stress; that is, the application of Si increased the strength and stability of cell membranes, reducing the oxidative damage of Cd to plant tissues. Si is absorbed by plants and deposited in large quantities in plant cells, enhancing the strength and stability of the cells and improving the tolerance of plants to Cd [64]. In addition, the addition of Si can promote the secretion of root secretions by plants, accelerate chelation with heavy metals, cause heavy metals to precipitate in the cell wall, and reduce the toxicity of Cd to plants [65]. In this study, Si treatment significantly reduced the Cd stress-induced increase in MDA content in sunflowers at different growth periods and alleviated oxidative stress damage in sunflowers under Cd stress (Figure 4). These findings are consistent with those of Khan et al. [66], who concluded that the use of silica nanoparticles reduced oxidative stress in wheat leaves in Cd-contaminated soil, evidenced by reduced hydrogen peroxide production, electrolyte leakage, and reduced malondialdehyde content. In summary, with the growth of sunflowers, leaf enzyme activity showed an increasing trend, malondialdehyde content showed a decreasing trend, and the use of sodium silicate increased the leaf enzyme activity of sunflowers, especially at the blooming stage.

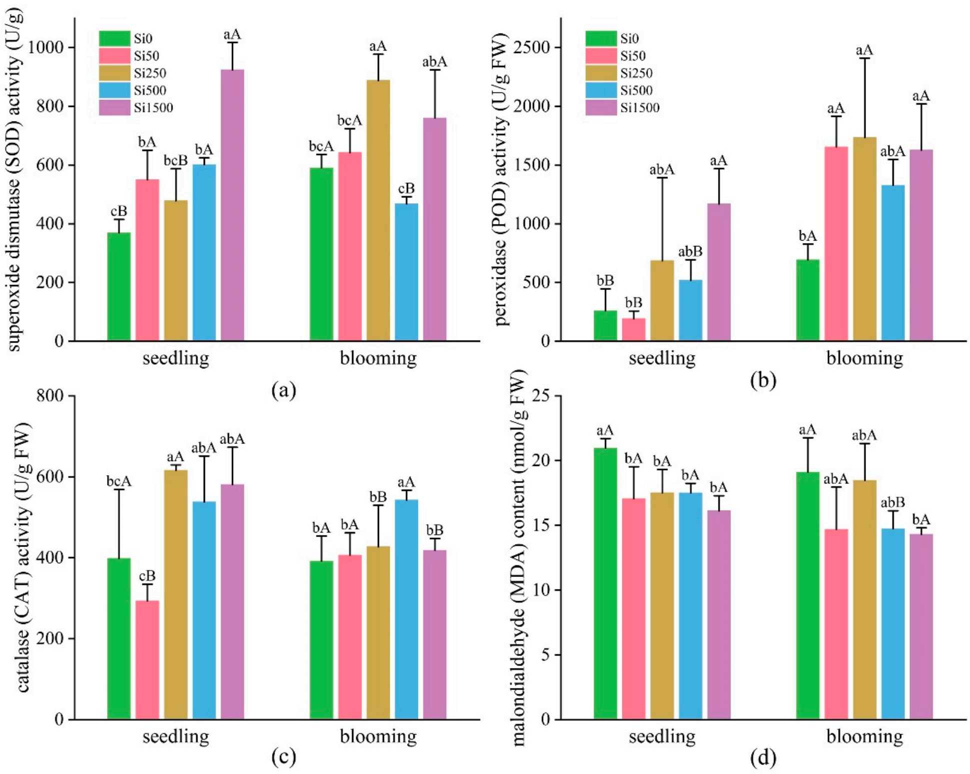

Figure 4. Effect of sodium silicate on antioxidant enzyme activities of sunflower at different reproductive stages. (**a**) Superoxide dismutase (SOD) activity, (**b**) peroxidase (POD) activity, (**c**) catalase (CAT) activity, and (**d**) malondialdehyde content. Small characters a, b, and c in the graphs represent significant ($p < 0.05$) differences between different Si levels at the same growth period; uppercase characters A and B represent significant ($p < 0.05$) differences between different growth periods at the same Si level.

3.6. Heat Map and Correlation Analysis between Parameters of Sunflower

Clustered heat maps were used to visualize the correlation between various variables. Heat map analysis showed the effect of different concentrations of sodium silicate on various parameters of sunflower under Cd stress (Figure 5a,b). The Si500 and Si1500 treatments increased Cd content and accumulation in the roots, stems, and leaves of sunflowers and increased ST, LBA, POD, SOD, and CAT activities during the seedling stage. Additionally, only for Cd-treated Si0 was MDA content highly expressed. Similarly, Si500 and Si1500 at the blooming stage increased Cd content and accumulation, enhanced PH, ST, LBA, AFW, ADW, WPFW, WPDW, RFW, RDW, Gs, Pn, Tr, POD, SOD, and CAT activities, and decreased Ci and MDA contents. The effects of the Si500 and Si1500 treatments on sunflower growth parameters, photosynthetic parameters, antioxidant enzyme activities, and Cd content were superior to those of the Si0 treatment.

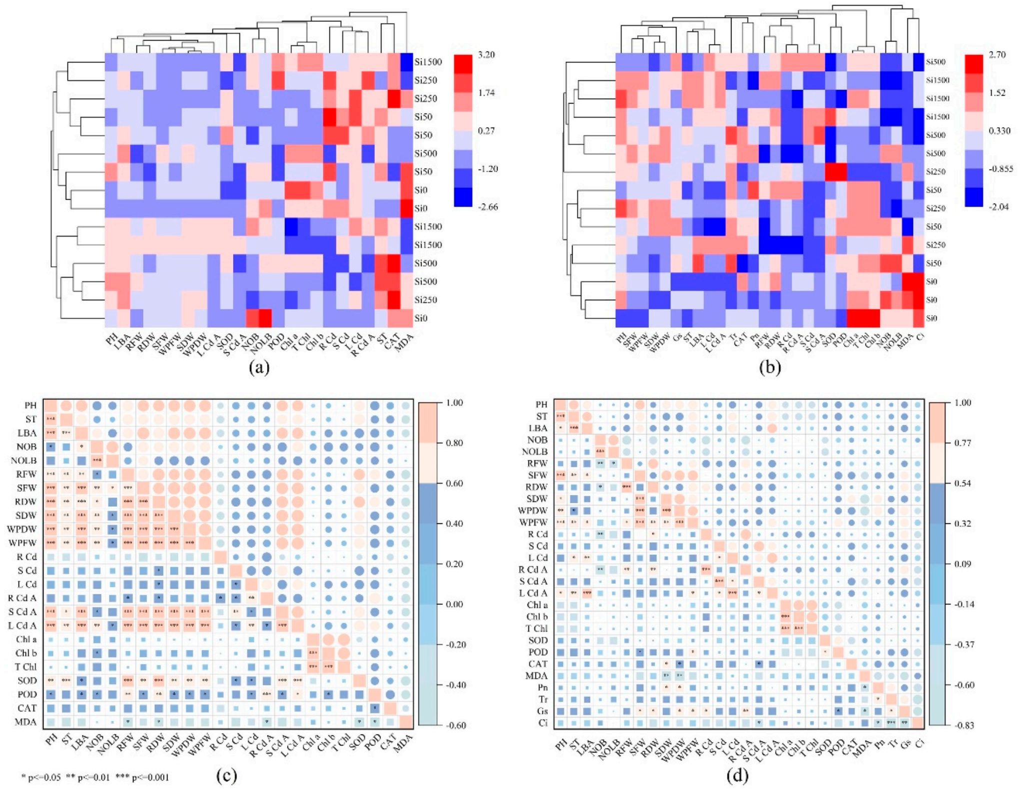

Figure 5. Heat map and Pearson correlation diagram of physiological and biochemical indicators of sunflower under different concentrations of sodium silicate treatment. (**a**) Heat map of physiological and biochemical indexes in sunflower at seedling stage, (**b**) heat map of physiological and biochemical indexes in sunflower at blooming stage, (**c**) Pearson correlation analysis of physiological and biochemical indexes in sunflower at seedling stage, (**d**) Pearson correlation analysis of physiological and biochemical indexes in sunflower at blooming stage. The main indicators were plant height (PH), stem thickness (ST), leaf area (LA), number of branches (NOB), number of leaf blades (NOLB), root fresh weight (RFW), aboveground fresh weight (AFW), root dry weight (RDW), aboveground dry weight (ADW), whole-plant dry weight (WPDW), whole-plant fresh weight (WPFW), root Cd content (R Cd), stem Cd content (S Cd), leaf Cd content (L Cd), root Cd accumulation (R Cd A), stem Cd accumulation (S Cd A), leaf Cd accumulation (L Cd A), chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (T Chl), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), malondialdehyde (MDA), net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and intercellular carbon dioxide (Ci). *, **, and *** indicate that each parameter of sunflower was significantly correlated at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$ levels, respectively.

The correlations between growth indexes, biomass, root, stem, and leaf Cd content, root, stem, and leaf Cd accumulation, chlorophyll content, photosynthetic parameters, antioxidant enzymes, and MDA were analyzed according to Pearson's correlation heatmap (Figure 5c,d). After sodium silicate treatment, the aboveground Cd content in the sunflower seedling stage was significantly and positively correlated with root dry weight, SOD, and POD activities ($p \leq 0.05$), and the root, stem, and leaf Cd content in the sunflower blooming stage was significantly and positively correlated with Gs, root dry weight, stem thickness, and leaf area ($p \leq 0.05$), and significantly and negatively correlated with the number of branches. Sunflower seedling Cd accumulation in roots, stems, and leaves showed a significant positive correlation ($p \leq 0.05$) with POD activity, SOD activity, plant height, stem thickness, leaf area, number of branches, number of leaves, root fresh weight, and root dry weight, and a significant negative correlation ($p \leq 0.05$) with MDA content; sunflower blooming stage Cd accumulation in roots, stems, and leaves showed a significant positive correlation ($p \leq 0.05$) with plant height, stem thickness, leaf area, whole-plant fresh weight, CAT activity, Gs, root fresh weight, and root dry weight and was significantly positively correlated ($p \leq 0.05$) and negatively correlated ($p \leq 0.05$) with the number of branches and Ci (Figure 5c,d). Plants have developed a complicated defense system to eliminate excessive intracellular ROS, including enzymatic antioxidants, such as POD, CAT, SOD, and APX. SOD converts superoxide anion radicals to hydrogen peroxide, CAT and APX catalyze the conversion of intracellular H_2O_2 to H_2O and O_2 in plant cells, and POD acts as a catalyst for the conversion of H_2O_2 while oxidizing and reducing substrates [67]. Based on our results, our conclusion was that Si treatment enhanced the activities of SOD, POD, and CAT in sunflowers during both growth periods (Figures 4 and 5). Enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) are protective mechanisms of plants in response to the formation of ROS generated by heavy metal stress, and the enhancement of their activities suggests that Si scavenges the high ROS produced due to heavy metal stress. Ahmad et al. also reported a significant increase in CAT and SOD activity and the scavenging of Cd-induced ROS in the roots of alfalfa plants after Si supplementation [48]. This indicates that Si enhances the activity of antioxidant enzymes and reduces ROS levels in plants. By contrast, Huang et al. [58,68] demonstrated that the addition of Si decreased POD and CAT activity in rice leaves under Cd and excess Zn stress, as well as SOD, POD, and CAT activity in lobelia leaves under Cd stress. These changes in antioxidant enzyme activity may be the cause of Si-related Cd resistance in sunflowers. In conclusion, sodium silicate effectively reduced Cd toxicity. These results demonstrate that, after sodium silicate treatment, sunflower growth indexes, biomass, antioxidant properties, and gas exchange characteristics improved, which helped reduce Cd stress in sunflowers, but the heavy metal content and accumulation in roots, stems, and leaves increased. This result is consistent with the conclusions drawn from the aforementioned analysis.

4. Conclusions and Future Prospects

Our analysis indicates that soil-applied Si improved the growth parameters and physiological and biochemical characteristics, and increased the Cd concentration in the roots, stems, and leaves, of sunflowers. For various photosynthetic parameters of sunflowers, Si application significantly alleviated Cd stress on Pn, Tr, and Gs more than the Cd-only control did. Additionally, soil Si application significantly reduced MDA content and oxidative stress in sunflowers, which increased the activities of the antioxidant enzymes SOD, POD, and CAT. The use of sodium silicate may be an environmentally non-polluting and sustainable technique to enhance plant development under metal stress, which requires further investigation at the molecular level. Silica-mediated increases in Cd content also facilitate soil heavy metal remediation. Specifically, Si-mediated mitigation showed similar trends during both sunflower growth periods. Therefore, our study provides a reference for environmentally sustainable strategies to address soil heavy metal pollution. Subsequently, more in-depth studies are needed to investigate the accumulation of heavy metals in sunflower grains at maturity after Si addition to provide insights for human health and agricultural production.

Author Contributions: Concept and design: H.W. and X.W.; data collection and analysis: H.W. and H.G.; drafting of the article: H.W.; critical revision of the article for important intellectual content: H.W. and J.C.; study supervision: H.W. and T.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This investigation was financially assisted by the Natural Science Foundation of China, grant number 42067026 and Xinjiang Autonomous Region Nature Fund Project, grant number 2023D01A113.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: I have to extend my heartfelt thanks to Gao Haifeng and my senior sister Chen Jiao. I thank them for their help with my experiments as well as my thesis.

Conflicts of Interest: Author Tingting Zhang was employed by the company Anhui Blue Shield Optoelectronics Co. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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