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Silicon Calcium Fertilizer Application and Foliar Spraying with Silicon Fertilizer Decreases Cadmium Uptake and Translocation in Rice Grown in Polluted Soil

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Abstract: Rice cultivated in Cd-polluted acidic paddy soil poses important health risks in China. Decreasing Cd accumulation in rice is important for food safety and human health. Early rice cultivar ZY-819 and late rice cultivar XWX-13 with low Cd-accumulation potentials, and early rice cultivar LY-996 and late rice cultivar YZX with high Cd-accumulation potentials, were grown in mildly polluted double-cropping paddy fields (Cd content 0.3–0.6 mg kg^{-1}). The effects of adding biochar (10 t ha^{-2}), lime (1500 kg ha^{-2}), and silicon–calcium fertilizer (SC; 2250 kg ha^{-2}) and foliar spraying with silicon fertilizer solution (Si; 1500 g ha^{-2}) on Cd uptake and transport in rice, were assessed in plot experiments. The soil amendments and foliar spraying decreased the Cd content of brown rice from the high Cd-accumulation potential cultivars. The soil amendments decreased the Cd content of LY-996 and YZX brown rice by 25.24–32.40% and 32.99–44.16%, respectively, and SC decreased the Cd content most. Foliar spraying with Si decreased the Cd content of LY-996 and YZC brown rice by 23.79% and 26.40%, respectively. When soil amendments and foliar spraying were combined, the Cd content of brown rice was decreased most by the SC–Si treatment. Compared with the control, the SC–Si treatment decreased the Cd content of LY-996, ZY-819, YZX, and XWX-13 brown rice by 45.63%, 35.67%, 52.79%, and 32.03%, respectively. Soil amendments can effectively decrease Cd uptake by rice roots and Cd migration from roots to shoots. Compared with the control, the soil amendments increased the soil pH and decreased Cd availability. The strongest effects were for the lime and SC treatments. Foliar spraying with Si can effectively decrease Cd translocation through stems and leaves to brown rice. Applying SC fertilizer and foliar spraying with Si is the best method for decreasing the Cd content of rice grown in mildly Cd-polluted paddy fields.

Keywords: cadmium (Cd); soil amendment; rice (*Oryza sativa* L.); mildly Cd-polluted paddy fields

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1. Introduction

Cadmium (Cd) is one of the most toxic and bioavailable heavy metals that can be found in soil. The Cd pollution in paddy fields is due to the presence of Cd in the land itself, and the Cd pollution of cultivated land due to the development of industrialization, waste water and waste gas emissions from mining and smelting, and the application of Cd-containing fertilizers [1]. The organic pollutant or heavy metal content of 19.4% of cultivated soil in China has been found to be excessively high, and the pollutants of most concern are arsenic, Cd, chromium, and lead [2]. Rice (*Oryza sativa* L.) is the staple food of more than half of the population of the world. Rice grown in Cd-contaminated soil usually strongly accumulates and transports Cd, particularly if the soil is acidic [3,4]. Rice is the main source of Cd in the diets of people living in Asia (including China, India, and Japan) [5]. It has been found in numerous studies that consumption of Cd in rice leads to serious risks of respiratory, renal, and skeletal problems [6,7]. It is therefore important to remediate Cd-contaminated soil, develop methods for safely using Cd-contaminated farmland, and establish and investigate models for efficiently restoring Cd-contaminated farmland.

Passivation is an effective technique for remediating Cd-contaminated soil. Passivation inhibits soil acidification and decreases the availability of Cd in soil to cereal plants [8,9]. Passivation can be achieved by applying amendments to soil and spraying foliage with inhibitors. Common soil amendments include clay minerals, certain nanomaterials, organic modifiers, and silicon–calcium materials [10–13]. Lime is widely used because it is cheap, can markedly increase the soil pH, and can decrease the availability of heavy metals in soil [14,15]. Biochar and clay minerals are also widely used because they have extremely high specific surface areas and are relatively environmentally benign [16,17]. Heavy metals in soil can adsorb to, form precipitates with, and form complexes with passivating agents applied to soil, meaning the mobilities and activities of the heavy metals in the soil will decrease and the Cd content of rice grown in the soil will decrease [18].

Foliar resistance control techniques mainly involve spraying fertilizer onto the foliage to increase the activities of antioxidant enzymes in the leaf cells, promote plant growth and development, and improve stress resistance [19], and spraying inhibitor onto the foliage to chelate with Cd and compete with Cd for binding sites on leaf cells and therefore decrease the physiological activity of Cd [20,21]. Applying silicon-containing foliar fertilizer after heading has occurred can inhibit Cd absorption and translocation in rice and markedly decrease the Cd content of the rice grains [22] while increasing the iron and manganese contents of the rice grains [23].

Most Cd-contaminated soil is mildly contaminated. In a survey of soil pollution in China, it was found that mild and slightly above mild pollution accounts for 85.05% of the total area affected by soil pollution [24]. However, few studies of large-scale concurrent soil amendment and foliar inhibitor application to mildly Cd-polluted double-cropping rice fields have been performed. The synergistic effects of applying soil amendments and foliar fertilizers on rice and the mechanisms involved need to be investigated. In view of this, early rice cultivars with markedly different abilities to take up and translocate Cd and late rice cultivars with markedly different abilities to take up and translocate Cd were grown using a double-cropping system on mildly Cd-contaminated paddy field soil with three types of soil amendment and foliar silicon fertilizer application to study the effects of the amendments and foliar fertilizer on Cd uptake, Cd transport, and soil properties. The main aims of the study were (1) to investigate the effects of different soil amendments combined with foliar spraying with silicon fertilizer on the Cd content of rice grains; (2) to assess Cd immobilization caused by applying different soil amendments to mildly Cd-polluted paddy field soil; and (3) to assess Cd absorption and transport by rice cultivars with different abilities to accumulate Cd after applying different soil amendments combined with foliar spraying of silicon fertilizer.

2. Materials and Methods

2.1. Test Site and Materials

The experiment was performed in a mildly Cd-contaminated paddy field in Hengyang County (26°97′ N, 111°37′ E), Hunan Province, China in 2021. A typical double-cropping rice-growing system was used in the study area, which is in the central continental part of China and has a subtropical monsoon climate with annual precipitation of 1452 mm and a mean annual temperature of 17.9 °C.

The mean Cd content of the soil at the study site was 0.47 mg kg^{-1}, and the mean soil pH was 6.02. According to Chinese National Soil Pollution Evaluation Technical Regulations, the soil was classed as mildly contaminated with Cd (Cd content 0.3–0.6 mg kg^{-1}). The study site had red soil with a bioavailable Cd content of 0.12 mg kg^{-1}, a cation exchange capacity of 7.57 cmol kg^{-1}, an alkaline hydrolysis nitrogen content of 119.88 mg kg^{-1}, an available phosphorus content of 8.54 mg kg^{-1}, an available potassium content of 57 mg kg^{-1}, an organic matter content of 29.49 g kg^{-1}, a total nitrogen content of 3.51 g kg^{-1}, a total phosphorus content of 0.91 g kg^{-1}, and a total potassium content of 10.13 g kg^{-1}.

The early rice cultivars Zhuliangyou 819 (ZY-819) and Luliangyou 996 (LY-996), which have low and high Cd accumulation potentials, respectively, and the late rice cultivars

Xiangwanxian 13 (XWX-13) and Yuzhenxiang (YZX), which have low and high Cd accumulation potentials, respectively, were used [5]. Experiments were performed using three soil amendments and one foliar inhibitor. Lime (CaO content ≥ 35% and MgO content ≥ 5%) was obtained from Hengyang Fulong Fertilizer Company (Hengyang, China) and had a Cd content of 0.15 mg kg^{-1}. Biochar (produced by pyrolyzing rice husks at 550–600 °C for 2 h) was purchased from Wangcheng (Changsha, China) and had a Cd content of 0.18 mg kg^{-1}. Silicon–calcium fertilizer (SC; CaO content ≥ 25% and SiO_2 content ≥ 20%) soil amendment was obtained from Hunan Runbang Bioengineering and had a Cd content of 0.10 mg kg^{-1}. Silicon fertilizer solution (organic silicon content ≥ 100 g L^{-1}) was obtained from the Silicon Valley brand and was used as a foliar inhibitor.

2.2. Experimental Design

A flat plot with uniform fertility was used for the experiment. Four soil treatments (blank control (CK treatment), biochar application at 10 t ha^{-2} (BC treatment), lime application at 1500 kg ha^{-2} (LM), and SC application at 2250 kg ha^{-2} (SC treatment)) were used and concurrent foliar silicon fertilizer spraying at 1500 g ha^{-2} (Si treatment) was performed at the booting stage and initial heading stage, giving a total of eight treatments (Table 1). Soil amendment was applied one week before early rice seedlings were transplanted. The soil amendment was spread evenly on the soil surface and the top soil was plowed to evenly mix the amendment and soil. Soil amendment was not applied late in the rice growing season. Foliar silicon fertilizer spraying was performed at the booting and initial heading stages of the early and late rice plants, and the application rate each time was 750 g ha^{-2}.

Table 1. Trial treatments and specific measures.

Soil Conditioning	Foliar Resistance Treatment	Specific Measure
Control	CK	Control
	CK-Si	Foliar spray silicon fertilizer
Bio-charcoal	BC	Biochar 10 t ha^{-2}
	BC-Si	Biochar 10 t ha^{-2} + foliar spray silicon fertilizer
Lime	LM	Lime 1500 kg ha^{-2}
	LM-Si	Lime 1500 kg ha^{-2} + foliar spray silicon fertilizer
Silicon–calcium fertilizer	SC	Silicon–calcium fertilizer 2250 kg ha^{-2}
	SC-Si	Silicon–calcium fertilizer 2250 kg ha^{-2} + foliar spray silicon fertilizer

A split-plot experimental design was used, with cultivars as the main plots and Cd-resistant treatments as the sub-plots with a protective row 1.5 m wide around each sub-plot. Each treatment was performed in triplicate. Two early rice cultivars and two late rice cultivars were used, so 48 plots, each 21 m^2, were established. The surrounding area was separated using protective rows 0.3 m wide and 0.3 m high covered with polyethylene film. Independent irrigation and drainage outlets were installed. Water management was the same for each plot to exclude the effects of water on the Cd content of the soil. Early rice was sown on 19 March and transplanted on 20 April, and late rice was sown on 21 June and transplanted on 21 July. The early rice transplanting density was 16.7 cm × 20 cm and the late rice transplanting density was 20 cm × 20 cm, and two or three seedlings were planted in each hole. Other management practices were consistent with conventional local practices.

2.3. Measurements and Methods

Samples of soil 0–20 cm deep were collected using a five-point sampling method before the soil amendment was added and once the early and late rice had matured. The soil samples were dried in air, ground, and passed through 20- and 100-mesh sieves. The soil pH was determined by extracting a sample with CO_2-free distilled water at a water:soil ratio of 2.5:1 and then determining the pH using a PHSJ-3FX pH meter. The total Cd content of each soil sample was determined after digesting 0.5 g of dry soil in a mixture of HF, $HClO_4$, and HNO_3 in a DS-360 graphite digestion box (China National Analytical Center, Guangzhou, China). The bioavailable Cd content was determined after incubating a mixture of 5 g of dry soil and 0.1 mol $CaCl_2$ at a soil:liquid ratio of 1:10 at 25 °C for 2 h with mixing at 250 rpm. The total Cd and $CaCl_2$-extracted Cd concentrations in the solutions were determined using an AA800 graphite furnace atomic absorption spectrometer (PerkinElmer, Waltham, MA, USA). A volumetric method described in a collection of agricultural soil chemical analysis methods was used to determine the organic matter and alkaline nitrogen content of the soil samples. The available phosphorus content was determined using a colorimetric method. The available potassium content was determined by flame photometry. The total nitrogen, total phosphorus, and total potassium contents were determined using a semi-micro Kjeldahl method.

Three rice plants from each treatment plot were sampled at maturity. Each plant was washed, then the roots were soaked in 0.1 mol L^{-1} hydrochloric acid for 15 min to remove Cd adsorbed to the root surfaces. The roots were then washed three times with tap water and then rinsed three times with deionized water. The surface moisture was removed, then the plant sample was divided into roots, stems, leaves, and grains (each grain sample was divided into a husk sample and a brown rice sample). Each sample was placed in an oven at 105 °C for 0.5 h and then dried to a constant weight at 80 °C. The sample was then ground. Each sample was digested in a mixture of nitric acid and perchloric acid at a high temperature, then the Cd concentration was determined by atomic absorption spectrophotometry.

2.4. Calculating the Immobilization Efficiency and Bioaccumulation Factor

The Cd immobilization efficiency was calculated using the equation

$$E_i = (C_o - C_i)/C_o$$

where E_i is the Cd immobilization efficiency of the soil, C_o is the available Cd content of the soil before the soil amendment was applied, and C_i is the available Cd content of the soil when the rice was mature.

The Cd translocation factor (TF) was defined as the ratio between the Cd content of the upper rice plant tissues m (Cd_m) and the Cd content of the rice plant lower tissues n (Cd_n), as shown below.

$$TF_{n\text{-}m} = Cd_m/Cd_{n.}$$

The Cd bioaccumulation factor (BAF) was calculated using the equation

$$BAF_i = Cd_i/Cd_{soil}.$$

where Cd_i is the Cd content of the plant roots, stems, leaves, or brown rice to give BAF_{root}, BAF_{stem}, BAF_{leaf}, or $BAF_{brown\ rice}$, respectively, and Cd_{soil} is the Cd content of the soil.

2.5. Statistical Analysis

One-way analyses of variance and Pearson correlation tests for the different treatments were performed using SPSS 24 software (IBM, Armonk, NY, USA). Plots were drawn using Origin 2021 software (OriginLab, Northampton, MA, USA).

3. Results

3.1. Effects of the Soil Amendments on the Soil pH and Cd Bioavailability

As shown in Table 2, the soil amendments markedly affected the soil pH for the treatments using both early and late rice. The pH values for the soil samples from the early and late rice treatment plots decreased in the order LM > SC > BC > CK. The pH values for the BC, LM, and SC treatments for early rice were, on average, 0.87, 1.32, and 0.96 units higher, respectively, than the pH for the CK treatment. The pH values for the BC, LM, and

SC treatments for late rice were, on average, 0.84, 1.37, and 0.99 higher, respectively, than the pH for the CK treatment.

Table 2. Effects of soil amendments on the soil pH and Cd bioavailability in the double-cropping rice experiment.

Season/Treatment	pH	Available Cd Content (mg kg^{-1})	Cd Immobilization Efficiency (%)	pH	Available Cd Content (mg kg^{-1})	Cd Immobilization Efficiency (%)
Early rice		**LY-996**			**ZY-819**	
CK	5.73 ^{c}	0.114 ^{a}	/	5.68 ^{c}	0.125 ^{a}	/
BC	6.54 ^{b}	0.099 ^{b}	17.50	6.50 ^{b}	0.111 ^{b}	7.50
LM	7.05 ^{a}	0.059 ^{c}	50.83	7.07 ^{a}	0.071 ^{c}	40.83
SC	6.71 ^{b}	0.067 ^{c}	44.17	6.69 ^{b}	0.082 ^{c}	31.67
Late rice		**YZX**			**XWX-13**	
CK	5.70 ^{c}	0.119 $_{a}$	/	5.62 ^{c}	0.127 ^{a}	/
BC	6.62 ^{b}	0.106 $_{b}$	11.67	6.47 ^{b}	0.107 ^{b}	10.83
LM	7.01 ^{a}	0.071 $_{c}$	40.83	6.97 ^{a}	0.079 ^{c}	34.17
SC	6.63 ^{b}	0.087 $_{c}$	27.50	6.60 ^{b}	0.085 ^{c}	29.17

The same letters indicate that no significant differences between the treatments for each cultivar were found using least significant difference tests ($p < 0.05$). Different letters indicate that significant differences were found between the treatments for each cultivar using least significant difference tests ($p < 0.05$). The lowercase letters in the subsequent tables and figures have the same meanings.

As shown in Table 2, the differences between the available Cd content of the early and late rice treatment soil samples decreased in the order LM > SC > BC > CK. After applying soil amendments, the available Cd content was 11.20–48.25% lower for the soil amendments for early rice than for the CK soil and 12.26–40.34% lower for the soil amendments for late rice than for the CK soil.

As shown in Table 2, all of the soil amendments decreased the available Cd content of the soil. The immobilization efficiency was higher for the LM treatment than for the other treatments. The immobilization efficiency was a mean of 48.83% higher for early rice and 37.50% higher for late rice after the LM treatment than after the CK treatment. The immobilization efficiency was next highest for the SC treatment. The immobilization efficiency was a mean of 37.92% higher for early rice and 28.34% higher for late rice after the SC treatment than after the CK treatment. The immobilization efficiency was lowest for the BC treatment. The immobilization efficiency was a mean of 12.50% higher for early rice and 11.25% higher for late rice after the BC treatment than after the CK treatment.

3.2. Effects of Soil Amendments Combined with Foliar Spraying of Silicon Fertilizer on Cd Uptake and Transport in Double-Cropping Rice

As shown in Figure 1, the three soil amendments combined with foliar spraying with silicon fertilizer effectively decreased the Cd content of early rice, but the degree to which the Cd content was decreased was different for the different cultivars. The Cd content of the LY-996 roots, stems, leaves, and brown rice was significantly lower after the single soil amendments than after the CK treatment. The Cd content of the roots, stems, leaves, and brown rice were 23.38–35.99%, 9.83–22.54%, 23.72–34.78%, and 25.24–32.40% lower, respectively, after the single soil amendments than after the CK treatment. The LM and SC treatments decreased the Cd content the most. However, the different soil amendments did not significantly affect the Cd content of the ZY-819 samples. The Cd content of the ZY-819 samples was somewhat lower after each soil amendment than after the CK treatment, but the differences were not significant. Foliar spraying of silicon fertilizer did not significantly affect the Cd content of the LY-996 root, but the Cd content of stems and leaves was significantly (19.65% and 14.23%, respectively) higher after foliar spraying than after the CK treatment and the Cd content of brown rice was significantly (23.79%) lower after foliar spraying than after the CK treatment. The Cd content of the ZY-819 stems, leaves, and brown rice was not significantly different after the different treatments.

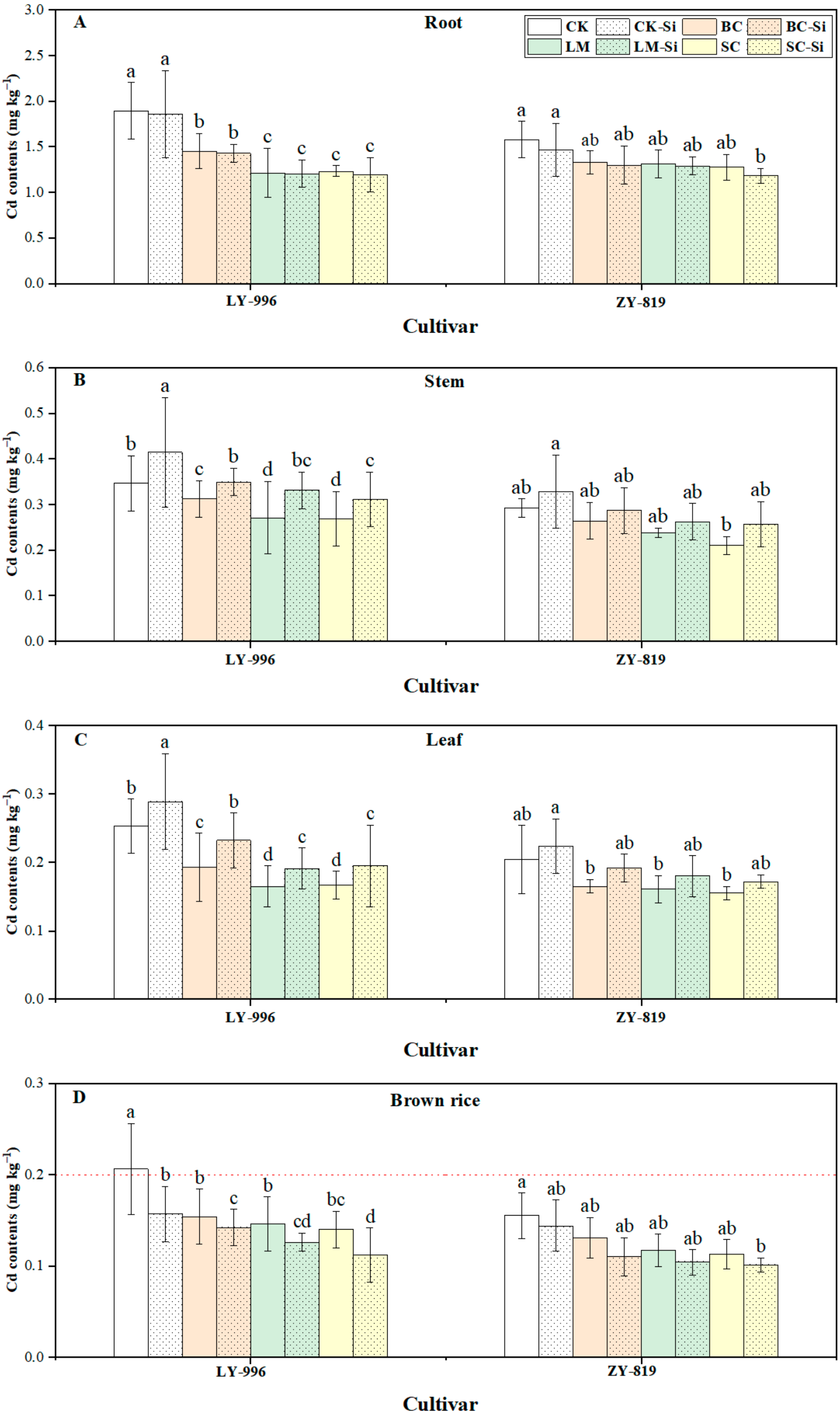

Figure 1. Effects of the soil amendments and foliar inhibitor on the Cd content of the early rice. (**A**) roots, (**B**) stems, (**C**) leaves, and (**D**) brown rice. The same letters indicate that no significant differences between the treatments for each cultivar were found using least significant difference tests ($p < 0.05$). Different letters indicate that significant differences were found between the treatments for each cultivar using least significant difference tests ($p < 0.05$).

The Cd content of LY-996 brown rice was >20% lower after the CK–Si, BC BC–Si, LM, and LM–Si treatments, >30% lower after the SC treatment, and 45.63% lower after the SC–Si treatment than after the CK treatment. The Cd content of ZY-819 brown rice was not significantly lower after the treatments (except for the SC–Si treatment) than after the CK treatment. The Cd content of ZY-819 brown rice was significantly (35.67%) lower after the SC–Si treatment than after the CK treatment.

As shown in Figure 2, the Cd content of the YZX roots, stems, leaves, and brown rice was lower after the three soil amendments than after the CK treatment. The Cd content of the roots, stems, leaves, and brown rice was 24.54–30.98%, 33.65–44.13%, 31.46–41.20%, and 32.99–44.16% lower, respectively, after the three soil amendments than after the CK treatment. The LM and SC treatments decreased the Cd content the most. The different soil amendments did not significantly affect the Cd content of the XWX-13 samples. Foliar spraying with silicon fertilizer did not significantly affect the Cd content of the YZC or XWX-13 roots but significantly increased the Cd content of the YZC stems and leaves (by 17.14% and 21.35%, respectively) and significantly decreased the Cd content of the YZC brown rice (by 26.40%). Foliar spraying with silicon fertilizer did not significantly affect the Cd content of the various XWX-13 samples.

The Cd content of YZX brown rice was >20% lower after the CK–Si treatment, >30% lower after the BC treatment, >40% after the BC–Si, LM, LM–Si, and SC treatments, and 52.79% lower after the SC–Si treatment than after the CK treatment. The Cd content of XWX-13 brown rice was significantly (32.03%) lower after the SC–Si treatment than after the CK treatment.

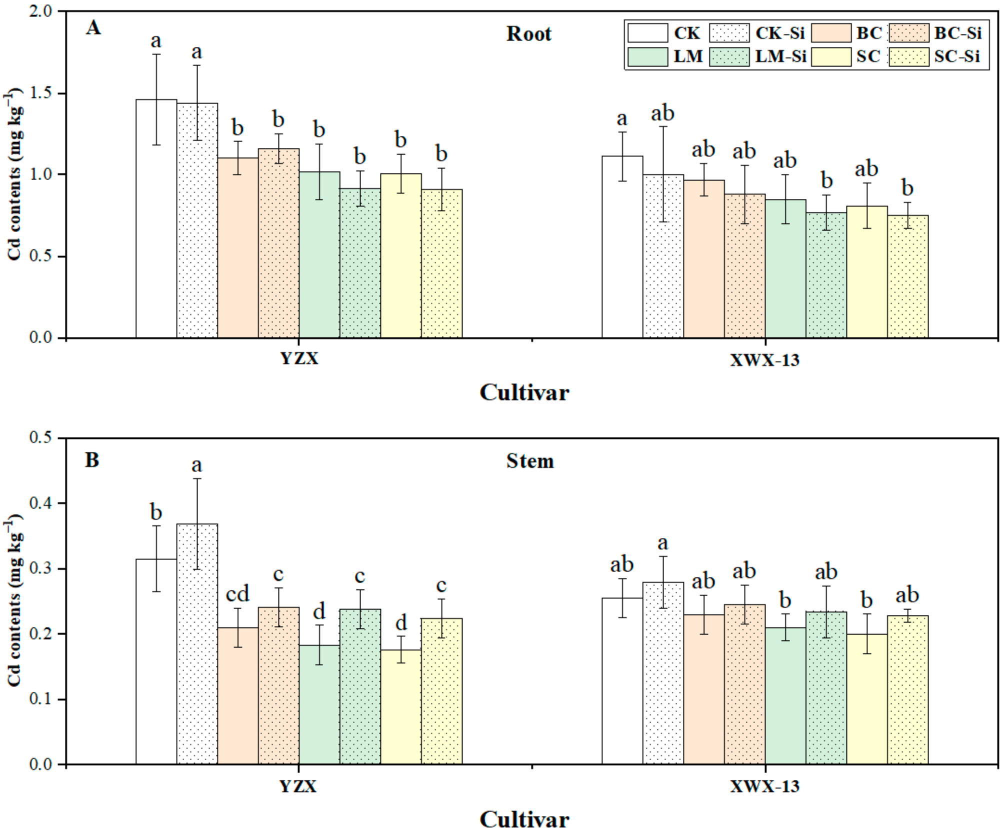

Figure 2. *Cont.*

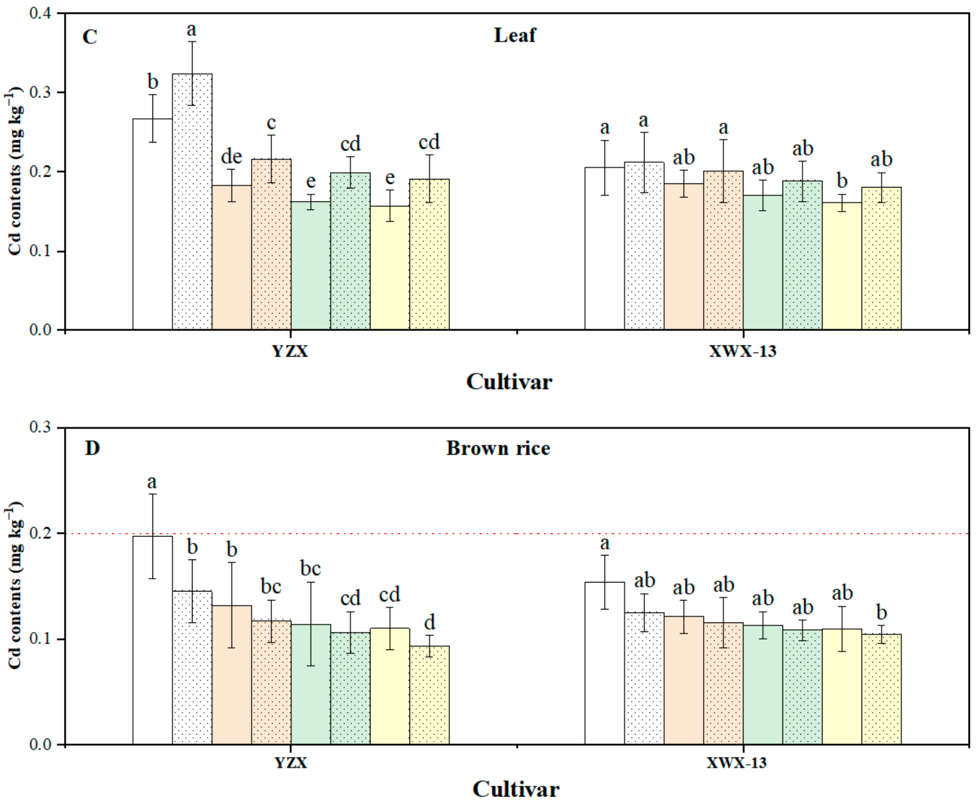

Figure 2. Effects of the soil amendments and foliar inhibitor on the Cd content of the late rice. (**A**) roots, (**B**) stems, (**C**) leaves, and (**D**) brown rice. The same letters indicate that no significant differences between the treatments for each cultivar were found using least significant difference tests ($p < 0.05$). Different letters indicate that significant differences were found between the treatments for each cultivar using least significant difference tests ($p < 0.05$).

The soil amendments and foliar inhibitor decreased the Cd content of brown rice produced by the early and late rice plants, and the effects of combined treatments were stronger than the effects of the separate treatments. However, the effects had different strengths for the different cultivars. The soil amendments and foliar inhibitor significantly decreased the Cd content of the brown rice produced by the high Cd accumulation potential cultivars LY-996 and YZX whether the treatments were used separately or in combination. Only the SC–Si treatment significantly decreased the Cd content of the brown rice produced by the low Cd accumulation potential cultivars ZY-819 and XWX-13.

3.3. Effects of the Soil Amendments Combined with Foliar Spraying with Silicon Fertilizer on the Cd Bioaccumulation and Translocation Factors for Double-Cropping Rice

As shown in Tables 3 and 4, the root-to-stem and leaf translocation factors for the early and late rice cultivars were lower after the soil amendments than after the CK treatment. The SC treatment had the largest effect. The soil amendments did not significantly affect the stem and leaf-to-brown rice translocation factors for the rice cultivars. This indicated that the soil amendments mainly affected Cd absorption by the roots and therefore affected translocation from the roots to the aboveground parts rather than translocation between the aboveground parts. Applying foliar silicon fertilizer decreased the root, stem, and leaf-to-brown rice translocation factors for the early and late rice cultivars and significantly increased the root-to-stem and leaf translocation factors. Foliar spraying with silicon fertilizer did not affect the Cd content of the roots but increased the Cd content of the stems and leaves (Figures 1 and 2). This indicated that foliar spraying with silicon fertilizer mainly affected Cd translocation between shoots, affected Cd redistribution in the shoots to some extent, and promoted Cd accumulation in the stems.

Table 3. Translocation factors (TFs) and bioaccumulation factors (BAFs) for Cd for different parts of the early rice plants.

Treatments	TF					BAF			
	Root-Stem	Root-Leaf	Root-Brown Rice	Stem-Brown Rice	Leaf-Brown Rice	Root	Stem	Leaf	Brown Rice
LY-996									
CK	0.286 ^{a}	0.151 ^{b}	0.126 ^{a}	0.537 ^{a}	0.848 ^{a}	3.968 ^{a}	0.736 ^{b}	0.538 ^{b}	0.438 ^{a}
CK-Si	0.292 ^{a}	0.167 ^{a}	0.105 ^{c}	0.379 ^{cd}	0.594 ^{bc}	4.038 ^{a}	0.881 ^{a}	0.615 ^{a}	0.334 ^{b}
BC	0.216 ^{d}	0.133 ^{c}	0.106 ^{c}	0.474 ^{b}	0.838 ^{a}	3.089 ^{b}	0.664 ^{c}	0.411 ^{c}	0.328 ^{b}
BC-Si	0.245 ^{bc}	0.163 ^{ab}	0.093 ^{d}	0.407 ^{c}	0.612 ^{bc}	3.036 ^{b}	0.743 ^{b}	0.494 ^{b}	0.302 ^{c}
LM	0.223 ^{cd}	0.136 ^{c}	0.120 ^{ab}	0.539 ^{a}	0.885 ^{a}	2.581 ^{c}	0.577 ^{d}	0.351 ^{d}	0.311 ^{b}
LM-Si	0.275 ^{a}	0.159 ^{ab}	0.100 ^{d}	0.381 ^{cd}	0.660 ^{b}	2.562 ^{c}	0.704 ^{bc}	0.406 ^{c}	0.268 ^{cd}
SC	0.200 ^{d}	0.136 ^{c}	0.117 ^{ab}	0.522 ^{ab}	0.798 ^{a}	2.621 ^{c}	0.570 ^{d}	0.355 ^{d}	0.298 ^{bc}
SC-Si	0.261 ^{ab}	0.163 ^{ab}	0.094 ^{d}	0.360 ^{d}	0.543 ^{c}	2.538 ^{c}	0.662 ^{c}	0.415 ^{c}	0.238 ^{d}
ZY-819									
CK	0.210 ^{ab}	0.133 ^{ab}	0.106 ^{a}	0.509 ^{a}	0.750 ^{a}	3.340 ^{a}	0.621 ^{ab}	0.434 ^{ab}	0.355 ^{a}
CK-Si	0.227 ^{a}	0.142 ^{a}	0.098 ^{ab}	0.426 ^{a}	0.673 ^{a}	3.360 ^{a}	0.719 ^{a}	0.477 ^{a}	0.306 ^{ab}
BC	0.191 ^{bc}	0.130 ^{ab}	0.098 ^{ab}	0.496 ^{a}	0.751 ^{a}	2.830 ^{ab}	0.562 ^{ab}	0.362 ^{b}	0.279 ^{ab}
BC-Si	0.213 ^{ab}	0.148 ^{a}	0.092 ^{ab}	0.421 ^{a}	0.655 ^{a}	2.768 ^{ab}	0.61 ^{ab}	0.409 ^{ab}	0.255 ^{ab}
LM	0.171 ^{c}	0.131 ^{ab}	0.092 ^{ab}	0.492 ^{a}	0.707 ^{a}	2.585 ^{ab}	0.506 ^{ab}	0.343 ^{b}	0.249 ^{ab}
LM-Si	0.192 ^{bc}	0.149 ^{a}	0.089 ^{b}	0.412 ^{a}	0.630 ^{a}	2.570 ^{ab}	0.557 ^{ab}	0.383 ^{ab}	0.230 ^{ab}
SC	0.179 ^{c}	0.124 ^{b}	0.091 ^{ab}	0.504 ^{a}	0.749 ^{a}	2.498 ^{ab}	0.468 ^{b}	0.309 ^{b}	0.240 ^{ab}
SC-Si	0.201 ^{ab}	0.148 ^{a}	0.089 ^{b}	0.409 ^{a}	0.648 ^{a}	2.515 ^{b}	0.547 ^{ab}	0.362 ^{ab}	0.223 ^{b}

The same letters indicate that no significant differences between the treatments for each cultivar were found using least significant difference tests ($p < 0.05$). Different letters indicate that significant differences were found between the treatments for each cultivar using least significant difference tests ($p < 0.05$).

Table 4. Translocation factors (TFs) and bioaccumulation factors (BAFs) for Cd for different parts of the late rice plants.

Treatments	TF					BAF			
	Root-Stem	Root-Leaf	Root-Brown Rice	Stem-Brown Rice	Leaf-Brown Rice	Root	Stem	Leaf	Brown Rice
YZX									
CK	0.226 ^{b}	0.183 ^{b}	0.141 ^{a}	0.668 ^{a}	0.715 ^{a}	3.104 ^{a}	0.670 ^{b}	0.568 ^{b}	0.406 ^{a}
CK-Si	0.267 ^{a}	0.225 ^{a}	0.112 ^{b}	0.485 ^{b}	0.548 ^{b}	3.060 ^{a}	0.785 ^{a}	0.689 ^{a}	0.309 ^{b}
BC	0.186 ^{c}	0.166 ^{c}	0.130 ^{a}	0.680 ^{a}	0.721 ^{a}	2.343 ^{b}	0.433 ^{cd}	0.389 ^{de}	0.281 ^{b}
BC-Si	0.218 ^{b}	0.217 ^{a}	0.111 ^{b}	0.415 ^{b}	0.542 ^{b}	2.470 ^{b}	0.513 ^{c}	0.460 ^{c}	0.249 ^{bc}
LM	0.190 ^{c}	0.159 ^{c}	0.122 ^{ab}	0.623 ^{a}	0.704 ^{a}	2.168 ^{b}	0.389 ^{d}	0.345 ^{e}	0.243 ^{bc}
LM-Si	0.270 ^{a}	0.210 ^{a}	0.126 ^{ab}	0.445 ^{b}	0.533 ^{b}	1.947 ^{b}	0.506 ^{c}	0.423 ^{cd}	0.226 ^{cd}
SC	0.185 ^{c}	0.156 ^{c}	0.121 ^{ab}	0.619 ^{a}	0.694 ^{a}	2.143 ^{b}	0.374 ^{d}	0.334 ^{e}	0.234 ^{cd}
SC-Si	0.256 ^{ab}	0.186 ^{b}	0.111 ^{b}	0.403 ^{b}	0.487 ^{b}	1.936 ^{b}	0.477 ^{c}	0.406 ^{cd}	0.198 ^{d}
ZWX-13									
CK	0.220 ^{b}	0.185 ^{c}	0.115 ^{a}	0.498 ^{a}	0.624 ^{a}	2.364 ^{a}	0.543 ^{ab}	0.436 ^{a}	0.272 ^{a}
CK-Si	0.268 ^{ab}	0.211 ^{ab}	0.104 ^{a}	0.373 ^{a}	0.565 ^{ab}	2.134 ^{ab}	0.594 ^{a}	0.451 ^{a}	0.221 ^{ab}
BC	0.226 ^{b}	0.191 ^{bc}	0.104 ^{a}	0.441 ^{a}	0.553 ^{ab}	2.062 ^{ab}	0.487 ^{ab}	0.394 ^{ab}	0.215 ^{ab}
BC-Si	0.269 ^{ab}	0.229 ^{ab}	0.109 ^{a}	0.392 ^{a}	0.546 ^{ab}	1.870 ^{ab}	0.521 ^{ab}	0.428 ^{a}	0.204 ^{ab}
LM	0.237 ^{ab}	0.200 ^{bc}	0.111 ^{a}	0.448 ^{a}	0.491 ^{ab}	1.806 ^{ab}	0.447 ^{b}	0.362 ^{ab}	0.200 ^{ab}
LM-Si	0.295 ^{a}	0.245 ^{a}	0.107 ^{a}	0.385 ^{a}	0.483 ^{b}	1.634 ^{b}	0.498 ^{ab}	0.400 ^{ab}	0.191 ^{ab}
SC	0.237 ^{ab}	0.199 ^{bc}	0.112 ^{a}	0.455 ^{a}	0.479 ^{b}	1.721 ^{ab}	0.426 ^{b}	0.343 ^{b}	0.194 ^{ab}
SC-Si	0.294 ^{a}	0.240 ^{a}	0.106 ^{a}	0.382 ^{a}	0.478 ^{b}	1.594 ^{b}	0.485 ^{ab}	0.383 ^{ab}	0.185 ^{b}

The same letters indicate that no significant differences between the treatments for each cultivar were found using least significant difference tests ($p < 0.05$). Different letters indicate that significant differences were found between the treatments for each cultivar using least significant difference tests ($p < 0.05$).

The rice bioaccumulation factor mainly reflects Cd migration from the soil to various parts of the rice plant. As shown in Tables 3 and 4, the bioaccumulation factors for the different parts of the early and late rice plants were significantly lower after the soil amendments than after the CK treatment. Foliar spraying with silicon fertilizer significantly increased the Cd bioaccumulation factors for the stems and leaves of the early and late rice plants but significantly decreased the Cd bioaccumulation factors for brown rice produced by the early and late rice plants. The lowest Cd bioaccumulation factor for brown rice produced by the early and late rice plants was found after the SC–Si treatment.

The soil amendments and foliar spraying with silicon fertilizer affected the Cd translocation and bioaccumulation factors to different extents for the different rice cultivars. The soil amendments and foliar spraying with silicon fertilizer most strongly affected Cd translocation and bioaccumulation in the high Cd accumulation potential cultivars LY-996 and YZX, and the effects for some treatments were significant. The effects for the low Cd accumulation potential cultivars ZY-819 and XWX-13 were not significant. After the CK treatment, the Cd translocation and bioaccumulation factors were generally lower for the low Cd accumulation potential cultivars than the high Cd accumulation potential cultivars. The Cd translocation and bioaccumulation factors for the low Cd accumulation potential cultivars were low, so in mildly Cd-polluted soil the external factors would have little effect on Cd absorption, transportation, and accumulation by plants.

4. Discussion

4.1. Effects of the Soil Amendments on Cd Activity in the Soil and Soil Acidification

Acidic precipitation and excessive chemical fertilizer application in recent years have caused soil acidification to become increasingly serious. Soil acidification (i.e., a decrease in the soil pH) strongly negatively affects rice growth and development. The three soil amendments used in this study were all alkaline, so markedly increased the soil pH. The pH of the unamended soil was 5.68, and the amendments increased the soil pH to 6.0–7.0, which is more suitable for growing rice. The BC and SC treatments increased the soil pH to 6.4–6.7, which is close to the optimum pH of 6.5 for growing rice [25]. It has previously been found that CaO in alkaline materials (e.g., lime and calcium and magnesium products) added to soil reacts with H_2O to produce $Ca(OH)_2$, which is strongly alkaline and increases the soil pH [9]. Biochar is alkaline because it has basic groups on the surfaces, so can also improve acidic soil [26]. However, further research into the long-term effects of such amendments on the soil pH and other soil properties is required.

The toxic effects of heavy metals in soil on organisms are mainly determined by the content of the heavy metals in biologically available states rather than the total heavy metal content [12]. The availability of Cd in soil is affected by many factors, such as the soil pH, cation exchange capacity, organic matter content, and microbial community. The soil pH is the most important of these factors. The Cd immobilization efficiency mainly indicates the ability of a soil amendment to cause Cd ions in soil to be adsorbed and complexed [27]. Adding an alkaline conditioner to soil can increase the soil pH and therefore decrease the bioavailability of Cd [28]. Increasing the soil pH will increase the net negative charge of the various charged components in the soil, which will promote Cd^{2+} adsorption to soil colloids and decrease the available Cd content of the soil [29]. The solid–liquid partition coefficient (Kd) of Cd represents the ratio between the total Cd content and water-soluble Cd content of soil. Novozamsky et al. [30] found that Kd increases by approximately a factor of four for every unit the pH increases, which indicates that increasing soil pH strongly decreases the availability of Cd.

4.2. Effects of the Treatments on Cd Uptake and Translocation by Rice

Soil amendments can decrease the Cd content of brown rice in several ways. First, applying an alkaline amendment will increase the soil pH, decrease the available Cd content of the soil, and promote Cd precipitation, meaning less Cd will be absorbed by a rice plant and therefore less Cd will be transferred to brown rice [31]. Lime is a common amendment for mitigating soil acidification. Applying lime increases the cation exchange capacity of the soil and decreases the exchangeable Cd content of the soil, which will decrease the degree to which Cd becomes enriched in plant roots and decrease the Cd content of the grain produced by the plant [32]. Liu et al. [33] found that the Cd content of brown rice was 47.75% lower after lime was applied than in the control treatment. However, Cd immobilization by lime is reversed when the soil pH decreases, and long-term application of lime can degrade the soil structure and cause compaction [34]. Biochar is porous, so interacts with free heavy metal particles in soil and affects Cd adsorption to soil particles. This can cause organic matter–heavy metal complexes to form, and these can inhibit Cd adsorption [35,36]. Organic matter contains many negatively charged active functional groups (e.g., hydroxyl and carboxyl groups) that can adsorb and undergo ion exchange with positively charged metal ions. This means that adding organic matter can decrease the Cd activity in soil and therefore decrease the Cd content of rice plants and grain [37]. However, biochar is expensive, and this has prevented the widespread application of biochar by farmers. Biochar can also have a high Cd content. In our experiment, the Cd content of brown rice was decreased more by the SC treatment than by the other treatments. The Cd content of brown rice produced by the high Cd accumulation potential cultivars was 32.40–44.16% lower after the SC treatment than the CK treatment. This would mainly have been because the SC treatment increased the available Cd content by decreasing the soil pH, and this would have decreased Cd accumulation in the plant roots and therefore decreased the amount of Cd transferred from the roots to the shoots. The SC contained $\geq$25% CaO and $\geq$20% SiO_2. Adding the SC would have increased the cation exchange capacity of the soil and provided Si for growth of the rice plants. Si in rice can induce Cd sequestration and detoxification because of chemical and physical interactions leading to the co-precipitation of Si and Cd [38,39]. Xiao et al. [14] found that applying blast furnace slag (which mainly contained CaO and SiO_2) decreased the Cd content of brown rice by 66%. SC is an effective amendment for mitigating acidic soil polluted with Cd.

Spraying foliage with inhibitors can inhibit Cd absorption by rice grains. Si absorbed through the leaf surfaces improves Cd adsorption and fixation to the cell walls and therefore inhibits Cd transport to the grains and may also decrease upward Cd migration by decreasing the transpiration rate [40]. Some elements in foliar inhibitor solutions may enter the leaves and directly form complexes and precipitates with heavy metals [41,42]. The Cd translocation factors for rice plants can indicate root–shoot (stem, leaf, and brown rice), shoot–brown rice, and other transfers. In our study, foliar spraying with silicon fertilizer did not significantly affect the Cd content of the rice roots but increased the Cd content of the stems and leaves and decreased the Cd content of the brown rice. The Cd content of grain produced by the early and late rice plants was 23.79% and 26.40% lower, respectively, after foliar spraying with silicon fertilizer than after the CK treatment. Foliar spraying with the silicon fertilizer affected the Cd redistribution process in the aboveground parts of the rice plants, decreasing Cd translocation from the stems to the rice grains and trapping Cd in the stems, and therefore promoting Cd accumulation in the rice stems. This decreased Cd accumulation in the grain.

The Cd content was lower for brown rice produced by early and late rice cultivars with low Cd accumulation potentials (ZY-819 and XWX-13) than for brown rice produced by early and late rice cultivars with high Cd accumulation potentials (LY-996 and YZX) grown in the mildly Cd-polluted soil. The Cd content of brown rice produced by the high Cd accumulation potential cultivars was close to or higher than the maximum limit of 0.2 mg kg^{-1} stipulated in the Chinese national food safety standards for contaminants in food (GB 2762-2017) but the Cd content of brown rice produced by the low Cd accumulation potential cultivars did not exceed the standard. Cd migration and distribution in the soil–plant system was affected by the genetic characteristics of the rice cultivars and the Cd content of the soil [43], so different cultivars will take up Cd to different degrees. The Cd content of the rice grains is mainly determined by Cd absorption through the roots and Cd transport to the shoots [44]. The differences in the Cd content of the grains produced by different cultivars would therefore have mainly been caused by differences in the abilities of the cultivars to become enriched in Cd and to transport Cd from the roots to the shoots. In our experiment, the soil amendments mainly decreased the available Cd content of the soil and decreased Cd absorption by the roots. Foliar spraying with silicon fertilizer mainly decreased Cd transport from the stems and leaves to the grains. ZY-819 and XWX-13 (low-Cd-accumulation potential cultivars) had low Cd bioaccumulation and transport capacities in the mildly Cd-polluted study area, and the Cd content of the grains did not exceed the relevant standard.

5. Conclusions

Soil amendments, foliar spraying with silicon fertilizer, and combined applications significantly decreased the Cd content of brown rice produced by cultivars with high Cd accumulation potentials, and the SC–Si treatment had the strongest effect. Applying SC decreased the available Cd content of soil by increasing the soil pH and effectively decreased Cd uptake by rice plant roots and Cd migration from the roots to the above-ground parts, and therefore decreased the Cd content of the brown rice. Foliar spraying with silicon fertilizer significantly decreased the Cd content of the brown rice by decreasing Cd transport from the stems and leaves to the grains. Cd uptake by high Cd accumulation potential rice cultivars grown in mildly Cd-polluted paddy fields could be most effectively decreased by applying SC combined with foliar spraying with silicon fertilizer.

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