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RESEARCH ARTICLE

Silicon application improved the yield and nutritional quality while reduced cadmium concentration in rice

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Abstract

Silicon (Si) is an essential nutrient for rice, but its effects on the yield and quality of rice under heavy metal stress remain uncertain. In this study, two typical paddy soils (acidic and calcareous purple soils) in the western region of Chongqing were selected for field plot experiment, with the purpose of understanding the effects of Si implementation methods on grain yields and cadmium (Cd) uptake, transport, and accumulation in the grain of a hybrid rice (*Oryza sativa* L, Changliangyou 772). Four treatments were set for the purposes including soil-based Si application, foliar spray of Si alone, foliar spray of selenium (Se)–containing Si fertilizer, and a control without Si application, respectively. The results indicated that the Si applications reduced Cd contents in brown rice by 11.45~51.85% in the slightly Cd-contaminated acidic purple soil (pH = 4.77, soil total Cd content 0.413 mg kg^{-1}) and 26.93~43.77% in the purple calcareous paddy soil (pH = 7.77) with similar Cd-polluting levels. It is worth noting that the Cd content of conventional fertilized rice exceeds the Chinese National Food Safety Standard limit (0.2 mg kg^{-1}, GB2762-2017) in the slightly Cd-contaminated acidic purple soil, and foliar spray treatments showed most effective effects that meets the safety threshold standard. Soil-based Si application reduced Cd accumulation in rice grains mainly by inhibiting the translocation of Cd from stem to the rice grain or root to stem, while foliar sprays of Si mainly by inhibiting the translocation of Cd from stem to brown rice. Si applications increased the rice yield by 17.15 to 25.45% in calcareous paddy soil with foliar spray being the best, while no significant yield increase was found in acidic paddy soil. Si and Se-containing Si fertilizer improved the nutritional quality of rice grain as indicated by the increases of Se, Si, and protein contents and the significant decreases of Cd contents in the rice grains. The comprehensive effects in improving the rice quality follow the order of foliar spray of Se-containing Si fertilizer > foliar spray of Si alone > soil-based Si application. Thus, foliar spray Si-containing fertilizer could be helpful in increasing rice yield while reducing the Cd uptake in rice grains, which might be a feasible approach in controlling Cd entry into the human body via crops.

Keywords Rice · Cd accumulation · Silicon fertilizer · Silicon application

In recent years, soil pollution has become a hot topic of social concern due to its impact on the security quality of agricultural products. Among them, heavy metal pollution is a common occurrence, especially cadmium (Cd), with an over-standard level of 7% in soils in China. Due to the higher mobility and bioavailability of Cd, it is assimilated in plants grown on Cd-contaminated soils (Choppala et al. 2014) and endangers human health through the food chain (Godt et al. 2006). Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population (Meharg et al. 2013; Kosolsaksakul et al. 2014). It was reported that Cd can be readily taken up by rice and translocated to shoot and then to grains (Wang et al. 2014; Song et al. 2015). Rice grains may accumulate excessive Cd while keeping normal growth under soil Cd stress, due to its tolerance to excess Cd via excluding Cd to less-sensitive tissues, chelating with organic acids and proteins, and enhancing PGRs, ion homeostasis, and overexpression of different genes (Rizwan et al. 2016). At present, soil cadmium pollution in

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rice planting area is common, which poses a serious threat to rice quality and safety (Zhu et al. 2016). Therefore, controlling and reducing the accumulation of Cd in rice and achieving safe production in moderately Cd-contaminated paddy soil have become a hot spot of research concern.

Accumulation of heavy metals in plants depends on the bioavailability of heavy metal in soil and crop physiological features. Heavy metal passivators are widely applied because of their abilities in promoting the transformation of heavy metal in labile forms to inactive forms in soils (Li et al. 2014). Soil passivation restoration, however, has unstable remediation effects, and long-term implementation may have potential adverse effects on soil physical, chemical, and biological properties (Sun et al. 2018; Cao et al. 2019). Thus, the screening of eco-friendly and high-effective passivators and the evaluation of their long-term implementation effects still remain to be solved. It is therefore worthwhile to explore new agents for the control of Cd accumulation in the crops. Physiological antagonists, such as Si and selenium (Se), which exert antagonism against heavy metals (Hu et al. 2011; Guo et al. 2017), have the potentials in reducing Cd accumulation in the edible parts of the crops by enhancing crop resistance to Cd stress, inhibiting Cd absorption, and/or altering Cd distribution in crop plants (Li et al. 2008; Zhu et al. 2009; Wan et al. 2016; 2018). Moreover, foliar application of such kind of antagonists may achieve the goals of decreasing Cd in rice grains and avoiding the adverse influences of passivators on soils.

Si is considered as a beneficial element for healthy growth and development of plants including rice which is a typical Si accumulator (> 10% of its dry weight) crop (Liu et al. 2013; Majumdar et al. 2019). It is highlighted that Si can improve the plant tolerance to Cd toxicity (Adrees et al. 2015; Yu et al. 2016). When the Si contents increased in plants, especially in shoots, the physical and biochemical defense mechanism boosted up in Cd-contaminated soil (Adrees et al. 2015). Studies have figured out that Si can reduce Cd toxicity by adsorbing ions (Greger et al. 2016), regulating heavy metal transport proteases (Kim et al. 2014), and improving antioxidant ability (Shi et al. 2005). Moreover, Si activates plant defense mechanisms, produces alterations in the photosynthetic apparatus, and simultaneously increases carboxylation, water, and light-use efficiency, thus further improves the Cd tolerance in plants (Adrees et al. 2015). It was also found that appropriate use of Si fertilizer could significantly decrease the content of Cd in rice and increase rice yield and its quality (Meharg and Meharg 2015). Si application has proven to be a potential technology for Cd pollution control in polluted paddy soils (Chen et al. 2014; Klotzbucher et al. 2015); its effectiveness depends on the dosage of Si and its application methods, as well as the available Si content in soil. Se is an essential element for animals and humans and low doses of Se have also been found to be beneficial to plants: it can relieve abiotic (e.g., salt and heavy metal toxicity) and biological stress (e.g., plant disease, pest) in plants (Feng et al. 2013). Besides, Se can also alleviate Cd toxicity by preventing oxidative stress (Wu et al. 2016), regulating photosynthesis (Feng et al. 2015), and protecting photosynthetic systems (Zhang et al. 2014). Its application can enhance its content in the edible parts of crops to satisfy the requirement for Se by individuals.

Even though many studies have proven that Si and Se can increase tolerance of crops to Cd pollution, their impacts on Cd accumulation in rice grains and Cd uptake, translocation, and distribution in rice plants still remain unclear. The effects of different application techniques (soil amendment and foliar spray) and the joint application of Se and Si need further investigation. Consequently, this study aimed at identifying the best way for the implementation of Si/Se for rice and knowing the joint effects of Si and Se in Cd accumulating through field plot experiments, which were carried out in both acidic and calcareous purple paddy soils using a low-Cd accumulating hybrid rice cultivar Changliangyou 772 as a representative crop. The results are predicted to supply theoretical and technical support for the safe production of rice in the Cd slightly polluted area.

Materials and methods

Experimental time and site

A field plot experiment was conducted from April 28 to August 16, 2018, in typical paddy fields located in Jiangjin and Tongnan Districts in western Chongqing, China. The soils are acidic purple paddy soil and calcareous purple paddy soil, respectively. Their basic properties are listed in Table 1. The soil Cd contents in both sites are similar and are slightly Cd-polluted.

Table 1 Physical and chemical properties of the experimental soils

Types	pH	SOM, g kg^{-1}	TN, g kg^{-1}	TP, g kg^{-1}	TK, g kg^{-1}	CEC, cmol kg^{-1}	Cd, mg kg^{-1}	Available Si, mg kg^{-1}
Acidic soil	4.75	26.19	0.93	0.256	15.59	19.99	0.413	305.76
Calcareous soil	7.77	43.69	1.32	0.557	18.15	17.60	0.471	69.96

Experimental materials

The rice cultivar tested was Changliangyou 772, a low-Cd accumulating hybrid rice variety selected by the Institute of Subtropical Agriculture, Chinese Academy of Sciences. The three Si/Se-containing materials used include (1) silicon-calcium fertilizer provided by Shandong Zibo Jinhe Fertilizer Co., Ltd. (pH = 10.01, $SiO_2 \geq 24\%$, $CaO \geq 32\%$); (2) high-purity silica sol provided by Foshan Tieren Environmental Protection Technology Co., Ltd. (pH = 5.0~7.0, Si ≥ 85 g L^{-1}); (3) nanometer Se-containing Si fertilizer (pH 7.0~9.0, Si ≥ 100 *g*/L, Se ≥ 1 *g*/L), which is synthesized by "hot sol-dialysis method," also provided by Foshan Tieren Environmental Protection Technology Co., Ltd.

Experimental method

Four treatments were set in the experiment, which include (1) soil implementation of Si-Ca fertilizer labeled as S-Si, (2) foliar spray of high-purity silica sol labeled as L-Si, (3) foliar spray of Se-containing nanometer Si labeled as L-SiSe, and (4) a control without Si application labeled as CK. The dosages of the Si fertilizers used were based on the recommendation doses of the corresponding Si fertilizer as shown in Table 2. Each of N 300 g/plot (urea), P_2O_5 120 g/plot (calcium superphosphate), and K_2O 90 g/plot (potassium sulfate) was applied as base fertilizers for all the treatments. There were three replications for each treatment. The area of each experimental plot was $4 \times 5 = 20\ m^2$; 12 plots in total were arranged by randomized block design. The plots were separated by soil ridge covered with a plastic film 0.3 m down to the soil ridge to avoid series flow. The rice seedlings with age of 30 days were transplanted to the plot on April 27, 2018, with a planting specifications of 30.5 cm × 20 cm. All field management practices were kept the same following the local traditional experiences. The rice was harvested on August 16, 2018, and the rice yields for each treatment were recorded. The whole rice plants were sampled for getting the parameters of biomass of root system, stems, and rice grains, and effective tiller number per plant, grain number per spike, the seed setting rate, and 1000-grain weight were calculated. Three rice plants from each soil plot were collected randomly and were stored in polyethylene bags. All samples were stored in polyethylene bags for transport. After plants were taken back to the laboratory, they were cleaned using tap water first and then distilled water, placed in a 105 °C drying oven for 30 min after airing, and then placed in a 70 °C drying oven until the weight of samples remained constant. Rice plants were then separated into four tissue parts (root, straw, leaf, and grain). Grain was hulled with a small huller (JLGJ4.5, China), husk and brown rice were collected, and straw was crushed using a micromill (RT-02B, China). The crushed powder was passed through a 100-mesh sieve and kept in a sealed plastic bag for analysis. The soil sample in each plot was a mixture of 5 random samples collected at the depth of 0–20 cm at harvest stage. All the collected samples naturally dried at ambient temperature. Large particles and biological debris were removed by sieving the dried soil through a nylon mesh (2 mm), and the sieved soil was collected for analysis.

Sample analyses

The basic physical and chemical properties of the soil such as pH, organic matter, CEC, alkaline hydrolysis nitrogen (N), available phosphorus (P), and available kalium (K) were determined by conventional methods (Yang et al. 2008).

The available Si contents in the soil A total of 10.00 g sample of soil (< 0.149 mm) was put into a 250-mL plastic bottle; 0.025 mol L^{-1} citric acid solution (100 mL) was added to incubate for 5 h in an incubator at 30 °C, and shaken it once every 1 h. Si concentration in the filtrate was determined using ICP-OES at a radio frequency of 1150 W, a peristaltic pump flow rate of 50 r/min, and an atomizer pressure of 250 kPa (Zhou et al. 2018).

The Si contents in the rice The rice sample (< 0.250 mm) was digested in a mixture of 3 mL of 62% (w/w) HNO_3, 3 mL of 30% (w/w) hydrogen peroxide, and 2 mL of 46% (w/w) HF, and the digested sample was diluted to 100 mL with 4% (w/v) boric acid. The Si concentration in the digest solution was determined by the colorimetric molybdenum blue method at 600 nm (Ma et al. 2002).

Table 2 Test treatment

Treatments	Application method and dosage
CK	No application of Si fertilizer, compatible with standard local fertilization.
S-Si	Applying silicon-calcium fertilizer, the dosage is 2.25 t hm^{-2}, and the equivalent plot is 4.5 kg. Other measures are the same as CK.
L-Si	Foliar spray of Si alone was sprayed twice from jointing stage to heading stage at a dose of 3.0 g L^{-1}, and other measures were the same as CK.
L-SiSe	Spraying foliar Se-containing Si fertilizer, the spraying time is the same as L-Si, the dose is 3.0 g L^{-1}, and other measures are the same as CK.

The total Cd concentration in the soil A total of 0.500 g sample of soil (< 0.149 mm) was put into a vessel. Then, concentrated HCl (10 mL) was added for digestion until the digest liquid was about 3 mL left. After the sample chill-down, each of 5 mL HF, 5 mL HNO_3, and 3 mL $HClO_4$ was added. The vessel was half-covered and digested again until the digestion became viscous. The digested solution was then washed and diluted with deionized water using a volumetric flask. Cd concentration in the filtrate was determined using inductively coupled plasma mass spectrometer (ICP-MS).

The total concentration of Cd and Se in plant and rice A total of 0.5 g (dry weight) plant or rice was weighed into digestion vessel, then digested with mixture acids of HNO_3 and $HClO_4$ (4:1, v/v). After cooling, the digestion solution was diluted to 25 mL using ultra-pure water and then filtered. Cd and Se concentration in the filtrate was determined using ICP-MS.

All glass utensils were soaked in 10% HNO_3 solution at least one night before being thoroughly washed with deionized water and dried. Disposable labware was used for all other analyses. Cd readings obtained from replicate analysis of a standard solution were reproducible with a variation of 5%. The range limit of duplicate sample values was < 20%. Reagent blanks were routinely analyzed to check for background contamination. During the experiment, the analytical quality was controlled by the soil composition analysis standard substance GBW07428 (GSS-14), the biological component analysis standard substance (Sichuan rice) GBW10044 (GSB-22), and the standard recovery method. The Cd recovery rate of soil samples was 98.5~103.1%, and the Cd recovery rate of rice samples was 97.5~102.3%.

Data analysis

The Cd bio-concentration factor (BCF) and transfer factor (TF) of rice under different treatments were calculated according to the following formula:

$$\text{Bio-concentration factor } \mathrm{BCF}_{\mathrm{root}} = \text{rice root Cd content } \left(\mathrm{mg{\cdot}kg^{-1}}\right) / \text{soil Cd content } \left(\mathrm{mg{\cdot}kg^{-1}}\right) \times 100\%$$

$$\text{Transfer factor } \mathrm{TF}_{A/B} = \text{Cd content of part A} \left(\mathrm{mg{\cdot}kg^{-1}}\right) / \text{Cd content of part B} \left(\mathrm{mg{\cdot}kg^{-1}}\right) \times 100\%$$

TF refers to the ratio of heavy metal concentration in part *A* to that in part *B* of the rice plant. A greater index means a greater transferring ability of heavy metals from one part to another in rice plants.

All data were processed with Excel 2010, and figures are drawn with the Origin 8.5 package. Three-way analysis of univariate ANOVA was performed using SPSS version 21.0 package (IBM Corp., Armonk, NY, USA). The level of significance was set at $P < 0.05$.

Results

Rice yield and its composition

The rice yield under different silicon treatments is shown in Fig. 1, which varied from 6.34 to approximately 7.40 t hm^{-2} and from 7.63 to approximately 9.57 t hm^{-2} for acidic and calcareous purple paddy soils, respectively. Calcareous soil produced higher rice yield as compared with acidic soil at the same treatment. There was no significant statistical difference in rice yields among different treatments for acidic soil. However, for the calcareous soil, all Si applications significantly increased the rice yields by 17.15 to 25.45%, with foliar spray of Se-containing Si fertilizer being the best. The results verified that Si application was beneficial to the rice growth.

Si application altered the rice yield composition and thus increased the grain yield (Fig. 2). For acidic paddy soil, Si application showed no influence on the effective tiller number per plant and 1000-grain weight, and increased the grain number per spike by 12.5% and 7.89% for treatment L-Si and L-SiSe, respectively, while the seed setting rates decreased by 12.86% and 8.57%, as compared with the control. Consequently, the rice grain yields showed no significant differences among treatments (Fig. 1). However, in calcareous paddy soil, S-Si increased grain number per spike by 10.59%; L-Si increased effective tiller number per plant and grain

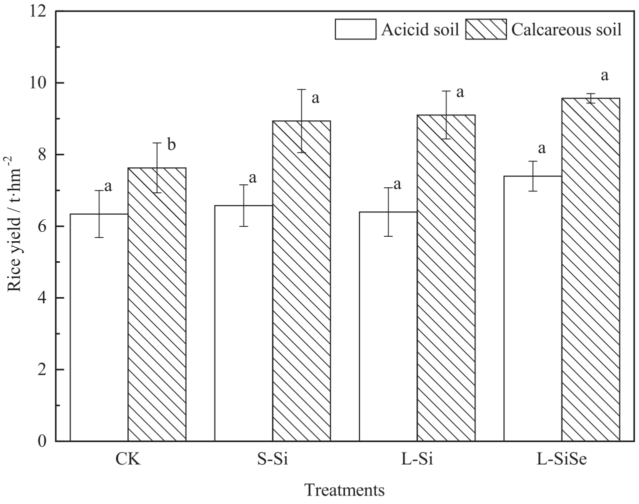

Fig. 1 Yield of rice under different silicon application methods. Details of CK, S-Si, L-Si, and L-SiSe are shown in Table 2. The letters (a, b, c) on the top of the column indicate the statistical difference at $P \leq 0.05$ between each treatment in the same soil, the same below

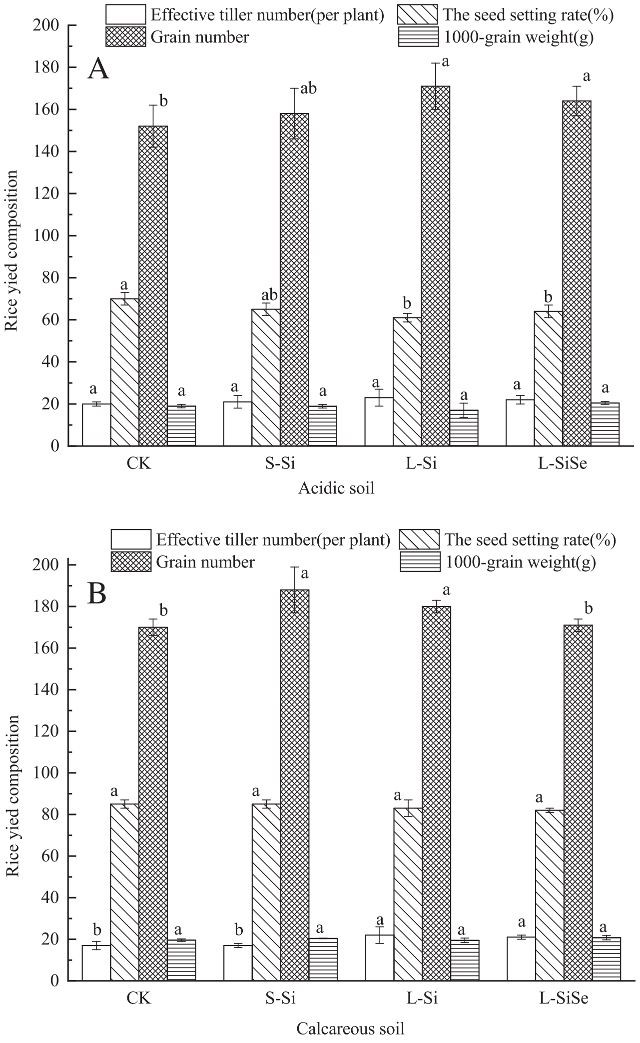

Fig. 2 Effects of different silicon application methods on rice yield composition. **A** Acidic soil. **B** Calcareous soil

number per spike by 29.41% and 5.88%, respectively; the effective tiller number per plant under L-SiSe treatment increased by 23.53%. As a result, the rice grain yields increased by 1.31~1.94 t hm^{-2} mainly due to the increase of effective tiller number and grain number per spike under Si treatments.

Cadmium contents of brown rice

Application of Si showed a significant impact on Cd contents of brown rice (Fig. 3). In acid paddy soil, the Cd contents of brown rice for CK were 0.297 mg kg^{-1}, which exceeded the Chinese National Standard Limit of Pollutants in Food (GB 2762-2017, 0.2 mg kg^{-1}). Si application reduced the Cd contents of brown rice by 11.45~51.85%; L-Si and L-SiSe showed most favorable effects, which resulted in a Cd content in brown rice of 0.179 mg kg^{-1} and 0.143 mg kg^{-1}, respectively, meeting the safe food standard limit. In calcareous soil, Cd contents in brown rice for different treatments were far lower than those in acidic soils, ranging from 0.017 to 0.030 mg kg^{-1}, which were all lower than the safety criteria. However, Si application still showed favorite effect in reducing the Cd contents in brown rice with a decline range of 26.93~43.77% as compared with the CK. Foliar spray of Si (L-Si and L-SiSe) exerted best effects in controlling the Cd accumulation in rice grains for both acidic and calcareous paddy soils.

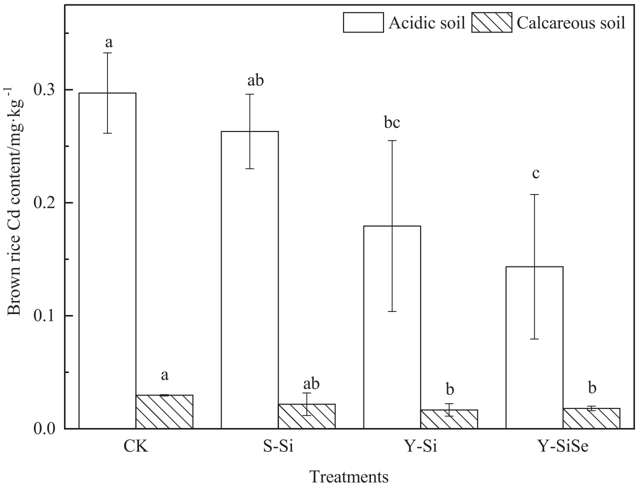

Fig. 3 Cd contents of brown rice under different silicon application methods

Cadmium accumulation and translocation in rice plants

The total Cd accumulations in roots, stems, and leaves of rice in acid soil were almost one order of magnitude higher than those in the corresponding parts of rice in calcareous soil (Fig. 4), indicating that rice plants could easily absorb and accumulate Cd in acid soils. The absorbed Cd primarily accumulated in roots for both soils as indicated by the much higher total Cd accumulation in rice roots compared with rice stems and

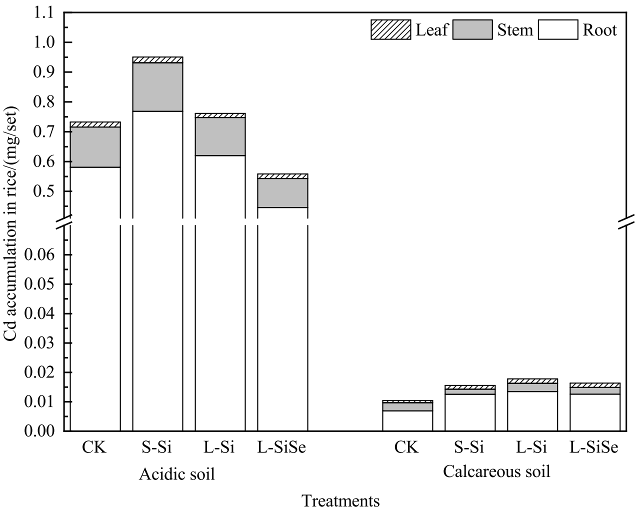

Fig. 4 Effect of Si application on Cd accumulation in each part of rice plant

leaves. Except for L-SiSe, Si treatments did not reduce the total Cd accumulation in rice plants for both paddy soils. Thus, the effect of Si on the reduction of Cd in rice grains is mainly ascribed to the alteration of Cd translocation in rice plants after the application of Si-containing fertilizers.

The bio-concentration factor (BCF) and the transfer factor (TF) can be used to reflect the Cd absorption ability of rice and the translocation trait of Cd in rice plant. The Si application affected the Cd translocation from soil to root, root to shoot, and shoot to grain (Table 3). In the acidic purple soil, the treatment S-Si increased the $\mathrm{BCF}_{\mathrm{root}}$ and $\mathrm{TF}_{\mathrm{stem/root}}$, but $\mathrm{TF}_{\mathrm{brown\ rice/stem}}$ decreased by 27.04%. Therefore, the final Cd content of brown rice was still reduced by 11.45% compared with CK (Fig. 3), which meant that S-Si might mainly affect the transfer of Cd from stem to the rice grain. L-Si and L-SiSe were effective in decreasing the Cd contents of roots and stems, accompanied by decreases of $\mathrm{BCF}_{\mathrm{root}}$ and the $\mathrm{TF}_{\mathrm{brown\ rice/stem}}$. Therefore, the Cd contents of brown rice were both decreased as compared with CK, which meant that foliar spray of Si fertilizer reduced the Cd accumulation in brown rice by affecting the enrichment of Cd in roots and the transport of Cd in rice plants. For the calcareous purple soil, although the Cd contents of brown rice under different treatments met the standard requirements, the application of Si fertilizer further reduced the Cd contents of brown rice, with foliar sprays of Si showing more significant effects, of which S-Si mainly reduced the $\mathrm{TF}_{\mathrm{shoot/root}}$ and L-Si and L-SiSe mainly reduced the $\mathrm{TF}_{\mathrm{shoot/root}}$ and the $\mathrm{TF}_{\mathrm{brown\ rice/stem}}$.

In general, the Cd accumulation in Changliangyou 772 was mainly concentrated in the roots, followed by roots, stems, leaves, and grains. The application of Si fertilizer could reduce the absorption and enrichment of Cd by roots, or change its distribution and translocation in rice plants, thereby reducing the accumulation of Cd in brown rice. Different methods of Si fertilizer application led to different directions and extents of influence, resulted in various Cd reduction effects in brown rice.

Rice nutrient quality

The contents of some indices reflecting rice nutrient quality, including Si and Se as well as starch and protein, under different treatments are shown in Fig. 5. For acidic soil, Si application did not affect the starch content of rice (Fig. 5a), but caused an apparent increase of protein content (Fig. 5b) in rice grain. L-Si and L-SiSe increased the rice protein content by 7.63% and 12.19%, respectively, as compared with the control (81.2 g kg^{-1}). For calcareous soil, the rice protein content for the control was 74.7 g kg^{-1}; Si application showed more significant effects in increasing rice protein contents by 13.92~25.30% compared with those in acidic soil, with foliar sprays of Si being more effective in improving rice protein contents.

The Se contents of rice in acid and calcareous purple soil were in the range of 0.101~0.175 mg kg^{-1} and 0.065~0.103 mg kg^{-1}, respectively (Fig. 5d). Foliar spray of Se-containing Si (L-SiSe) significantly increased the Se content of rice by 70.00% and 66.67%, respectively, in two types of soils, matching the national standard for Se-rich rice (DB/T 22499-2008). S-Si and L-Si had no significant influence on rice Se contents, indicating that these two methods of Si application did not inhibit the absorption of Se while preventing Cd accumulation in rice grains. Si application significantly increased the Si contents of rice by 20.58~49.57% (Fig. 5c), as could be predicted.

In conclusion, Si application could improve the rice quality by reducing Cd accumulation in rice grains and increasing protein content, with foliar spray showing more profitable effects. Moreover, application of Se-containing Si gel may result in a higher Se content in rice, which is beneficial to the rice quality in the region lack of Se.

Basic physical and chemical properties of soil

Adverse influences on soil properties might occur when passivators are used for remediation of soil Cd pollution, which may in turn affect the crop growth. Foliar spray of antagonist theoretically should have less influence on soil properties. Some soil property parameters such as pH and contents of organic matter, available nutrients, and available silicon were measured after Si applied with different methods (Figs. 6 and 7).

Table 3 Root BCF and Cd transmission coefficients of various parts of rice

Treatments	Acidic soil				Calcareous soil			
	$\mathrm{BCF}_{\mathrm{root}}$	$\mathrm{TF}_{\mathrm{stem/root}}$	$\mathrm{TF}_{\mathrm{leaf/stem}}$	$\mathrm{TF}_{\mathrm{brown\ rice/stem}}$	$\mathrm{BCF}_{\mathrm{root}}$	$\mathrm{TF}_{\mathrm{stem/root}}$	$\mathrm{TF}_{\mathrm{leaf/stem}}$	$\mathrm{TF}_{\mathrm{brown\ rice/stem}}$
CK	54.954	0.076	0.212	0.159	0.925	0.128	0.612	0.543
S-Si	57.289	0.084	0.212	0.116	1.408	0.044	1.344	0.802
L-Si	40.971	0.078	0.197	0.141	1.730	0.057	0.922	0.400
L-SiSe	34.145	0.092	0.281	0.110	1.230	0.061	1.249	0.500

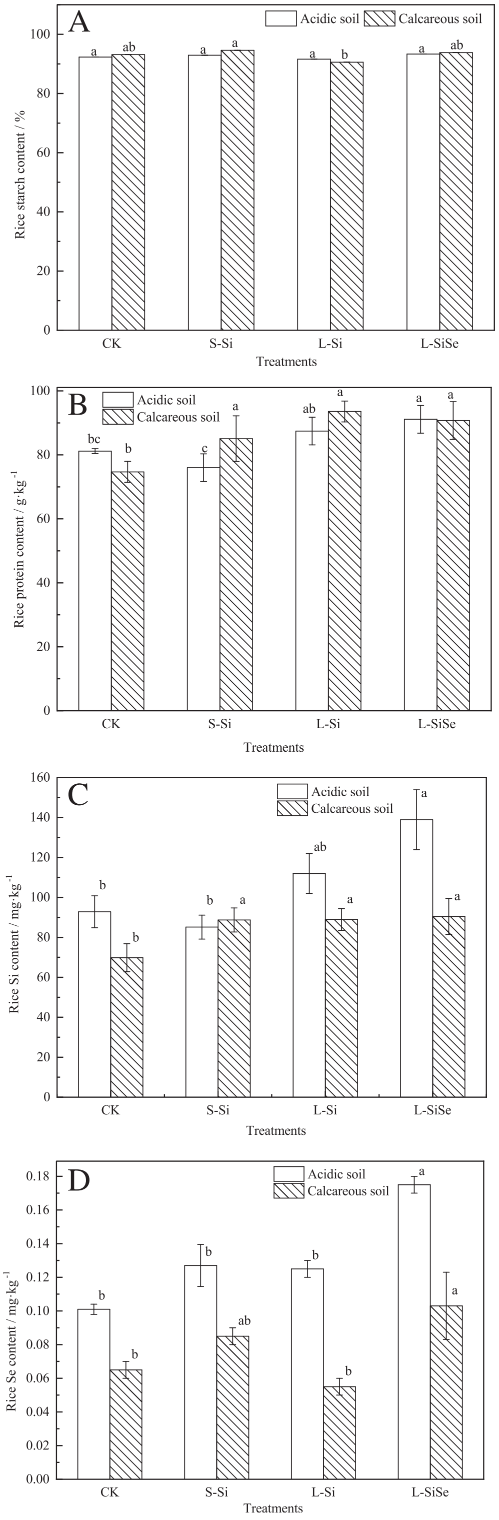

Fig. 5 The impact of silicon treatments on rice starch content (**A**), protein content (**B**), Si content (**C**), Se content (**D**)

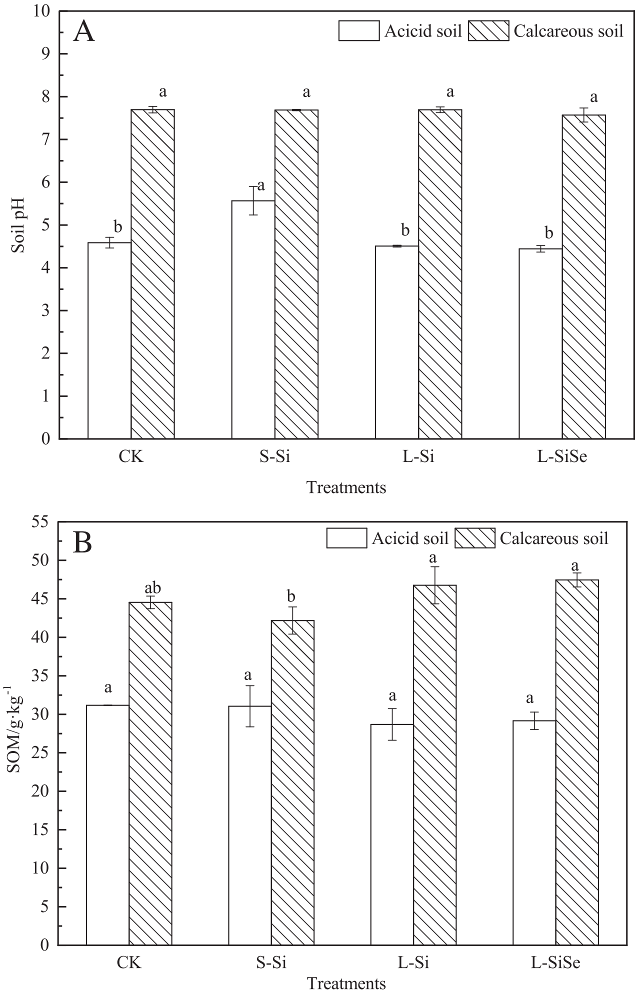

Fig. 6 The impact of silicon treatments on soil pH value (**A**) and organic matter content (**B**)

Application of Si has no influence on soil organic matter. While S-Si treatment increased the soil pH value by 0.98 unit in acidic purple soil, which was beneficial for the inhibition of Cd activity. Meantime, nutrient conditions of the soil were also improved: alkaline hydrolysis N, available K, and available Si contents were increased by 19.81%, 10.71%, and 16.93%, respectively, compared with CK. Similar results were also found in the purple calcareous soil, where soil available P and available Si contents increased by 32.50% and 17.49%, respectively. In contrast, foliar spray of Si did not have influences on soil properties.

Discussions

Cadmium stress significantly inhibited the plant growth and yields of rice, while this situation was diminished by the application of Si (Figs. 1 and 2). These observations were similar to the previous studies (Rehman et al. 2019; Deng et al. 2011). Silicon application under metal stress may improve the plant growth by enhancing the nutrient elements, chlorophyll contents, root volume, and secretion of organic acids and histological features (Keller et al. 2015; Fan et al. 2016; Hussain et al. 2019; Merwad et al. 2018). Silicon-binding protein

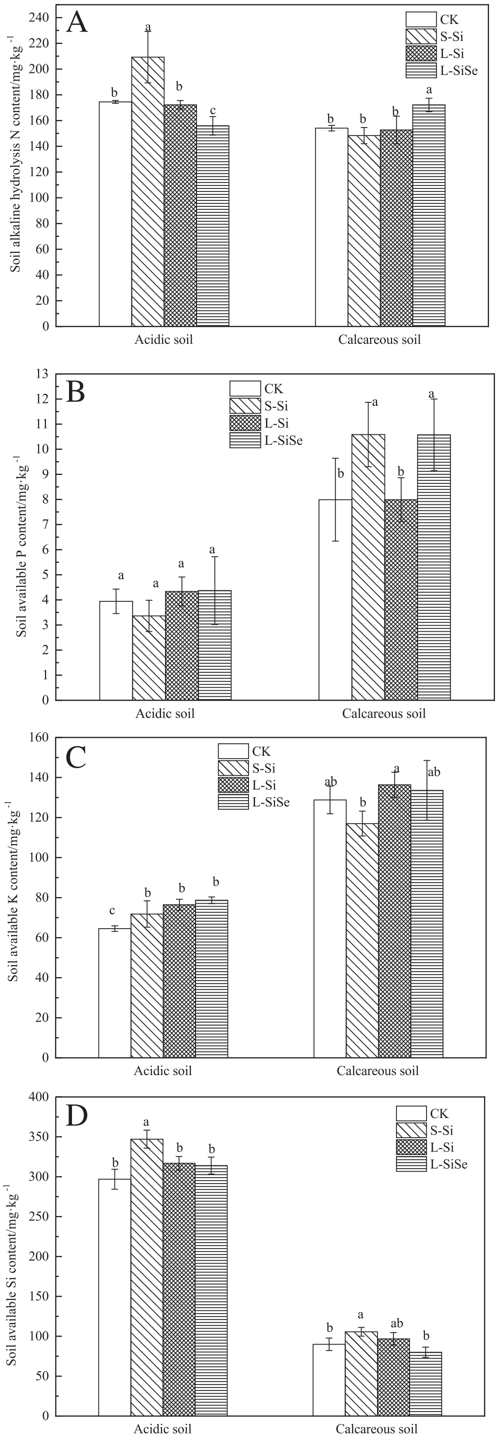

Fig. 7 The impact of silicon treatments on soil alkaline hydrolysis N content (**A**), available P content (**B**), available K content (**C**), available Si content (**D**) (mg kg^{-1})

mainly reduced peroxidase activity induced by Cd toxicity on rice, and the toxic effect of Cd on rice can be alleviated (Shi et al. 2006). Si may also diminish the toxic effects of Cd and probably other metals by enhancing the plant defense by reducing the ROS production and enhancing the antioxidant defense system (Ali et al. 2016; 2019; Khaliq et al. 2016; Khan et al. 2019). In this study, the yield-increasing effects of Si varied with the manner of Si supply and soil types. Significant rice yield increase was observed in the calcareous paddy soil for both soil apply (S-Si) or foliar spray of Si agents with the latter being the best, while no such effects were found in acidic soil. This phenomena may be attributed to the much higher available Si content in acidic soil as shown in Table 1.

The distribution of Cd in rice plant followed an order of root > shoots and leaves > gran irrespective of the Si application methods and soil types (Fig. 4). This is in line with the previous studies (Rizwan et al. 2016; Qayyum et al. 2017; Rehman et al. 2018). The higher amount of Cd retained in the roots can be due to several factors such as chelation, compartmentalization, apoplastic barriers, and adsorption (Xu et al. 2017). Overall, higher retention of Cd in the roots is considered a defense mechanism of the plant to mitigate metal stress (Rehman et al. 2019). Cd content in brown rice is the main concern regarding to its health risk. Our results showed that Si application took significant role in reducing Cd contents in brown rice both in acidic paddy soil (11.45~51.85%) and in calcareous paddy soil (26.93~43.77%). The Cd-reducing ability varied with Si application method; in both soils, foliar spray of Se-containing Si (L-SiSe) exerted best effect followed by foliar spray of Si alone (L-Si); soil amendment of Si showed lowest Cd-reducing effect. It should be noticed that the low-Cd accumulating hybrid rice cultivar Changliangyou 772 alone still obtained a Cd content in brown rice exceeding the national standard in acidic soil, while when it combined with foliar application of Si, rice Cd content could be decreased to match the requirement of food standard.

Application of siliceous material improved rice growth, thus increased its yield while depressed Cd accumulation in brown rice, which seems to be contradictory. Improvement of plant growth in general would be accompanied by more nutrients (elements) to be absorbed. However, application of Si increased rice tolerance to Cd stress as discussed above; meanwhile, soil-based Si application reduced Cd accumulation in rice grains mainly by inhibiting the translocation of Cd from stem to the rice grain or root to stem, while foliar sprays of Si mainly by inhibiting the translocation of Cd from stem to brown rice (Table 3). This is similar to the previous study by Guo et al. (2017). It is reported that the Si application may decrease the Cd uptake and translocation in rice by suppressing the expression of transporter genes involved in Cd accumulation, and Cd uptake in the rice cell may be inhibited due to the wall-bound form of Si (Feng et al. 2017; Liu et al. 2013). The Cd^{2+} of the aboveground part of rice is deposited in the cell wall of the stem and leaf to form a Si-Cd complex under the foliar spray with Si fertilizer, which increases the deposition of Cd in the cell wall and reduces the proportion of Cd in the symplast, thus inhibiting the Cd uptake by rice gains and the Cd upward translocation (Huang et al. 2007)

Si fertilizer is a partial alkaline fertilizer, and soil-based application can increase soil pH, which has a certain effect on inactivating soil Cd and reducing its availability to plants (Hu et al. 2011). However, in this experiment, although the soil-based application of Si fertilizer could significantly increase the pH values of acidic soil, the bio-concentration factor of Cd in rice roots was increased. This may be due to the fact that Cd is a non-essential metal ion and is often absorbed and transported in rice through a transport system of basic cations such as Ca and Fe (Palmgren et al. 2008; Clemens 2006). Si fertilizer used in this experiment contains calcium oxide (CaO $\geq 32\%$), on this account, which promoted the absorption of Cd by rice roots. Therefore, the solid-based application of Si fertilizer led to an increase in the Cd bio-concentration factor of rice roots. However, TF $\text{brown}_{\text{rice/stem}}$ in acid soil and $\text{TF}_{\text{stem/root}}$ in calcareous soil decreased under the influence of Si, and the final Cd contents of brown rice were decreased by 11.45% and 26.93%, respectively, compared with the control. Foliar spray of Si agents acts directly on the foliage; the Si-Cd complex which increased the deposition of Cd was formed in the stem and leaf cell walls, so the effect of reducing cadmium was more obvious than soil-based Si application.

Se could relieve Cd toxicity by preventing oxidative stress (Wu et al. 2016), regulating photosynthesis (Feng et al. 2015), and protecting photosynthetic systems (Zhang et al. 2014). Studies have shown that the addition of selenium can significantly reduce the bio-concentration factor of Cd in rice roots, thus effectively reduce the transport of Cd from the roots to the rice stems (Wan et al. 2016; Wan et al. 2018). Si and Se mixture enhanced photosynthetic capacity and decreased Cd accumulation in rice stems (Gao et al. 2018) to inhibit Cd upward translocation. As a result, L-SiSe was most effective in reducing Cd accumulation in brown rice.

The results of our study depicted that the foliar spray of Si fertilizer was effective in reducing the Cd concentrations in rice grains (Fig. 3); meanwhile, the cost of L-Si and L-SiSe treatments is only about 1/3 and 1/2 of the soil-based silicon fertilizer application, respectively. Thus, foliar spray of Si-containing fertilizer could be a feasible approach in controlling Cd accumulation in rice grains, and thus mitigating its risk to human health via food chain.

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