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Effects of Nano-Silicon and Common Silicon on the Growth and Cadmium Concentrations in Different Rice Cultivars

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Abstract

The effects of Nano-Silicon (Si) and common Si on the growth and Cd uptake in rice plants were studied under different soil Cd levels, and two rice cultivars of different cadmium (Cd) accumulation abilities were used. The results showed that the rice cultivars differed in Cd tolerance, and Yangdao 6 may be more sensitive than Yu 44 to soil Cd stress. The biomasses of the two rice cultivars were decreased significantly ($P < 0.05$) by 10 mg/kg soil Cd treatment. The alleviative effects of Si on Cd toxicities were higher for Nano-Si than for common Si, under 10 mg/kg soil Cd treatment than under 5 mg/kg soil Cd treatment, and in Yangdao 6 than in Yu 44. The effects of Si in reducing Cd concentrations of different rice organs were in the orders: Nano-Si treatment > common Si treatment, Yangdao 6 > Yu 44, 10 mg/kg soil Cd treatment > 5 mg/kg soil Cd treatment > Non-Cd-treatment, and grain > shoot > root. Under soil Cd stress (5 mg/kg and 10 mg/kg), grain Cd concentrations of two rice cultivars were reduced by 40.00% - 70.27% and 26.67% - 45.95% by Nano-Si and common Si respectively. Therefore, Nano-Si is superior to common Si in reducing Cd level of rice grain and alleviating Cd toxicities to rice growth in soil Cd pollution areas.

Keywords

Rice (*Oryza sativa* L.), Silicon (Si), Cadmium (Cd), Uptake, Grain

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1. Introduction

Cadmium (Cd) is naturally found in low concentrations in most of environments, but it tends to accumulate to high and toxic levels in connection with mining, metal smelting, fuel burning, and excessive use of fertilization, wastewater and sewage sludge in agriculture [1, 2]. It is one of the most important pollutants in terms of food-chain contamination, because it is readily taken up by plants and transported to different parts of plants [1, 3]. Literatures showed that people consuming Cd-contaminated rice would develop 'itai-itai disease' that caused renal abnormalities and weak bones [4]. More than half the world's population depend on rice as staple food. For these peoples, the major route of Cd exposure is rice food. Therefore, the rice grain contaminated with Cd represents a major risk to their health [5].

Silicon (Si) is the second most abundant element both on earth surface and in soils [6]. It is considered as a beneficial element to plant growth and development, and it can improve plants' resistance to biotic and abiotic stresses induced by diseases, salinity and metal toxicity [7-9]. It was reported that Si enhanced plant tolerance to heavy metals, such as cadmium (Cd) [10], chromium (Cr) [11], manganese (Mn) [12], and zinc (Zn) [13], which might be due to activation of antioxidant system, mitigation of inhibition on photosynthesis and complexation of Si with metals. Researches also presented that Si application reduced metal uptake by and translocation in crops [14, 15]. Therefore, Si is

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recommended as a candidate for the tolerance of plants to heavy metal stress and the diminution of heavy metal contamination in crops.

Paddy rice is one of the most important crops in the world, especially in China. However, little is known about effects of Si (specifically Nano-Si) on Cd toxicity, uptake and translocation in rice plants. With two rice cultivars of different Cd accumulation abilities [16], the objective of this study was to investigate influences of Nano-Si and common Si on the growth and Cd uptake in rice plants exposed to different levels of soil Cd stress.

2. Materials and Methods

2.1. Soil and Plant Materials

The soil for the experiment was collected from uncontaminated fields (0–20 cm). After air-dried and passed through a 2-mm sieve, the soil samples were measured for some properties. The soil properties are shown in Table 1.

Table 1. Selected Properties of the Soil Used in This Experiment.

Soil Type	Particle Size (g/kg)			pH	OM [a] (g/kg)	CEC [b] (cmol/kg)	Available Si (mg/kg)	Total Cd (mg/kg)
	Sand	Silt	Clay					
Paddy Soil	581.2	232.8	186.0	6.6	27.1	14.3	101.7	0.14

Notes: a), organic matter; b), cation exchange capacity.

Four kilograms of soil was placed in a pot (18 cm in diameter and 20 cm in height). Cd in the form of $CdCl_2$ was added to the soil to obtain Cd levels of 5 mg/kg and 10 mg/kg. Based on our previous study [16, 17], two rice cultivars varying largely in Cd accumulation abilities were used in this experiment. The cultivars were Yangdao 6 (high Cd accumulator) and Yu 44 (low Cd accumulator). Rice seeds were germinated under moist condition at 32°C for 30 h. The germinated seeds were grown in uncontaminated soil for 30 d. Then, uniform seedlings were selected and transplanted into the pots (3 seedlings per pot).

2.2. Nano-Silicon Synthesis and Experimental Design

Nano-silicon was synthesized from sodium silicate [18]. 0.3584 g of sodium silicate ($Na_2SiO_3 \cdot 9H_2O$) was dissolved in 475 mL of distilled water. 10 mL of anhydrous alcohol was added, and the solution was stirred for 30 min. Then, the mixture of 10 mL anhydrous alcohol and 5 mL polysorbate 80 was added drop wise under vigorous stirring. The solution was further stirred for 2 h, and 2.5 mM Nano-silicon was obtained. 2.5 mM common silicon was prepared by dissolving 0.3584 g sodium silicate into 500 mL distilled water.

The Si treatments were 2.5 mM Nano-Si and 2.5 mM common Si solutions. Distilled water was served as control. From seedling transplanting to panicle heading, the Si solutions and distilled water were applied to the rice plants as leaf spray at one time every 10 d, 7 times of Si application in total. The experiments were carried out under open-air condition. The pots were arranged in a randomized complete block design with three replicates.

2.3. Determination of Cd Concentrations in Rice Plants

Whole rice plants were sampled at maturity. The plants were divided into roots, shoots, and grains. The plant parts were oven-dried at 70°C to a constant weight, and ground with a stainless steel grinder to pass through a 100-mesh sieve. Cd concentrations of the samples were determined with AAS.

2.4. Statistical Analysis

Data were analyzed with the statistical package SPSS 16.0. Means were compared through one-way ANOVA using Tukey's test at $P < 0.05$.

3. Results and Discussion

3.1. Effects of Silicon Treatments on the Growth of Different Rice Cultivars

The toxicity of Cd on rice growth differed with soil Cd levels and rice cultivars (Table 2). In the control (non-Si-treatment), the biomass of Yangdao 6 was increased significantly ($P < 0.05$) by 5 mg/kg soil Cd treatment, but reduced significantly ($P < 0.05$) by 10 mg/kg soil Cd treatment. The biomass of Yu 44 was also decreased significantly ($P < 0.05$) by 10 mg/kg soil Cd treatment, but slightly and insignificant ($P > 0.05$) influenced by 5 mg/kg soil Cd treatment.

It was proved that heavy metal pollutants, such as Cd, Cr, Ai, etc., have adverse effects on plant growth and development [19-21]. Heavy metals can inhibit many plant biochemical and physiological processes, such as nutrient uptake, photosynthesis and chlorophyll synthesis, which would result in decreases of growth, productivity and quality in crops [22-25]. It was reported that Cd stress can also cause oxidative stress in plants by influencing the roles of different antioxidant enzymes [26].

Table 2. Effects of Silicon on Biomasses of Rice Plants (g/pot).

Rice Cultivars	Silicon Treatments	Soil Cd Treatments (mg/kg)		
		NCdT (0.14) [a)]	Cd5	Cd10
Yangdao 6	Control	101.59 a	107.41 a	95.07 a
	Common Si	104.37 ab	111.93 a	101.65 b
	Nano-Si	108.85 b	118.59 b	107.70 c
Yu 44	Control	81.37 a	83.43 a	76.24 a
	Common Si	86.21 ab	86.26 ab	80.12 b
	Nano-Si	87.61 b	89.86 b	84.33 c

Notes: a), Non-Cd-treatment, the soil Cd concentration is 0.14 mg kg^{-1}.

Different letters in a column for a rice cultivar indicate significant difference between Si treatments at $P < 0.05$.

The present research indicates that rice cultivars differed in Cd tolerance, and Yangdao 6 may be more sensitive than Yu 44 to soil Cd stress.

Alleviative effects of Si on Cd toxicities were higher for Nano-Si than for common Si, under 10 mg/kg soil Cd treatment than under 5 mg/kg soil Cd treatment, and in Yangdao 6 than in Yu 44. Under 5 mg/kg soil Cd treatment, the biomasses of Nano-Si and common Si treatment were 10.41% and 4.21% higher than that of the control respectively in Yangdao 6, and the biomasses were 7.71% and 3.39% higher than that of the control respectively in Yu 44. Under 10 mg/kg soil Cd treatment, the biomasses of Nano-Si and common Si treatment were 13.28% and 6.93% higher than that of the control respectively in Yangdao 6, and the biomasses were 10.61% and 5.09% higher than that of the control respectively in Yu 44.

With regard to the mechanisms on Si-enhanced tolerance of heavy metal in plants may include chelation of Si with metals, decrease of metal activities in growth media, metal compartmentation, stimulation of antioxidants, reduction of metal translocation in different parts of plants, etc. [15]. Doncheva et al. presented that Si could alleviate the disorder of cell ultra-structure in pea and maize plants under Mn and Zn stress [27]. It was reported that Si can increase plant biomass in Cd stress environment, and the dilution effect may also be one of the mechanisms for Si-mediated alleviation [14].

The present study present that under all the soil Cd levels, the biomasses of Nano-Si treatment were significantly ($P < 0.05$) higher than those of the control in two rice cultivars.

3.2. Effects of Silicon Treatments on Cd Concentrations in Different Parts of Different Rice Cultivars

In general, Si treatments reduced Cd concentrations of rice roots, but the effects differed with Si types, soil Cd levels and rice cultivars (Table 3). The Cd-decreasing effects were in the order: Nano-Si > Common Si, Yangdao 6 > Yu 44, 10 mg/kg soil Cd treatment > 5 mg/kg soil Cd treatment > Non-Cd treatment. Under 5 mg/kg soil Cd treatment, root Cd concentrations were reduced by 7.26% and 13.84% by Common Si and Nano-Si treatment respectively for Yangdao 6, and by 2.74% and 6.21% respectively for Yu 44. Under 10 mg/kg soil Cd treatment, root Cd concentrations were decreased by 7.82% and 17.86% for Yangdao 6, and by 5.63% and 10.83% respectively for Yu 44.

Table 3. Effects of Silicon on Cd Concentrations of Rice Roots (mg/kg).

Rice Cultivars	Silicon Treatments	Soil Cd Treatments (mg/kg)		
		NCdT (0.14)	Cd5	Cd10
Yangdao 6	Control	4.17 a	46.67 a	84.29 a
	Common Si	4.05 ab	43.28 b	77.07 b
	Nano-Si	3.73 b	40.21 c	69.24 c
Yu 44	Control	3.72 a	34.32 a	61.15 a
	Common Si	3.51 a	33.38 a	57.71 ab
	Nano-Si	3.46 a	32.19 a	54.53 b

Table 4. Effects of Silicon on Cd Concentrations of Rice Shoots (mg/kg).

Rice Cultivars	Silicon Treatments	Soil Cd Treatments (mg/kg)		
		NCdT (0.14)	Cd5	Cd10
Yangdao 6	Control	0.39 a	2.47 a	4.38 a
	Common Si	0.34 b	1.86 b	2.90 b
	Nano-Si	0.30 c	1.33 c	1.95 c
Yu 44	Control	0.27 a	1.81 a	3.06 a
	Common Si	0.25 a	1.47 b	2.29 b
	Nano-Si	0.21 b	1.20 c	1.82 c

Effects of Si treatments on Cd concentrations of rice shoots (stems and leaves) are displayed in Table 4. Cd concentrations of rice shoots were largely reduced by Si applications. The magnitudes of the reductions were in the order: Nano-Si > common Si, Yangdao 6 > Yu 44, and 10 mg/kg soil Cd treatment > 5 mg/kg soil Cd treatment > Non-Cd-treatment. Under 5 mg/kg soil Cd treatment, the reduction rates were 24.70% and 46.15% (compared to the control) for common Si and Nano-Si treatment respectively for Yangdao 6, and 18.78% and 33.70% respectively for Yu 44. Under 10 mg/kg soil Cd treatment, the reduction rates were 33.79% and 55.48% for common Si and Nano-Si treatment respectively for Yangdao 6, and 25.17% and 50.33% respectively in Yu 44.

Effects of Si treatments on Cd concentrations of rice grains are presented in Table 5. Cd concentrations of rice grains were greatly decreased by Si applications. The magnitudes of the decreases were also in the order: Nano-Si > common Si, Yangdao 6 > Yu 44, and 10 mg/kg soil Cd treatment > 5 mg/kg soil Cd treatment > Non-Cd-treatment. Under 5 mg/kg soil Cd treatment, the decreasing rates of grain Cd concentrations were 30.43% and 52.17% (compared to the control) for common Si and Nano-Si treatment respectively in Yangdao 6, and 26.67% and 40.00% respectively in Yu 44. Under 10 mg/kg soil Cd treatment, the decrease rates were 45.95% and 70.27% for common Si and Nano-Si treatment respectively in Yangdao 6, and 33.33% and 52.38% respectively in Yu 44.

Table 5. Effects of Silicon on Cd Concentrations of Rice Grains (mg/kg)

Rice Cultivars	Silicon Treatments	Soil Cd Treatments (mg/kg)		
		NCdT (0.14)	Cd5	Cd10
Yangdao 6	Control	0.077 a	0.23 a	0.37 a
	Common Si	0.061 b	0.16 b	0.20 b
	Nano-Si	0.049 c	0.11 c	0.11 c
Yu 44	Control	0.052 a	0.15 a	0.21 a
	Common Si	0.044 b	0.11 b	0.14 b
	Nano-Si	0.035 c	0.09 c	0.10 c

Liu et al. presented that Si enhanced Cd tolerance in *Solanum nigrum*, and the reason may be the reduction of Cd uptake and less transportation to leaves, as well as the lower Cd-induced oxidative stress [28]. The present reports indicate that the reduction rates of Si applications on Cd concentrations in different parts of rice plants were in the order: grain > shoot > root.

4. Conclusion

The rice cultivars differed in Cd tolerance, and Yangdao 6 may be more sensitive than Yu 44 to soil Cd stress. The biomasses of the two rice cultivars were decreased significantly ($P < 0.05$) by 10 mg/kg soil Cd treatment. Under soil Cd stress, alleviative effects of Si on Cd toxicities were higher for Nano-Si than for common Si. Si treatments reduced Cd concentrations in rice roots, shoots and grains. The effects were in the order: Nano-Si treatment > common Si treatment, Yangdao 6 > Yu 44, 10 mg/kg soil Cd treatment > 5 mg/kg soil Cd treatment > Non-Cd-treatment, and grain > shoot > root.

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