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Effects of Different Types of Silicon on Cadmium Translocation, Accumulation and Distribution in Rice Plants

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Abstract

Effects of different types of silicon (Si) applications (Nano-Si and common Si) on Cd translocation, accumulation and distribution in rice plants were investigated with different rice cultivars of different Cd uptake abilities under different soil Cd levels. The results present that Si applications reduced the translocation factors (TFs) of Cd from roots to shoots and from shoots to the grains largely and generally significantly ($P < 0.05$). Under soil Cd treatments (5 and 10 mg/kg), the TFs from roots to shoots were reduced by 16.98% - 26.92% and 30.19% - 46.15% by common Si and Nano-Si treatment respectively, and the TFs from shoots to the grains were reduced by 7.53% - 17.86% and 39.64% - 33.33% respectively. Si applications also decreased Cd accumulations and distribution proportions in rice shoots and grains largely and generally significantly ($P < 0.05$). Under soil Cd treatments, Cd accumulations in rice shoots were decreased by 17.57% - 29.80% and 28.74% - 50.50% by common Si and Si Nano-Si respectively. Cd accumulations in rice grains were decreased by 22.54% - 42.09% and 35.61% - 66.38% by common Si and Nano-Si respectively. The effects were in the order: Nano-Si > common Si, high Cd accumulation cultivar (Yangdao 6) > low Cd accumulation cultivar (Yu 44), and heavy soil Cd pollution (10 mg/kg) > moderate soil Cd pollution (5 mg/kg). The results indicate that Nano-Si is better than common Si in cutting down Cd translocation from rice roots to shoots and from shoots to the grains, and in lowering Cd accumulation and distribution in rice grains.

Keywords

Cadmium (Cd), Rice (*Oryza sativa* L.), Silicon (Si), Translocation, Accumulation

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1. Introduction

Due to development of industries, the heavy uses of chemical fertilizer, pesticides and Herbicides, cadmium (Cd) pollution in agricultural soils has become a serious problem in many parts of the world [1, 2]. It produces serious threatens to human health. With rapid industrial development and population expansion, the situation is also urgent in China where Cd has become one of the main pollutants in paddy field [3]. Cd can be absorbed and transported effectively by rice plants, so it could enter human food easily [4]. Moreover, Cd may pose risk to human and animal health when the concentrations in plant tissues are not generally phytotoxic [5].

The amount of Cd that enters human diet from rice depends on the amount of Cd accumulated in rice plant and the translocation of Cd within rice plant, especially transport to and accumulation in rice grain. It was reported that Si can restrict Cd uptake by crops and decrease the transport from vegetate organs to fruit organs in crops [6, 7]. Therefore, Si may be used as a candidate for the diminution of Cd pollution in rice grains in Cd contaminated soils. However, little is known about effects of Si (specifically Nano-Si) on Cd uptake and translocation in rice plants.

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Based on our previous studies [8], two rice cultivars with different Cd accumulation abilities were used in the present experiment, and the effects of Nano-Si and common Si on Cd transfer, accumulation and distribution in rice plants were addressed under different soil Cd levels. The information will be useful for reducing Cd in human diet in soil Cd-contaminated areas.

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 following properties were determined: soil texture, pH, cation exchange capacity (CEC), organic matter (OM) content and Cd concentration. It is a sandy loam (sand 58.1%, silt 23.3%, clay 18.6%), with pH 6.6, CEC 14.3 cmol/kg, OM 27.1 g/kg, and Cd concentration 0.14 mg/kg.

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 [8], 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).

2.2. Nano-Silicon Synthesis and Experimental Design

Nano-silicon was synthesized from sodium silicate [9]. 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.

3. Results

3.1. Effects of Silicon Treatments on Cadmium Translocation in Rice Plants

Effects of Si treatments on the translocation factors (TFs) of Cd from roots to shoots (Cd concentration ratio of shoot to root) are displayed in Table 1. In general, Si applications diminished the TFs from roots to shoots largely, and the diminishing effects were in the order: Nano-Si treatment > common Si treatment, Yangdao 6 > Yu 44. The effects also increased with the increase of soil Cd levels. In the soil of 5 mg/kg Cd treatment, the decrease rates on the TFs were 18.87% and 37.74% (compared to the control) for common Si treatment and Nano-Si treatment respectively in Yangdao 6, and 16.98% and 30.19% respectively in Yu 44. Under 10 mg/kg soil Cd treatment, the reduction rates were 26.92% and 46.15% respectively in Yangdao 6, and 20.00% and 34.00% respectively in Yu 44.

Table 1. Effects of Silicon on Translocation Factors (TF) of Cd from Roots to Shoots.

Rice Cultivars	Silicon Treatments	Soil Cd Treatments (mg/kg)		
		NCdT (0.14) [a)]	**Cd5**	**Cd10**
Yangdao 6	Control	0.094 a	0.053 a	0.052 a
	Common Si	0.084 b	0.043 b	0.038 b
	Nano-Si	0.080 b	0.033 c	0.028 c
Yu 44	Control	0.073 a	0.053 a	0.050 a
	Common Si	0.071 a	0.044 b	0.040 b
	Nano-Si	0.061 b	0.037 c	0.033 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 $P<0.05$.

Table 2. Effects of Silicon on Translocation Factors (TF) of Cd from Shoots to Grains.

Rice Cultivars	Silicon Treatments	Soil Cd Treatments (mg/kg)		
		NCdT (0.14)	**Cd5**	**Cd10**
Yangdao 6	Control	0.197 a	0.093 a	0.084 a
	Common Si	0.179 b	0.086 ab	0.069 b
	Nano-Si	0.163 c	0.083 b	0.056 c
Yu 44	Control	0.193 a	0.083 a	0.069 a
	Common Si	0.176 b	0.075 b	0.061 b
	Nano-Si	0.167 b	0.075 b	0.055 c

Effects of Si treatments on Cd TFs from shoots to grains (Cd concentration ratio of grain to shoot) are presented in Table 2. The TFs from shoots to grains were also reduced by Si treatments. The magnitudes of the reductions were generally in the order: Nano-Si > common Si, Yangdao 6 > Yu 44, and 10 mg/kg soil Cd treatment > 5 mg/kg soil Cd treatment. Under soil Cd stress (5 and 10 mg/kg), the reduction rates were from 7.53% to 17.86% for common Si treatment, and from 9.64% to 33.33% for Nano-Si treatment.

3.2. Effects of Silicon Treatments on Cadmium Accumulation and Distribution in Rice Plants

The effects of Si treatments on Cd accumulation and distribution in rice roots are displayed in Table 3. Compared to the control, Si treatments decreased Cd accumulation in roots, but increased Cd distribution proportions in roots. The effects were generally small and insignificant ($P > 0.05$), expect for the differences between Nano-Si treatment and the control under 10 mg/kg soil Cd treatment.

Table 3. Effects of Silicon on Cd Accumulation and Distribution in Rice Roots.

Rice Cultivars	Silicon Treatments	Cd Accumulation (μg/pot)			Cd Distribution Proportion (%)		
		NCdT	Cd5	Cd10	NCdT	Cd5	Cd10
Yangdao 6	Control	78.06 a	944.13 a	1446.42 a	79.82 a	88.66 a	88.44 a
	Common Si	76.30 a	930.09 a	1434.27 a	81.38 a	90.89 a	91.63 ab
	Nano-Si	75.42 a	936.89 a	1411.11 a	82.66 a	92.88 a	93.92 b
Yu 44	Control	40.85 a	396.05 a	600.49 a	77.53 a	84.05 a	84.00 a
	Common Si	40.75 a	398.22 a	621.54 ab	77.78 a	86.58 a	87.46 ab
	Nano-Si	41.35 a	408.17 a	656.00 b	80.75 a	88.47 a	89.90 b

The effects of Si treatments on Cd accumulation and distribution in rice shoots are presented in Table 4. In general, Si treatments reduced Cd accumulations and distribution proportions in rice shoots, but the effects differed with Si types, soil Cd levels and rice cultivars. The 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. Under 5 mg/kg soil Cd treatment, shoot Cd accumulations were reduced by 17.57% - 22.45% and 28.74% - 39.86% by Common Si and Nano-Si treatment respectively, and Cd distribution proportions in the shoots were cut down 2.01 - 2.32 and 3.81 - 4.06 percentage points respectively. Under 10 mg/kg soil Cd treatment, shoot Cd accumulations were decreased by 21.53% - 29.80% and 34.73% - 50.50% respectively, and Cd distribution proportions in the shoots were lowered 2.85 - 3.18 and 4.93 - 5.44 percentage points respectively.

Table 4. Effects of Silicon on Cd Accumulation and Distribution in Rice Shoots.

Rice Cultivars	Silicon Treatments	Cd Accumulation (μg/pot)			Cd Distribution Proportion (%)		
		NCdT	Cd5	Cd10	NCdT	Cd5	Cd10
Yangdao 6	Control	16.63 a	111.10 a	175.02 a	17.01 a	10.43 a	10.70 a
	Common Si	14.92 b	86.16 b	122.87 b	15.91 ab	8.42 b	7.85 b
	Nano-Si	13.72 b	66.81 c	86.66 c	15.04 b	6.62 c	5.77 c
Yu 44	Control	10.14 a	70.19 a	107.80 a	19.33 a	14.90 a	15.08 a
	Common Si	10.13 a	57.86 b	84.59 b	19.32 a	12.58 b	11.90 b
	Nano-Si	8.65 b	50.02 c	70.36 c	16.89 b	10.84 c	9.64 c

Table 5. Effects of Silicon on Cd Accumulation and Distribution in Rice Grains.

Rice Cultivars	Silicon Treatments	Cd Accumulation (μg/pot)			Cd Distribution Proportion (%)		
		NCdT	Cd5	Cd10	NCdT	Cd5	Cd10
Yangdao 6	Control	3.10 a	9.71 a	14.04 a	3.17 a	0.91 a	0.86 a
	Common Si	2.54 b	7.06 b	8.13 b	2.71 b	0.69 b	0.52 b
	Nano-Si	2.10 c	4.96 c	4.72 c	2.30 c	0.49 c	0.31 c
Yu 44	Control	1.71 a	4.97 a	6.55 a	3.25 a	1.05 a	0.92 a
	Common Si	1.50 a	3.85 b	4.54 b	2.86 a	0.84 b	0.64 b
	Nano-Si	1.21 b	3.20 c	3.36 c	2.36 b	0.69 c	0.46 c

Cd accumulations and distributions in rice grains were largely reduced by Si applications (Table 5). The magnitudes of the reductions 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. Under 5 mg/kg soil Cd treatment, Cd accumulations in the grains were decreased by 22.54% - 27.29% by common Si treatment, and by 35.61% - 48.92% by Nano-Si treatment. Cd distribution proportions in the grains were cut down by 0.21 - 0.22 percentage points by common Si treatment, and by 0.36 - 0.42 percentage points by Nano-Si treatment. Under 10 mg/kg soil Cd treatment, the reduction rates of Cd accumulations in the grains were 30.69% - 42.09% and 48.70% - 66.38% for common Si and Nano-Si treatment respectively. The reductions of Cd distribution proportions in the grains were 0.28 - 0.34 and 0.46 - 0.55 percentage points respectively.

The reduction effects of Si applications on Cd accumulations and distributions in rice plants were in the order: grain > shoot > root.

It was reported that Si application inhibited Cd accumulation in rice plant [10]. However, other study showed that Si application decreased Cd translocation from root to shoot at a high Cd treatment level (50 mM), but exerted little effect at a lower Cd level (5 mM) [11]. Our present study indicates that the effects of Si application on Cd accumulation and distribution proportions in rice roots were generally small and mostly insignificant ($P > 0.05$). But Si application reduced Cd translocation factors from roots to shoots and from shoots to grains, and diminished Cd accumulations and distribution proportions in rice shoots and grains. The magnitudes of the reductions were in the order: Nano-Si treatment > common Si treatment, Yangdao 6 (high Cd accumulator) > Yu 44 (low Cd accumulator), and 10 mg/kg soil Cd treatment (heavy pollution) > 5 mg/kg soil Cd treatment (moderate pollution). Our previous study also showed that Si restrained Pb translocation from rice roots to the shoots and from shoots to the grains, specifically the transfer from roots to the shoots [12]. The mechanisms of the inhibition effects of Si on Cd transport in plants are possibly in two aspects: (1) Si induces deposition of lignin and bounding of Cd in cell wall, thus reduces Cd transport from root to shoot [13]. (2) The formation of Si-Cd complex or co-precipitation of Cd with Si [14]. However, Ye et al. reported that Si supply did not change the amount of Cd in plant cell wall, but reduced the proportion of easily extractable Cd [15]. Therefore, the roles of Si in Cd uptake and transport in plants need further researches.

4. Conclusions

Si applications reduced Cd translocation factors from roots to shoots and from shoots to grains, and decreased Cd accumulations and distribution proportions in rice shoots and grains largely and significantly ($P < 0.05$). However, Si increased Cd distribution proportions in roots considerably, and the difference between Nano-Si treatment and the control was significant ($P < 0.05$) under 10 mg/kg soil Cd treatment. The above decrease or increase effects were in the orders: Nano-Si treatment > common Si treatment, high Cd accumulation cultivar (Yangdao 6) > low Cd accumulation cultivar (Yu 44), and heavy soil Cd stress (10 mg/kg) > moderate soil Cd stress (5 mg/kg). The results indicate that Nano-Si is better than common Si in reducing Cd translocation from rice roots to shoots and from shoots to the grains, and in cutting down Cd accumulations and distributions in rice shoots and grains in Cd-contaminated soils.

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