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RESEARCH ARTICLE

Effects of nano-silicon and common silicon on lead uptake and translocation in two rice cultivars

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Abstract The current study investigated the effects of nano-silicon (Si) and common Si on lead (Pb) toxicity, uptake, translocation, and accumulation in the rice cultivars Yangdao 6 and Yu 44 grown in soil containing two different Pb levels (500 $mg \cdot kg^{-1}$ and 1000 $mg \cdot kg^{-1}$). The results showed that Si application alleviated the toxic effects of Pb on rice growth. Under soil Pb treatments of 500 and 1000 $mg \cdot kg^{-1}$, the biomasses of plants supplied with common Si and nano-Si were 1.8%–5.2% and 3.3%–11.8% higher, respectively, than those of plants with no Si supply (control). Compared to the control, Pb concentrations in rice shoots supplied with common Si and nano-Si were reduced by 14.3%–31.4% and 27.6%–54.0%, respectively. Pb concentrations in rice grains treated with common Si and nano-Si decreased by 21.3%–40.9% and 38.6%–64.8%, respectively. Pb translocation factors (TFs) from roots to shoots decreased by 15.0%–29.3% and 25.6%–50.8%, respectively. The TFs from shoots to grains reduced by 8.3%–13.7% and 15.3%–21.1%, respectively, after Si application. The magnitudes of the effects observed on plants decreased in the following order: nano-Si treatment > common Si treatment and high-grain-Pb-accumulating cultivar (Yangdao 6) > low-grain-Pb-accumulating cultivar (Yu 44) and heavy Pb stress (1000 $mg \cdot kg^{-1}$) > moderate Pb stress (500 $mg \cdot kg^{-1}$) > no Pb treatment. The results of the study indicate that nano-Si is more efficient than common Si in ameliorating the toxic effects of Pb on rice growth, preventing Pb transfer from rice roots to aboveground parts, and blocking Pb accumulation in rice grains, especially in high-Pb-accumulating rice cultivars and in heavily Pb-polluted soils.

Keywords silicon (Si), lead (Pb), rice (*Oryza sativa* L.), toxicity, accumulation

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1 Introduction

Lead (Pb) is a toxic metal pollutant spreaded widely, originating mainly from gasoline and road traffic, mining and smelting activities, disposal of municipal sewage sludge, paints, and paper pulp [1,2]. Pb has accumulated at very high levels in some agricultural soils of China. For instance, Pb content in the soil of paddy field near a Pb and Zn mine was found as high as 1486 $mg \cdot kg^{-1}$. The Pb contents were 419 $mg \cdot kg^{-1}$ in rice roots, 69.1 $mg \cdot kg^{-1}$ in rice straw, 13.2 $mg \cdot kg^{-1}$ in rice grain and 4.67 $mg \cdot kg^{-1}$ in brown rice [3]. Pb contents above 25000 $mg \cdot kg^{-1}$ have been reported in urban soils of Baoji, China [4].

Pb is highly toxic to the human health. Pb reduces sperm numbers and increases abnormal sperm counts in males. Pb is also related to the increased occurrence of miscarriages in females. Low levels of Pb exposure (blood concentration of 10–20 $\mu g \cdot dL^{-1}$) at prenatal and early postnatal stages will cause damage in the central nervous system: this damage can be irreversible and untreatable [5]. It was observed that consumption of Pb-polluted vegetables and rice around a mine in China could be related to increased health damages to the local inhabitants [6]. Therefore, development of technologies to prevent or decrease Pb uptake and transport to edible plant organs is receiving increasing attention.

Silicon (Si) is the second most abundant element on the Earth's surface and within soils [7]. It is considered a beneficial element for plant growth and development. Si can also improve plant resistance to biotic and abiotic stress induced by diseases, high salinity, and metal toxicity [8–10]. It was reported that Si enhanced the tolerance of plants to heavy metals, such as cadmium (Cd) [11], chromium (Cr) [12], manganese (Mn) [13], and zinc (Zn) [14]. The effects observed can possibly be explained by the activation of the antioxidant system induced by Si, mitigation of photosynthetic inhibition, and complexation of Si with metals. Previous research showed that Si application reduced metal uptake by and translocation in crops [15,16]. Therefore, application of Si is recommended for decreasing heavy metal contamination in crops and enhancing the tolerance of plants to heavy metal stress.

Paddy rice represents very important food crop in China. However, studies addressing the effects of Si (specifically nano-Si) on the toxicity, uptake, and translocation of Pb in rice plants are scarce. The current study aimed to investigate the effects of nano-Si and common Si on the growth of and Pb uptake and transport in rice plants exposed to different soil Pb levels. The study was carried out using two rice cultivars characterized by different Pb accumulation abilities [17].

2 Materials and methods

2.1 Soil and rice materials

The soil used in the current study was collected from a paddy field (0–20 cm), air-dried and passed through a 2-mm sieve. Then, some soil properties were measured. The list of the soil properties analyzed is provided in Table 1.

Two Pb levels in soils were designed: $500\,mg\cdot kg^{-1}$ represented moderate pollution and $1000\,mg\cdot kg^{-1}$ represented heavy pollution. Four kilograms of soil was kept in pots (18 cm in diameter and 20 cm in height). $PbCl_2$ was dissolved and added to the soil to obtain two different Pb concentrations in soil. The rice cultivars Yangdao 6 (high-grain-Pb-accumulating cultivar) and Yu 44 (low-grain-Pb-accumulating cultivar) characterized by different grain Pb accumulation rates [17] were used in the experiment. Rice seeds were germinated under moist conditions at 32°C for 30 h. The germinated seeds were grown in uncontaminated soil for 30 d. After that, the uniform seedlings were selected and transplanted into the pots (3 seedlings per pot) filled with soil containing different Pb levels.

2.2 Nano-Si synthesis and experimental design

Nano-Si was synthesized from sodium silicate ($Na_2SiO_3\cdot 9H_2O$) [18]. A total of 0.3584 g of sodium silicate was dissolved in 475 mL of distilled water. After that, 10 mL of anhydrous alcohol was added, and the solution was stirred for 30 min. Then, the mixture of anhydrous alcohol (10 mL) and polysorbate 80 (5 mL) was added drop-wise under vigorous stirring. The solution was stirred for 2 h. Subsequently, $0.0025\,mol\cdot L^{-1}$ nano-silicon was obtained. Common silicon ($0.0025\,mol\cdot L^{-1}$) was prepared by dissolving 0.3584 g sodium silicate ($Na_2SiO_3\cdot 9H_2O$) in 500 mL of distilled water. The Si treatments tested included $0.0025\,mol\cdot L^{-1}$ nano-silicon and $0.0025\,mol\cdot L^{-1}$ common silicon solutions. Distilled water was used as the control treatment.

The pots were arranged in a randomized manner to achieve a complete block design with three replicates. The rice plants were grown under open-air conditions. Si solutions and distilled water were sprayed onto the rice plants, starting from the day of seedling transplantation and continuing until panicle heading, once every 10 d. In total Si was applied to rice plants 7 times.

2.3 Determination of Pb concentrations in rice plants

Whole rice plants were sampled at the time of maturity. The plants were divided into roots, shoots, and grains. The plant parts were oven-dried at 70°C to a constant weight. After that, plants were ground with a stainless steel grinder and passed through a 100-mesh sieve. Pb concentrations in the samples were determined with an atomic absorption spectrophotometer (AAS) (ICE3500M series, Thermo Scientific, USA). First, 10 repeated measurements of Pb concentration were carried out with standard Pb solution provided by the Institute of Geophysical and Geochemical Exploration, China, for quality control. Reagent blanks and certified plant reference material (GBW07602, GSV-3) provided by the National Research Center for CRM's, China were run simultaneously with the plant samples.

2.4 Statistical analysis

Data were analyzed using statistical software SPSS 16.0. Means were compared using one-way ANOVA based on Tukey's test. The differences were considered statistically significant at $P < 0.05$.

3 Results

3.1 Effects of Si treatments on rice growth

The toxic effect of Pb on rice growth differed among rice cultivars used in the experiment and soil Pb levels (Fig. 1). In the control (no Si supply), the biomass of Yu 44 was slightly affected by $500\,mg\cdot kg^{-1}$ Pb treatment; this effect was not significant ($P > 0.05$). However, the biomass decreased significantly with $1000\,mg\cdot kg^{-1}$ Pb treatment ($P < 0.05$). Adverse effects of Pb on the biomass of Yangdao 6 were noted for both soil Pb treatments

Table 1 Selected properties of the soil used in this experiment

soil type	particle size/$(g\cdot kg^{-1})$			pH	OM [a)]/$(g\cdot kg^{-1})$	CEC [b)]/$(cmol\cdot kg^{-1})$	available Si/$(mg\cdot kg^{-1})$	total Pb/$(mg\cdot kg^{-1})$
	sand	silt	clay					
paddy soil	557.8	242.4.	199.8	6.3	26.9	14.6	103.5	32.7

Notes: a) Organic matter; b) cation exchange capacity

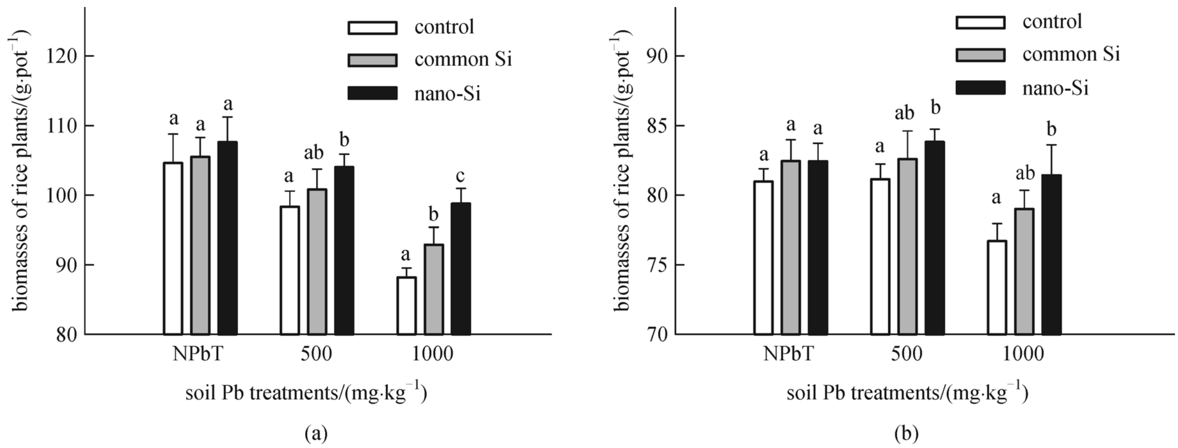

Fig. 1 Effects of silicon on biomasses of rice plants. (a) The rice cultivar Yangdao 6, (b) the rice cultivar Yu 44. NPbT: no Pb treatment, the soil Pb concentration is 32.7 mg·kg^{-1}. Different letters above the columns of a Pb treatment indicate significant difference between Si treatments at $P < 0.05$ within the Pb treatment

(500 mg·kg^{-1} and 1000 mg·kg^{-1}) and were significant ($P < 0.05$). Therefore, the rice cultivar Yangdao 6 was more sensitive to soil Pb stress than Yu 44.

The alleviative effects of Si on Pb toxicity in rice were greater for nano-Si treatment than for common Si treatment, and stronger in Yangdao 6 than in Yu 44. For example, for soil Pb treatment of 1000 mg·kg^{-1}, the biomasses of Yangdao 6 for nano-Si and common Si treatments were 11.8% and 5.2% higher, respectively, than the biomass of control plants. The biomasses of Yu 44 were 6.1% and 3.0% higher, respectively, than the biomass of control plants. Under soil Pb stress (Pb treatments of 500 and 1000 mg·kg^{-1}), the biomass of plants grown with nano-Si treatment was significantly higher ($P < 0.05$) than that in the control treatment in both rice cultivars.

3.2 Effects of Si treatments on Pb uptake and accumulation

The results pertaining to the effects of Si treatments on Pb concentrations in rice roots are presented in Fig. 2. Generally, Si treatment had little effect on the root Pb uptake; this effect was not significant ($P > 0.05$). However, for Yangdao 6 grown with soil Pb treatment of 1000 mg·kg^{-1}, the root Pb concentration with nano-Si treatment was significantly higher ($P < 0.05$) than that of the control.

Pb concentrations in rice shoots (stems and leaves) for different Si treatments are displayed in Fig. 3. Pb concentrations in rice shoots were largely reduced by Si applications. The magnitude of Pb reduction in rice shoots was observed in the following order: nano-Si > common Si, Yangdao 6 > Yu 44, 1000 mg·kg^{-1} soil Pb treatment > 500 mg·kg^{-1} soil Pb treatment > no Pb treatment. For 500 mg·kg^{-1} soil Pb treatment, the Pb reduction rates in Yangdao 6 rice shoots treated with common Si and nano-Si were 26.5% and 42.9%, respectively, compared to the control. In Yu 44 plants, Pb reduction rates were 14.3% and 27.6% for common Si and nano-Si treatments, respectively. For 1000 mg·kg^{-1} soil Pb treatment, the Pb

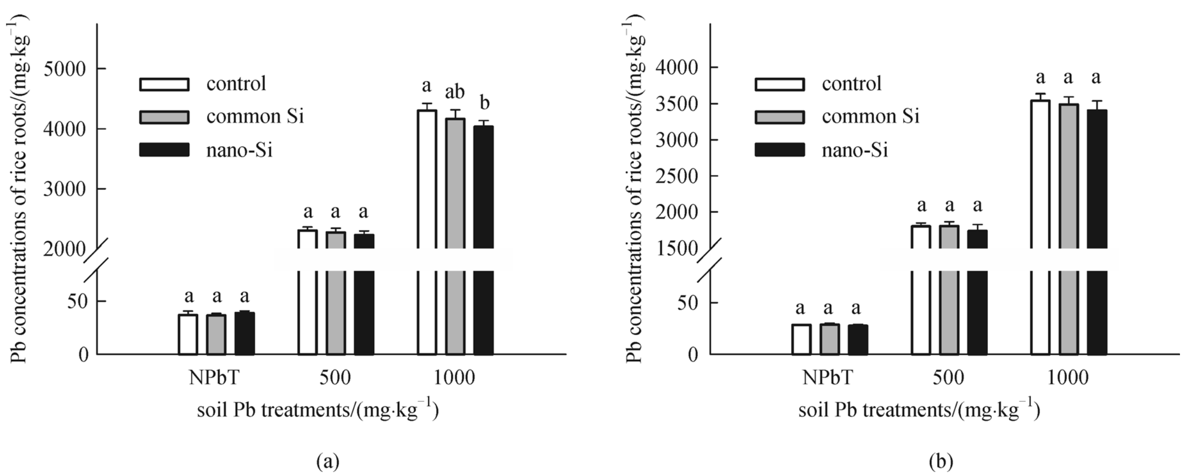

Fig. 2 Effects of silicon on Pb concentrations in rice roots. (a) Yangdao 6, (b) Yu 44. Different letters above the columns of a Pb treatment indicate significant difference between Si treatments at $P < 0.05$ within the Pb treatment

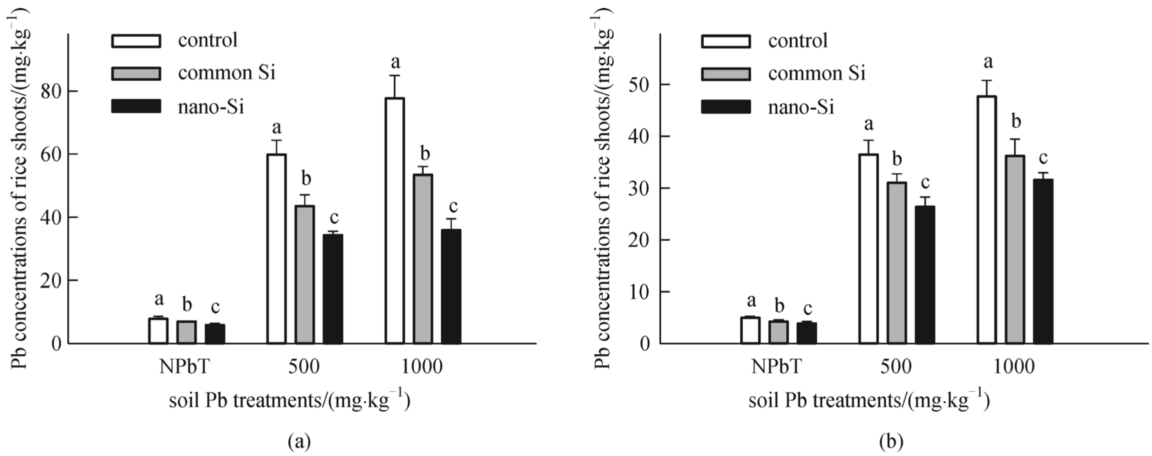

Fig. 3 Effects of silicon on Pb concentrations in rice shoots. (a) Yangdao 6, (b) Yu 44. Different letters above the columns of a Pb treatment indicate significant difference between Si treatments at $P < 0.05$ within the Pb treatment

reduction rates in Yangdao 6 plants were 31.4% and 54.0% for common Si and nano-Si treatments, respectively; in Yu 44 plants, Pb reduction rates were 24.2% and 33.8%.

Pb concentrations in rice grains supplied with different Si treatments are shown in Fig. 4. Pb concentrations in rice grains decreased greatly following Si applications. The magnitude of the Pb reduction in rice grains was observed in the following order: nano-Si > common Si, Yangdao 6 > Yu 44, 1000 mg·kg^{-1} soil Pb treatment > 500 mg·kg^{-1} soil Pb treatment > no Pb treatment. For 500 mg·kg^{-1} soil Pb treatment, the rates of reduction of Pb concentrations in Yangdao 6 grains were 33.7% and 52.3% for common Si and nano-Si treatments, respectively, compared to the control, and 21.3% and 38.6%, respectively, in Yu 44 grains. For 1000 mg·kg^{-1} soil Pb treatment, the Pb reduction rates in Yangdao 6 grains were 40.9% and 64.8% for common Si and nano-Si treatments, respectively, and 30.9% and 44.2%, respectively, in Yu 44 grains.

The effects of Si applications on reduction of Pb concentration in different parts of rice plants followed the order: grain > shoot > root.

3.3 Effects of Si treatments on Pb translocation in rice plants

The translocation factors (TFs) of Pb from roots to shoots (Pb concentration ratio of shoot to root) for different Si treatments are shown in Fig. 5.

Si applications largely decreased the TFs from roots to shoots. The reduction effects were observed in the following order: nano-Si > common Si, Yangdao 6 > Yu 44. The effects increased following an increase in soil Pb levels. For 500 mg·kg^{-1} soil Pb treatment, the Pb reduction rates in Yangdao 6 were 24.9% and 40.9%, compared to the control, for common Si and nano-Si, respectively, and 15.0% and 25.0%, respectively, in Yu 44. For 1000 mg·kg^{-1} soil Pb treatment, the Pb reduction rates for common Si and nano-Si were 29.3% and 50.8%,

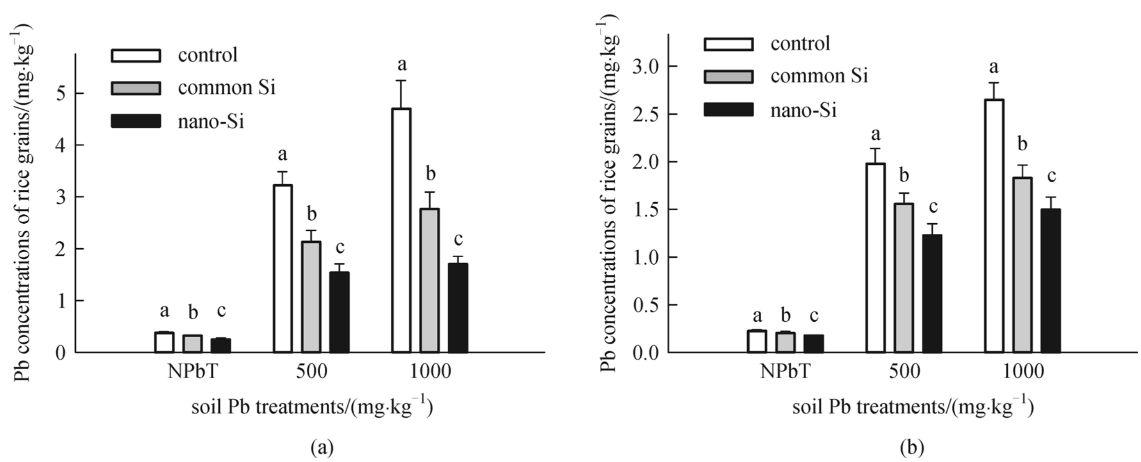

Fig. 4 Effects of silicon on Pb concentrations in rice grains. (a) Yangdao 6, (b) Yu 44. Different letters above the columns of a Pb treatment indicate significant difference between Si treatments at $P < 0.05$ within the Pb treatment

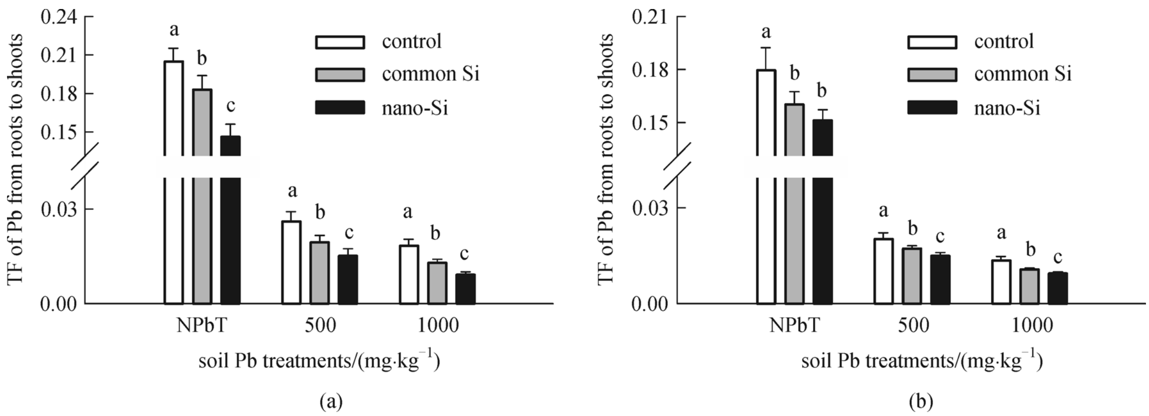

Fig. 5 Effects of silicon on translocation factors (TFs) of Pb from roots to shoots (Pb concentration ratio of shoot to root). (a) Yangdao 6, (b) Yu 44. Different letters above the columns of a Pb treatment indicate significant difference between Si treatments at $P < 0.05$ within the Pb treatment

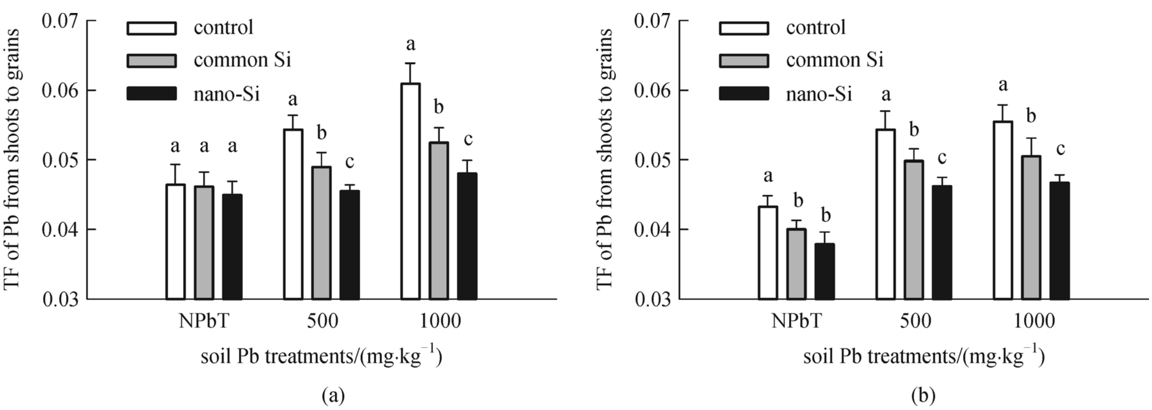

Fig. 6 Effects of silicon on translocation factors (TFs) of Pb from shoots to grains (Pb concentration ratio of grain to shoot). (a) Yangdao 6, (b) Yu 44. Different letters above the columns of a Pb treatment indicate significant difference between Si treatments at $P < 0.05$ within the Pb treatment

respectively, in Yangdao 6 and 23.0% and 31.1%, respectively, in Yu 44.

The TFs from shoots to grains (Pb concentration ratios of grain to shoot) at different Si treatments are shown in Fig. 6. The TFs from shoots to grains were also reduced by Si treatments. The magnitude of reduction was observed in the following order: nano-Si > common Si, Yangdao 6 > Yu 44, 1000 mg·kg^{-1} soil Pb treatment > 500 mg·kg^{-1} soil Pb treatment > no Pb treatment. For both soil Pb treatments (500 and 1000 mg·kg^{-1}), the Pb reduction rates ranged from 8.3% to 13.7% for common Si and from 15.3% to 21.1% for nano-Si.

4 Discussion

In the current study, Si was found to alleviate Pb toxicity. The alleviative effects of Si were higher for nano-Si treatment versus common Si treatment, heavy Pb stress (1000 mg·kg^{-1}) versus moderate Pb stress (500 mg·kg^{-1}), and the more sensitive rice cultivar (Yangdo 6) versus the more tolerant cultivar (Yu 44).

The mechanisms underlying Si-mediated heavy metal tolerance in plants may include reduction of heavy metal activities in growth media induced by Si, stimulation of antioxidants, chelation of Si with metal and metal compartmentation, decrease in heavy metal transport, regulation of gene expression, and structural changes in plants [16]. It was reported that Si alleviated ultrastructural disorders induced by Mn and Zn in maize and pea cells [19]. $CaCO_3$-forming idioblasts were found to be capable of co-depositing Zn and Si in their cap regions in mulberry leaves, which may play an important role in the mechanism of toxic metal detoxification [20].

Previous research showed that Si ameliorated Cd toxicity in *Solanum nigrum*. This effect was explained by the reduced Cd concentrations in the roots and leaves, and the decreased oxidative stress in the plants [21]. Rizwan et al. found that Si supplementation increased the biomass of plants under Cd stress, suggesting that the dilution effect may be one of the mechanisms of Si-mediated alleviation [15]. Si-modulated plants responded to Cu more efficiently by maintaining or increasing Cu binding molecules, and the changes were related to increased gene expression [22].

Nwugo and Huerta found that Si application inhibited Cd uptake and accumulation in rice plants [23]. The present study indicates that leaf Si application had little effect on Pb accumulation in rice roots, but Pb concentrations in rice shoots and grains decreased following Si application. The magnitude of the reduction was observed in the following order: nano-Si treatment > common Si treatment, high-grain-Pb-accumulating cultivar (Yangdao 6) > low-grain-Pb-accumulating cultivar (Yu 44), heavy Pb stress ($1000\ mg \cdot kg^{-1}$) > moderate Pb stress ($500\ mg \cdot kg^{-1}$) > no Pb stress. Si also suppressed Pb translocation from rice roots to the shoots and from shoots to the grains, especially the transfer from roots to the shoots. The magnitude of the inhibition effects also followed the order described above.

The inhibitory effects of Si on heavy metal transport in plants can possibly be explained by two mechanisms: 1) Si induces deposition of lignin into and binding of heavy metals to the cell wall, resulting in reduced metal transport from roots to shoots [24,25]; 2) formation of the Si-metal complex or coprecipitation of metal with Si [26]. Less Mn was found in symplasts (< 10%) and more Mn was located in the cell wall (> 90%) in Si-treated plants than in non-Si-treated plant (Mn, approximately 50% found in each of these locations) [27]. However, another study showed that Si application on maize under Cd stress influenced the development of suberin lamellae, Casparian strips and vascular tissues in roots. Si decreased Cd translocation from root to shoot at the high Cd level ($0.05\ mol \cdot L^{-1}$), but exerted little effect on that parameter at the low Cd level ($0.005\ mol \cdot L^{-1}$) [28]. Si application did not affect the amount of Cd in the plant cell wall, but reduced the proportion of easily extractable Cd [29].

5 Conclusions

Leaf Si applications enhanced rice tolerance to Pb toxicity, decreased Pb concentrations in rice shoots and grains, and reduced Pb translocation from the roots to the shoots and from shoots to the grains. The observed effects were greater for nano-Si treatment than for common Si treatment. The effects of Si treatment were higher in the high-grain-Pb-accumulating cultivar than in the low-grain-Pb-accumulating cultivar. Si application affected plants in the following order: heavy soil Pb stress ($1000\ mg \cdot kg^{-1}$) > moderate soil Pb stress ($500\ mg \cdot kg^{-1}$) > no Pb stress. However leaf Si treatment generally had little effect on Pb accumulation in rice roots. The results of this study indicate that nano-Si is more efficient than common Si in terms of alleviation of the toxic effects of Pb on rice growth, prevention of Pb transfer from rice roots to the aboveground parts of the plant, and reduction of Pb accumulation in rice grains, especially in high-Pb-accumulating-cultivars and the soils with high levels of Pb pollution.

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