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Silicate-Mediated Alleviation of Pb Toxicity in Banana Grown in Pb-Contaminated Soil

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Abstract Silicate (Si) can enhance plant resistance or tolerance to the toxicity of heavy metals. However, it remains unclear whether Si can ameliorate lead (Pb) toxicity in banana (*Musa xparadisiaca*) roots. In this study, treatment with 800 mg kg^{-1} Pb decreased both the shoot and root weight of banana seedlings. The amendment of 800 mg kg^{-1} Si (sodium metasilicate, $Na_2SiO_3 \cdot 9H_2O$) to the Pb-contaminated soil enhanced banana biomass at two growth stages significantly. The amendment of 800 mg kg^{-1} Si significantly increased soil pH and decreased exchangeable Pb, thus reducing soil Pb availability, while Si addition of 100 mg kg^{-1} did not influence soil pH. Results from Pb fractionation analysis indicated that more Pb were in the form of carbonate and residual-bound fractions in the Si-amended Pb-contaminated soils. The ratio of Pb-bound carbonate to the total Pb tended to increase with increasing growth stages. Treatment with 100 mg kg^{-1} Si had smaller effects on Pb forms in the Si-amended soils than that of 800 mg kg^{-1} Si. Pb treatment decreased the xylem sap greatly, but the addition of Si at both levels increased xylem sap and reduced Pb concentration in xylem sap significantly in the Si-amended Pb treatments. The addition of Si increased the activities of POD, SOD, and CAT in banana roots by 14.2% to 72.1% in the Si-amended Pb treatments. The results suggested that Si-enhanced tolerance to Pb toxicity in banana seedlings was associated with Pb immobilization in the soils, the decrease of Pb transport from roots to shoots, and Si-mediated detoxification of Pb in the plants.

Keywords Banana seedling · Pb fractionation · Pb toxicity · Si alleviation · Xylem sap

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Introduction

Due to geological activities, anthropogenic impacts, combustion of fossil fuels, mining, etc., substantial heavy metals have been reported to be released into agricultural fields [1, 2]. Pb is toxic to plants. It inhibits root elongation, decreases photosynthetic rate, and reduces the yield and quality of crops [3, 4]. Pb toxicity can trigger an accumulation of lipid peroxides, oxidize proteins, and cause oxidative damages. When Pb enters the food chain, it is harmful to human health as a cumulative poison [5].

Banana (*Musa xparadisiaca*) is one of the major fruits in South China. Each year, the total planted area for banana in South China is over 100,000 hectares. However, some banana-planted soils were contaminated by heavy metals due to fertilization, man-made mining, atmospheric bulk deposition, etc. [6, 7]. Since a banana plant needs more water and nutrients than common crops such as maize, soybean, etc., banana seedlings might absorb more Pb than common crops when exposed to heavy metal-contaminated soils. It is of importance to reduce the harmfulness of Pb to banana and human being. Traditionally, Pb-contaminated soils are remediated by covering other soils, application of organic manure, lime, etc. However, these amendment measures need lots of labor and financial support. Si is abundant on earth. Though Si is a non-essential element for many higher plants, it is beneficial to plants. It has been reported that Si (calcium silicate) can enhance the resistance or tolerance of some plant species to abiotic and biotic stresses [8, 9]. Si (silicic acid, H_4SiO_4) can ameliorate aluminum toxicity in maize [10], rice [11], and suspension cells [12]. As effective substances for the alleviation of heavy metal toxicity, Si (sodium metasilicate) could enhance the resistance to Cd toxicity in maize [13, 14] and *Brassica chinensis* L. [15]. Iwasaki et al. [16] observed that Si (potassium silicate) lowered the apoplastic Mn concentration in cowpea by Si modifying the cation binding capacity of the cell wall. Although many reports indicated the ameliorative effects of Si on heavy metal toxicity, it remains unclear whether Si detoxifies Pb toxicity in banana seedlings. The objective of this study is to investigate the ameliorative effects of Si on Pb toxicity in banana seedlings in Pb-contaminated soils.

Materials and Methods

Cultivation of Plant Materials

The experiments were conducted in the greenhouse of College of Resources and Environment of South China Agricultural University. Banana (*M. xparadisiaca* cv Brazil) seedlings were used as plant material (purchased from Institute of Fruit Tree, Guangdong Academy of Agricultural Sciences). The physical–chemical properties of soil used for the experiments were pH 5.5, organic matter 18.1 gkg^{-1}, hydrolysable N 55 mg kg^{-1}, available P 20 mg kg^{-1}, NH_4Ac-extractable K 101 mg kg^{-1}, and 18.5 gkg^{-1} of NaAc-HAc extractable Si, respectively. After the sieving (1 mm) process, the soil was mixed abundantly with 10.8 g kg^{-1} N in the form of urea, 0.18 gkg^{-1} P in the form of KH_2PO_4, and 0.25 gkg^{-1} K in the form of K_2SO_4 and KH_2PO_4. Four treatments were performed as follows: the control (neither Pb nor Si was added), Pb800 (800 mg kg^{-1} Pb was added), Pb800+Si100 (800 mg kg^{-1} Pb and 100 mg kg^{-1} Si were added), Pb800+Si800 (both Pb and Si were added at 800 mg kg^{-1}). Each treatment was replicated five times. Silicon was added in the form of sodium metasilicate ($Na_2SiO_3{\cdot}9H_2O$) and Pb in the form of $Pb(NO_3)_2$. To avoid heterogeneous distribution, $Pb(NO_3)_2$ was firstly mixed thoroughly with 500 g soil, and then the resulting soil was mixed with 1.5 kg of soil. When the soil was saturated overnight, banana seedlings with four leaves of similar size were transplanted into the pots. Banana seedlings were irrigated when the soil moisture was less than 70% of field capacity. Experiments were performed in a greenhouse where temperature ranges from 25 to 35°C (the highest temperature was 35°C at noon, while the lowest temperature was 25°C at night). Due to the big size of the banana seedling, a mature banana plant cannot grow well in a small pot. Only the earlier stage of banana seedlings was investigated in pots. The banana seedlings were cultured in pots for 70 or 110 days.

Harvest of Banana Tissues

After 70- or 110-day transplanting, banana seedlings were harvested. The seedlings were separated into roots and shoots. The shoots were firstly washed with tap water and then with distilled water. The roots were firstly rinsed with 0.5 mM $CaCl_2$ to remove ions on the surface of roots and then washed with tap water and distilled water successively. Water on the surface of seedlings was absorbed by filter paper. For the measurement of dry weight, banana tissues were oven-dried for 72 h at 70°C. Dry weight values of shoot and root tissues were recorded. Then, the tissues were ground and used for Pb and Si analysis.

Measurement of Pb and Si

Banana tissues were ground and passed through a 1.0-mm sieve and 0.5 g of root or shoot sample was digested in a nitric–perchloric acid (4:1) solution. After appropriate dilutions, Pb in the digest solution was measured by atomic absorption spectrophotometry (Shimadzu: Z-5300) [17]. Si in the digest solution was determined by molybdenum blue spectrophotometric method according to Liang et al. and Ma et al. [13, 18].

Collection of Xylem Sap

Prior to the collection of xylem sap, a banana seedling was decapitated at 9 o'clock in the morning at 3 cm above the shoot base, and the decapitated stem was immediately covered with a plastic tube and sealed with cotton for the collection of xylem sap. Xylem sap for the first 10 min of collection was discarded to avoid the contamination of injured sap, and then xylem sap was collected for 6 h. Xylem sap was obtained by weighing the plastic tubes before and after xylem sap collection according to the protocols described by Liang et al. [13]. Then, the solution was used for Pb and Si analysis or kept at −20°C for further use.

Measurement of Activity of Antioxidant Enzymes

Fresh banana roots of 0.5 g were excised and ground in a 2-mL ice-cold 20 mM HEPES buffer (pH 7.8) containing 0.2 mM EDTA, 2 mM reduced ascorbate, and 2% PVP. The homogenate was centrifuged at 4°C for 20 min at 15,000× *g* and then the supernatants were collected as enzyme solution for further measurements [19]. For the analysis of superoxide dismutase (SOD) (EC1.15.1.1) activity, nitroblue tetrazolium (NBT) was used to inhibit the photochemical reduction. One unit of the activity of SOD was defined as being present in the volume of extract that caused the inhibition of the photoreduction of NBT by 50%. Catalase (CAT) (EC1.11.1.6) activity was measured by calculating the decline in absorbance at 240 nm due to the decline of extinction of H_2O_2. The reaction mixture was composed of 25 mM sodium phosphate buffer (pH 7.0), 10 mM H_2O_2, and 0.1 mL enzyme extracts. The reaction was started by adding hydrogen peroxide. POD activity was detected by measuring the increase in absorbance at 470 nm due to guaiacol oxidation. An increase in absorbance at 470 nm/min was defined as one unit of enzyme activity.

Soil Pb Fractionation

Pb fractionation was performed using sequential extraction [20–23]. Pb speciation in the soil was partitioned into four fractions, i.e., exchangeable-bound, carbonate-bound, Fe–Mn oxide-bound, and residual forms according to Okbah et al. [24]. The soil sample was firstly extracted with 0.1 M acetic acid as exchangeable Pb. The residue was extracted with 0.1 M hydroxylamine hydrochloride acidified with HNO_3 to pH 2 as carbonate-bound Pb. The resulting residue was extracted by 1 M ammonium acetate as Fe–Mn-bound Pb. Finally, the remaining residue was analyzed as residual Pb. The sequential extractions were performed in acid-rinsed borosilicate glass centrifuge tubes. The suspension solution was centrifuged for 15 min at 1,500× *g*. The resulting suspensions were filtered by gravity through a paper filter. The extracted Pb was determined by atomic absorption spectrophotometry (Shimadzu: Z-5300).

Statistical Analysis

The experiments were conducted as a completely randomized design. The data in this study were the average values of five replications. Each experiment was replicated twice independently. The data were analyzed statistically by Microsoft Office Excel 2003 and by Duncan's new multiple-range test at 0.05 probability levels using SAS software (SAS Institute Inc., 2002).

Results

Plant Growth

Banana seedlings were firstly grown in sand culture for the 7-day exercise, then healthy seedlings of similar size were transplanted into the soils of the pots. Banana plants were incubated in the Pb-contaminated soil with or without Si amendment for 70 days or 110 days. Results from Fig. 1 indicated that the treatment with 800 mg kg^{-1} Pb decreased the growth of banana seedlings significantly. The seedling under Pb treatment was smaller than those under other treatments, and some necroses in banana leaves were also observed (Fig. 1A, C). Shoot and root biomass with 800 mg kg^{-1} Pb treatment after 70-day transplanting were 62.5% and 72.2% of those of the control. While for 110-day transplanted plants, the corresponding values were 58.8% and 56.1%, respectively. It is noteworthy that obvious ameliorating effects of Si amendment on Pb toxicity were observed in Si-amended Pb-contaminated soils. Shoot and root biomass were significantly higher in 800 mg kg^{-1} Si-amended Pb-contaminated treatment compared with non-Si- or less Si-amended Pb treatments (Fig. 1C, D). For example, the dry weight values of shoots and roots for 70-day transplanting in Pb+800 mg kg^{-1} Si treatment were 57.5% and 54.6% higher than those in non-Si-amended Pb treatment and 38.6% and 44.6% higher than those in 100 mg kg^{-1} Si-amended Pb treatment. A similar phenomenon was also observed for 110-day transplanted plants.

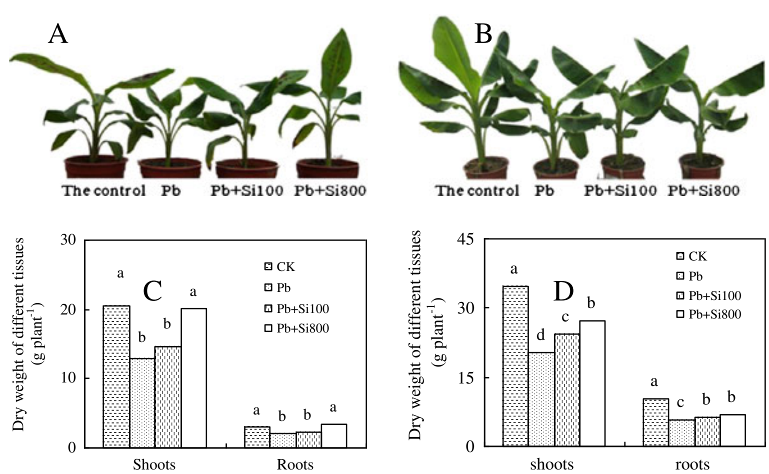

Fig. 1 Photographs (**A** seedlings for 70-day growth; **B** seedlings for 110-day growth) and the biomass of banana seedlings grown on Pb-contaminated soil amended with either 100 mg kg^{-1} Si or 800 mg kg^{-1} Si for 70 days (**C**) or 110 days (**D**) after transplanting. Different *letters* above the columns indicate significant differences in the same tissue ($p<0.05$). Data indicated average value ($n=5$). Each experiment was repeated twice independently

Pb and Si Uptake in Banana Tissues

To explore the effects of Pb and Si on banana growth, Pb and Si uptake amounts in banana seedlings were measured. Results from Fig. 2 indicated that Si amendment to the Pb-contaminated soil decreased the Pb concentration of either shoot or root of banana seedling significantly. For example, after 70-day transplanting, the shoot and root Pb concentrations of the Pb+Si800 treatment were 41.9% and 64.9% of those of the Pb treatment (Fig. 2A), while for the 110-day transplanting seedlings the corresponding values were 58.3% and 60.9%, respectively (Fig. 2B). The amendment of less Si (100 mg kg^{-1}) had a less ameliorating effect on the Pb concentration of banana seedlings, suggesting the importance of Si application rate. The amendment of Si to the Pb-contaminated soil increased the uptake of Si in both shoots and roots of banana significantly. Si concentration in either shoots or roots increased with growth period (Fig. 2C, D). For 110-day transplanting seedlings, the Si concentration values in the shoots and roots of the Pb+Si800 treatment were 344.8% and 371% of those of the Pb treatment.

Since a banana seedling has a large size compared with crops such as soybean, rice, etc., the concentration and content of Pb and Si might represent different responses to different treatments. For example, the Pb concentration of banana seedling under Pb treatment might be high due to its small biomass (Figs. 1 and 2). The amounts of Pb and Si absorbed in a single plant were calculated. The amendment of Si to the Pb-contaminated soil decreased the Pb uptake in both shoots and roots significantly at both two Si levels. A greater decrease of Pb uptake in shoots and roots was observed with a higher amount of Si amendment (Fig. 3). For 110-day transplanted plants, the total Pb in shoots and roots was 13.3% and 24.7% lower in the Pb+Si100 than those in the Pb treatment and 20.4% and 65.7% lower in the Pb+Si800 than in the Pb treatment, respectively (Fig. 3B). Consistent with our results, Song et al. found that the amendment of 1.5 mM Si decreased Cd uptake in *B. chinensis* L. by 13–45.6% in Cd-contaminated soil [15].

Rhizosphere pH

When treated with different levels of Pb and Si, soil pH in the rhizosphere of banana seedlings varied from 4.5 to 5.8. Compared with the control, Pb addition to the soil decreased its pH by 1.1 units, and treatment with 800 mg kg^{-1} Si+800 mg kg^{-1} Pb decreased the soil pH by 0.6 units (Table 1). After 70- and 110-day transplanting, the soil pH was slightly increased compared with those of pre-transplanting. In thecase of 800 mg kg^{-1} Si+800 mg kg^{-1} Pb treatment, the soil pH was increased by 0.4 units (Table 1). The phenomenon was probably related to the chemical properties of $Pb(NO_3)_2$ and Na_2SiO_3. In addition, banana plants might prefer to absorb NO_3^- and SiO_3^{2-} rather than Pb^{2+} and Na^+ during their growth stages.

Pb and Si Concentration in Xylem Sap

The amount of banana xylem sap in the Pb treatment was much reduced in comparison to that of the control due to the poor growth triggered by Pb toxicity (Table 2). The addition of Si to the Pb-contaminated soil increased the amount of xylem sap significantly. For example, the amounts of xylem sap of the 70-day transplanted banana in the Pb+Si100 and Pb+Si800 treatments were 1.35 and 1.65 times of those of Pb treatment; the corresponding values in a 110-day transplanted plant were 1.29 and 1.49 times. Soil Pb contamination increased Pb concentration in the xylem sap of banana

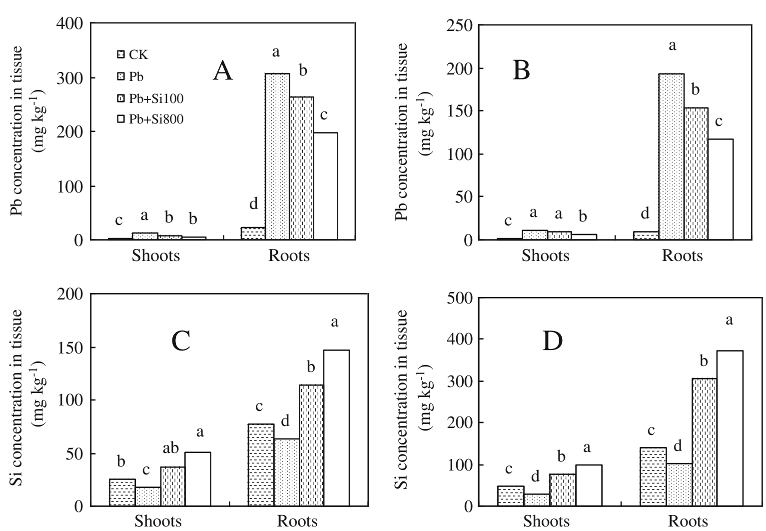

Fig. 2 Pb (**A**, **B**) and Si (**C**, **D**) concentration in banana seedlings grown on Pb-contaminated soil amended with either 100 mg kg^{-1} Si or 800 mg kg^{-1} Si for 70 days (**A**, **C**) or 110 days (**B**, **D**) after transplanting. Different *letters* above the columns indicate significant differences in the same tissue ($p<0.05$). Data indicate average value ($n=5$). Each experiment was repeated twice independently

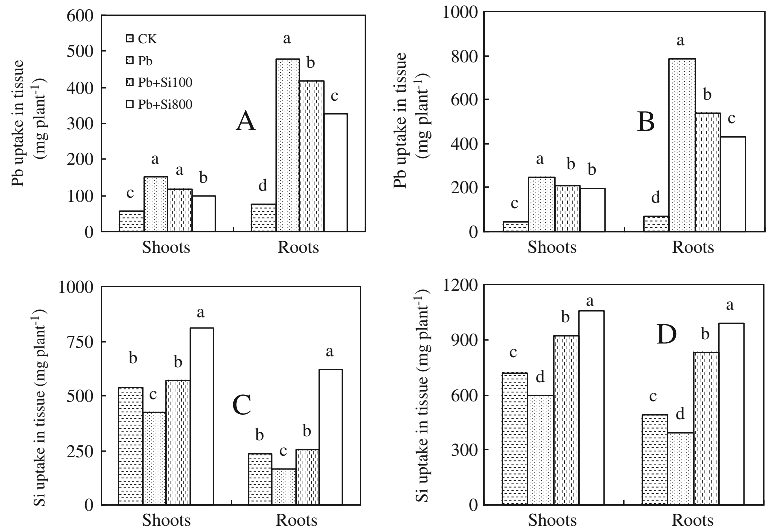

Fig. 3 Pb (**A**, **B**) and Si (**C**, **D**) uptake in a banana seedling grown on Pb-contaminated soil amended with either 100 mg kg^{-1} Si or 800 mg kg^{-1} Si for 70 days (**A**, **C**) or 110 days (**B**, **D**) after transplanting. Different *letters* above the columns indicate significant differences in the same tissue ($p<0.05$). Data indicate average values ($n=5$). Each experiment was repeated twice independently

seedlings significantly. The addition of 800 mg kg^{-1} Si to the Pb-contaminated soil decreased Pb concentration by 60.2% and 51.2% for the 70- and 110-day transplanted plants, respectively. The Pb concentration in xylem sap declined with increasing the levels of Si to the Pb-contaminated soil. Si concentration in xylem sap was increased significantly in response to exogenous Si amendment to the Pb-contaminated soil (Table 2).

Activity of Antioxidant Enzymes in Response to Si and Pb Treatment

To investigate the toxic mechanism of Pb-inhibited growth of banana seedlings, the activities of antioxidant enzymes (POD, SOD, and CAT) in the roots of banana seedlings were measured (Table 3). In comparison to the controls, soil Pb contamination decreased the activities of POD, SOD, and CAT by 35.5%, 41.3%, and 41.8% in the roots of 70-day transplanted banana seedlings. The corresponding values for 110-day transplanted plants were 40.7%, 42.9%, and 41.8%, respectively. Addition of Si to the Pb-contaminated soil facilitated the Pb-induced inhibition of activity of antioxidant enzymes (POD and SOD) significantly. For example, the activities of POD and SOD in the roots of 70-day transplanted plants at Pb+Si800 treatment were 28.3% and 72.1% higher than those with Pb treatment. A higher activity of POD and SOD was observed with increasing levels of Si amendment. For the 110-day plants after transplanting, the corresponding values were 39.4% and 60.8%, respectively (Table 3).

Table 1 Soil pH in the rhizosphere of banana seedlings

Treatment	pH after transferring	pH after 70-day growth	pH after 110-day growth
Control	5.6 a	5.7 a	5.8 a
Pb	4.5 c	4.6 c	4.8 c
Pb+Si100	4.7 c	4.8 c	4.9 c
Pb+Si800	5.0 b	5.1 b	5.4 b

Different letters following the data indicate significant differences in the same column ($p<0.05$). Data indicate average values ($n=5$). Each experiment was repeated twice independently

Soil Pb Fractions in the Rhizosphere of Banana Seedlings

To investigate the mechanism of Si-reduced Pb concentration in xylem sap of banana seedlings in Si-amended Pb treatments, soil Pb fractions in the rhizosphere of banana seedlings were examined (Table 4). Soil Pb in the rhizosphere of banana seedlings at two growth stages existed predominantly as exchangeable Pb, which accounted for 5.15% to 83.1% of the total Pb in soils. The second largest form of soil Pb was residual-bound Pb. The amendment of Si to the Pb-contaminated soils reduced the concentration of exchangeable Pb and increased the concentration of carbonate-bound Pb and Fe–Mn-bound Pb significantly.

Discussion

Effects of Pb Toxicity on Banana Growth

Pb is one of the most dangerous toxic elements to plants, animals, and humans [25]. It was reported that Pb at the level of 10^{-2} to 10^{-6} M was toxic to plant species [26]. In this study, the concentration of Pb in banana seedlings ranged from 100 to 300 mg kg^{-1}, which was

Table 2 Pb and Si concentration in xylem sap of banana seedlings

Treatment	Xylem sap for 70-day after transplanting			Xylem sap for 110-day after transplanting		
	Xylem sap (mL h^{-1} $plant^{-1}$)	Pb concentration (μM)	Si concentration (μM)	Xylem sap (mL h^{-1} $plant^{-1}$)	Pb concentration (μM)	Si concentration (μM)
Control	3.1 a	6.8 d	89.8 c	3.58 a	21.8 c	109 b
Pb	1.7 c	82.1 a	64.5 c	2.0 c	117.3 a	86.3 b
Pb+Si100	2.3 b	45.3 b	236.2 b	2.6 b	73.4 b	288.8 a
Pb+Si800	2.8 a	32.7 c	324.1 a	3.0 a	57.3 b	376.3 a

Different letters following the data indicate significant differences in the same column ($p<0.05$). Each experiment was repeated twice independently ($n=5$)

tenfold higher than the toxic concentration. Furthermore, the biomass of banana seedling with Pb treatment was much lower than its control at two growth stages (Fig. 1C, D), suggesting that Pb toxicity existed in banana seedlings. Some symptoms of brown pots and necrosis were shown in banana leaves (Fig. 1A, B). In addition, banana roots in soils of Pb treatment were more brittle, stunted, and blackish, which are believed to be the typical symptoms of heavy metal toxicity. Obroucheva et al. indicated that Pb treatment inhibited the primary root growth and reduced the branching pattern [27]. Due to exposure to Pb toxicity, a shorter branching zone with more compact lateral roots was observed in banana roots (photograph not shown). Pb phytotoxicity resulted in the inhibition of the activities of enzymes containing sulphydryl (−SH) groups, which are necessary for their activity [28]. In this study, the activities of antioxidant enzymes (POD, SOD, and CAT) in banana roots were reduced by 35.5% to 42.9% when exposed to Pb treatment (Table 3). The decreases of activities of the antioxidative metalloenzymes were probably associated with the Pb-induced displacement of metals that are an essential part of the enzyme [29].

Ameliorative Effects of Si on Pb-Induced Inhibition of Banana Growth

Many studies indicated that Si can enhance the resistance of plants to biotic and abiotic stress [8, 11, 30, 31]. The main mechanisms of Si-mediated alleviation of abiotic stresses in higher plants include the stimulation of the activities of antioxidant enzymes in plants, complexation of toxic metal ions with silicate, immobilization of toxic metal ions in growth media, transferring toxic metal ion in shoots, and compartmentation of metal ions within plants. In this study, Si amendment to the Pb-contaminated soil inhibited Pb uptake and ameliorated the Pb-induced inhibition of growth significantly (Fig. 1). This is consistent with the reports that Si reduced the uptake and transport of Cd in maize [13] and rice [32]. This might be associated with the enhanced uptake of calcium and potassium triggered by Si in banana

Table 3 The activity of antioxidant enzyme in banana roots under different Pb and Si treatments

Treatment	Activity of antioxidant enzymes		
	POD (unit g^{-1} min^{-1})	SOD (unit g^{-1})	CAT (unit g^{-1} min^{-1})
Seedlings for 70 days after transplanting			
Control	547 a	414 a	184 a
Pb	353 c	243 b	107 c
Pb+Si100	403 b	405 a	130 b
Pb+Si800	453 b	418 a	173 a
Seedlings for 110 days after transplanting			
Control	557 a	469 a	196 a
Pb	330 c	268 b	114 c
Pb+Si100	440 b	423 a	148 b
Pb+Si800	460 b	431 a	182 a

Different letters following the data indicated significant differences in the same column at the same growth stage ($p<0.05$). Data indicate average values ($n=5$). Each experiment was repeated twice independently

Table 4 Soil Pb fractions in the rhizosphere of banana seedlings

Treatment	Exchangeable (mg kg^{-1})	Carbonate	Fe–Mn	Residual	Total Pb
Rhizosphere soil with a banana seedling after 70-day transplanting					
Control	31.5 (66.3%) b	3.7 (7.8%) c	5.4 (11.4%) d	6.8 (14.3%) d	47.4 c
Pb	792.8 (83.1%) a	29.5 (3.1%) b	18.0 (1.9%) c	113.3 (11.9%) c	953.6 b
Pb+Si100	762.6 (65.8%) a	130 (11.2%) a	90.6 (7.8%) b	174.9 (15.1%) b	1158.1 a
Pb+Si800	743.2 (59.9%) a	174 (13.1%) a	145 (10.9%) a	267.5 (20.1%) a	1329.7 a
Rhizosphere soil with a banana seedling after 110-day transplanting					
Control	13.4 (54.0%) b	2.3 (9.3%) c	2.6 (10.5%) d	6.5 (26.2%) d	24.8 c
Pb	561.8 (80.2%) a	18.3 (2.6%) b	16.6 (2.4%) c	103.7 (14.8%) c	700.4 b
Pb+Si100	548.5 (61.5%) a	123.9 (13.9%) a	75.4 (8.5%) b	143.9 (16.1%) b	891.7a
Pb+Si800	522.2 (51.5%) a	151.3 (14.9%) a	115 (11.4%) a	224.7 (22.2%) a	1013.8 a

Data in parentheses indicate the percentage of each fraction over the total. Different letters following the data indicate significant differences in the same column at the same growth stage ($p<0.05$). Data indicate average values ($n=5$). Each experiment was repeated twice independently

seedlings [33], which competes with Pb for uptake sites in banana roots [34] and inhibits root-to-shoot Pb transport. Our results shown in Table 2 support the above view. The effects of Si on reducing Pb concentration in banana shoots are practically important with respect to fruit safety. It can be expected that Si amendment in the Pb-contaminated soils can help to reduce fruit safety risks by inhibiting Pb uptake and transport into the edible parts. However, further field studies are needed to verify the beneficial effects of Si on blocking the transport of heavy metals from banana roots to shoots.

Si amendment of 800 mg kg^{-1} to the Pb-contaminated soil increased soil pH by 0.5 to 0.6 units in the rhizosphere of banana seedlings (Table 1), decreased Pb transportation from roots to shoots of banana seedlings (Table 2), and reduced the concentration of exchangeable Pb significantly (Table 4). In comparison to Pb+Si100 treatment, the ratio of the exchangeable Pb over the total Pb under Pb treatment was decreased by 17.3% and 18.7% and those of carbonate-combined Pb was increased by 8.1% and 11.3% for the 70- and 110-day plants after transplanting, respectively. The increased application of Si resulted in a greater decrease of exchangeable Pb and a higher increase of carbonate-bound Pb, suggesting that Si played an important role in immobilizing Pb mobility. The results were in agreement with the study reported by Liang et al. [31]. Tan et al. performed synchrotron-based X-ray microfluorescence and extended X-ray absorption fine structure spectroscopy analysis and found that Pb was predominantly restricted to the vascular bundles of both leaf and stem of the accumulator (*Sedum alfredii*, Crassulaceae) [35]. The dominant chemical form of Pb (>60%) in tissues existed mostly as Pb–cell wall complex.

Another important finding in this study is the Si-mediated enhancement of antioxidant defense system in banana roots in the Si-amended Pb-contaminated soils. The activities of POD, SOD, and CAT in banana roots were much reduced under Pb treatment, while the amendment of Si to the Pb-contaminated soil increased the activities of antioxidant enzymes significantly (Table 3). Si amendment of 800 mg kg^{-1} stimulated the activity of POD and SOD in banana roots for 70-day transplanting by 28.3% and 60.8%, respectively, in comparison to those with Pb treatment significantly. Consistent with our results, Song et al. reported the Si-mediated enhancement of antioxidant defense system in pakchoi plants [18]. In conclusion, our results in this study indicated that Si could effectively alleviate the toxicity of Pb to banana seedlings in Si-amended Pb-contaminated soils. The alleviative effect of Si on Pb toxicity could be attributed not only to Pb immobilization and its low phytoavailability but also to the Si-mediated Pb detoxification in plants.

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