Title: Efficiency evaluation for remediating paddy soil contaminated with cadmium and arsenic using water management, variety screening and foliage dressing technologies

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Abstract

Paddy soils in many regions of China have been seriously polluted by multiple heavy metals or metalloids, such as arsenic (As), cadmium (Cd) and lead (Pb). In order to ensure the safety of food and take full advantage of the limited farmland resources of China, exploring an effective technology to repair contaminated soils is urgent and necessary. In this study, three technologies were employed, including variety screening, water management and foliage dressing, to assess their abilities to reduce the accumulation of Cd and As in the grains of different rice varieties, and meanwhile monitor the related yields. The results of variety screening under insufficient field drying condition showed that the As and Cd contents in the grains of only four varieties [Fengliangyouxiang 1 (P6), Zhongzheyong 8 (P7), Guangliangyou 1128 (P10), Y-liangyou 696 (P11)] did not exceed their individual national standard. P6 gained a relatively high grain yield but accumulate less As and Cd in the grains despite of the relatively high As and Cd concentrations in the rhizosphere soil. However, long-playing field drying in water management trial significantly increased Cd but decreased As contents in the grains of all tested three varieties including P6, suggesting an important role of water supply in controlling the accumulation of grain As and Cd. Selenium (Se) showed a stronger ability than silicon (Si) to reduce As and Cd accumulation in the grains of Fengliangyou 4 (P2) and Teyou 524 (P13), and keep the yields. The results of this study suggest that combined application of water management and foliage dressing may be an efficient way to control

As and Cd accumulation in the grains of paddy rice exposing to As- and Cd-contaminated soils.

Keywords: paddy rice; water management; variety screening; foliage dressing; heavy metal pollution

1. Introduction

Anthropologic activities such as mining, emission of industrial waste, and agricultural production have led to increasing soil contamination with cadmium (Cd) and arsenic (As) (Cheng, **2003**). In China, the loss of food production due to heavy metal (metalloid) contamination is greater than 10,000,000 tons per year, resulting in a total economic loss of more than 20 billion Yuan (Williams et al., **2009**; Zhuang et al., **2009**). Although Cd and As are not essential nutrients for plants, they can accumulate at high contents in plant tissues (Sun et al., **2010**), and thus enter the food chain and harm the health of humans (Liu et al., **2008**; Zhai et al., **2008**; Zhao et al., **2010**).

To reduce the amounts of certain heavy metal in crops, researchers have developed technologies including in-situ passivation, foliage dressing, and water management (Friesl et al., **2003**; Guo et al., **2006**; Hu et al., **2013a**; Zahedi et al., **2009**). Water management can not only affect the pH but also change the redox conditions of the soil so as to affect plant uptake of Cd and As (Arao et al., **2009**). Flooding has been reported to markedly reduce the Cd content in different parts of paddy rice plants (roots, stems, and leaves) and brown rice (Hu et al., **2013b**). In contrast, cultivation management practices such as water-saving aeration and dry farming substantially increase the Cd content in rice grains (Atkinson et al., **2007**; Hu et al., **2013a**; Li et al., **2009**). However, flooding significantly increases the bioavailability of As in soil, making soil As more active and facilitating plant accumulation of this element (Arao et al., **2009**). Additionally, foliage dressing of trace elements can significantly affect plant uptake of

heavy metals (metalloids). Silicon (Si) has been shown to improve plant growth and enhance stress resistance in crops (Bogdan and Schenk, **2008**), and it markedly inhibits the translocation of Cd and lead (Pb) to rice grains (Liu et al., **2009**). Moreover, numerous studies have shown that selenium (Se) can reduce plant uptake of heavy metals (metalloids) and mitigate the toxic effects of heavy metals (metalloids) (Feng et al., **2013a, 2013b, 2013c**; He et al., **2004**; Mora et al., **2008**); this element also promotes growth and increases crop yields (Shah et al., **2001**; Terry et al., **2000**). Se deficiency exists in large populations in 72% of China's territory (Feng et al., **2013a**). Selenium deficiency has been found to directly damage human health, and more than 40 types of diseases have been found to be associated with Se deficiency, such as Keshan disease, Kashin–Beck disease, cancer, cardiovascular disease, liver disease and cataracts (Cox and Bastiaans, **2007**). Foliage dressing with Se can markedly increase the Se accumulation in the grains of paddy rice. This enrichment will increase Se intake by people in Se-deficient regions and help improve public health in China.

Currently, extensive studies have focused on soil contaminated with a single heavy metal. Less research has been conducted on multiple-species heavy metal (metalloid) contamination in soils, although such contamination is common in the world, especially in China. Importantly, there are differences in the properties of heavy metals (metalloids), and their behavior patterns may even be opposite in soil. These factors will undoubtedly increase the difficulty to remediate multiple heavy metal (metalloid) contaminated soils. Therefore, in this study, we assessed several typical technologies of soil remediation for

heavy metal (metalloid) contamination and analyzed their remedial efficacy and technical limitations based on field trials. This study provides a foundation for combined application of multiple remediation technologies in multiple-species heavy metal (metalloid) contaminated soil.

2. Materials and Methods

2.1. Field trial site

The field trial site is in the vicinity of Guantian Lake, Shishou City, Hubei Province, China. This lake has received the discharge of municipal wastewater for many years. Preliminary investigations revealed that the soil contamination is mainly due to the irrigation using contaminated water in the region. Some properties of the soil, including pH and the concentrations of Cd and As, were as follows: pH of 7.46, Cd concentration of 3.39 mg kg^{-1} , and As concentration of 47.63 mg kg^{-1} in the field for the variety screening trial (S1); pH of 6.27, and Cd and As concentrations of 2.74 mg kg^{-1} and 41.96 mg kg^{-1} , respectively, in the field for the water management trial (S2); and pH of 6.87 and Cd and As concentrations of 1.58 mg kg^{-1} and 54.10 mg kg^{-1} , respectively, in the field for the foliage dressing trial (S3). According to the China Soil Environmental Quality Standards (GB 15618-2008, pH within a range of 5.5 to 6.5 for a paddy field, 30 mg kg^{-1} for As and 0.30 mg kg^{-1} for Cd; pH within a range of 6.5 to 7.5 for a paddy field, 25 mg kg^{-1} for As and 0.50 mg kg^{-1} for Cd), the soil Cd concentration of S1, S2 and S3 was 6.78, 9.13 and 3.16 times higher than the individual Quality Standard, respectively;

and the As concentration of S1, S2 and S3 was 1.91, 1.40 and 2.16 times higher than the individual Quality Standard, respectively.

2.2. Trial design and implementation

2.2.1. Trial I: Variety screening

Fifteen rice varieties were selected (see Table 1). These varieties were assigned to 15 plots (7 m × 5 m each). Before the seedlings were transplanted, each plot was basal dressed with 1 kg of compound fertilizer (51% N₂₆P₁₀K₁₅, Fuguan Manufacture, City, China). For weeding and to facilitate reviving and tillering of paddy rice, each plot was top dressed with 0.75 kg of fertilizer specific for transplanted rice (Zhongli Bioengineering Co., Ltd., Chongqing, China; containing 10% mefenacet and 0.01% bensulfuron-methyl) in mid-June. Thereafter, each plot was top dressed with 0.45 kg of compound fertilizer in early July to facilitate tillering into spikes and large panicles. The field was dried for 5 days from late tillering stage to young ear differentiation stage. Rain fell continuously in mid-July during the trial period. As a result, the paddy field drying was insufficient except that of the water management trial.

2.2.2. Trial II: Water management

Three rice varieties were selected from the 15 varieties for the water management trial: P2, P6 and P12. The water management was performed in three treatments: treatment 1: flooding throughout the entire rice growth period; treatment 2: field drying for 5 days

from late tillering stage through young ear differentiation stage; and treatment 3: field drying for 10 days from late tillering stage through young ear differentiation stage. Each treatment was assigned three replicates. The trial was conducted using a randomized block design. Each plot had an area of $6\text{ m} \times 4.5\text{ m}$. Soil fertilization and other practices followed the same procedure described in Section 2.2.1.

2.2.3. Trial III: Foliage dressing

Two rice varieties were selected from the 15 varieties for the foliage dressing trial: P2 and P13. The foliage dressing was conducted in five treatments: treatment 1: no foliage dressing; treatment 2: foliage dressing with 0.568 g Si L^{-1} (Si1); treatment 3: foliage dressing with 1.42 g Si L^{-1} (Si2); treatment 4: foliage dressing with 5 mg Se L^{-1} (Se1); and treatment 5: foliage dressing with 8 mg Se L^{-1} (Se2). Each treatment was assigned three replicates, and each plot had an area of $6\text{ m} \times 6.5\text{ m}$. The foliage dressing was applied twice for each plot, separately at the tillering and grain-filling stages; and each time 10 L prepared solution containing associated compound was sprayed on the leaves of paddy rice growing in a certain plot. The foliar fertilizer consisted of $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ or Na_2SeO_3 of analytical grade. Soil fertilization and other practices followed the same procedure described in Section 2.2.1.

2.3. Sample collection and analysis

2.3.1. Soil and plant sample collection and processing

Five seedlings as a specimen were sampled from each plot according to the five point sampling method. The whole plant was pulled out together with the roots and soil. The five seedlings were separated into two parts (aboveground and roots). The aboveground part was placed in a mesh bag, and the roots were gently shaken to remove most of the soil adhering to the roots and then placed in the other mesh bag.

After being washed with tap water followed with de-ionized water, the aboveground part was separated into two parts: straws and grains. The grains were air dried and then performed a yield measurement. After that, the rice grains were dehulled, and the brown rice was processed using a small pulverizer. The remained straws were oven-dried at 75 °C for 48h and then pulverized.

The roots were air dried, and the attached soil was brushed off and assigned as rhizosphere soil. After that, the roots were washed carefully with tap water followed with de-ionized water, and then were oven-dried at 75 °C for 48h and pulverized. The rhizosphere soil was passed through a 100 mesh sieve. The pulverized samples (including soils, straws, brown rice, roots) were digested before the Cd and As analyses.

2.3.2. Digestion methods

The samples were digested using an ED54 DigiBlock digestion system (LabTech, Inc., Hopkinton, MA, USA). The process of plant sample digestion was as follows: 0.5000 g of rice grain powder (or 0.2000 g of straw and root) was weighed into digestion tubes, followed by addition of 10 mL of concentrated HNO₃. The mixture was allowed to stand overnight and was then heated at 80°C for 1.5 h. Then, the temperature was raised to

120°C for 1.5 h and finally to 150°C for 3 h. The cap of the tube was left off, and the temperature was adjusted to 170°C to heat the solution until the volume was approximately 1 mL. The remainder was cooled, diluted to a constant volume, and filtered into a 50 mL volumetric flask (Wei et al., **2006**).

Digestion of the rhizosphere soil was as follows: 0.2500 g of soil was weighed into digestion tubes, followed by addition of 10 mL of concentrated HNO₃ and 4 mL of HF. The mixture was allowed to stand overnight and then heated to 120°C for 2 h and then to 150°C. The cap of the tube was left off, and the temperature was adjusted to 170°C to heat the solution until the volume was approximately 1 mL. The remainder was cooled, diluted to a constant volume, and filtered into a 50 mL volumetric flask (Chand et al., **2013**; Krishna et al., **2009**). After digestion, the Cd and As concentrations were analyzed using inductively coupled plasma mass spectrometry (iCAP Qc ICP-MS, Thermo Fisher, USA).

2.4. Statistical analysis

Data were analyzed using one-way ANOVA. Statistical analysis was performed using SPSS 17.0 (SPSS Inc., Chicago, IL, USA). Plots were generated using SigmaPlot.

3. Results

3.1. Trial I: Variety screening

In this study, we screened 15 rice varieties (Table 1). As shown in Figs. 1a, the grain Cd content of all the 15 varieties did not exceed the national standard. However, the grain As content of most rice varieties was higher than the national standard except for four varieties of P6, P7, P10, and P11, whose grain As content was lower than the national standard (Figs. 1b).

In Table 2, compared with the other varieties, P12 contained the highest concentration of As in the rhizosphere soil, up to 27.14 mg kg⁻¹; however, its root and straw As contents were not the highest, up to 350.36 and 8.32 mg kg⁻¹, respectively. The grain yield from P12 was 13.5 kg, which was moderate among the 15 varieties. The lowest As concentration in the rhizosphere soil was observed in P5; nonetheless, its root and straw As contents were moderate. The highest Cd concentration in the rhizosphere soil was 0.82 mg kg⁻¹ in P6; its root Cd content was also the highest, whereas its straw Cd content was the lowest at 0.18 mg kg⁻¹. The grain yield from P6 was 17.7 kg, which was relatively high among the 15 varieties. The grain As content in P6 was below the national standard. The lowest Cd concentration in the rhizosphere soil was 0.27 mg kg⁻¹ in P15, which also presented the lowest root As content of 0.19 mg kg⁻¹. Although P15 had a relatively low As concentration in the rhizosphere soil and straw, its grain yield was also low as 14.4 kg.

3.2. Trial II: Water management

As shown in Fig. 2, the field drying effectively reduced the rice grain As content of all three rice varieties. When the seedlings of three rice varieties were not treated with field

drying, the grain As content in variety P6 and P12 was higher than P2; however, 10d field drying resulted in the grain As content in variety P6 and P12 being equal to or lower than P2, respectively (Fig. **2a**). After 5 days of field drying, the grain As content of P6 and P12 was markedly reduced but being still higher than the national standard. When the field drying time was increased to 10 days, the grain As content of all three varieties was significantly reduced to be below the national standard, where the mean grain As content in P2 and P6 was identical at 0.15 mg kg^{-1} , and the mean grain As content in P12 was 0.13 mg kg^{-1} (data not shown).

As shown in Fig. **2b**, the grain Cd contents of all the three varieties were below the national standard under the flooded conditions. After 5 days of field drying, the grain Cd content reached 0.46 , 0.79 , and 0.23 mg kg^{-1} in P2, P6, and P12, respectively, all being higher than the national standard. When the time of field drying increased to 10 days, the grain Cd content markedly increased to 5.62 , 2.08 , and 3.12 mg kg^{-1} in P2, P6, and P12, respectively, all seriously exceeding the national standard. With increasing field drying time, the increased extent in grain Cd content of P6 appeared to be much smaller than that in P2 and P12.

Fig. **2c** shows that field drying increased the grain yields from P2 and P6, whereas no significant effect was observed in the yield from P12.

Table **3** shows that the As concentration in the rhizosphere soil markedly increased with increasing field drying time among the three varieties; however, different change trends in As and Cd contents in the roots and straws with increasing field drying time

were noted. With increasing field drying time, the straw As content of P2 increased after 5d of field drying but then returned to the level as the treatment of 0d field drying. However, the straw As content of P12 decreased with increasing field drying time. P6 showed the opposite trend as P2: the straw As content of P6 significantly decreased at a treatment of 5d field drying but 10d field drying resulted in it returning to the level as the treatment of 0d field drying. The root As content in the three varieties was markedly reduced with increasing field drying time.

With increasing field drying time, the changes in Cd concentrations in the rhizosphere soils of three varieties were not inconsistent (Table 3). The Cd concentration in the rhizosphere soil increased in P2 but decreased in P6 with increasing field drying time; however, the Cd concentration in the rhizosphere soil in P12 was enhanced by 5d field drying but decreased by 10d field drying. Straw and root Cd contents of all three varieties markedly increased with increasing field drying time (Table 3).

3.3. Trial III: Foliage dressing

Fig. 3a shows that foliage dressing appeared to show limited effects on the grain As content in P13, which still exceeded the national standard regardless of the supply of foliage fertilizers; however the grain Cd content of P13 was always lower than the national standard with or without the addition of foliage fertilizers. The foliage dressing with a treatment of Se2 could significantly reduce the grain Cd content of P13 when compared with the control. Foliage dressing with Si could not significantly affect the grain Cd content of P13.

As shown in Fig. **3b**, regardless of the application of foliage dressing, the grain Cd content of P2 was always lower than its national standard; however the foliage dressing with Se could further significantly reduce the grain Cd content. In the control of P2, the grain As content exceeded its national standard. The foliage dressing with 5 mg L⁻¹ Se (Se1) did not significantly affect, but, a higher level of Se as 8 mg L⁻¹ (Se2) markedly reduced the grain As content, driving it lower than its national standards. The foliage dressing with Si appeared to show non-significant effects on the grain As and Cd contents in P2 except for a treatment containing 0.568 g L⁻¹ Si (Si1), where the grain As content was significantly reduced as compared to the control. However, the grain As content at the treatment of Si1 was still higher than its national standard.

Fig. **3c** shows that the foliage dressing had no remarkable effects on the grain yields from the two rice varieties except a treatment of Se2, where a significant increase in the grain yield of P13 was observed when compared to the control.

4. Discussion

In this study, we assessed the effects of three technologies for remediating multiple heavy metal (metalloid) contaminated soil and their effects on rice grain yields. The results of Trial I indicate that there were differences in the capacities of the uptake and accumulation of Cd and As among the 15 rice varieties (Figs. **1** and **2**, Table **2**). In this study, the roots of paddy rice concentrated the most of As and Cd, followed by the straw and grain, which was in agreement with the results of Abedin et al. (2002), Bose et al. (2008), Das et al. (2004) and Lin et al. (2014). Among the 15 varieties, P6 (Fengliangyou

Xiang No. 1) contained lower grain As and Cd contents than their respective national standards. This variety, relative to other varieties, displayed a relatively high tolerance to the soil contamination, accumulated relatively low contents of As and Cd in its grain, and produced a relatively high grain yield. Therefore, P6 is suggested to be most suitable for growing in soil contaminated with As and Cd in this study.

The results of Trial I also indicate that the As and Cd concentrations in the rhizosphere soil has no direct relationship with their accumulation capacities in the grains of different rice varieties. Because, the concentrations of Cd in the rhizosphere soil and roots of P6 were higher than those of other varieties; however, P6 exhibited a weak capacity for translocating Cd from its roots to its aboveground parts, i.e., a lower Cd content in the straw and grains than those of other varieties. It is well established that the As content in plants does not depend on the As levels of growth substrates. Duxbury et al. (2009) reported that soil As concentration negatively correlated with rice grain As content but positively correlated with straw As; Hossain et al. (2009) found that rice grain As content was poorly correlated with soil and water As.

The results of all three trials indicate that the rice variety may be a secondary factor affecting the grain As and Cd contents in rice, whereas the soil moisture may be the pivotal factor controlling the uptake and accumulation of As and Cd in rice. Because, the grain As and Cd contents in P6 were both below the respective national standards in the Trial I (Fig. 1a, b); however, with increasing field drying time, the grain contents of both elements in P6 increased to above the respective national standards in the Trial II (Fig. 2a,

b). It is worth raising that during the trial period of the present study, continuous rain fell in mid-July led the paddy soil to be submerged for a long time. This might be an important reason for the grain As contents mostly exceeding its national standard and the grain Cd contents generally being below its national standard in different rice varieties both in the Trial I (Fig. **1a, b**) and Trial III (Fig. **3a, b**). Reports have shown that in aerated soils, As can be quickly adsorbed by iron hydroxides and unavailable to plants; however, in anaerobic soils (e.g., waterlogged soil), As is dissolved in the soil solution and thus more available to plant roots (Brammer and Ravenscroft, **2009**). Furthermore, rainfed cultivation can facilitate grain Cd accumulation but reduce grain As content compared with flooding cultivation (Hu et al., **2013**). Our results are consistent with this earlier conclusion. In the Trial II, the grain As content in the three rice varieties markedly decreased with increasing field drying time; the opposite trend was observed regarding the grain Cd content. These results indicate that field drying may result in a high grain Cd content above the national standard, whereas it will not increase the grain As content above the national standard. Therefore, to harmonize these opposing patterns, water management should be combined with other technologies to simultaneously reduce grain Cd and As contents in rice planted in soil contaminated with these two elements. Moreover, field drying at different growth stages of rice has different effects on Cd and As accumulation in rice. Reports have shown that waterlog after the stage of head sprouting can result in less Cd accumulation in grains of paddy rice relative to waterlog

before that stage, and at the same time did not significantly affect the grain As content (Arao et al., **2009**; Takahashi et al., **2004**).

In this study, field drying significantly increased the As concentrations in the rhizosphere soil of all three tested varieties; however, the Cd concentrations in the rhizosphere soil differed with different rice varieties (Table **3**). The roots of rice plants can use oxygen, being transported from the air to the individual root, to oxidize Fe (II) to Fe (III) so as to form an iron plaque (Liu et al., **2006**); Sequential extraction and XANES data showed that As in iron plaque was sequestered mainly with amorphous and crystalline iron (oxyhydr) oxides, and that arsenate was the predominant species (Brammer and Ravenscroft, **2009**). Therefore, aerobic condition will facilitate the formation of iron plaque and thus help the roots adsorb more As, which might be a reason for the enhanced rhizosphere soil As concentration with increasing field drying time in this study. However, the amount of iron plaque around rice roots may be affected by many factors, such as rice variety (Brammer and Ravenscroft, **2009**; Liu et al., **2006**), phosphate concentration in soils (Hu et al., **2005**), sulphur concentration in soils (Hu et al., **2007**). In addition, different rice varieties have varying capacities to take up Cd and field drying is also conducive to the uptake and accumulation of Cd by rice roots. Therefore, these mechanisms operated jointly to result in the complicated changes in the rhizosphere soil Cd concentration among the three varieties in trial II (Table **3**).

Foliage dressing with Si or Se fertilizer is presently a common technology of foliar fertilization to reduce plant uptake of heavy metals. Si is an essential nutrient for the rice

plant. It has been reported that Si application can significantly reduce Cd accumulation in rice grains and improve grain yield from rice under Cd stress (Liang et al., **2001**; Neumann et al., **2001**). Hydroponic culture experiments indicate that Si can mitigate As toxicity and reduce the As content in rice seedlings (Guo et al., **2007**). In the present study, foliage dressing with Si fertilizer generally reduced the grain Cd content, although it did not produce a desired effect on the As content, possibly due to rainfall, the rice variety, or other factors.

This study indicates that foliage dressing with Se reduced the grain Cd content, although it did not significantly affect the grain As content in rice. Research indicates that Se primarily relieves the toxicity of heavy metals or metalloids to plants via two pathways: (1) Se directly reduces the uptake and accumulation of heavy metals or metalloids. Se can reduce the uptake of Cd, As, Pb, zinc (Zn), antimony (Sb), copper (Cu), mercury (Hg), and chromium (Cr) by direct addition to the culture substrate (Ding et al., **2015**; Feng et al., **2013b**, **2013c**). Our previous study has shown that Se affects the morphologic characteristics of plant roots and thereby affects plant uptake of Sb and Cd. However, Se was applied by foliage dressing in the present study. Thus, foliage dressing with Se might have affected other physiological and biochemical processes (e.g., transpiration) in the rice, thereby regulating the uptake and translocation of As and Cd. (2) Se regulates the antioxidant system to mitigate the oxidative stress of heavy metals or metalloids to plants (Feng et al., **2013a**; Filek et al., **2008**).

5. Conclusion

The results of this study indicate that P6 is most suitable for planting in soil contaminated with As and Cd, due to: (1) its lower grain As and Cd contents below their respective national standards, and (2) a relatively high grain yield. High concentrations of As and Cd in the rhizosphere soil did not infer high accumulation of As and Cd in the grain of different rice varieties. The soil moisture rather than rice variety is the pivotal factor controlling the uptake and accumulation of As and Cd in rice. Rainfed cultivation can significantly reduce grain As contents, but, increase grain Cd contents. In order to simultaneously reduce the accumulation of As and Cd in the rice grain, water management technology should be used combining with other technologies, such as foliage dressing technology. The results showed that Se had a higher efficiency than Si to reduce grain Cd and As contents in this study.

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Fig. 1 The contents of Cd and As in the grains of fifteen rice varieties in Trial I. The abbreviations of P1 to P15 denote the names of 15 rice varieties already illustrated in Table 1. Dotted line in Fig. 1a and Fig. 1b refers to the national standard of Cd and As in rice grains, respectively.

Fig. 2 The yields and contents of As and Cd in the grains of P2, P6 and P12 in Trial II. The abbreviations of P2, P6 and P12 denote the names of 3 rice varieties already illustrated in Table 1. Bars are means and standard error for the mean of three replications. Different letters above bars indicate significant difference at $P < 0.05$ (lowercase letters, (lowercase letters) and capital letters denote significance within the variety of P2, P6 and P12 at different field drying time). Dotted line in Fig. 2a and Fig. 2b refers to the national standard of As and Cd in rice grains, respectively.

Fig. 3 The yields and contents of As and Cd in the grains of P13 and P2 in Trial III. The abbreviations of P13 and P2 denote the names of 2 rice varieties already illustrated in Table 1. Bars are means and standard error for the mean of three replications. Different letters above bars indicate significant difference at $P < 0.05$ between treatments (lowercase letters and (lowercase letters) denote significance for As and Cd, respectively, in P13 and P2 at different doses of Se and Si). Se1 and Se2 indicate foliage dressing with 5 mg Se L⁻¹ and 8 mg Se L⁻¹, and Si1 and Si2 indicate foliage dressing with 0.568 g Si L⁻¹ and 1.42 g Si L⁻¹. CK indicates no foliage dressing. Dotted line in Fig. 3a and Fig. 3b refers to the national standard of As and Cd in rice grains.

Fig. 1

Fig. 2

Fig. 3

Table 1 The names and their related abbreviations of selected 15 rice variations

Serial number	Names of variations
P1	D-Xiang287
P2	Fengliangyou 4
P3	F-you 498
P4	H-liangyou-6839
P5	Jinkeyou 651
P6	Fengliangyouxiang 1
P7	Zhongzheyong 8
P8	Quanliangyou 681
P9	Deyou 8258
P10	Guangliangyou 1128
P11	Y-liangyou 696
P12	Lvyou 1
P13	Teyou 524
P14	Y-liangyou 087
P15	Guangliangyou 15

Table 2 As and Cd concentrations in the rhizosphere soil, and their contents in the straws and roots of 15 rice variations in Trial I

Names of variations	Rhizosphere soil (mg kg ⁻¹)		Straws (mg kg ⁻¹)		Roots (mg kg ⁻¹)		Yield (kg)
	As	Cd	As	Cd	As	Cd	
P1 ^a	25.71	0.64	2.79	0.32	253.43	1.38	21.2
P2	21.08	0.49	5.58	0.28	261.04	1.12	23.7
P3	19.04	0.46	5.49	0.19	172.75	0.75	22.1
P4	13.11	0.42	8.18	0.31	537.54	0.69	14.2
P5	11.97	0.45	4.50	0.28	430.97	0.09	17.4
P6	26.51	0.82	6.04	0.18	244.61	1.63	17.7
P7	21.66	0.78	4.40	0.19	211.40	1.62	16.9
P8	23.40	0.60	6.55	0.27	250.06	1.08	16.8
P9	17.32	0.50	3.77	0.36	216.91	0.62	18.0
P10	15.87	0.46	3.99	0.29	218.17	0.93	17.2
P11	26.46	0.57	5.05	0.33	351.14	1.63	12.4
P12	27.14	0.58	8.32	0.26	350.36	0.83	13.5
P13	25.36	0.42	6.82	0.30	377.19	0.40	11.9
P14	19.93	0.49	\ ^b	\	407.84	0.37	13.1
P15	18.13	0.27	3.90	0.35	439.89	0.19	14.4

^a P1 to P15 denote the name abbreviations of 15 rice varieties already illustrated in Table 1.

^b“\” means the sample failed to be obtained.

Table 3 As and Cd concentrations in the rhizosphere soil, and their contents in the straws and roots of P2, P6 and P12 in Trial II. P2, P6 and P12 denote the name abbreviations of 3 rice varieties already illustrated in Table 1

Rice variations	Time (d)	Rhizosphere soil (mg kg ⁻¹)		Straws (mg kg ⁻¹)		Roots (mg kg ⁻¹)	
		As	Cd	As	Cd	As	Cd
P2	0	26.38±1.11c ^a	0.82±0.06b	3.74±0.88b	0.27±0.08b	362.88±36.13a	0.87±0.16c
	5	29.48±3.54b	1.19±0.28a	4.18±1.57a	0.35±0.08b	267.58±13.72b	6.81±1.53b
	10	33.31±3.62a	1.34±0.20a	3.73±1.05b	8.40±0.97a	215.82±45.79c	43.25±8.05a
P6	0	27.50±2.92(b)	1.21±0.27(a)	3.50±0.49(a)	0.33±0.12(b)	443.47±26.68(a)	1.51±0.13(c)
	5	27.38±2.02(b)	0.94±0.24(b)	3.06±0.39(b)	0.41±0.58(b)	367.63±50.03(b)	6.83±1.99(b)
	10	30.30±1.55(a)	0.78±0.15(c)	3.38±1.39(a)	7.49±1.05(a)	247.75±54.05(c)	35.05±7.05(a)
P12	0	24.59±4.15C	0.97±0.14B	4.70±0.54A	0.29±0.09B	421.28±54.66A	1.75±0.48C
	5	29.57±1.91B	1.06±0.09A	2.23±0.58B	0.28±0.05B	301.17±59.97B	7.42±1.72B
	10	30.23±5.47A	0.83±0.19C	2.82±0.69B	5.43±0.25A	221.97±40.77C	27.84±4.81A

^aValues are means ± SE (n=3). The lowercases letters, (lowercases letters) and capital letters in the same column indicate significant differences among different treatments in the variety of P2, P6, and P12, respectively ($p < 0.05$).

Table 4 As and Cd concentrations in the rhizosphere soil, and their contents in the straws and roots of P2 and P13 in Trial III. P2 and P13 denote the name abbreviations of 2 rice varieties already illustrated in Table 1. Se1 and Se2 indicate foliage dressing with 5 mg Se L⁻¹ and 8 mg Se L⁻¹, and Si1 and Si2 indicate foliage dressing with 0.568 g Si L⁻¹ and 1.42 g Si L⁻¹. CK indicates no foliage dressing.

Rice variations	Treatments	Straws (mg kg ⁻¹)		Roots (mg kg ⁻¹)	
		As	Cd	As	Cd
P13	CK	7.96±1.44b ^a	0.12±0.03b	730.82±76.15a	1.54±0.18a
	Se1	8.20±2.85b	0.14±0.03b	677.52±15.24b	1.49±0.05a
	Se2	8.15±1.71b	0.26±0.06a	713.03±35.41b	1.14±0.26b
	Si1	11.62±2.47a	0.12±0.02b	757.52±140.01a	1.20±0.36b
	Si2	5.59±1.71c	0.12±0.03b	779.66±157.08a	1.29±0.40b
P2	CK	4.97±1.46(c)	0.30±0.07(a)	393.02±112.04(c)	0.69±0.25(b)
	Se1	6.23±0.45(b)	0.24±0.05(b)	664.39±17.75(b)	0.32±0.25(c)
	Se2	4.93±0.90(c)	0.26±0.06(a)	586.59±85.41(b)	0.64±0.08(b)
	Si1	4.49±0.75(c)	0.26±0.08(a)	821.83±144.45(a)	1.00±0.37(a)
	Si2	7.33±1.11(a)	0.19±0.02(b)	755.03±38.11(a)	0.53±0.16(b)

^aValues are means ± SE (n=3). Lowercases letters and (lowercases letters) in the same column indicate significant differences among different treatments in the variety of P13 and P2, respectively ($p < 0.05$).