Effect of selenium fertilization on the accumulation of cadmium and lead in rice plants

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Abstract

Background and Aims The accumulation of cadmium and lead in rice (*Oryza sativa* L.) grains is a potential threat to human health. In this study, the effect of selenium fertilization on the uptake and translocation of cadmium and lead in rice plants was investigated.

Methods Rice plants were cultivated using cadmium and lead contaminated soils with selenium addition at three concentrations (0, 0.5 and 1 mg kg⁻¹). At maturity, plants were harvested, and element concentrations in rice tissues were analyzed by using ICP-MS.

Results Selenium application significantly increased selenium accumulation in rice grain, and markedly decreased

cadmium and lead concentrations in rice tissues. In brown rice grains, selenium application reduced cadmium concentrations by 44.4 %, but had no significant effect on lead accumulation. Selenium application significantly decreased metal mobility in soils, at 0.5 mg kg⁻¹ treatment, the translocation factor of cadmium and lead from soil to iron plaque decreased by 71 and 33 % respectively.

Conclusions The mechanism of selenium mitigating of heavy metal accumulation in rice could be decreasing metal bioavailability in soil. Selenium fertilization could be an effective and feasible method to enrich selenium and reduce cadmium levels in brown rice.

Keywords Selenium · Cadmium · Lead · Rice · Se-biofortification · Translocation factor

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Introduction

Cadmium is a heavy metal which has been classified as a Group-1 carcinogen (human carcinogen) by the International Agency for Research on Cancer (IARC, 1993) and the National Toxicology Program (NTP, 2000). Chronic exposure to cadmium causes a variety of health problems including Itai-Itai disease (Murata et al., 1970; Yamagata and Shigematsu, 1970; Bhattacharyya et al., 1992). Cadmium is widespread in the environment through both natural pedogenic processes and anthropogenic activities. For farm lands, especially paddy fields, the major sources of cadmium are from cadmium contaminated irrigation water, and mining and industrial

processes (Yamagata and Shigematsu, 1970; Bolan et al., 2003). Cadmium in soils is readily taken up by plant roots and efficiently transported to the above ground tissues of plants; this efficient transfer of cadmium from soil to plants poses a potential threat to human health through the food chain (Kuboi et al., 1986; Grant et al., 1998; Clemens et al., 2013). According to the reports of FAO/WHO (Food and Agriculture Organization/World Health Organization) (2010) and UNEP (United Nations Environment Programme) (2008), food accounts for approximately 90 % of the cadmium exposure in the general non-smoking population.

Lead is a persistent toxic heavy metal to humans, which has been considered by the International Agency for Research on Cancer (IARC, 1993) as a possible human carcinogen (group 2B) (Francek, 1992; Silbergeld et al., 2000). Exposure to lead can cause direct DNA damage, clastogenicity, or inhibition of DNA synthesis and repair, and it is particularly toxic to the central nervous systems of children (Juberg et al., 1997; Silbergeld et al., 2000). Lead is a major anthropogenic contaminant, released to the environment mainly from mining, smelters and industrial production discharge (Small et al., 1995; Caussy et al., 2003; Deng et al., 2004; Marchiol et al., 2004). In soil, lead is mainly derived through air deposition, such as vehicular emissions, fuel and trash burning and disposal. Plants, including rice (*Oryza sativa* L.) and vegetables, can accumulate lead through several pathways, including uptake from lead contaminated soil (Verma and Dubey, 2003; Yoon et al., 2006; Liu et al., 2013). It has been reported that rice and vegetables growing in lead contaminated mining areas can pose a potential health risk to the local population through the food chain (Zhang et al., 1998; Capdevila et al., 2003; Yang et al., 2004; Zhuang et al., 2009).

Rice is the staple food for about 60 % of the world's population, particularly in Asia. Unfortunately, rice is efficient in heavy metal uptake and translocating metals to grains when compared to other crops (Williams et al., 2007). Cadmium accumulation in rice grains contributes significantly to dietary cadmium intake for populations who live on rice (McLaughlin et al., 1999; Clemens et al., 2013). In Japan it has been demonstrated that rice contributes on average 44 % to the total cadmium intake (UNEP United Nations Environment Programme 2008). The rice contribution to cadmium intake is similar in other countries where rice is the staple food, such as

China and Korea (FAO/WHO Food and Agriculture Organization/World Health Organization 2010). Even for Europeans, grains and grain products contribute 26.9 % of the total cadmium intake (EFSA European Food Safety Authority 2012). In addition to cadmium, in mining regions, lead accumulation in rice plants has been also shown to pose a potential health risk to the local population (Zhang et al., 1998; Capdevila et al., 2003; Yang et al., 2004; Zhuang et al., 2009).

Selenium is an essential micronutrient and has important benefits for human health (Allan et al., 1999). Recently several studies have shown that, in plants, selenium exhibited protective effects against toxic elements such as cadmium, arsenic, lead, antimony, mercury and copper (Gotsis, 1982; He et al., 2004; Srivastava et al., 2009; Taspinar et al., 2009; Feng et al., 2013; Zhou et al., 2013). It is known that selenium is a component in both glutathione peroxidase and thioredoxin reductase. Therefore, in plants, selenium can either act as an antioxidant or activate plant protective mechanisms, alleviating oxidative stress (Hartikainen et al., 2000; Pedrero et al., 2008; Kumar et al., 2012). As well as the protective effect against the toxicity, selenium can also affect the accumulation and distribution of toxic metals in plants (Zembala et al., 2010; Duan et al., 2013). It has previously been demonstrated that selenite significantly inhibited the translocation of As from roots to shoots of rice seedlings. In this study, the effect of selenium fertilization on the uptake and accumulation of both cadmium and lead in rice plants and grains was explored.

Materials and methods

Plant culture

Seeds of the rice cultivar Jiahua 1 were surface sterilized with 30 % H₂O₂ for 15 min and then rinsed thoroughly with distilled water. Once surface sterilized, the seeds were sown and germinated in moist perlite. After 3 weeks, uniform seedlings were transferred to PVC pots (7.5-cm diameter and 14-cm height, one plant per pot). Each pot contained 500 ml of 1/3 strength nutrient solution. The composition of the full strength nutrient solution was 50 µM Fe (II)-ethylenediaminetetraacetic acid (EDTA), 10 µM H₃BO₄, 1.0 µM ZnSO₄·7H₂O, 1.0 µM CuSO₄·5H₂O, 5.0 µM MnSO₄·H₂O, 0.5 µM Na₂MoO₄·2H₂O, 0.2 µM CoSO₄·7H₂O, 5 mM

NH_4NO_3 , 2 mM K_2SO_4 , 4 mM CaCl_2 , 1.5 mM $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ and 1.3 mM KH_2PO_4 . The pH of the solution was adjusted to 5.5 using 0.1 M KOH or HCl. The nutrient solution was renewed twice every week. Plants were grown in a controlled-environment growth room with a 14-h light period ($260\text{--}350 \mu\text{mol m}^{-2} \text{s}^{-1}$) and a 10-h dark period. The temperature was regulated to 28 °C during the daytime and 20 °C at night, and the relative humidity was maintained at 70 %. After two weeks, the plants were transferred to soil filled pots.

Soil preparation

Surface soil (0–10 cm) for the pot experiment was collected from a paddy field known to have elevated concentrations of cadmium and lead in Zhuzhou, Hunan province, China. After air-drying and passing through a 2-mm sieve, the soils were mixed with a solid fertilizer (P as $\text{CaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$ at 0.15 g $\text{P}_2\text{O}_5 \text{ kg}^{-1}$, K as KCl at 0.2 g $\text{K}_2\text{O kg}^{-1}$, and N as $\text{CO}(\text{NH}_2)_2$ at 0.2 g N kg^{-1}). The soil properties and total heavy metal concentrations were determined following standard procedures, shown in Table 1. The pH of the soil was determined using a water extraction with a soil:water ratio of 1:2.5. Organic matter was measured with hot $\text{K}_2\text{Cr}_2\text{O}_4$ oxidization and FeSO_4 titration, and cation exchange capacity (CEC) was measured using the NH_4OAC method. Selenium, cadmium and lead were determined by ICP-AES (Optima 2000 DV, Perkin-Elmer Co. USA) after the digestion with $\text{HNO}_3/\text{HCl}/\text{HClO}_4$ (Tang et al., 2006).

A total of 4 kg of soil was placed in each pot (20 cm in diameter and 25 cm in height). Selenium in the form of Na_2SeO_3 was added to the soil to add additional concentrations of 0 (Se 0), 0.5 (Se 0.5) and 1.0 mg kg^{-1} soil (Se 1), therefore the total concentrations of the treatments were 0.22 mg kg^{-1} for Se 0, 0.72 mg kg^{-1} for Se 0.5, and 1.22 mg kg^{-1} for Se 1. After amending with selenium the pots were flooded and a water depth of 2–3 cm above the soil level was maintained for 14 days prior to seedling transplantation.

Rice plants which had been cultivated in hydroponic solution for 2 weeks were transplanted into the pots containing soil (one plant per pot). For each treatment (Se 0, Se 0.5 and Se 1) there were four replications. After transplanting, the pots with rice plants were placed randomly in a greenhouse with a day temperature of 35 °C and a night temperature of 22 °C. The experiment was conducted with ambient light intensity. The soil was kept submerged throughout the rice growing period. Mature rice was harvested after nearly 6 months.

Sample collection and iron plaque extraction

At maturity, plants were harvested and were separated into grain, shoot, and root. Rice grains and shoots were washed with deionized water to remove potential soil and dust contamination, and then they were oven-dried at 70 °C for 72 h until a constant weight was reached. Rice grains were divided into husk and brown grain using a motorized dehusker (JLGJ4.5, TZYQ, Zhejiang, China). The root samples were carefully washed with tap water to remove soil and then rinsed using deionized water at least three times.

Iron plaque on fresh root surfaces was extracted using dithionite–citrate–bicarbonate (DCB) solution (Taylor and Crowder, 1983; Otte et al., 1991), and the whole root system was incubated at room temperature (20–25 °C) in a 40 mL solution containing 0.03 mol L^{-1} sodium citrate ($\text{Na}_2\text{C}_6\text{H}_5\text{O}_7 \cdot 2\text{H}_2\text{O}$) and 0.125 mol L^{-1} sodium bicarbonate (NaHCO_3) for 10 min. After incubation 1.0 g of $\text{Na}_2\text{S}_2\text{O}_4$ was added into the extraction, mixed and then incubated for a further one hour. Then the roots were removed and rinsed three times with deionized water. The root rinsing water was collected and added to the DCB-extracts, and the extraction was made up to 100 mL with deionized water and filtered for analysis. After DCB extraction, roots were dried in an oven at 70 °C for 72 h and weighed. All the samples (roots, shoots, grain and husk) were milled to a fine powder using a blender (Langjia, China).

Table 1 Physical-chemical properties of and total selenium, cadmium and lead concentrations in the soil

Soil type	pH	OM (g·kg ⁻¹)	CEC (cmol/kg)	Selenium (mg·kg ⁻¹)	Cadmium (mg·kg ⁻¹)	Lead (mg·kg ⁻¹)
Paddy soil	5.80±0.1	4.43±0.34	4.23±0.19	0.22±0.06	1.03±0.11	98.10±6.47.

OM: organic matter, CEC: cation exchange capacity

Data are mean±SD (n=4)

Chemical analysis

For the analysis of selenium, lead and cadmium in dry rice tissues, a 0.2 g subsamples of the roots, shoots, grain or husk was weighed into 100 mL Teflon tubes, to which 5 mL concentrated high-purity HNO_3 was added. After standing overnight at room temperature, the samples were digested in a microwave digestion oven (Mars 5, CEM Corporation, USA) at 180 °C for 15 min. Standard reference material GBW07605 (tea) was used for quality control of the digestion procedure and the analysis process. After digestion the solutions were cooled, diluted to 50 mL with ultra-pure water (Easy-pure) and filtered. The concentrations of selenium, lead and cadmium in DCB extraction solution and in the digestion solution were analyzed by ICP-MS (Agilent-7500, Agilent Technology Co. Ltd, Palo Alto, CA, USA).

Data analysis

Translocation factors (TFs) of cadmium and lead from soil to iron plaque, from iron plaque to root, from root to shoot, from shoot to husk and from husk to brown rice were calculated based on the following equations:

$$\text{TF}_{a \text{ to } b} = [C_{b-x}] / [C_{a-x}]$$

Where a represents respectively soil, iron plaque, roots, shoots, husk; b represents respectively iron plaque, roots, shoots, husk and brown rice; x represents respectively cadmium or lead; $[C_{b-x}]$ represents respectively cadmium or lead concentration in b ; $[C_{a-x}]$ represents respectively cadmium or lead concentration in a .

Bio-accumulation factors (BAF) were calculated based on the following equations:

$$\text{BAF} = [C_{\text{root} / \text{shoot}-x}] / [C_{\text{soil}-x}]$$

Where x represents respectively cadmium or lead; $[C_{\text{shoot}-x}]$ represents respectively cadmium and lead concentration in root or shoot; $[C_{\text{soil}-x}]$ represents respectively cadmium and lead concentration in soil.

Statistical analysis

All data were subjected to analysis by one-way of variance (ANOVA) followed by Student-Newman-Keuls multiple comparisons ($p < 0.05$) using windows-based SPSS 11.5. Data presented are means $\pm$ SD ($n=4$). Curve fitting was performed using SigmaPlot 10.0.

Result

Effect of selenium application on selenium, cadmium and lead accumulation in iron plaque and rice tissues

Selenium concentrations in iron plaque were significantly increased by selenium application ($p < 0.05$), while selenium application significantly decreased cadmium and lead concentrations in the iron plaque ($p < 0.05$) (Fig. 1). Compared to the control, selenium application at 0.5 mg kg^{-1} decreased cadmium and lead concentrations in iron plaque by 71.7 and 33.1 %, respectively (Fig. 1). However, the concentrations of cadmium and lead in iron plaque did not further decrease with the higher selenium application (Fig. 1).

Selenium concentrations in rice roots, shoots, husk and brown rice significantly increased with selenium application ($p < 0.05$) (Fig. 2). In brown rice, selenium concentrations from 0.5 and 1.0 mg kg^{-1} selenium treatments were 2.3- and 4.4-fold higher than that from control, respectively. In roots, shoots and husk, selenium application at 0.5 and 1.0 mg kg^{-1} levels also caused a 2 fold or greater increase in selenium concentration (Fig. 2).

Cadmium concentrations in rice roots, shoots, husk and brown rice were significantly reduced by selenium application ($p < 0.05$) (Fig. 2). Selenium application at 0.5 mg kg^{-1} reduced cadmium concentrations in rice roots, shoots, husk and brown rice by 72.6 %, 47.1 %, 36.4 and 44.4 % respectively (Fig. 2). Cadmium concentrations in rice tissues harvested from plants treated with 1.0 mg kg^{-1} selenium were similar to those from

Fig. 1 Concentrations of selenium, cadmium and lead in extracted iron plaque on the surface of rice roots treated with different selenium concentrations. Data are means $\pm$ SD ($n=4$). Bars with different letters indicate significant difference ($p < 0.05$) among different selenium treatments

Fig. 2 Concentrations of selenium, cadmium and lead in rice roots **a**, shoots **b**, husk **c** and brown rice **d** treated with different selenium concentrations. Data are means $\pm$ SD (n=4). Bars with

different letters indicate significant difference ($p < 0.05$) among different selenium treatments

0.5 mg kg⁻¹ selenium treated plants, except in the husk, where selenium application at 1.0 mg kg⁻¹ significantly decreased cadmium concentration by 46.4 % compared with the 0.5 mg kg⁻¹ selenium treatment (Fig. 2).

Lead concentrations in rice roots and brown rice were not significantly affected by selenium application (Fig. 2). However, in rice shoots and husk, selenium application at 0.5 mg kg⁻¹ reduced lead concentrations in rice shoots and husk by 42.0 and 36.4 % respectively (Fig. 2). Lead concentration in rice husk was further decreased by the 1.0 mg kg⁻¹ selenium treatment (Fig. 2).

Correlation between selenium and cadmium or lead concentration in iron plaque and rice tissues

The concentrations of selenium in the iron plaque were not significantly correlated with cadmium or lead concentrations in iron plaque (Table 2). Also the concentrations of selenium in the iron plaque were not correlated

to the cadmium or Pb concentrations in the different tissues of the rice plants. However, selenium concentrations in rice tissues significantly correlated with cadmium and lead concentrations in a number of different rice tissues (Table 2). All the observed significant correlations between selenium concentration and cadmium or lead were negative relationships (Table 2).

Cadmium accumulations in brown rice were significantly negatively correlated with selenium concentrations in roots, shoots, husk and brown rice, while lead concentrations in brown rice were not significantly correlated with selenium concentrations in any of the rice tissues.

Selenium, cadmium and lead distribution in iron plaque and rice tissues

Selenium was mainly sequestered in iron plaque, accounting for 30–47 %, and about 10 % of selenium was

Table 2 Correlation coefficients (*r*) between selenium and cadmium and lead in iron plaque, root, shoot, husk and brown rice (*n*=12, NS=*p*>0.05 **p*≤0.05, ***p*≤0.01)

Selenium	Cadmium					Lead				
	Iron plaque	Root	Shoot	Husk	Brown rice	Iron plaque	Root	Shoot	Husk	Brown rice
Iron plaque	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Root		−0.708**	NS	−0.580*	−0.609*		NS	−0.584*	−0.596*	NS
Shoot			NS	NS	−0.582*			NS	NS	NS
Husk				−0.651*	−0.630*				−0.625*	NS
Brown rice					−0.624*					NS

distributed in brown rice (Fig. 3). selenium application significantly decreased the distribution ratio of selenium in iron plaque (*p*<0.05), and increased selenium distribution in rice tissues (*p*<0.01). For example, when comparing the 1.0 mg kg^{−1} selenium application to the control there was a decrease in the proportion of selenium in the iron plaque by 35.1 %, while there was a 78.2 %, increase in selenium in the brown rice .

Cadmium was predominantly distributed in rice roots (39–42 %) and shoots (29–39 %), while approximately 10 % of cadmium was sequestered in the iron plaque and about 2 % of cadmium was transported to the brown rice grain. Selenium application did not significantly affect this distribution pattern of cadmium, though slightly increased cadmium in shoot, and decreased cadmium in husk (*p*>0.05).

Lead was distributed predominantly in iron plaque (42–48 %) and roots (28–36 %), with about 20 % of lead

transported to above ground tissues, and with less than 0.5 % of lead being distributed in the brown rice grain (Fig. 3). Selenium application did not significantly affect the distribution pattern of lead either (*p*>0.05).

Effect of selenium application on translocation and bio-accumulation factors for cadmium and lead

Translocation factors (TFs) from soil to iron plaque, iron plaque to root, root to shoot, shoot to husk and husk to brown rice were calculated for both cadmium and lead (Fig. 4). For the control plants that did not have any selenium addition cadmium had high TFs from soil to iron plaque (3.1) and from iron plaque to root (3.6), suggesting that cadmium could be effectively accumulated from the soil to the rice roots. In addition, the TFs of cadmium from root to shoot were almost 1, indicating that cadmium could be effectively translocated from rice

Fig. 3 Distribution of selenium, cadmium and lead in iron plaque and in different rice tissues treated with different selenium concentrations. Data are means ± SD (*n*=4)

Fig. 4 Effects of selenium application on translocation factors (TFs) of cadmium **a** and lead **b**, and on bio-accumulation factors of cadmium **c** and lead **d**. Data are means $\pm$ SD ($n=4$). Bars with different letters indicate significant difference ($p<0.05$) among

different selenium treatments. Bars without letter in **a** and **b** indicate no significant difference ($p>0.05$) among different selenium treatments

root to shoot. The TFs of cadmium from shoot to husk (0.40) and from husk to brown rice (0.13) were <1 , implying that cadmium was less effectively translocated from shoot to husk or from husk to brown rice grain. Selenium application decreased the TFs of cadmium from soil to iron plaque by 71 %; under selenium application conditions the TFs of cadmium from soil to iron plaque were <1 . For the other TFs of cadmium, selenium application did not cause significant differences. This result suggests that selenium application greatly reduced cadmium availability in soil, but did not significantly affect cadmium translocation in rice plants.

All the TFs of lead were <1 (Fig. 4), suggesting that lead was not being effectively translocated from soil to rice plants. Selenium application decreased the TFs of lead from soil to iron plaque by 33 %, and from root to shoot by 31 %, but increased the TFs of lead from iron plaque to root by about 30 %. selenium application did not significantly affect the TFs of lead from shoots to husk and husk to brown rice.

In addition, bio-accumulation factors (BAFs) were calculated to determine the ability of rice plants to extract cadmium and lead from soil (Fig. 4). The results showed that selenium application decreased the BAFs of cadmium in rice roots by about 66 % and in shoots by 59 %. selenium application did not significantly affect the BAFs of lead in rice roots, but decreased the BAFs of lead in rice shoots by 42 %.

Discussion

Selenium is an essential trace element for humans and animals (Allan et al., 1999); selenium deficiency can lead or contribute to Keshan disease and Kashin-Beck disease, which have been reported in areas characterized by extremely low selenium content in the soil and food (Fordyce et al., 2000; Williams et al., 2009). Cereals and cereal products are the main source of dietary intake of

selenium for populations living in the low selenium areas (Rayman, 2008). In this study the application of selenium significantly ($p < 0.05$) increased selenium concentration in rice tissues (Fig. 1); in particular, selenium application increased selenium translocation from root to brown rice and increased the selenium distribution ratio in brown rice (Fig. 3). Therefore, agronomic biofortification of rice with selenium fertilization could be an effective way to improve selenium intake for target populations (Hawkesford and Zhao 2007).

The BAF of rice roots for cadmium was 11.3, and the TFs of cadmium from roots to shoots and from shoots to husk were 0.74 and 0.40, respectively for the non-selenium treat plants (Fig. 4). These results indicate that rice is efficient in cadmium uptake and translocation to grains. This efficient ability of rice to accumulate cadmium from the environment and then totranslocate cadmium from the roots to the grain potentially makes rice a major source of dietary cadmium intake for populations which live on rice subsistence diets (Clemens et al., 2013). For lead, the BCF for rice roots was 0.24, and the TF from roots to shoots was 0.79 for the non-selenium treated plants. These results suggest that rice is not efficient at accumulating lead from soil, but has relative efficiency in transferring lead from roots to shoots. In this study the lead concentration in the soil was 98 mg kg^{-1} , which was within the Chinese Soil Environmental Quality Standard, Grade II (Chinese Environmental Quality Standard for Soils 1995), while lead concentration in brown rice was about 0.3 mg kg^{-1} (Fig. 2), which is higher than the allowable levels of the Chinese Food Hygiene Standards (2005). Therefore, the contribution of rice to lead intake should be considered in mining regions where lead concentration in the soil is relatively high.

Selenium application not only increased selenium accumulation in brown rice, but significantly ($p < 0.05$) decreased cadmium concentration in rice tissues, with a 44.4 % decrease in grain cadmium observed (Fig. 2). Previously, similar results were observed in the shoots of rice seedling growing in hydroponics. For example, Lin et al. (2012) found that selenium addition decreased cadmium levels by 92 % and 57 % in leaves and roots respectively. Our data clearly demonstrated the mitigation of cadmium accumulation in rice grains grown in paddy soil. Selenium application also significantly ($p < 0.05$) decreased lead accumulation in rice shoots and husk, though the lead concentration in brown rice was not significantly affected (Fig. 2). The effect of

selenium application on lead accumulation in plants has previously been reported in other plants. He et al. (2004) reported that selenium supplementation depressed lead accumulation by about 20 % in Chinese cabbage and lettuce. Fargasova et al. (2006) found that selenium reduced lead concentration by about 84.9 % in the shoots of white mustard (*Sinapis alba* L.) seedlings. The results indicate that the application of selenium as a fertilizer could have a significant effect on the reduction of cadmium in rice grains. The effect on lead is less clear as the selenium fertilization does decrease the amount of lead in the shoots and the husk, but does not decrease the lead concentration in the grains.

The mechanism of selenium application for reducing heavy metal accumulation in rice grains is not clear. In this study, we found that selenium application decreased the cadmium concentration in iron plaque by 71 %, but did not significantly affect the TFs from iron plaque to roots or from roots to other plant tissues. Selenium application also decreased lead concentration in iron plaque by 33 %, and as with cadmium the selenium treatment did not affect the TFs. These results indicate that the main mechanism of selenium reducing heavy metal accumulation in rice grain is by decreasing the bioavailability of heavy metals in soil. This conclusion is also supported by the effects of selenium application on BAFs, selenium application decreased the BAFs of cadmium by about 60 % (Fig. 4). In addition, selenium application did not significantly affect this distribution pattern of cadmium and lead within rice plants, though the distribution ratios among rice tissues were slightly affected and the concentration between selenium and metals were negatively correlated. It has been speculated that SeO_3^{2-} can interact with Cd^{2+} or Pb^{2+} ions to form a 1:1 complex (CdSeO_3 or PbSeO_3), thus reducing the bioavailability of Cd^{2+} and Pb^{2+} in soil (Badiello et al., 1996).

Conclusion

Fertilization with optimal amounts of selenium could increase selenium content in rice grains, which is conducive to mitigate selenium deficiency in target regions. Selenium fertilization could also significantly decrease the bioavailability of cadmium and lead in soil, thus halved cadmium accumulation in rice grains, while no effect on lead accumulation in grains. The results of this study would provide helpful information for cultivating

rice for both selenium deficiency and heavy metal contaminated areas.

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