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Research article

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

Guojian Liao [a, b], Qianhua Wu [a, b], Renwei Feng [a, b, c, *], Junkang Guo [b, c], Ruigang Wang [b, c], Yingming Xu [b, c], Yongzhen Ding [b], Zhilian Fan [a], Liangyu Mo [a, **]

[a] Agricultural College, Guangxi University, Nanning, China
[b] Institute of Agro-Environmental Protection, The Ministry of Agriculture, Tianjin 300191, China
[c] Innovation Team of Remediation of Heavy Metal Contaminated Farmland Soil, Chinese Academy of Agricultural Sciences, China

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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), Zhongzheyou 8 (P7), Guangliangyou 1128 (P10), Y-liangyou 696 (P11)] did not exceed their individual national standard. P6 gained a relatively high grain yield but accumulated 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 content 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.

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).

* Corresponding author. Agricultural College, Guangxi University, Nanning, China.
** Corresponding author.
E-mail addresses: frwzym@aliyun.com (R. Feng), moly@gxu.edu.cn (L. Mo).

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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 5.5–6.5 for a paddy field, 30 mg kg^{-1} for As and 0.30 mg kg^{-1} for Cd; pH within a range of 6.5–7.5 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% $N_{26}P_{10}K_{15}$, 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 m × 4.5 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 m × 6.5 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 $Na_2SiO_3 \bullet 9H_2O$ or Na_2SeO_3 of analytical grade. Soil fertilization and other practices followed the same procedure described in Section 2.2.1.

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	Zhongzheyou 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