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RESEARCH ARTICLE

Effect of amendments on bioavailability of cadmium in soil-rice system: a field experiment study

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Abstract

The field experiment study investigated the effect of lime (L), manure compost (M), combination of lime and manure (LM), and combinations of lime with four kinds of passivators (LP1, LP2, LP3, and LP4) on the bioavailability of cadmium (Cd) in soil and Cd accumulation in rice plants. These four passivating products were composed of organic and inorganic compounds such as silicon–sulfhydryl group, CaO, SiO_2, and so on. The results indicated that the application of these amendments improved soil pH, organic matter content, and cation exchange capacity (CEC) by 0.19–0.73 unit, 0.6–8.2%, and 5.7–38.9%, respectively; meanwhile, decreased soil acid–extractable Cd by 4.0–13.9% compared with before remediation. Alleviating Cd stress to rice also resulted in a significant increase in rice grains yield, whereas the LP4 showed an increment of 15.8–27.6%. Among these amendments, LP4 had a relatively high effectiveness, it promoted the decrease of extractable Cd by 13.9% and the increase of residual Cd by 8.1%; meanwhile, the bioconcentration factor of rice grain in LP4 decreased by 71.3%. The high pH, CEC, and rich functional groups in amendments might cause soil Cd transform from mobile fraction to residual fraction, and the cation ions in amendments also competed with Cd ions due to the antagonism. Taken all of these effects, the amendments alleviated Cd pollution in soil–rice system, decreasing Cd migration from soil to grain. In future, the long-term field experiment will need to be done for verify the long-term effect of soil amendments.

Keywords Cadmium · Combined amendment · Paddy soil · Phytotoxicity · Rice

Introduction

Cadmium (Cd) is a toxic element with a relatively high risk of being transferred from soil to the food chain (Zhao and Wang 2020). Daily diet is the major source of Cd exposure for the nonsmoking populations (Chen et al. 2018a). Among the plant-derived foods, rice (*Oryza sativa* L.) is one of the most important crops for human beings, and it has a long cultivation history in China (Zou et al. 2021). Rice plants absorb essential elements from the paddy soil; meanwhile, they inevitably uptake some non-essential elements and even toxic metals like Cd. Due to the rapid modernization in recent years, parts of human activities have caused paddy soil contaminated by Cd to varying degrees, such as mining, smelting, sludge, fertilizer, and pesticide (Feng et al. 2022). In some contaminated areas, long-term intake of Cd from consumption of rice by the local residents lead to serious health problems, such as anemia, cancer, heart attack, proteinuria, lung disorder, emphysema, and osteoporosis (Mei et al. 2017). The itai-itai disease, which occurred in Japan in the 1950s, was the result of excessive ingestion of Cd through contaminated rice (Nordberg et al. 2002).

Guizhou province is located in the karst landform region of China; the paddy soil developed in carbonate rocks in Guizhou has the characteristics of high geological background value of heavy metals (Kong et al. 2018). According to China's National Environmental Monitoring

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Center, the background content of Cd in Guizhou soil is 1.24 mg/kg, which is the highest value in China (CNEMC 1990). During the weathering and pedogenesis process, the easy-soluble components of carbonate rocks were leached and the insoluble components like Cd were reserved by complexation with clay or Fe and Mn oxides (Pu et al. 2015; Xia et al. 2020). Therefore, the soil formed in this natural process was with high total Cd concentration and relatively low bioavailability. However, the human activities, such as industrial production, traffic, application of fertilizers, and wastewater irrigation, have inevitably caused heavy metals activated by the rapid development in the past few decades, thereby increasing Cd bioavailability in paddy soils. Totally, Cd-contaminated paddy soils are becoming one of the critical concerns, both the natural sources and human disturbances lead to the need to search for effective ways to repair Cd-polluted soil.

As a non-essential element for plants, Cd is absorbed by rice roots and migrates to grains along with essential divalent cations like Mn^{2+}, Zn^{2+}, Fe^{2+}, Mg^{2+}, and Ca^{2+} (Zhao and Wang 2020). Due to its toxicity, Cd has adverse impacts on rice yields and qualities by affecting plants nutrient uptake and disturbing metabolism (Wang et al. 2021a; Yang et al. 2019). Cd uptake by plant roots depends on its bioavailability in paddy soil. The soil bioavailable Cd, an important factor influencing Cd uptake, is determined by the physical, chemical, and biological characteristics of soil (Wang et al. 2020). The physicochemical changes in paddy soil lead to the distinctiveness in the mobility, bioavailability, and fraction of Cd (Wang et al. 2020). Therefore, reducing Cd bioavailability and its migration from soil to rice are effective measures for Cd-contaminated soil remediation.

Many measures have been used for remediating Cd pollution in paddy soils to guarantee rice security, including phytoremediation (Liu et al. 2019), water management (Huang et al. 2022), soil amendment application (Chen et al. 2018b; Hamid et al. 2020a), and microbe-assisted remediation (Li et al. 2017; Luo et al. 2019). Among them, the in situ soil amendments such as lime and biochar have received widespread attention for their relatively high remediation efficiency and cost-effectiveness. The selection of raw materials for amendments is the key for this measure. Passivation materials like lime, alkaline materials, clay minerals, and biochar are widely used in acidic soils in China (He et al. 2022; Li et al. 2022a; Yin et al. 2022). The previous studies have shown that the soil amendments exhibited a great level of improving soil pH and reducing soil Cd bioavailability by serious reactions such as adsorption, precipitation, complexation, chelation, ion exchange, and the redox reactions (Hamid et al. 2019; Lu et al. 2012; Porter et al. 2004). The CaO, SiO_2, K_2O, and MgO contained in passivators could react with Ca^{2+} as follows:

$$CaO + H_2O + Cd^{2+} = Cd(OH)_2 + Ca^{2+}$$

$$SiO_2 + 2H_2O + 2Cd^{2+} = 2Cd(OH)_2 + Si^{4+}$$

$$K_2O + H_2O + Cd^{2+} = Cd(OH)_2 + 2K^{+}$$

$$MgO + H_2O + Cd^{2+} = Cd(OH)_2 + Mg^{2+}$$

Meanwhile, the specific surface areas, pore structures, and facilitated electron transfer of soil amendments enhance the physical adsorption of heavy metals in soil, while the functional groups and aromatic properties of amendments affect the chemisorption and precipitation of heavy metals in soil (Chen et al. 2014; Qiao et al. 2018; Tang et al. 2017).

In the past decade, a large number of studies have been carried out on the remediation of Cd pollution in paddy soil by pot experiments, and satisfactory results have been achieved. However, due to the complex external factors, the effectiveness of soil amendments in field trials remains to be verified. In this study, different soil amendments, including lime, manure compost, passivators, and their combinations, were applied in a field experiment, the effects of amendments on soil pH, organic matter (SOM), cation exchange capacity (CEC), the total content and fractionation of Cd, and the Cd accumulation in rice were analyzed to verify the effectiveness of soil amendments.

Materials and methods

Study area

Both the two experimental paddy fields were located in Zhenyuan County, Guizhou Province, China, one in Jinbao Town and the other in Qingxi Town. The regional climate was a typically humid subtropical monsoon climate, with a mean annual temperature of 18.19℃ and an annual average precipitation of about 1182.45 mm. The Jinbao site was situated in a rolling valley, where mountain streams irrigated rice fields, the soil was derived from slate and classified as the hydromorphic paddy soil series in the Chinese Soil Taxonomy. About 2 km northwest of the experimental fields was an abandoned lead–zinc mine that had been closed for about 15 years. At the Qingxi site, the research fields were located on the terrace of the Wuyang River, and the soil was derived from river alluviums, which belonged to the hydromorphic paddy soil series.

According to our previous study, 21 and 27 plots were collected in Jinbao Town and Qingxi Town, respectively, to investigate the distribution of heavy metals in paddy soils (Guo et al. 2021). The soil pH of the Jinbao site was

4.94 ± 0.19, and the average Cd content was 0.91 ± 0.48 mg/kg, while that of the Qingxi site were 5.75 ± 0.34 and 1.50 ± 0.82 mg/kg, respectively. The Cd contents of paddy soils in both study areas exceeded the Cd pollution risk screening value for soil contamination of agricultural land of China (GB 15618–2018). The variation coefficient of Cd content in Qingxi Town and Jinbao Town was 54.67% and 52.32%, respectively, reflecting large spatial variations of Cd concentrations. The Cd concentrations in irrigation water of the Jinbao and Qingxi sites were 0.009 and 0.002 mg/kg, respectively, which could be ignored.

Materials and experiment design

Three rice varieties, Zhongzheyou 1, Yixiang 2115, and Yuxiang 203, were purchased from the native seed station in Qingxi town.

Eight field treatments were designed with each rice cultivar to investigate the effects of the individual or mixed application of these amendments on paddy soil remediation (Table 1), including control (CK), lime alone (L), manure compost alone (M), lime + manure compost (LM), lime + passivator 1 (LP1), lime + passivator 2 (LP2), lime + passivator 3 (LP3), lime + passivator 4 (LP4). Two rice varieties (Zhongzheyou 1 and Yixiang 2115) were conducted in two paddy fields in Qingxi Town, and another experiment was conducted with the rice variety Yuxiang 203 in Jinbao Town. A total of 24 field plots (8 treatments × 3 rice cultivars) were conducted, with three replicates per pot. Each plot covered an area of 20m^2 (5 m × 4 m), and all plots were designed as random blocks. Protective ridges were established around the plots and plastic film was covered to prevent the water seepage between the plots. Details about the main components of lime, manure compost, and the four kinds of passivators were shown in the Table 2. The application rate of amendments was determined by the dosage recommended in the instruction manuals provided by the manufacturers.

Table 1 Design of amendments in paddy soil

Treatments	Lime (kg ha^{-1})	Manure compost (kg ha^{-1})	Passivators (kg ha^{-1})
CK	0	0	0
L	3000	0	0
M	0	3000	0
LM	3000	3000	0
LP1	3000	0	225 (Passivator1)
LP2	3000	0	1875 (Passivator2)
LP3	3000	0	2250 (Passivator3)
LP4	3000	0	3000 (Passivator4)

Field management

Paddy field preparation and amendments application: From April to May, the paddy field plowing and raking were completed according to the local rice planting method. Manure compost and passivators were applied from May 10 to May 11, each of them was first applied to the surface of the paddy field and then mixed evenly by plowing. Lime was implemented at the end of tillering stage (about 1 month after transplanting).

Rice transplanting and water management: Transplanting of rice seedlings was conducted from May 18 to May 21. Rice sowing followed the local traditional methods. The fields were kept flooded until the end of tillering stage, and then drained to inhibit ineffective tillering. After tillering, flooded again until 7 days before harvest.

Sample collection

Soil samples were collected in March (before repairing) and October (after harvest) 2016, respectively. Topsoil samples from each plot were collected according to the 5-point sampling method and then air-dried after the removal of visible stones and plant residues. The soil samples were ground and sieved through 2-, 0.25-, and 0.149-mm nylon mesh to measure the soil pH, CEC, SOM, and Cd.

Rice samples were collected from each corresponding plot in October 2016, placed in nylon net bags, and taken

Table 2 Main components of amendments

Materials	Main component	pH	Cd (mg/kg)
Manure compost	Chicken manure; $N+P_2O_5+K_2O \geq 6\%$; organic matter ≥ 45%	7.80	0.38
Lime	CaO	12.73	/
Passivator 1	Active ingredient of silicon-sulfhydryl group ≥ 45%	11.30	0.12
Passivator 2	CaO ≥ 20%; SiO_2:4%; K_2O:4%; MgO:5%; S:2%; moisture content: 8%; organic carbon: 8%	11.32	0.15
Passivator 3	CaO:24%; SiO_2:3%; moisture content: 8%; organic carbon: 8%	12.59	0.17
Passivator 4	CaO:30%; SiO_2:35%; MgO:5%; Fe $(OH)_2$.3%; moisture content: 5%; organic carbon: 8%	9.01	0.13

back to the laboratory. At the same time, the number of rice effective and ineffective panicles were recorded to calculate grain yields. Rice grain yield was determined from all plants in a 5-m^2 area in each plot and was adjusted to a moisture content of 14%. Rice plants were cleaned with tap water and then rinsed with deionized water at least three times. Rice plants were then separated into four parts: roots, stems, husks, and grains. Roots and stems were first dried in the oven at 110℃ for 30 min, and then dried at 70℃ to constant weight. Grains were air-dried and hilled manually. All plant samples were fully sieved through a 0.149-mm nylon mesh to measure the total Cd concentration.

Sample analysis and quality control

Soil pH was measured at a soil (m) to water (V) ratio of 1:2.5 with an acidity meter (PHS-3C, Ray Magnetic, China). The soil organic matter was determined calorimetrically by oxidation with potassium dichromate. The soil cation exchange capacity was measured using the ammonium acetate saturation method. According to the sequential extraction procedure from the modified European Union Bureau of Reference (BCR) proposed by Arain et al. (2008), Cd forms in soil were divided into four Cd fractions: the acid extractable Cd (acid-soluble fraction) extracted by 0.11 M acetic acid; the fraction bound to Fe/Mn oxides (reducible fraction) extracted by 0.5 M hydroxylamine hydrochloride (pH 2); the fraction bound to organic matter (oxidizable fraction) extracted by 30% H_2O_2 (pH 2–3) and 1 M NH_4OAc (pH 2); and the residual fraction (residual fraction) digested with HNO_3–HCl. The total Cd content of soil samples was determined using acid digestion with HCl-HNO_3-$HClO_4$. All rice samples were digested using the dry ashing method.

Cd contents were analyzed using an inductively coupled plasma optical emission spectrometer (ICP-OES, Thermo Fisher 7400). Certified reference material for soil (GBW07429) and rice (GBW10010 (GSB-1) provided by National Standard Materials Center were used for quality control, the average recovery rates of Cd in soil and rice samples were 96.8% and 95.1%, respectively.

Data analysis

Assessment of the repairing effect of the amendments on soil and rice plant

Due to this field experiment was conducted in two towns with 24 paddy pots, the various external environments and Cd background content affected the quantitative value and caused large deviations of soil pH, SOM, CEC, and Cd content, then influenced the accuracy of effectiveness evaluation. Therefore, we chose the change percentage of soil pH, SOM, CEC, and Cd content as the evaluation indexes. The calculation method was as follows:

$$\mathrm{Index}_{\mathrm{red}} = \frac{C_{\mathrm{pre}} - C_{\mathrm{post}}}{C_{\mathrm{pre}}} \times 100\%$$

$$\mathrm{Index}_{\mathrm{imp}} = \frac{C_{\mathrm{post}} - C_{\mathrm{pre}}}{C_{\mathrm{pre}}} \times 100\%$$

The $\mathrm{Index}_{\mathrm{red}}$ and $\mathrm{Index}_{\mathrm{imp}}$ represented the reduction percentages and improvement percentages of the soil indexes (i.e., soil pH, SOM, CEC, and Cd concentration), respectively. C_{pre} represented the concentration (value) of the indexes before reparing. C_{post} represented the concentration (value) of the indexes after rice grain harvest.

Considering the different Cd concentration in different fields, it was not feasible to calculate Cd content in rice alone. We considered the Cd contents of soil and rice plants together, so we used the bioconcentration factor (BCF) as the assessment index. The BCF was the ratio of the Cd concentration in plant organs to that in soil (Peng et al. 2020), and it was calculated as follows:

$$\mathrm{BCF}_{\mathrm{plant}} = \frac{C_{\mathrm{plant}}}{C_{\mathrm{soil}}}$$

where C_{plant} and C_{soil} represented the Cd concentrations of rice plant and soil, respectively. The $\mathrm{BCF}_{\mathrm{root}}$, $\mathrm{BCF}_{\mathrm{stem}}$, $\mathrm{BCF}_{\mathrm{husk}}$, and $\mathrm{BCF}_{\mathrm{grain}}$ were also calculated.

Statistical analysis

The statistical relationship among all data was analyzed using one-way analysis of variance (ANOVA), and the least significant difference (LSD) was utilized to determine if significant differences existed between the mean values ($P < 0.05$) with SPSS 19.0 (SPSS Inc., Chicago, IL, USA). All data was expressed as the mean ± SD ($n = 3$). All of the figures were generated utilizing Origin 9.2 (OriginLab Corporation, Northampton, MA, USA), CorelDRAW X8 (Corel Corporation, Ottawa, Canada), and Adobe Photoshop 2020 and Adobe Illustrator 2021 software (Adobe Systems Inc., Mountain View, California, USA).

Results

Effects of amendments on soil pH, organic matter, and CEC

As shown in Fig. 1, the application of different amendments increased soil pH to varying degrees, among which CK treatment had the lowest pH value. The pH increase

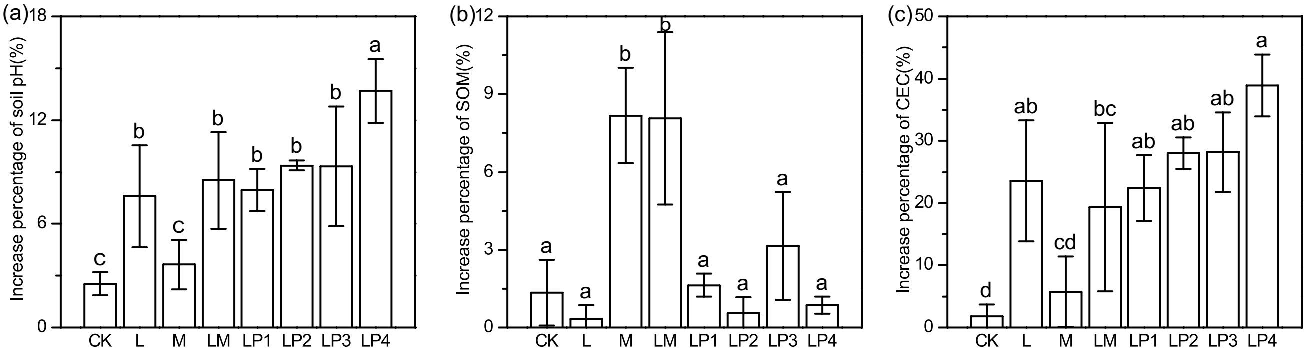

Fig. 1 Effect of amendments on the increase percentages of soil pH (**a**), SOM (**b**), and CEC (**c**). Error bars indicate standard deviation. Different letters above the bars indicate a significant difference ($p < 0.05$) among amendments

rate of manure compost treatment was only 1.1% higher than CK, and their difference did not reach a significant level. Lime, LM, LP1, LP2, and LP3 treatments increased soil pH by 7.6 ± 2.9%, 8.5 ± 2.8%, 8.0 ± 1.2%, 9.4 ± 0.3%, 9.3 ± 3.5%, respectively. What was noteworthy was that LP4 treatment increased soil pH by 13.7 ± 1.5%, which was significantly higher than others. It could be seen that compared with the lime treatment and passivators treatments, the manure compost treatment had relatively less impact on soil pH. Lime and passivators consisted of alkaline materials, especially passivator 4, which could neutralize hydrogen ions, then improve soil pH.

SOM contained various organic acids and soil colloid, and it had a two-sided effect on Cd ions. Among them, organic acids could act as chelators that increased the mobilization of Cd, meanwhile, the ligands and functional groups in SOM could complex with Cd ions to reduce Cd bioavailability in paddy soils. As shown in Fig. 1, all treatments improved SOM by different degrees. The L, LP1 LP2, LP3, and LP4 treatments had no significant difference with CK treatment. The increase rate of SOM in M treatment was the highest (8.2 ± 2.3%), followed by LM treatment (8.1 ± 4.1%), both of them were significantly higher than other treatments. The manure compost contained organic humus and other organic materials, which was important to improve soil fertility and adsorb heavy metals in soil.

The cation exchange capacity was a critical index representing the Cd adsorption capacity of soils. It could be seen from Fig. 1 that the improvement percentage of CEC in CK treatment was only 1.8 ± 2.0%, which was the least among all treatments. The M treatment increased CEC by 5.7 ± 5.6%, but it had no significant difference with CK treatment. Each of the lime and passivators treatments improved CEC by more than 19%, and the LP4 treatment made the biggest increase (38.9 ± 5.0%). These results indicated both lime and passivators could effectively improve soil CEC, while manure compost had a limited effect.

Effects of amendments on soil Cd content and fraction

The amendments had little effect on the soil total Cd content. Apart from the lime treatment, the change rates of total Cd in other treatments were less than 5%, and there was no significant difference among treatments.

The acid-extractable Cd was considered the most active fraction of Cd in soil, while the residual Cd is stable and had a low bioavailability. It could be seen from Fig. 2 that the acid-extractable fraction accounted for almost half of the total Cd, indicating the paddy soils had a certain risk of Cd migration to rice plants. The amendments promoted acid-extractable Cd transformed to reducible fraction and residual fraction. Compared with CK, lime alone and combined with manure or passivators significantly improved the reduction effect on soil acid-extractable Cd. LP4 treatment reduced the acid-extractable Cd most, with an average reduction percentage of 13.9 ± 0.3%, followed by LP2 treatment with an average reduction of 11.3 ± 3.4%. There were no

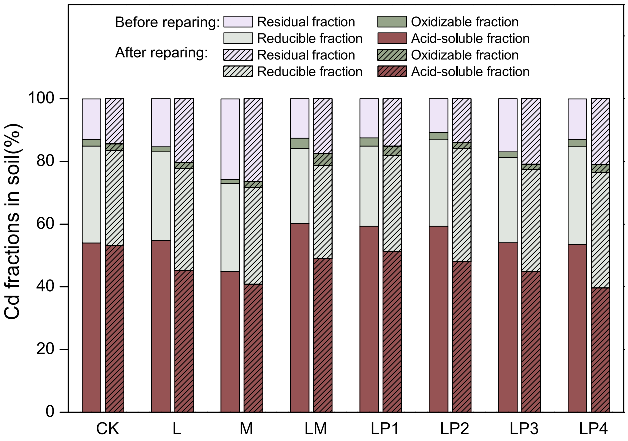

Fig. 2 Effect of amendments on the distributions of Cd in the acid-soluble, reducible, oxidizable, residual fractions of paddy soil

significant differences in the reduction rate of exchangeable Cd between the M treatment and the control (CK). These results indicated lime alone and its combinations with passivators could effectively reduce acid-extractable Cd content, while manure compost treatment had relatively few effects on acid-extractable Cd.

Compared with before repairing, the reducible Cd (Fe–Mn oxide-bound Cd) was improved in all amendment treatments, whereas that in CK was decreased. In CK, the organic acids secreted by rice root possibly caused the release of iron and manganese oxide-bound Cd and promote its transformation to other forms. Manure compost, lime, and passivators combinations increased reducible Cd by 5.4–28.1%, with LP3 treatment having the most significant effect.

No marked changes in the oxidizable Cd contents were observed after treatment in CK, LP3, and LP4 groups. L and M treatments increased oxidizable Cd by 26.1% and 26.7%, respectively. All amendments promoted the increase of residual fraction, except for the manure compost alone treatment. The LP4 treatment improved residual fraction by 66.2%, these results indicated applying amendments enhanced the role of residual fractions in Cd forms.

Effects of combinations of amendments on Cd accumulation and translocation in rice

As shown in Fig. 3 that compared with CK treatment, the amendments decreased the BCF of rice root, stem, rice husk, and grain by 7.3–36.4%, 12.5–55.8%, 12.1–9.0%, and 32.5–71.3% respectively. Among all treatments, the LP4 treatment had the best effect on decreasing Cd BCF in each rice organ. The grain BCF of all amendment treatments were lower than CK, while the LP1, LP2, LP3, and LP4 treatments showed a significant level. The decrease of root BCF in LP4 treatment was largest, implying amendments inhibited the migration of Cd from soil to roots, thus reducing the Cd translocation from underground parts to edible parts. The order of the decrease of rice grain Cd was as the following: LP4 > LP1, LP2, LP3 > L > L, LM > M > CK. It could be seen that the combination of lime and passivator 4 had a great effect on reducing Cd enrichment in each part of rice, followed by lime combined with other passivators. Translocation factors were calculated at the same time, there was no significant difference between CK and other treatments for Cd translocation in rice plants.

Effects of amendments on rice grain yields

As shown in Fig. 4, compared with CK, the application of amendments increased rice grain yields of Zhongzheyou 1, Yixiangyou 2115, and Yuxiang203 cultivars by 15.8–27.6%, 8.1–15.9%, and 5.1–18.4%, respectively. Among the various amendments, the LM treatment obtained the highest yields in Yixiangyou 2115, and Yuxiang203 varieties, and that was M treatment in Zhongzheyou 1 variety. Despite the combined application of passivators and lime having a positive effect on rice yield, the increase of grain yield did not reach a significant level. The L and LM treatments in Zhongzheyou 1 rice cultivar were significantly higher than CK. These results

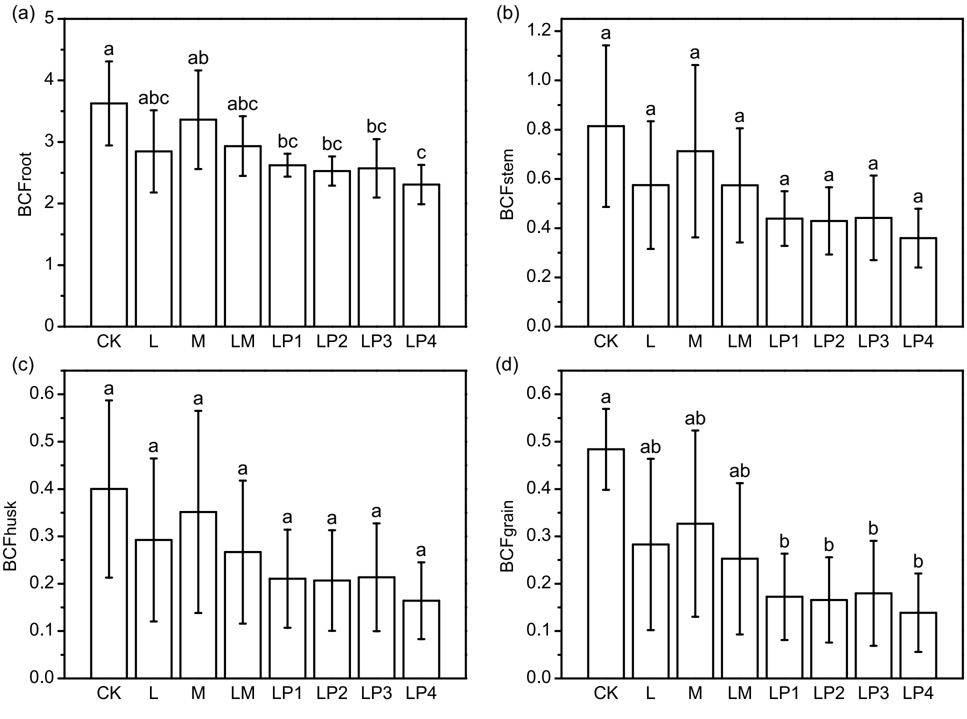

Fig. 3 Effect of amendments on the BCF of rice root (**a**), stem (**b**), husk (**c**), and grain (**d**). Error bars indicate standard deviation. Different letters above the bars indicate a significant difference ($p < 0.05$) among amendments

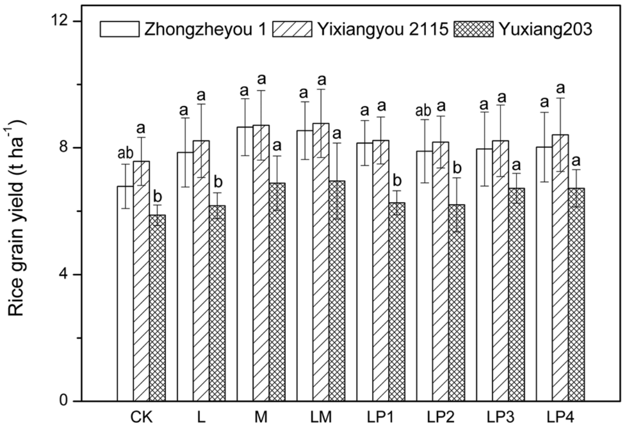

Fig. 4 Effect of amendments on the rice grain yield. Error bars indicate standard deviation. Different letters above the bars indicate a significant difference ($p < 0.05$) among rice cultivars

showed that the manure compost could effectively improve rice grain yield, which might be due to the rich nutrient elements in it, alleviating the phytotoxicity of Cd to rice.

Discussion

Effects of amendments on the distributions of Cd in soil

The results showed that amendments effectively reduced soil acid–extractable Cd contents and Cd accumulation in rice, meanwhile increased soil pH, CEC, reducible Cd, and residual Cd. Lime, manure compost, and the four kinds of passivators used in this experiment contained organic anions and mineral components, such as carbonates, oxides, and hydroxides. These components are alkaline materials, which could neutralize soil hydrogen ions and increase pH, promoting the conversion of Cd from acid-solvable fraction to immobile fraction (Chen et al. 2018b). At the same time, the increasing pH enhanced the negative charge of paddy soil, which could be complexed with Cd^{2+} ions to $Cd(OH)_2$ or form precipitation of $CdCO_3$, thus binding Cd to soil colloids and reducing Cd bioavailability (El-eswed 2020). In this study, the LP4 treatment resulted in the biggest increase in soil pH, it was related to the high contents of CaO in passivator 4, causing the decrease of soil acid–extractable Cd and reducing Cd accumulation.

Except for lime, the manure compost and passivators also contained a certain content of organic matter. The dissociation of carboxyl and phenolic groups in organics also improved paddy soil pH (Hamid et al. 2020b). Meanwhile, ligands and functional groups in organics could bind Cd by metal-matter complex (Laurent et al. 2009). The carbonates, sulfides, and hydroxides of humus in organics formed precipitation with Cd ions and reduced Cd mobility (Thanh et al. 2016). However, the dissolved organic matter of organics could compete with Cd^{2+} ions on soil surface adsorption sites, and the organics released the low molecular organic acids, which could make chelates with Cd, enhancing Cd absorption by rice (Qiao et al. 2022; Xu et al. 2022; Zhu et al. 2019). It might be one of the reasons why the effects of LM and parts of passivators treatments were inferior to the lime alone treatment.

The cation exchange capacity was an indicator of good adsorptive capabilities via ion exchange which affected the translocation of heavy metals in the soil-rice system (Harvey et al. 2011). The dissolved Cd ions were exchanged with other divalent cation ions with similar charges and bond characteristics (Hamid et al. 2020b). Amendments with high CEC, which promoted the ion exchange process, had a strong sorption ability due to hydrogen ion deprotonation and subsequent exchange (Pan et al. 2009). In this study, the calcium, magnesium, silicon ions, and organic functional groups in amendments enhanced soil CEC, competing with Cd ions for uptake site in rice roots.

The amendments consisted of various essential elements, such as calcium and magnesium, which were antagonistic to cadmium. Moreover, these essential elements improved the rice growth conditions and reduced Cd toxicity by adjusting rice physiological functions and alleviating reactive oxide species caused by Cd stresses, improving photosynthesis and enzyme activity in rice plants (Kanu et al. 2019).

The passivator 1 contained more than 45% of silicon-sulfhydryl groups. Previous research showed sulfhydryl grafted palygorskite had an excellent immobilization effect and effectively reduced gain Cd contents (Wu et al. 2022). The soil available sulfur contents could be increased with the application of silicon-sulfhydryl groups. The more sulfur contents facilitated the formation of cadmium sulfides (CdS) during the flooding period, thus decreasing Cd bioavailability. Researchers put forward novel mechanisms: the voltaic effect among chalcophile trace metals possibly promotes the oxidative dissolution of Cd sulfides subsequently drained; meanwhile, the free radicals produced from the oxidation of ferrous sulfides could promote the remobilization of cadmium (Huang et al. 2021a, b). It might be the reason that the effect of LP1 treatment on acid-extractable Cd was not apparent as others.

The passivator 4 contained a small amount of $Fe(OH)_2$, previous studies found that the mobilization of Cd upon soil drainage was related to the release of Cd from Fe–Mn (oxyhydro)oxides to exchangeable fraction, Fe–Mn (oxyhydro)oxides played important roles in controlling the mobilization of Cd in paddy system (Wang et al. 2019). The iron oxides in passivator 4 provided more absorption sites, improving the transformation of Cd from exchangeable fraction to Fe–Mn oxide fraction. Therefore, the LP4 treatment obtained the best passivating effect among the eight treatments.

Effects of amendments combinations on soil properties and rice yields

All treatments displayed an increase in grain yield. One of the reasons was the amendments improved soil fertility for rice plants to respond to Cd stress. The amendments application in soil increased the SOM and other mineral nutrients such as Ca, Mg, and Si. Moreover, manure compost and the four kinds of passivators possibly contained abundant microorganisms, which might improve the abundance of soil microorganisms and enzyme activities. Studies found that the combined use of lime and biochars increased the activities of soil urease and invertase (Lu et al. 2015). With these microbes and enzymes, rice plants could effectively absorb nutrients from the soil and increase grain yields.

Another reason was the application of amendments reduced the Cd toxic effect on rice. Previous studies found that Ca, Mg, and Si ions could compete with Cd for transporters and channels owing to the chemical similarity, thus reducing Cd absorption by root and translocation in rice plants (Wang et al. 2021b; Zhang et al. 2019). Our previous study found both Ca and Mg had an apparent antagonism with Cd in different parts of the rice plant, and the antagonism was more obvious in the high Cd stress treatments (Li et al. 2022b). With the similar surface charge and ionic radius, Ca and Mg competed with Cd for the transport channels of plant cell membranes (Treesubsuntorn and Thiravetyan 2019; Wang et al. 2021b). Despite contained in passivator 4, Si was not an essential element for rice plants, a previous study found it could ameliorate the toxic effects of excessive heavy metals and essential elements on plants (Vaculik et al. 2020). Meanwhile, Si could decrease Cd concentrations in the symplast and apoplast sap of rice root by enhancing Cd binding to the cell walls, thus inhibiting Cd translocation to the aboveground parts (Wu et al. 2018). The organic functional groups contained in organic materials could be complexed with Cd, leading to the decrease of Cd phytoavailabe fraction and Cd toxicity. The Ca, Si, Mg, and organic carbon in passivators apparently inhibit the translocation of Cd in rice, but the interaction of the three elements should be further studied.

Conclusion

The use of lime, manure compost, and the combination of lime and manure or passivators effectively improved soil pH and CEC. The lime and passivator treatments significantly decreased the soil acid-extractable Cd content. Moreover, amendments reduced the absorption and accumulation of Cd in each part of the rice plants. Amendments also increased grain yield, which was caused by the enhancement of soil fertility and the reduction of negative effects of Cd stress. Totally, the high pH and some nutrients contained in amendments were important factors to reduce bioavailable Cd and decrease Cd content in rice. This field study verified the feasibility of remediating Cd-contaminated paddy field by the amendments combination of lime and passivators.

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Declarations

Competing interest The authors declare no competing interests.

References

Arain MB, Kazi TG, Jamali MK, Afridi HI, Jalbani N, Sarfraz RA, . . ., Memon MA (2008) Time saving modified BCR sequential extraction procedure for the fraction of Cd, Cr, Cu, Ni, Pb and Zn in sediment samples of polluted lake. J Hazard Mater 160 (1):235-239. https://doi.org/10.1016/j.jhazmat.2008.02.092

Chen H, Yang X, Wang P, Wang Z, Li M, Zhao F-J (2018a) Dietary cadmium intake from rice and vegetables and potential health risk: a case study in Xiangtan, southern China. Sci Total Environ 639:271–277. https://doi.org/10.1016/j.scitotenv.2018.05.050

Chen H, Zhang W, Yang X, Wang P, McGrath SP, Zhao F-J (2018b) Effective methods to reduce cadmium accumulation in rice grain. Chemosphere 207:699–707. https://doi.org/10.1016/j.chemosphere.2018.05.143

Chen S, Rotaru AE, Shrestha PM, Malvankar NS, Liu F, Fan W, . . ., Lovley DR (2014) Promoting interspecies electron transfer with biochar. Sci Rep 4:5019. https://doi.org/10.1038/srep05019

China National Environmental Monitoring Center (1990) Chinese soil element background content. Chinese Environmental Science Press, Beijing

El-eswed BI (2020) Chemical evaluation of immobilization of wastes containing Pb, Cd, Cu and Zn in alkali-activated materials: a critical review. J Environ Chem Eng 8(5):104194. https://doi.org/10.1016/j.jece.2020.104194

Feng W, Fan D, Li K, Wang T, Zhang H, Zhou X, . . ., Wang R (2022) Removal of cadmium from rice grains by acid soaking and quality evaluation of decontaminated rice. Food Chem 371:131099. https://doi.org/10.1016/j.foodchem.2021.131099

Guo C, Wang P, Yao M-M, Mu L, Fu T-L, He T-B (2021) Study on the heavy metal contents in cultivated layer soil of rice fields in valleys and river terraces of Guizhou Provence. J Mountain Agric Biol 40:22–27. https://doi.org/10.15958/j.cnki.sdnyswxb.2021.01.004. (in Chinese)

Hamid Y, Tang L, Hussain B, Usman M, Gurajala HK, Rashid MS, . . ., Yang X (2020a) Efficiency of lime, biochar, Fe containing biochar and composite amendments for Cd and Pb immobilization in a co-contaminated alluvial soil. Environ Pollut 257:113609. https://doi.org/10.1016/j.envpol.2019.113609

Hamid Y, Tang L, Hussain B, Usman M, Lin Q, Rashid MS, . . ., Yang X (2020b) Organic soil additives for the remediation of cadmium contaminated soils and their impact on the soil-plant system: a review. Sci Total Environ 707:136121. https://doi.org/10.1016/j.scitotenv.2019.136121

Hamid Y, Tang L, Sohail MI, Cao XR, Hussain B, Aziz MZ, . . ., Yang XE (2019) An explanation of soil amendments to reduce cadmium phytoavailability and transfer to food chain. Sci Total Environ 660:80-96. https://doi.org/10.1016/j.scitotenv.2018.12.419

Harvey OR, Herbert BE, Rhue RD, Kuo L-J (2011) Metal interactions at the biochar-water interface: energetics and structure-sorption relationships elucidated by flow adsorption microcalorimetry. Environ Sci Technol 45(13):5550–5556. https://doi.org/10.1021/es104401h

He L, Wang B, Cui H, Yang S, Wang Y, Feng Y, . . ., Feng Y (2022) Clay-hydrochar composites return to cadmium contaminated paddy soil: reduced Cd accumulation in rice seed and affected soil microbiome. Sci Total Environ 835:155542. https://doi.org/10.1016/j.scitotenv.2022.155542

Huang B-Y, Zhao F-J, Wang P (2022) The relative contributions of root uptake and remobilization to the loading of Cd and As into rice grains: implications in simultaneously controlling grain Cd and As accumulation using a segmented water management strategy. Environ Pollut 293:118497. https://doi.org/10.1016/j.envpol.2021.118497

Huang H, Chen HP, Kopittke PM, Kretzschmar R, Zhao FJ, Wang P (2021a) The voltaic effect as a novel mechanism controlling the remobilization of cadmium in paddy soils during drainage. Environ Sci Technol 55(3):1750–1758. https://doi.org/10.1021/acs.est.0c06561

Huang H, Ji XB, Cheng LY, Zhao FJ, Wang P (2021b) Free radicals produced from the oxidation of ferrous sulfides promote the remobilization of cadmium in paddy soils during drainage. Environ Sci Technol 55(14):9845–9853. https://doi.org/10.1021/acs.est.1c00576

Kanu AS, Ashraf U, Mo Z, Sabir SUR, Tang X (2019) Calcium amendment improved the performance of fragrant rice and reduced metal uptake under cadmium toxicity. Environ Sci Pollut Res 26(1):24748–24757. https://doi.org/10.1007/s11356-019-05779-7

Kong X, Liu T, Yu Z, Chen Z, Lei D, Wang Z, . . ., Zhang S (2018) Heavy metal bioaccumulation in rice from a high geological background area in Guizhou Province, China. International Journal of Environmental Research and Public Health, 15 (10). https://doi.org/10.3390/ijerph15102281

Laurent J, Pierra M, Casellas M, Dagot C (2009) Fate of cadmium in activated sludge after changing its physico-chemical properties by thermal treatment. Chemosphere 77(6):771–777. https://doi.org/10.1016/j.chemosphere.2009.08.024

Li D, Liu H, Gao M, Zhou J, Zhou J (2022a) Effects of soil amendments, foliar sprayings of silicon and selenium and their combinations on the reduction of cadmium accumulation in rice. Pedosphere 32(4):649–659. https://doi.org/10.1016/S1002-0160(21)60052-8

Li X, Teng L, Fu T, He T, Wu P (2022b) Comparing the effects of calcium and magnesium ions on accumulation and translocation of cadmium in rice. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17923-3

Li Y, Pang HD, He LY, Wang Q, Sheng XF (2017) Cd immobilization and reduced tissue Cd accumulation of rice (*Oryza sativa* wuyun-23) in the presence of heavy metal-resistant bacteria. Ecotoxicol Environ Saf 138:56–63. https://doi.org/10.1016/j.ecoenv.2016.12.024

Liu S, Ali S, Yang R, Tao J, Ren B (2019) A newly discovered Cd-hyperaccumulator *Lantana camara* L. J Hazard Mater 371:233–242. https://doi.org/10.1016/j.jhazmat.2019.03.016

Lu HL, Zhang WH, Yang YX, Huang XF, Wang SZ, Qiu RL (2012) Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar. Water Res 46(3):854–862. https://doi.org/10.1016/j.watres.2011.11.058

Lu HP, Li Z, Fu SL, Mendez A, Gasco G, Paz-Ferreiro J (2015) Combining phytoextraction and biochar addition improves soil biochemical properties in a soil contaminated with Cd. Chemosphere 119:209–216. https://doi.org/10.1016/j.chemosphere.2014.06.024

Luo LY, Xie LL, Jin DC, Mi BB, Wang DH, Li XF, . . ., Liu F (2019) Bacterial community response to cadmium contamination of agricultural paddy soil. Appl Soil Ecol 139:100-106. https://doi.org/10.1016/j.apsoil.2019.03.022

Mei H, Yao P, Wang S, Li N, Zhu T, Chen X, . . ., Wang JM (2017) Chronic low-dose cadmium exposure impairs cutaneous wound healing with defective early inflammatory responses after skin injury. Toxicol Sci 159:327-338. https://doi.org/10.1093/toxsci/kfx137

Nordberg G, Jin T, Bernard A, Fierens S, Buchet JP, Ye T, . . ., Wang H (2002) Low bone density and renal dysfunction following environmental cadmium exposure in China. Ambio A J Human Environ 31(6):478-481

Pan XL, Wang JL, Zhang DY (2009) Sorption of cobalt to bone char: kinetics, competitive sorption and mechanism. Desalination 249(2):609–614. https://doi.org/10.1016/j.desal.2009.01.027

Peng C, Tong H, Shen C, Sun L, Yuan P, He M, Shi J (2020) Bioavailability and translocation of metal oxide nanoparticles in the soil-rice plant system. Sci Total Environ 713:136662. https://doi.org/10.1016/j.scitotenv.2020.136662

Porter SK, Scheckel KG, Impellitteri CA, Ryan JA (2004) Toxic metals in the environment: thermodynamic considerations for possible immobilization strategies for Pb, Cd, As, and Hg. Crit Rev Environ Sci Technol 34(6):495–604. https://doi.org/10.1080/10643380490492412

Pu J, Yuan D, Xiao Q, Zhao H (2015) Hydrogeochemical characteristics in karst subterranean streams: a case history from Chongqing, China. Carbonates Evaporites 30(3):307–319. https://doi.org/10.1007/s13146-014-0226-1

Qiao D, Han Y, Zhao Y (2022) Organic acids in conjunction with various oilseed sunflower cultivars promote Cd phytoextraction through regulating micro-environment in root zone. Ind Crops Prod 183:114932. https://doi.org/10.1016/j.indcrop.2022.114932

Qiao JT, Liu TX, Wang XQ, Li FB, Lv YH, Cui JH, . . ., Liu CP (2018) Simultaneous alleviation of cadmium and arsenic accumulation in rice by applying zero-valent iron and biochar to contaminated paddy soils. Chemosphere 195:260-271. https://doi.org/10.1016/j.chemosphere.2017.12.081

Tang W, Zhong H, Xiao L, Tan Q, Zeng Q, Wei Z (2017) Inhibitory effects of rice residues amendment on Cd phytoavailability: a matter of Cd-organic matter interactions? Chemosphere 186:227–234. https://doi.org/10.1016/j.chemosphere.2017.07.152

Thanh PM, Ketheesan B, Yan Z, Stuckey D (2016) Trace metal speciation and bioavailability in anaerobic digestion: a review. Biotechnol Adv 34(2):122–136. https://doi.org/10.1016/j.biotechadv.2015.12.006

Treesubsuntorn C, Thiravetyan P (2019) Calcium acetate-induced reduction of cadmium accumulation in *Oryza sativa*: expression of auto-inhibited calcium-ATPase and cadmium transporters. Plant Biol 21(5):862–872. https://doi.org/10.1111/plb.12990

Vaculik M, Lukacova Z, Bokor B, Martinka M, Tripathi DK, Lux A (2020) Alleviation mechanisms of metal (loid) stress in plants by silicon: a review. J Exp Bot 71(21):6744–6757. https://doi.org/10.1093/jxb/eraa288

Wang F, Tan H, Zhang Y, Huang L, Bao H, Ding Y, . . ., Zhu C (2021a) Salicylic acid application alleviates cadmium accumulation in brown rice by modulating its shoot to grain translocation in rice. Chemosphere 263:128034. https://doi.org/10.1016/j.chemosphere.2020.128034

Wang J, Li D, Lu Q, Zhang Y, Xu H, Wang X, Li Y (2020) Effect of water-driven changes in rice rhizosphere on Cd lability in three soils with different pH. J Environ Sci 87:82–92. https://doi.org/10.1016/j.jes.2019.05.020

Wang J, Wang P-M, Gu Y, Kopittke PM, Zhao F-J, Wang P (2019) Iron-manganese (oxyhydro)oxides, rather than oxidation of sulfides, determine mobilization of Cd during soil drainage in paddy soil systems. Environ Sci Technol 53(5):2500–2508. https://doi.org/10.1021/acs.est.8b06863

Wang Y, Xu Y, Liang X, Wang L, Sun Y, Huang Q, . . ., Zhao L (2021b) Soil application of manganese sulfate could reduce wheat Cd accumulation in Cd contaminated soil by the modulation of the key tissues and ionomic of wheat. Sci Total Environ 770:145328. https://doi.org/10.1016/j.scitotenv.2021.145328

Wu Y, Yang H, Wang M, Sun L, Xu Y, Sun G, . . ., Liang X (2022) Immobilization of soil Cd by sulfhydryl grafted palygorskite in wheat-rice rotation mode: a field-scale investigation. Sci Total Environ 826:154156. https://doi.org/10.1016/j.scitotenv.2022.154156

Wu Z, Xu S, Shi H, Zhao P, Liu X, Li F, . . ., Wang F (2018) Comparison of foliar silicon and selenium on cadmium absorption, compartmentation, translocation and the antioxidant system in Chinese flowering cabbage. Ecotoxicol Environ Saf 166:157-164.https://doi.org/10.1016/j.ecoenv.2018.09.085

Xia X, Ji J, Yang Z, Han H, Zhang W (2020) Cadmium risk in the soil-plant system caused by weathering of carbonate bedrock. Chemosphere 254:126799. https://doi.org/10.1016/j.chemosphere.2020.126799

Xu W, Liu C, Zhu J-M, Bu H, Tong H, Chen M, . . ., Liu Y (2022) Adsorption of cadmium on clay-organic associations in different pH solutions: the effect of amphoteric organic matter. Ecotoxicol Environ Saf 236:113509. https://doi.org/10.1016/j.ecoenv.2022.113509

Yang X, Lin R, Zhang W, Xu Y, Wei X, Zhuo C, . . ., Li H (2019) Comparison of Cd subcellular distribution and Cd detoxification between low/high Cd-accumulative rice cultivars and sea rice. Ecotoxicol Environ Saf 185:109698. https://doi.org/10.1016/j.ecoenv.2019.109698

Yin Z, Sheng H, Xiao H, Xue Y, Man Z, Huang D, Zhou Q (2022) Inter-annual reduction in rice Cd and its eco-environmental controls in 6-year biannual mineral amendment in subtropical double-rice cropping ecosystems. Environ Pollut 293:118566. https://doi.org/10.1016/j.envpol.2021.118566

Zhang Y, Wang X, Ji X, Liu Y, Lin Z, Lin Z, . . ., Zhang X (2019) Effect of a novel Ca-Si composite mineral on Cd bioavailability, transport and accumulation in paddy soil-rice system. J Environ Manag 233:802-811. https://doi.org/10.1016/j.jenvman.2018.10.006

Zhao FJ, Wang P (2020) Arsenic and cadmium accumulation in rice and mitigation strategies. Plant Soil 446(1–2):1–21. https://doi.org/10.1007/s11104-019-04374-6

Zhu X, Lv B, Shang X, Wang J, Li M, Yu X (2019) The immobilization effects on Pb, Cd and Cu by the inoculation of organic phosphorus-degrading bacteria (OPDB) with rapeseed dregs in acidic soil. Geoderma 350:1–10. https://doi.org/10.1016/j.geoderma.2019.04.015

Zou M, Zhou S, Zhou Y, Jia Z, Guo T, Wang J (2021) Cadmium pollution of soil-rice ecosystems in rice cultivation dominated regions in China: a review. Environ Pollut 280:116965. https://doi.org/10.1016/j.envpol.2021.116965

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