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Effects of combined soil amendments on the availability and migration of Cd in soil and rice

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To achieve safe production of severe cadmium (Cd)-contaminated paddy fields, the effects of a combination of red mud, silicon fertilizer, and phosphorus fertilizer on the absorption, transportation, and accumulation of Cd in rice were studied by a field plot orthogonal experiment. The results showed that soil pH, biomass of straw, and grain increased after applying the combined soil amendments. Compared with the control (CK), soil-available Cd decreased by 16.90%–47.09%. Cd content decreased by 42.30%–65.62% in roots, 16.05%–67.98% in stems, 26.09%–66.30% in leaves, and 48.39%–74.19% in grain. Variance and range analysis showed the effect of the three amendments on Cd reduction in grain was in descending order: red mud > silicon fertilizer > phosphate fertilizer. The optimal combination of soil amendments to control Cd pollution was 1,800 kg/ha red mud, 600 kg/ha silicon fertilizer, and 675 kg/ha phosphorus fertilizer. Results showed that safe production from severely Cd-contaminated paddy fields could be achieved by applying a combination of soil amendments and provided a method for remediating a severely Cd-contaminated paddy field.

KEYWORDS

soil, Cd contamination, combined soil amendments, rice, pollution control

1 Introduction

Cadmium (Cd), a toxic pollutant, has been increasingly released into soil with rapid urbanization and industrialization and is widely used in agricultural inputs, which poses a severe threat to human health (Zhao et al., 2017a; 2017b; Yu et al., 2022). Rice (*Oryza sativa* L.) is a naturally Cd-loving plant that absorbs and accumulates Cd from paddy fields, resulting in Cd contamination of the rice grain. Large quantities of Cd in food are absorbed and accumulated in human bodies and can cause health issues such as fractures, mutagenesis, carcinogenesis, and teratogenesis (Song et al., 2003; Zhong et al., 2021). Rice is the most common food worldwide and feeds more than half of the world's population (Fukagawa and Ziska, 2019; Nawaz et al., 2022; Tang et al., 2022), making rice quality a most important issue for food security and global health. Thus, there is an urgent and critical strategic need to control Cd pollution in rice.

In order to reduce the effect of Cd on human health, many remediation technologies such as water management (Zhong et al., 2021), planting low-Cd-affinity rice varieties (Zhao et al., 2015), microbial remediation (Mao et al., 2022), and amendment remediation

(Deng et al., 2020) have been created and deployed to decrease Cd uptake and accumulation in rice grain from Cd-contaminated paddy fields. Of them, *in situ* chemical amendment remediation methods have been proven to be the most economical and convenient method of controlling Cd contamination in rice because of their low cost, simple operation, high efficiency, and large-scale applicability (Li et al., 2018; Xu et al., 2021). Because of large population and limited amount of cultivated land, Cd-contaminated paddy fields must be remediated during the crop production seasons in China (Wang et al., 2019; Zou et al., 2021).

Red mud, a byproduct of aluminum production (Zhu et al., 2020; Guo et al., 2022; Huang et al., 2022), has been proven to be an inexpensive and effective chemical amendment for *in situ* remediation of Cd-contaminated paddy fields (Lombi et al., 2002; Garau et al., 2007). Many studies found that the red mud mechanism was a reduction of soil Cd activity by improving soil pH (Li et al., 2018; Meng et al., 2022; Zhou et al., 2024). Rice is a typical Si-loving plant, and application of silicon fertilizer has also been confirmed to be highly efficient at controlling Cd pollution in rice in pot and field experiments (Rehman et al., 2019; Cai et al., 2020; Hussain et al., 2020; Xiao et al., 2021). Numerous studies have shown that the mechanism of silicon fertilizer was a reduction of soil Cd availability (Rehman et al., 2019; Zhao et al., 2020a), and Si inhibited the expressions of Cd transporter genes: *OsNramp5* and *OsHMA2* (Feng Shao et al., 2017). Phosphate fertilizer, such as alkaline calcium-magnesia-phosphate, has been proven to effectively to reduce Cd content in rice (Seshadri et al., 2017; 2016; Zhao et al., 2020b; Wu et al., 2023), and studies also shown the mechanism of phosphate fertilizer for controlling Cd pollution in rice was reduction of soil Cd availability (Seshadri et al., 2016; 2017).

Although a single application of red mud, silicon fertilizer, and phosphorus fertilizer had been proved efficiently to control Cd pollution in rice of mild and moderate Cd-contaminated paddy fields (Meng et al., 2022; Rehman et al., 2019; Zhao et al., 2020b), their effectiveness was limited in severely Cd-contaminated paddy fields, and previous studies had not been able to achieve safe production of Cd-contaminated paddy fields (Wang et al., 2021; Chao et al., 2022). Combined soil amendments were more effective and stable than any single component (Pei et al., 2021; Jiang et al., 2022). Based on the effects and mechanisms of the three amendments, we think that their combination could result in better remediation of severely Cd-contaminated paddy fields.

In this study, the effects of the combination of red mud, silicon fertilizer, and phosphate fertilizer on Cd accumulation in rice and its mechanism were studied by field plot orthogonal experiments to screen some low-cost, high-efficiency, stable, and universal combined soil amendments to achieve safe production in Cd-contaminated paddy fields, especially for acidic severely Cd-contaminated paddy fields.

2 Materials and methods

2.1 Field experimental site

The field experiment was implemented in Liuyang City, Hunan Province, with a latitude and longitude of 28°13'27.49"N and 113°32'35.65"E, respectively. The soil type in the study area is

acidic red soil, and the basic physical and chemical properties of paddy fields (0–20 cm) in the study site are shown in Table 1. The soil total Cd content was 1.98 mg/kg, approximately five times higher than the Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land (GB 15618-2018) (0.40 mg/kg) (MEEPRC and SAMR, 2018). Thus, the field was considered a severely Cd-contaminated paddy field. The local climate is a subtropical monsoon climate type with an annual temperature of 16.8–17.5°C and a precipitation of 1,400–1,700 mm on average.

2.2 Experimental materials

Red mud was purchased from Changxing Industrial Co., Ltd., Henan Province. It contains large amounts of Fe₂O₃ and Al₂O₃ and smaller amounts of SiO₂, TiO₂, CaO, and Na₂O. The pH value and content of organic matter of the red mud are 11.25 g/kg and 5.00 g/kg, respectively, and contents of Cu, Zn, Pb, Cd, and As in the red mud are 27.58 mg/kg, 31.13 mg/kg, 36.75 mg/kg, 0.13 mg/kg, and 11 mg/kg, respectively, lower than the limit (Pb < 200 mg/kg, Cd < 10 mg/kg, As < 50 mg/kg) of the standard: Limitation Requirements of Toxic and Harmful Substance in Fertilizers (GB 38400-2019) (SAMR and SAPRC, 2019). Silicon fertilizer was purchased from Mingyuan Chemical Raw Materials Co., Ltd., Zhengzhou, Henan Province. Its content of SiO₂ is more than 26%. Phosphate fertilizer (Ca(H₂PO₄)₂·H₂O) was purchased from Tongguanshan Chemical Co., Ltd., Tongling, Anhui Province, and the P and Ca contents are more than 22% and 18%, respectively.

The test rice variety is Yuzhenxiang, which is known for its high Cd accumulation capacity and was specifically selected to evaluate the Cd uptake performance under different soil amendment treatments. It was purchased from the Hunan Rice Research Institute and proved to be suitable for double rice cropping in areas with mild rice blast in Hunan Province. The growth period of the test rice variety was 114 days on average.

2.3 Field experimental design and sample collection

In this study, a three-factor, three-level orthogonal experiment was conducted in a field plot. The specific factors and levels were red mud (900 kg/ha, 1,350 kg/ha, and 1,800 kg/ha), silicon fertilizer (600 kg/ha, 900 kg/ha, and 1,200 kg/ha) and phosphorus fertilizer (225 kg/ha, 450 kg/ha, and 675 kg/ha). Ten treatments, including CK and CK, were employed as a control without any amendments. The composition of each treatment is shown in Table 2, and each treatment was repeated three times. The area of each plot was 20 m², and the plots were separated by ridges covered with a plastic membrane. Combined soil amendments were applied as base fertilizers and mixed by a rototiller 1 week prior to rice transplantation. In order to prevent mutual interference, separate irrigation and drainage were applied at all plots. Field management was taken according to local habits, including irrigation, weeding, fertilization, and pest control.

One week before the trial, soil samples were collected from the tested field with the five-point sampling method. At harvest, rice

TABLE 1 Basic physical and chemical properties of the paddy soil.

pH	OM	CEC	Total N	Total K	Total P	Total Cd	Total Zn	Total Pb
	g/kg	cmol/kg	g/kg	g/kg	g/kg	mg/kg	mg/kg	mg/kg
5.61	28.91	12.98	1.82	23.81	0.52	1.98	246.23	61.92

Note: OM: organic matter, CEC: cation exchange capacity.

TABLE 2 Experimental design (kg/ha).

Treatments	Red mud	Silicon fertilizer	Phosphorus fertilizer
CK	0	0	0
C1	900	600	225
C2	1,800	900	675
C3	1,350	600	675
C4	1,350	1,200	450
C5	1,350	900	225
C6	1,800	600	450
C7	1,800	1,200	225
C8	900	1,200	675
C9	900	900	450

and soil samples were collected separately from each plot with the five-point sampling method. Rice samples were washed with tap water followed by ultrapure water, and divided into four organs: root, stem, leaf, and grain. All rice samples were put into brown-paper envelopes, dried at 70°C to a constant weight, followed by 105°C for 1 h, and then ground into powder. Soil samples were ground and sieved by nylon mesh (0.15 mm) after being air-dried in an indoor ventilated room and placed in a desiccator in a sealed bag.

2.4 Sample analysis

After rice was harvested in the field, a threshing machine was used to separate the rice straw and grain. The biomass of the straw and grain was then weighed separately using an electronic scale. Soil pH was determined by pH meter PHS-3C (Leici Instrument, China) with a soil-to-water ratio of 1:2.5 (w/v) (Yang et al., 2008). Soil cation exchange capacity (CEC) and organic matter (OM) were measured using the barium chloride and sulfuric acid forced exchange method, respectively. Alkaline-N, Olsen-P, and Olsen-K in soil were analyzed by soil agrochemical analysis and environmental monitoring (Yang et al., 2008). Soil and rice samples were digested by mixed acids (HCl-HNO₃-HClO₄ for soil and HNO₃-HClO₄ for rice organs) and filtered after diluting to the mark. The Cd content in the solution was measured by inductively coupled plasma optical emission spectroscopy (ICP-OES) (PerkinElmer, United States) for soil and flame atomic spectroscopy (AA-240FS) (Varian, United States) for rice organs (Bao, 2000). The content of the soil-available Cd was measured by ICP-OES (PerkinElmer,

United States) after extraction by 0.01 mol/L CaCl₂ with a soil-to-solution ratio of 1:10 (w/v) (Bao, 2000).

2.5 Statistical data analysis

Means and standard deviations were calculated using MS Excel 2019. Range analysis, variance analysis of the orthogonal experiments, and one-way analysis of variance (ANOVA) were conducted using SPSS 24. Significant differences between treatments were detected with Tukey’s highly significant differences (HSD) test ($P < 0.05$) and marked by different lowercase letters. The Pearson correlation coefficient was analyzed by SPSS 24 and used to determine the correlation between the plant Cd content and various soil indicators. All figures were plotted using Origin 2024.

The bioconcentration factor (BCF) was calculated using Equation 1 to represent the accumulation of Cd in rice organs relative to total Cd content in soil.

$$BCF = C_1/C_2 \tag{1}$$

where C_1 (mg/kg) is Cd content in different organs of rice, and C_2 (mg/kg) is the total Cd content of soil.

The translocation factor (TF) was calculated using Equation 2 to represent the transport characteristics of Cd in different organs of rice.

$$TF = C_3/C_4 \tag{2}$$

where C_3 (mg/kg) is Cd content in the preceding organ of the rice, and C_4 (mg/kg) is Cd content in the succeeding organ of the rice.

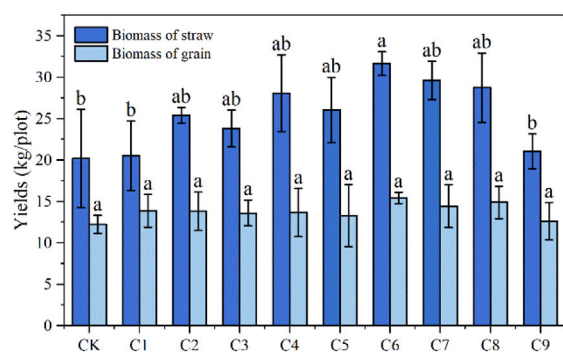


FIGURE 1
Effects of different treatments on the biomass of straw and grain.

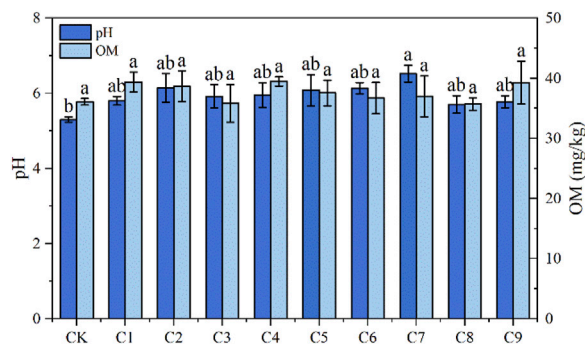


FIGURE 2
Effects of different treatments on the soil pH and OM.

3 Results

3.1 Biomass of straw and grain

Compared with CK, the biomass of straw increased by 1.78%–56.92% after applying the combined soil amendments, but no significant increase was found ($P > 0.05$) except in C6. The biomass of the grain increased by 3.19%–26.06% after applying the combined soil amendments. The highest increase in biomass of grain was also in C6 (Figure 1). However, no significant increase was found between all treatments and the CK ($P > 0.05$).

3.2 Soil basic characteristics

Compared with the CK, soil pH increased by 7.55%–23.02% after applying the combined soil amendments, but no significant increase was found ($P > 0.05$) except in C7 (Figure 2). Soil OM changed –0.67% to 9.33% compared with the CK, and all treatments showed a slight increase except for C3 and C8. No significant difference was found between all treatments and the CK ($P > 0.05$) (Figure 2).

Alkaline-N, Olsen-P, and Olsen-K are significant factors of soil, and thus, the levels of these contents are the key indicators to measure soil fertility. Compared with the CK, the contents of

alkaline-N and Olsen-K were maintained at the same level, but the content of Olsen-P increased 6.27–19.73 mg/kg after application of the combined soil amendments. No significant difference was found between all treatments and the CK in terms of Olsen-K and alkaline-N ($P > 0.05$), but significant differences were found between all treatments and the CK in terms of Olsen-P ($P < 0.05$) (Figure 3).

3.3 Soil total Cd and available Cd

After applying the combined soil amendments, the total soil Cd of all treatments was maintained at the same level, and no significant difference was found between all treatments and CK ($P > 0.05$). The content of soil-available Cd decreased by 16.90%–47.09% compared with the CK, and significant decreases were detected for all treatments ($P < 0.05$), except for C9 (Figure 4). The content of soil-available Cd of C7 was 0.25 mg/kg, which was the greatest decrease among all treatments. The percentage of available Cd in all treatments decreased compared with the CK. This is to say, application of the combined soil amendments could reduce the content of soil-available Cd and decrease its proportion of the soil total Cd.

3.4 Content of Cd in rice organs

After applying the combined soil amendments, the contents of Cd in different rice organs (root, stem, leaf, and grain) decreased by different magnitudes (Table 3). Compared with the CK, the contents of Cd in root, stem, leaf, and grain decreased by 35.53%–65.62%, 16.05%–67.98%, 26.09%–66.30%, and 48.39%–74.19%, respectively. Significant decreases were detected for treatments ($P < 0.05$) except for C1, C4, and C9 of the stem and C1 of the leaf. Of all the treatments, only the Cd contents in grain of C2 and C3 were lower than the limit (Cd < 0.20 mg/kg in grain) of the standard: National Food Safety Standard–Maximum Levels of Contaminants in Foods (GB 2762-2022) (SAMR and SAPRC, 2022), at 0.16 mg/kg and 0.19 mg/kg, respectively.

3.5 BCF and TF

After application of the combined soil amendments, the BCF values of Cd in root, stem, leaf, and grain were found to decrease in different magnitudes in the descending order of root, stem, leaf, and grain. All treatments resulted in significant decreases of BCF of Cd in rice root and grain compared with the CK, while significant decreases were only found for C2, C3, C5, C6, and C8 in the stem and for C3, C4, C5, and C9 in the leaf ($P < 0.05$) (Figure 5A).

TF values were highest for root to stem, followed by, in descending order, leaf to grain, stem to leaf, and stem to grain (Figure 5B). Compared with the CK, TF (root to stem) increased for C1, C2, C3, C4, C7, and C9 and decreased for C5, C6, and C8. TF (stem to leaf) increased for C2, C6, and C8, decreased for C1, C4, and C9, and had no change for C3, C5, and C7. TF (leaf to grain) decreased for all treatments except C8, which was higher than the CK. TF (stem to grain) decreased for all treatments except C8, which was higher than the CK. No significant difference was found in TF

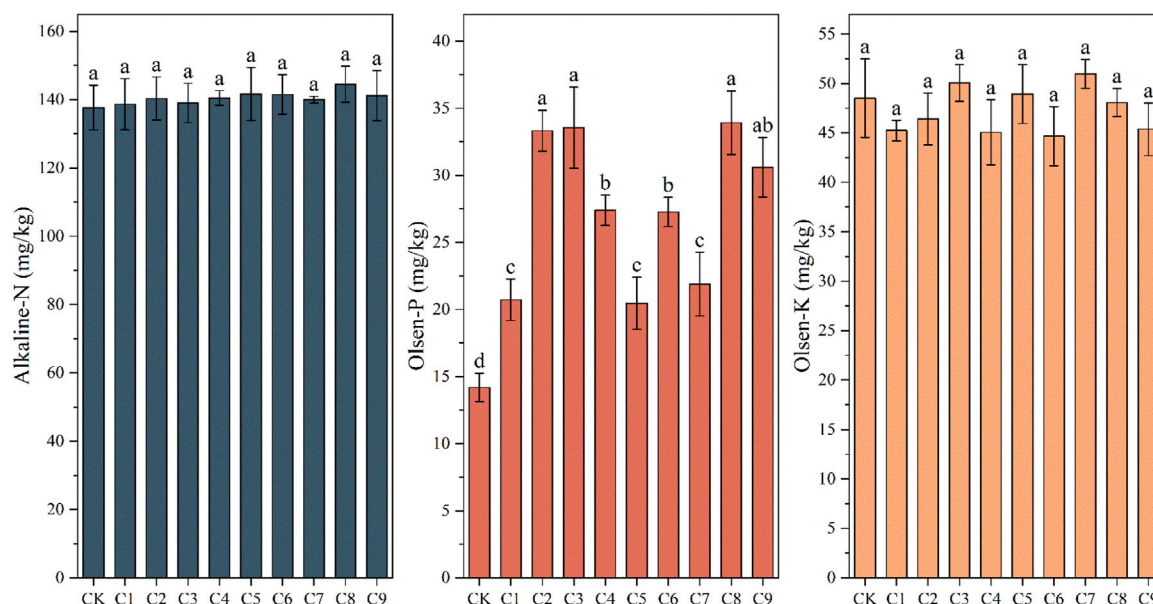


FIGURE 3
Effects of different treatments on alkaline-N, Olsen-P, and Olsen-K.

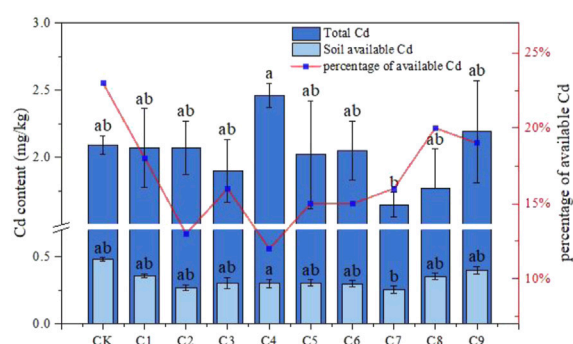


FIGURE 4
Effects of different treatments on the soil total Cd and available Cd.

values, including TF (root to stem), TF (stem to leaf), TF (leaf to grain), and TF (stem to grain) of all treatments compared with the CK ($P > 0.05$) (Figure 5B).

3.6 Orthogonal analysis

Four indicators with significant impact after application of the combined soil amendments were selected for range analysis to assess the effects of amendment application levels on pH, soil-available Cd, Cd content in grain, and Olsen-P. The results of the range analysis showed that pH increased with increased application levels of red mud and silicon fertilizer but decreased with increased application levels of phosphate fertilizer; among these, red mud had the most significant effect on pH, while the other two had smaller impacts. Soil-available Cd decreased with increased application levels of red mud and silicon fertilizer, but

initially increased and then decreased with increasing phosphate fertilizer levels. Red mud application had the most significant effect on soil-available Cd. Cd content in grain decreased with increasing application levels of red mud and phosphate fertilizer but increased with increased application levels of silicon fertilizer. Red mud had the most significant effect on Cd content in grain, followed by phosphate fertilizer, and then silicon fertilizer. Olsen-P increased with the increased application of phosphate fertilizer, while changes in red mud and silicon fertilizer application levels had little effect on Olsen-P (Figure 6).

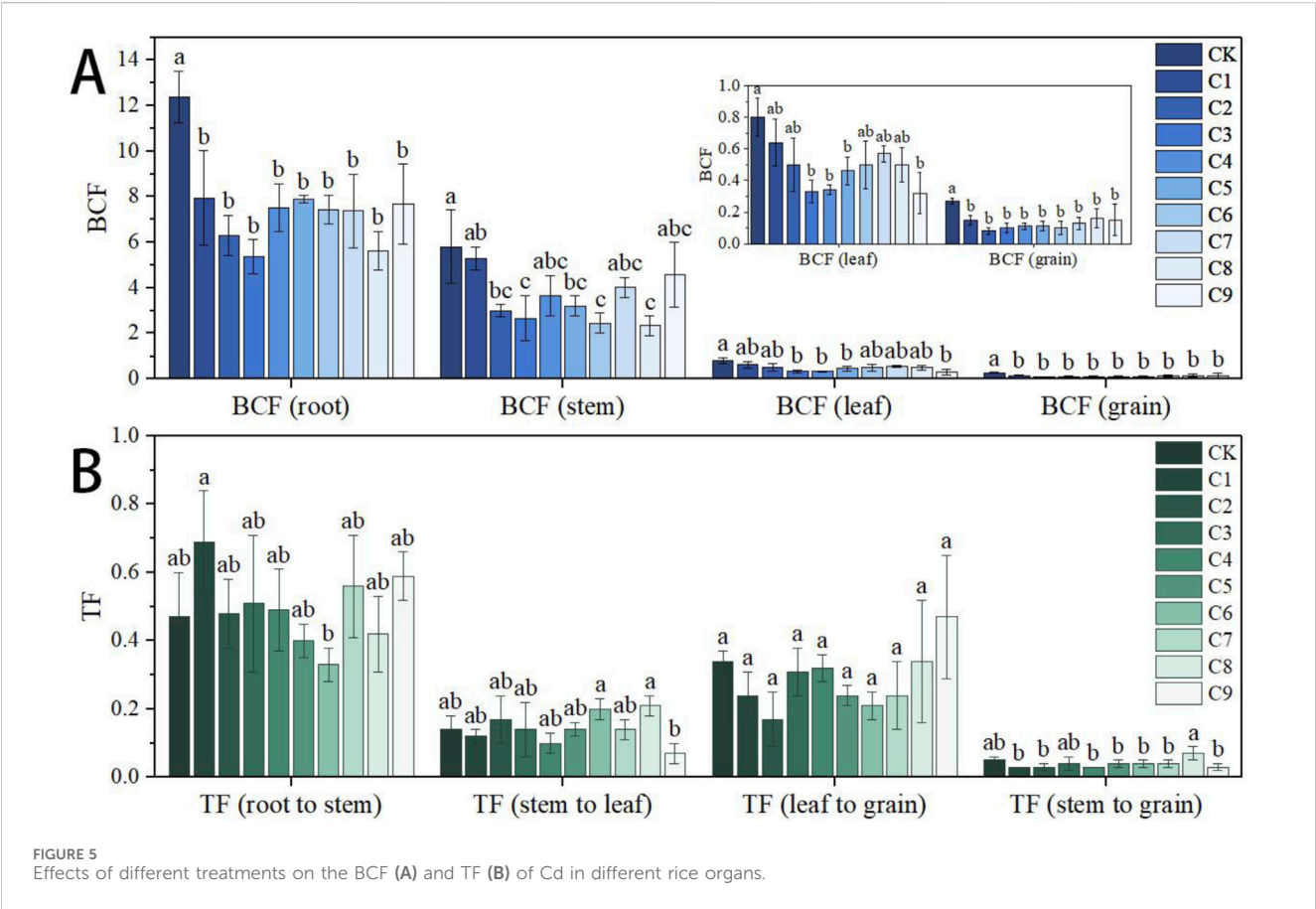
Range analysis provides a direct assessment of the magnitude of the influence of the application levels of the three amendments on the four indicators, while variance analysis evaluates the statistical significance of these application levels' effects on the four indicators. The results of variance analysis showed that red mud had the most significant effect on soil pH, soil-available Cd, and Cd content in grain ($P < 0.01$); phosphorus fertilizer had most significant effect on Olsen-P ($P < 0.01$) and significant effect on Cd content in grain ($P < 0.05$); and the silicon fertilizer had no significant effect on the four indicators ($P > 0.05$) (Table 4). The results of the variance analysis are consistent with range analysis, indicating that as the application levels of red mud increased, soil pH increased significantly ($P < 0.01$), and soil-available Cd and Cd content in grain decreased significantly ($P < 0.01$). Similarly, as the application levels of phosphate fertilizer increased, Cd content in grain decreased significantly ($P < 0.05$), while Olsen-P increased significantly ($P < 0.01$).

3.7 Correlation analysis

In terms of pH, the most significant positive correlation was detected between pH and OM ($P < 0.01$) (Figure 7A); the most significant negative correlations were detected between

TABLE 3 Effects of different treatments on Cd content (mg/kg) and decrease in rice organs.

Treatments	Root		Stem		Leaf		Grain	
	Content	Decrease	Content	Decrease	Content	Decrease	Content	Decrease
CK	28.65 ± 1.46a		13.21 ± 0.89a		1.84 ± 0.18a		0.62 ± 0.02a	
C1	16.53 ± 2.40bc	42.30%	11.09 ± 1.69a	16.05%	1.36 ± 0.21ab	26.09%	0.31 ± 0.05b	50.00%
C2	13.12 ± 2.06bc	54.21%	6.18 ± 0.48bcd	53.22%	1.04 ± 0.22bc	43.48%	0.16 ± 0.05b	74.19%
C3	10.12 ± 1.52c	64.68%	4.92 ± 1.46cd	62.76%	0.62 ± 0.13c	66.30%	0.19 ± 0.04b	69.35%
C4	18.47 ± 2.03b	35.53%	8.91 ± 0.72abc	32.55%	0.84 ± 0.09bc	54.35%	0.27 ± 0.02b	56.45%
C5	15.87 ± 2.99bc	44.61%	6.39 ± 0.82bcd	51.63%	0.92 ± 0.08bc	50.00%	0.23 ± 0.03b	62.90%
C6	15.25 ± 2.08bc	46.77%	4.96 ± 0.54cd	62.45%	1.00 ± 0.14bc	45.65%	0.20 ± 0.05b	67.74%
C7	12.10 ± 2.10bc	57.77%	6.65 ± 1.07bcd	49.66%	0.93 ± 0.05bc	49.46%	0.23 ± 0.04b	62.90%
C8	9.85 ± 0.70c	65.62%	4.23 ± 0.50d	67.98%	0.89 ± 0.13bc	51.63%	0.28 ± 0.03b	54.84%
C9	16.39 ± 1.27bc	42.79%	9.66 ± 1.41ab	26.87%	0.68 ± 0.10bc	63.04%	0.32 ± 0.02b	48.39%



pH and soil-available Cd, pH and Cd content in root, and pH and Cd content in grain ($P < 0.01$) (Figure 7B). This may be related to the presence of a certain amount of OM in the amendments and the changes induced after their application. In terms of soil-available Cd, the most significant positive correlations were detected between soil-available Cd and Cd content in root and soil-available Cd and Cd content in grain ($P < 0.01$) (Figure 7C). In terms of Cd content in

the root, the most significant positive correlations were detected between Cd content in the root and Cd content in the stem, Cd content in the leaf, and Cd content in the grain ($P < 0.01$) (Figure 7D). This is because red mud is a highly alkaline substance that increases the soil pH, causing bioavailable Cd to convert to other non-bioavailable forms. The result of correlation analysis indicates that the mechanism of the combined soil

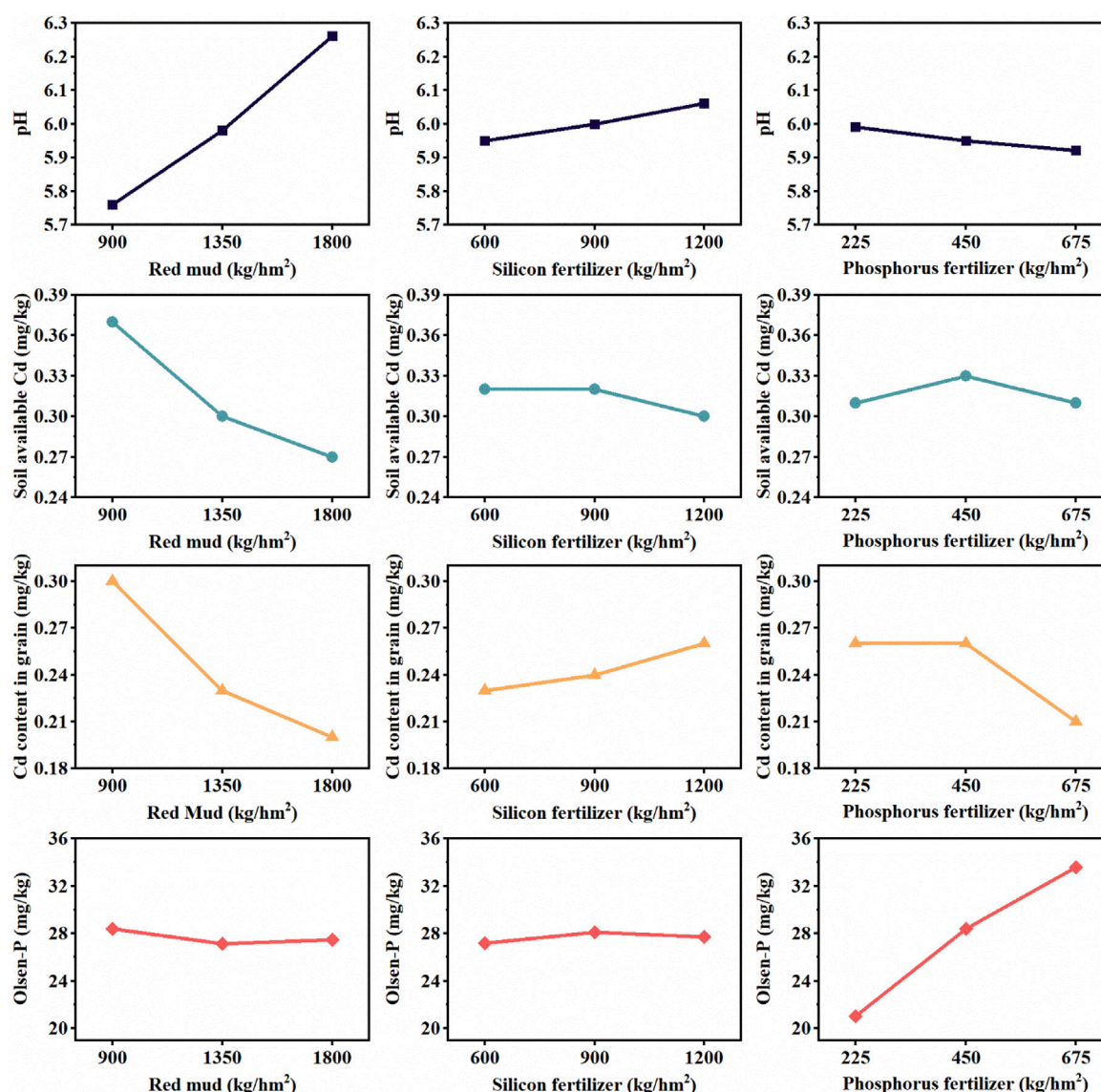


FIGURE 6
Range analysis of soil pH, Cd content in grain, soil-available Cd, and Olsen-P.

amendments controlling Cd pollution in rice was significantly decreased soil-available Cd, which was caused by an increase in the soil pH and thereby decreasing the transfer of Cd from the soil to rice.

4 Discussion

Cd accumulation in rice grain is mainly due to soil Cd pollution. The process of Cd accumulation in grain from soil can be divided into four steps (Davidson et al., 1998; Yang et al., 2017): 1) Cd^{2+} transported from soil to the surface of rice root and absorbed by it; 2) Cd^{2+} translocated within rice root and loaded into the xylem; 3) Cd^{2+} transported and stored in the rice stem and leaf; 4) Cd in the rice stem and leaf is activated and re-transferred to rice grain. Therefore, controlling Cd pollution in rice grain involves preventing Cd

absorption by rice from the soil and blocking its transportation within the rice plant. Red mud, silicon fertilizer, and phosphorus fertilizer have been proven to be promising materials for controlling Cd pollution in rice by reducing soil Cd availability and inhibiting Cd uptake and translocation in rice (Meng et al., 2022; Rehman et al., 2019; Zhao et al., 2020b). However, further study is needed to determine their effectiveness with different crops and in various regions, as well as the optimal application rates for controlling Cd pollution. In this study, we found that Cd content in rice decreased after application of the combined soil amendments, particularly in the content of rice root and grain, which were significantly lower than the CK. Furthermore, the Cd contents in the grain of C2 and C3 were found to be below the safety limit (0.20 mg/kg) of standard GB 2762-2022 (SAMR and SAPRC, 2022). This indicated that the Cd pollution of acidic, severely Cd-contaminated paddy fields could be controlled by applying the combined soil amendments. Because

TABLE 4 Variance analysis of soil pH, Cd content in grain, soil-available Cd, and Olsen-P.

Sources	Indicators	DF	MS	F	P
Red mud	pH	2	0.575	8.005	<0.01
	Soil-available Cd	2	0.023	33.241	<0.01
	Cd content in grain	2	0.027	19.374	<0.01
	Olsen-P	2	3.907	0.905	0.42
Silicon fertilizer	pH	2	0.029	0.406	0.672
	Soil-available Cd	2	0.001	1.792	0.192
	Cd content in grain	2	0.002	1.233	0.313
	Olsen-P	2	2.031	0.471	0.631
Phosphorus fertilizer	pH	2	0.122	1.694	0.209
	Soil-available Cd	2	0.002	2.722	0.090
	Cd content in grain	2	0.007	5.373	<0.05
	Olsen-P	2	359.315	83.233	<0.01

single applications of red mud, silicon fertilizer, and phosphorus fertilizer had been proved effective in moderately and mildly Cd-contaminated farmland for different crops and in various regions (Gray and Wise, 2020; Mamun et al., 2021; Xu et al., 2022), and numerous studies have confirmed that combined soil amendments are more effective than single soil amendments (Jiang et al., 2022; Zeng et al., 2023), we think the combined soil amendments screened in this study can be attempted to be applied to other crops and regions. Based on variance and range analysis, the optimal application rate for controlling Cd pollution in rice grain was found to be 1,800 kg/ha red mud, 600 kg/ha silicon fertilizer, and 675 kg/ha phosphorus fertilizer.

Many studies have confirmed that the mechanisms by which soil amendments control Cd pollution in rice primarily involve reducing the Cd availability in soil and inhibiting its uptake and translocation by rice plants (Lombi et al., 2002; Garau et al., 2007; Li et al., 2018). In this study, the decrease in soil-available Cd was detected after application of the combined soil amendments. Furthermore, the most significant positive correlation was found between soil-available Cd and the Cd content in both root and grain. This indicated that the reduction of Cd availability in soil was one of the mechanisms of the combined soil amendments. The effectiveness of red mud in reducing Cd availability in soil is not only attributed to its strong alkalinity ($\text{pH} > 11$), which increases soil pH, but also to its high content of Fe and Al oxides (such as Fe_2O_3 and Al_2O_3), large surface (Xue et al., 2020), and abundant surface hydroxyl groups. Studies have shown that in addition to physically adsorbing Cd^{2+} onto their surface, Fe and Al oxides and hydroxides can further form stable inner-sphere complexes with Cd^{2+} , thereby reducing its availability in soil (Hua et al., 2017; Lombi et al., 2002; Garau et al., 2007). Silicon fertilizer can combine with available Cd to form a polysilicate gel Si-Cd complex (Ma et al., 2002; Liang et al., 2005). Phosphate fertilizer releases large amounts of PO_4^{3-} into soil, which form Cd-P precipitates (Gupta et al., 2014; Ren et al., 2018). These processes also reduce Cd availability in the soil, thereby

reducing Cd uptake by rice. At the rice uptake sites, due to the high content of divalent cations such as Ca^{2+} , Mg^{2+} , and Fe^{2+} in combined soil amendments, these cations can exchange with Cd^{2+} in rice root cell walls and compete with Cd^{2+} for transporter sites in rice (Ye et al., 2020). This competition interaction effectively inhibits absorption and transportation of Cd^{2+} in rice (Solti et al., 2011), ultimately resulting in decreased Cd content in rice. Additionally, silicon can form natural barriers, effectively preventing Cd^{2+} from penetrating the rice root cell wall (Ma et al., 2015; Wei et al., 2021). Thus, competition for absorption and transport channels with Cd^{2+} may be another mechanism by which the combined soil amendment functions and the reason for the most significant positive correlation between Cd content in the root and the Cd content in both stem and leaf.

Soil pH has been proven to be one of the most significant factors affecting Cd availability in soil (Yu et al., 2014). As soil pH increases, the availability of soil Cd diminishes correspondingly, thereby resulting in decreased absorption and accumulation of cadmium by rice plants (Li et al., 2018; Zhou et al., 2024). Therefore, alkaline substances are the most important components to control Cd pollution in rice. In this study, alkalinity was the most important reason for the effectiveness of the combined soil amendments. Because of its alkaline nature, soil pH increased significantly after application of the combined soil amendments, and the more combined soil amendments were added, the more soil pH increased. Due to higher pH, the effects of red mud on soil pH were found to be significantly higher than those of silicon fertilizer and phosphate fertilizer alone. Studies have shown that when the pH reaches a certain level ($\text{pH} > 6.5$), even if the soil Cd content exceeds the limit, the Cd content in grain remains below the limit (Römkens et al., 2009; Chen et al., 2021). Thus, increasing soil pH is a primary measure for mitigating Cd pollution in rice. However, excessively high soil pH can lead to soil salinity and alkalinity, which negatively affect rice growth (Jiang et al., 2023). Therefore, the quantity of alkaline substances must be rigorously regulated to prevent detrimental impacts when utilized as a soil amendment to control Cd pollution in rice.

Effectiveness and safety are key considerations for soil amendments. If soil amendments contain harmful components, they will bring secondary pollution into soils and plants, which in turn harm our health (Liu et al., 2025). Some researchers think that red mud, as an industrial waste byproduct, contains harmful components, rendering it unsuitable for remediation of Cd pollution in rice (Chao et al., 2022). However, in this study, total Cd contents in soil showed no significant changes, whereas Cd content in rice decreased after application of the combined soil amendments. This indicates that the addition of red mud did not lead to an increase in Cd pollution in either soil or rice. Moreover, our previous studies also confirmed that applying red mud did not lead to an increase in the content of heavy metals in either soil or rice. What is more, the results also showed that the contents of heavy metals in red mud used in this study were lower than the safe limit of standard GB 38400-2019 (SAMR and SAPRC, 2019). All results indicate that using red mud to remediate Cd pollution in rice is safe and effective. To ensure that red mud does not pose potential ecological risks to paddy fields and rice, its content of heavy metals must be measured before it is used.

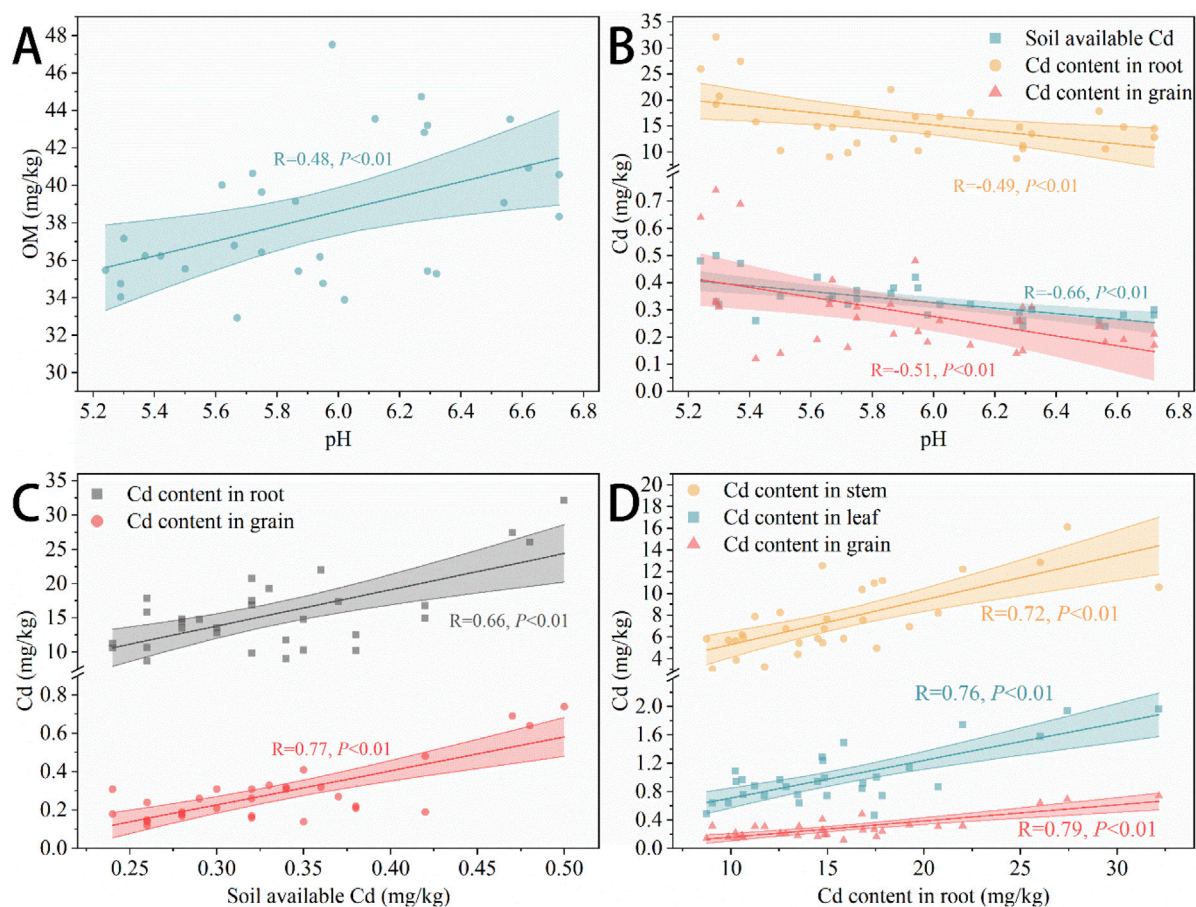


FIGURE 7

Correlation analysis of pH and OM (A), pH and soil available Cd, Cd content in root, Cd content in grain (B), soil available Cd and Cd content in root, Cd content in grain (C), Cd content in root and Cd content in stem, Cd content in leaf, Cd content in grain (D).

Cost is also another crucial factor for the application of soil amendments to control cadmium pollution in rice grain (Fang et al., 2021). Total cost includes the cost of the soil amendment, transportation, and labor (Liu et al., 2025). In this study, based on the optimal rate of the combined soil amendments, the cost of the combined soil amendments and transportation was approximately 2,498 yuan/ha, and the labor cost was approximately 450 yuan/ha, resulting in a total cost of 2,948 yuan/ha. Notably, the total cost of our screened combined soil amendments was lower than that of many reported soil amendments (Liu et al., 2025). Compared with the CK, application of our screened combined soil amendments resulted in an increase in rice grain biomass by 195–1,595 kg/ha, which, at the price of 2.6 yuan/kg, translated to an income increase of 507–4,147 yuan/ha. Additionally, the Cd content in rice grain was reduced below the standard, leading to an increase in price by 0.4 yuan/kg and an additional profit of 2,448 yuan/ha. Overall, the total benefit of application of our screened combined soil amendments ranged from 2,955 to 6,595 yuan/ha, with a minimum benefit of 7 yuan/ha, which exceeds the total cost. This indicates that applying our screened combined soil amendments not only reduces the health effects of Cd pollution in rice grain but also generates economic benefits. All results showed that the combined

soil amendments screened in this study were low cost, safe, and efficient soil amendments, worthy of being used on a large scale.

Although this study provides an effective soil remediation strategy for addressing Cd pollution, it still has certain limitations. First, the research was conducted under specific acidic soil conditions in Hunan Province, and the results may be influenced by regional climate, soil types, and crop varieties. Second, while the combination of soil amendments showed promising short-term effects, their long-term efficacy remains unclear. Future studies should focus on the impacts of these amendments on soil health, crop yield, and sustained cadmium control over time. Moreover, although the cost of soil amendments is relatively low, the actual cost and feasibility of large-scale application require further evaluation.

This study also aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2: Zero Hunger and SDG 12: Responsible Consumption and Production. By offering an effective solution for reducing Cd contamination in rice, a staple food for more than half of the global population, the research contributes to ensuring food safety and improving public health. Additionally, the use of low-cost, high-efficiency soil amendments in severely Cd-contaminated paddy fields has policy relevance for promoting sustainable agricultural practices,

enhancing environmental protection, and strengthening food security strategies.

5 Conclusion

After applying the combined soil amendments, the Cd content in the edible part of rice can be reduced to below the safe limit. The safe production in acidic, severely Cd-contaminated paddy fields could be achieved by applying the combined soil amendments, providing a method for the remediation of severely Cd-contaminated paddy fields and a reference for global Cd-contaminated field remediation. Due to its low-cost, high efficiency, and simple operation, it can be promoted on a large scale for the remediation of Cd-contaminated paddy fields to achieve safe production.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

JY: writing – original draft and writing – review and editing. ZZ: data curation and writing – original draft. HY: funding acquisition and writing – original draft. JW: formal analysis and writing – original draft. ZY: software and writing – original draft. CF: validation and writing – original draft. XW: funding acquisition and writing – review and editing.

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Conflict of interest

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