

Characteristics of Three Organic Fertilizers and Their Influence on the Mobility of Cadmium and Arsenic in a Soil-Rice (*Oryza Sativa* L.) System

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Abstract

The properties and effects of organic fertilizers are different, including the ability to improve soil fertility and the potential of stabilizing heavy metals in soils that have not been explored in depth. In this study, three organic fertilizers from different raw materials were characterized and evaluated. The mushroom residue organic fertilizer (MO) had higher C, H, and O contents and more functional groups (-OH, C-H, and C=O), and its application significantly increased pH (1.00~1.32 units), organic matter (OM) content (26.58%~69.11%) and cation exchange capacity (CEC) (31.52%~39.91%) of soil. MO treatment also reduced the toxicity characteristic leaching procedure (TCLP)-Cd (24.21%) and TCLP-As (18.44%) concentration in the soil. That inhibited the mobilization of Cd and As from soil to plant, especially to plant shoots, and positively affected the plant growth and biomass. Redundancy analysis (RDA) showed that 40.09 % of total plant variation was related to soil properties (pH, OM, and CEC). Furthermore, the heavy metal risk assessment for all organic fertilizers was at safe levels. This study provides a valuable reference for the selection of organic fertilizers. Besides, it recommends organic fertilizers as economic and multi-effect amendments with safe use and provides a new option for the 'simultaneous production and remediation' of farmlands with low pollution.

Introduction

Heavy metal pollution has become an increasingly significant threat to the global soil quality (Cui et al. 2016), and heavy metals such as cadmium (Cd) and arsenic (As) have been increased due to the continued use of large quantities of chemicals in soils in the form of fertilizers and pesticides (Atafar et al. 2008). In contrast to the degradation characteristics of organic pollutants, heavy metals are not affected by microbial or chemical degradation (Wang et al. 2020a). Therefore, their total concentration and toxicity can persist for a long time in soils (Koptsik 2014). In addition, plant roots can take up and translocate heavy metals from the soil, even in low concentrations of soil contamination (Wångstrand et al. 2007), so the grains produced with heavy metal accumulations will be potentially harmful when ingested by both humans and animals (Radziemska, 2018; Rehman et al., 2017). Furthermore, excessive accumulation of the Cd and As in the human body can cause various acute or chronic diseases (Aziz et al., 2015; Song et al., 2015). Therefore, to reduce the dependency on chemical fertilizers, there is an urgent need to develop safe organic fertilizers with low cost, which not only can improve the soil quality and maintain crop production yields, but also can be expected to reduce the negative impact of heavy metal pollution (Vrînceanu et al. 2019).

In agricultural areas, soil pollution has historical reasons in common (Qin et al. 2021). Even if there is a risk of toxicity in low-medium polluted farmland, it is very likely that the farmers are not aware of the pollution circumstance or can't ignore its economic value and will continue to grow crops in it (Wang et al. 2019). Organic fertilizers have the advantages of low cost, wide availability, and high organic matter (OM) content. Urged by the promotion of relevant national subsidy policies, the wide use of organic fertilizer instead of chemical ones to improve agricultural soil has attracted more and more attention recently (Wang et al. 2018). To date, most researches on organic fertilizers focused on improving soil

properties and increasing crop yields (Wang et al. 2020b, Wei et al. 2016), and only a few studies explored the differences in properties and functions of organic fertilizers prepared from different raw materials, as well as their potentials to stabilize heavy metals in the soil and their impact on the migration and accumulation of heavy metals to plants. Few studies were found on the combined pollution of cadmium (Cd) and arsenic (As) in soils, these two metals have antagonistic and synergistic effects, and their available contents are affected by a lot of factors such as soil properties changes, thus making it difficult to remedy.

Various raw materials can be used for organic fertilizers, including human and livestock manure (Martinez-Alcantara et al. 2016), crop straw, agricultural production waste (Ferrari et al. 2019), and industrial waste (Antil et al. 2012). And the fertilizer compositions and properties may vary with different raw materials (Hossain et al. 2016). The contribution of organic fertilizer to soil fertility and its influence on heavy metal speciation may also be significantly different (Iwasaki et al. 2017). As the key factor in evaluating the activity and transferability of heavy metals in soil (Cao et al. 2019), the heavy metal availability is closely related to its speciation in the soil (Xian 1987), and also related to soil properties, such as soil pH, OM content, etc. (Antoniadis et al. 2017).

In this study, three types of organic fertilizers prepared with different raw materials were selected, and they were fermented by human manure (HO), mushroom residue (MO), and soybean meal (SO), respectively. Their different characteristics were analyzed, and their stabilization effects on Cd and As in soil (TCLP method), migration of Cd and As in rice (BCF and TF factors), and their effects on rice growth indexes were studied. These results provided a reference for the selection of organic fertilizer types and a new option for remediation of low heavy metal contaminated farmland. By application of safe organic fertilizers instead of chemical fertilizers, high crop yields can be ensured, and meanwhile, the risk of heavy metal pollution be reduced.

Materials And Methods

Collection and preparation of soil amendments and soil samples

Human manure organic fertilizer (HO) was obtained by human manure fermentation; mushroom residue organic fertilizer (MO) was obtained by fermentation of mushroom waste; soybean meal organic fertilizer (SO) is produced with soybean meal, and soybean meal is the residue waste after soybean oil extraction.

The plant species used for pot experiments were *Oryza Sativa* L., a high-quality rice species purchased directly from the soil sampling sites. The soil for Cd and As pollution tests were sampled from a paddy soil cultivation layer in Liuyang City (Hunan Province, China, 113°13'E, 25°54'N). The collected soil was air-dried, ground, screened by a 2 mm sieve before use.

Experimental design

Pot experiments were implemented in a plant incubator (LRH-250, Shanghai YI HENG, China), cylindrical plastic pots (height of 15 cm and radius of 5 cm) without covers were used as the experimental unit. Each pot contained 1 kg of soil. Three organic fertilizers were all set at three levels of addition and aged for two weeks, with each treatment including three replicates (Table 1). Rice seedlings were transplanted on May 22nd, with two holes per pot and two plants per hole. The base fertilizer applied during plant growth contained N (0.10 g kg^{-1}), P_2O_5 (0.06 g kg^{-1}), and K_2O (0.1 g kg^{-1}). Plants were harvested on July 12th. Throughout the whole growth period, plants were irrigated with tap water and cared for with the continual removal of weeds.

Table 1
Details of the types and quantity of amendments added.

Amendment name and code abbreviation	Quantity added		
	Low (X_L)	Medium (X_M)	High (X_H)
CK	0%	0%	0%
Human manure organic fertilizer (HO)	0.50%	1.00%	2.00%
Mushroom residue organic fertilizer (MO)	0.50%	1.00%	2.00%
Soybean meal organic fertilizer (SO)	0.50%	1.00%	2.00%
Note: X indicates the abbreviated code for each amendment.			

Sample collection and pretreatment

Plant roots were carefully and wholly stripped from the soil during plant collection, washed with deionized water (DI), and then wiped away the surface free water. The plant height, fresh and dry weight, and root length were measured. Subsequently, the plants were divided into aboveground parts (shoots) and underground parts (roots). Enzyme deactivation was performed at $105 \text{ }^\circ\text{C}$, and plant material was air-dried after rice harvesting. And after being screened by 10 mesh and 100 mesh sieves, the soil was analyzed for pH, OM content, CEC, total Cd concentration, total As concentration, TCLP extractable Cd concentration (TCLP-Cd), and TCLP extractable As concentration (TCLP-As).

Sample analysis method

The surface morphology of organic fertilizers was examined using scanning electron microscopy (SEM) with elemental distribution mappings (Gemini 300, ZEISS, Germany). The surface area was analyzed using a surface area analyzer (ASAP 2460, Micromeritics, USA) with the Bruanuer-Emmett-Teller (BET) nitrogen adsorption method. The C, H, O, N, and S contents were determined using an Elemental Analyzer (Vario EL cube, Germany). Functional groups on the samples' surfaces were characterized by Fourier transform infrared spectroscopy (FTIR, Tensor II, Bruker, Germany). Soil pH was measured using a pH meter (PHSJ-4A, Shanghai REX, China) in a 1:2.5 (w/v) solution of soil to DI. The OM content of the soil

was determined by wet oxidation with $H_2SO_4-K_2Cr_2O_7$ according to a reference method (Walkley & Black 1934). The CEC of soil was analyzed by the substitution method using $BaCl_2$, referencing Huang's method (Huang et al. 2014).

The heavy metal concentration of organic fertilizers and soil (0.1g) were determined following digestion in a closed high-pressure reactor, with strong acids (3 mL HNO_3 and 1 mL HF) used for digestion at $160^\circ C$ for 10 h. After filtering the suspension, the filtrate was diluted to 10 mL with DI to measure heavy metal concentrations. The concentrations of TCLP-Cd and TCLP-As in soil were determined following the USEPA method (USEPA 1992), with inductively coupled plasma optical emission spectrometry (ICP-OES, PerkinElmer, US).

Plant height and root length were measured using a stainless-steel ruler; fresh biomass and dry biomass were measured using a digital weighing balance (BSA124S-CW, Sartorius, Germany).

A redundancy analysis (RDA) was performed between soil pH, soil OM, soil CEC, TCLP-Cd/As in soils, Cd and As contents in roots and shoots of rice.

Calculation methods of accumulation factors

Bioaccumulation and transport of heavy metals from soils to plants are two essential factors for the evaluation of plant uptake of metals. The bioaccumulation factor (BCF) refers to the ratio of heavy metals in plant extracts to the total heavy metal content of soil extracts (Cui et al. 2005), while the transport factor (TF) refers to the ratio of heavy metal concentrations in the shoots and roots of plants (Bose et al. 2008). Some studies showed that these two factors depended on heavy metal concentrations in soil, environmental conditions, and the plant species, and different genetic characteristics of plants led to various uptake, accumulation, and transfer capabilities (Cui et al. 2004, Peris et al. 2007). The BCF and TF indicated the ability of plants to take up and translocate heavy metals. And they were calculated according to Equation (3) and Equation (4) below, respectively:

$$BCF = \frac{C_{plant}}{C_{soil}} \#(1)$$

$$TF = \frac{C_{shoot}}{C_{root}} \#(2)$$

where, C_{plant} is the heavy metal concentration in the plant; C_{soil} is the heavy metal concentration in soil; C_{root} is the heavy metal concentration in the plant root; and C_{shoot} is the heavy metal concentration in the plant shoot.

Results And Discussion

Characterization of organic fertilizers

The elemental analysis results were shown in Table 2. The contents of C, H, O, N, and S were 10.05%~37.03% (MO>HO>SO), 1.27%~4.76% (MO>HO>SO) and 20.52%~50.73% (MO>SO>HO), 0.89%~2.29% (HO>MO>SO), and 0.19%~0.5% (HO>SO>MO), respectively. This indicated that the main components of MO were C, H, and O, which were present at significantly higher abundances than in the HO and SO. Therefore, it might be assumed that MO contained more functional groups than HO and SO.

Table 2
Elemental content of HO, MO and SO.

Sample	Elemental content (%)				
	C	H	O	N	S
HO	16.77	1.96	20.52	2.29	0.5
MO	37.03	4.76	50.73	2.11	0.19
SO	10.05	1.27	20.58	0.89	0.4

It was seen from the SEM analysis that the surface of three organic fertilizer particles was rough and uneven (Fig. 1), and the structure with more obvious pores was observed on the MO surface. The BET surface area of MO ($14.60 \text{ m}^2\cdot\text{g}^{-1}$) was also larger than those of HO ($1.10 \text{ m}^2\cdot\text{g}^{-1}$) and SO ($0.87 \text{ m}^2\cdot\text{g}^{-1}$). The elemental mapping analysis was performed to study the distribution of C, O, N, P, and S elements in HO, MO, and SO (Fig. 2d, e, f). The O and N distribution were matched with those of organic fertilizer. It was well-noted that MO had higher C content than HO and SO, although EDS was not sensitive to the detection of C element (red), which was matched with the result of elemental analysis (Table 2).

Organic fertilizers exhibited similar FTIR spectra characteristics (Fig. 2) with characteristic peaks for nutrients such as phosphate (483 cm^{-1} , 555 cm^{-1}) (Mazeika et al. 2016) and amorphous SiO_2 (805 cm^{-1}). The peak at 896 cm^{-1} was attributed to the C-H deformation vibration of cellulose (Hussain et al. 2017), where the higher cellulose content in SO results in higher peak strength. Strong intensity at 1048 cm^{-1} was attributed to C-O stretching vibration. The high protein substances in soybean meal will decompose during fermentation (Yasar et al. 2020), the higher peak of COO symmetric stretching of amino acids or COH in-plane bending vibration of carboxylic acids (1430 cm^{-1}) can be observed in SO. The broadband at 1638 cm^{-1} was attributed to C=O in amides (Jegatheesan et al. 2012), with higher peak intensity in MO, which indicated the presence of more humic-like substances (A et al. 2000). The peaks observed between 2960 and 2850 cm^{-1} in HO and MO were attributed to C-H stretching (Carballo et al. 2008), while the broadband between 3360 and 3392 cm^{-1} in MO was attributed to -OH groups. Overall, MO contains more -OH, C-H, and C=O groups, and humic-like substances which could exchange ions and complexes with heavy metals. In addition, SO contains many amino acids and carboxylic acids decomposed by amino acids, which can provide lots of active adsorption sites for As.

Effects of organic fertilizers on general chemical properties of soil

The application of all organic fertilizers to soil can improve the general chemical properties of the soil, such as pH, OM, and CEC values (Fig. 3). The increase of these values was proportional to the application rates of organic fertilizer added. In this study, the addition of MO increased soil pH by 0.33~0.59, which was higher than HO and SO (< 0.3 unit). With the increase of pH, Cd in the soil is more likely to precipitate and reduce Cd availability (Wen et al. 2020), while As is more likely to be reduced to arsenate and gradually released, increasing As availability (Liu et al. 2006). The soil pH after MO treatment was close to the optimum pH of 6.8 by evaluating the trade-off value, which can control the availability of Cd and As in paddy soil simultaneously (Yao et al. 2021). Under the MO treatments, the OM content in soil increased by 26.58%~69.11%. Compared with SO, there was no significant difference but showed a more noticeable increase than HO. SO treatments increased the CEC content in the soil to a greater extent (30.69%~51.05%), followed by MO treatments (31.52%~39.91%). The pH, OM, and CEC, as critical factors of soil properties, affected the chemical speciation of heavy metals in the soil primarily via their adsorption/desorption, precipitation/dissolution, and complex formation reactions (Cao et al. 2019), and finally decided their mobility and availability (Brokbar et al. 2012).

TCLP extractable heavy metals concentration in soil

Currently, the Toxicity Characteristic Leaching Procedure (TCLP) method is most widely used for evaluating the availability of heavy metals in soil globally. This study also referred to this method to evaluate the immobilizing effects of different organic fertilizers on heavy metals Cd and As. The results of TCLP-Cd were shown in Fig. 4a, where the leaching amount was inversely proportional to the application rates of treatment agents. Compared to the CK treatment ($513.67 \mu\text{g}\cdot\text{kg}^{-1}$), the lowest TCLP-Cd concentrations were observed under MO_M ($425.33 \mu\text{g}\cdot\text{kg}^{-1}$) and MO_H ($389.33 \mu\text{g}\cdot\text{kg}^{-1}$) treatments, showing a reduction by 17.20%, and 24.21%, respectively. That might be due to MO significantly increasing the soil pH, as confirmed by the soil pH changes observed (Section 3.2) and the experimental results previously reported (Wang et al. 2021, Xun et al. 2016). The increased soil pH resulted in soil colloids with negative charge increased on the soil surface, which enhanced the adsorption capacity of soil for cationic heavy metals (Wei et al. 2021), thereby reducing their migration throughout the soil and reducing their capacity for absorption and accumulation by plants (Zhong et al. 2020).

HO treatments increased the concentration of TCLP-As in the soil (Fig. 4b), while MO and SO significantly reduced the leaching concentration of TCLP-As by 9.10%~19.04% and 9.82%~36.93%. However, the reduction was inversely proportional to the application rates of the treatment agent, which may be attributed to the increase of soil pH value making As more activated in the soils (Wei et al. 2021). Under a low application rate, more TCLP-As concentration reduced by SO than the others might be due to the presence of more amino acid and carboxyl functional groups (Fig. 3), the separation of carboxyl groups can produce three active adsorption sites for As (Deeprasert et al. 2021). MO treatment reduced the concentration of TCLP-Cd and TCLP-As in the soil simultaneously. This may be because the MO surface has more functional groups (C = O, C = C, - OH) (Fig. 3), and the treated soil is at the optimal pH, while reducing the availability of Cd and As (Yao et al. 2021), thus increasing the immobilized heavy metals in the soil (Li et al. 2016).

Effects of organic fertilizers on heavy metal concentration in rice

The concentrations of Cd and As in different parts of rice under different treatments are shown in Fig. 5. Based on the results shown in Fig. 5a, the Cd concentration in the shoots was significantly reduced under MO treatments ($P < 0.05$). Compared with CK, the Cd concentration in the shoots decreased by 23.35%, 34.24%, and 44.36% following MO_L , MO_M , and MO_H treatments. All treatments had no significant effect on the Cd concentration in the rice roots. The MO and SO treatments reduced the As concentrations in the shoots shown in Fig. 5b. MO_L , MO_M , MO_H , SO_L , SO_M , and SO_H treatments reduced the As concentrations in the shoots by 11.30%, 16.19%, 17.61%, 17.75%, 15.97%, and 18.24%. It was shown that MO reduced the accumulation of Cd and As in rice shoots simultaneously. HO treatment reduced the accumulation of Cd in the shoots but promoted the accumulation of As in the roots of rice. Section 3.3 showed that the availability of As increased under HO treatment, more As was accumulated in rice, and most of them were retained in Fe-plaque on the root surface (Yin et al. 2017).

Effects of organic fertilizers on accumulation factors

As two valuable indicators of the accumulation and mobilization of metals in plants, BCF and TF were calculated based on metal availability and uptake by plants in soil-plant systems (Mendez Monica & Maier Raina 2008, Radziemska 2018). BCF value > 1 indicated that the metal tended to transfer from soils to plants and accumulated in plant tissues (Yoon et al. 2006). TF value was used to measure the transportability of the plant for the accumulated metal from plant roots to shoots. It was reported previously that rice was characterized by a BCF > 1 and TF < 1 (Yang et al. 2020), and smaller BCF and TF values indicated a more effective treatment agent (Li et al. 2019). The BCF and TF results obtained were shown in Fig. 6, which were determined from the characteristic analysis mentioned above. The BCF indexes of Cd were higher than those of As, but its TF indexes were lower than the latter, indicating that a larger proportion of Cd was absorbed by the rice and accumulated in rice roots. MO reduced the BCF and TF index values of Cd and As simultaneously, while HO only reduced the BCF and TF index values of Cd, and SO only reduced the BCF and TF index values of As compared with CK. It meant that under the combined pollution of Cd and As, the application of MO to the soil reduced the mobility of Cd and As effectively, made them more stable in the soil, and reduced their accumulation and toxicity into the plants. It was well-noted that the BCF indexes of Cd after SO treatments were slightly lower than those of CK, but the TF indexes increased slightly, indicating that when the plants absorbed Cd and As at the same time, the As content in rice decreased due to the antagonism of the two metals, the transport of Cd in rice might be increased accordingly (Sun et al. 2009).

Plant growth and biomass

Improving plant growth and biomass is the fundamental attribute of organic fertilizer. In this study, after rice harvesting at the tillering stage, the conditions of plant growth and biomass (plant height, root length, fresh weight, and dry weight) of rice grown after different treatments were analyzed (Fig. 7). This may be because the low concentration of heavy metal stress in contaminated soil in this study did not inhibit the

plant height of rice. Application of several organic fertilizers might help plant height increase, but there was no significant difference compared with CK. The medium and high application of HO and all MO treatments promoted root length ($P < 0.05$). The application of HO, MO, and SO increased the fresh weight of plants by 18.48-24.72%, 9.82-13.41%, and 18.05-21.18%, increasing the dry weight of plants by 12.48-15.53%, 5.98-8.86%, and 13.57-18.98%, respectively, which was proportional to the application rates of organic fertilizer.

Redundancy analysis

Figure 8 presented the results of redundancy analysis between soil properties and TCLP-Cd/As, accumulation factors (BCF and TF), and heavy metal concentrations in rice plants. The results of RDA revealed that 40.09% of total plant variation was related to the soil properties (pH, OM, and CEC), 44.74% of total plant variation was related to the TCLP extractable heavy metals concentration of soil (TCLP-Cd and TCLP-As). Fig. 7a showed that the Shoot-Cd and accumulation factors were not significantly correlated with OM and CEC content but negatively correlated with soil pH. The Shoot-As and accumulation factors were negatively correlated with soil properties. However, for Root-As, the increase in OM and CEC content might promote the uptake of As by rice roots due to rhizosphere reaction. It was seen from Fig. 7b that the Shoot-Cd/As and corresponding accumulation factors were strongly positive-correlated with TCLP-Cd/As, while the Root-Cd/As were inversely related to them. These results indicated a strong relationship between the application of organic fertilizers and metal concentrations in rice plants. After the application of organic fertilizers, the improvement of soil properties and the adsorption or complex mechanism between heavy metals and organic fertilizers might reduce the availability of heavy metals in the soil, thus resulting in reduced metal absorption and bioaccumulation by rice.

Safe utilization of organic fertilizer

Among the various methods available for evaluating the potential environmental risks of heavy metal accumulation, the single pollution index and Nemerow comprehensive pollution index (NIPI) were widely used (Hu et al. 2018, Krcmar et al. 2018). The advantage of the NIPI lied in its considerations of the comprehensive pollution risks caused by all heavy metals existed (Yari et al. 2020). This method of organic fertilizer evaluation was also used to determine the safety of organic fertilizer application in the soil to a certain extent. And the single pollution index method and Nemerow comprehensive pollution index method were used for evaluation of the heavy metal's safety assessment of organic fertilizers as shown in supporting information. It was implied from Table S3 that the single pollution index values of heavy metals in HO were ranked in the order of $Cu > Zn > Pb > Cr > Ni > Cd > As$. While for MO, the index values were ranked as $Ni > Cr > Cu > Zn > Cd > Pb > As$. The ranked order of the pollution index values for SO was $Cd > As > Pb > Cr > Ni > Cu > Zn$. The Nemerov comprehensive pollution index for heavy metals in the three organic fertilizers was ranked in $MO > HO > SO$, with all of them at a safe level. Therefore, it might be speculated that these organic fertilizers could be safely applied to soils as fertilizers and treatment agents.

In daily agricultural activities, organic fertilizer replacing chemical fertilizer seems to be a feasible idea. We found that the application of specific organic fertilizer under low heavy metal pollution can not only improve the growth of rice but also reduce the accumulation of heavy metals in rice. This method can realize the simultaneous restoration and production of contaminated agricultural land, ensure food safety, and improve economic benefits. The medium-severe polluted soil should seek other pollution control measures, such as planting low-accumulation economic crops, or production after remediation. The selection of organic fertilizer types is extremely important. As this study found, the organic fertilizer prepared from human manure can significantly increase the biomass and reduce the accumulation of Cd in rice, but it will promote As accumulation in roots due to antagonism. The organic fertilizer prepared from soybean meal waste is rich in carboxylic acids after amino acid decomposition, which provides a large number of active adsorption sites for As, thus reducing the migration of As to plants, but has no significant effect on Cd. Organic fertilizer prepared with mushroom residue as raw material is a rare multi-effect and low-cost soil remediation material because its surface is rich in -OH, C-H, and C=O groups, and humic-like substances which can exchange ions and complexes with heavy metals (both Cd and As), to achieve the stabilization of two types of heavy metals at the same time. Therefore, organic fertilizer should be selected according to the actual situation.

Conclusions

This study verified the properties and effects of organic fertilizer prepared from three raw materials as soil amendments, and MO had the best effect. The application of MO significantly improved soil properties (pH, OM, and CEC), and because it contained more functional groups and humic substances, it could effectively adsorb and combine heavy metals (Cd and As), thus reducing the availability of Cd and As in soil. The BCF and TF values of MO treatment plants were significantly lower than those of CK, indicating that MO treatment reduced the absorption of Cd and As, and reduced the translocation of Cd and As from roots to shoots. In addition, MO effectively improved plant growth and biomass, and heavy metal content was also at a safe level. The practical application potential of MO as a soil amendment for Cd and As combined pollution was verified. This study not only provided a valuable reference for the selection of organic fertilizer instead of chemical fertilizer in agricultural production but also provided a new idea for the simultaneous production and remediation of low-pollution farmland.

Declarations

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Availability of data and materials All data generated or analyzed during this study are included in this published article.

Author contribution **Xiao Tan:** Design of experiment, Data collection, Formal analysis, Writing original draft; **Jinman Cao:** Investigation. **Jiahao Liu:** Validation. **Jinhang Wang:** Validation. **Guilan Duan:** Writing–review. **Yinjie Zang:** Validation. **Aijun Lin:** Supervision, Conceptualization, Funding acquisition.

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Figures

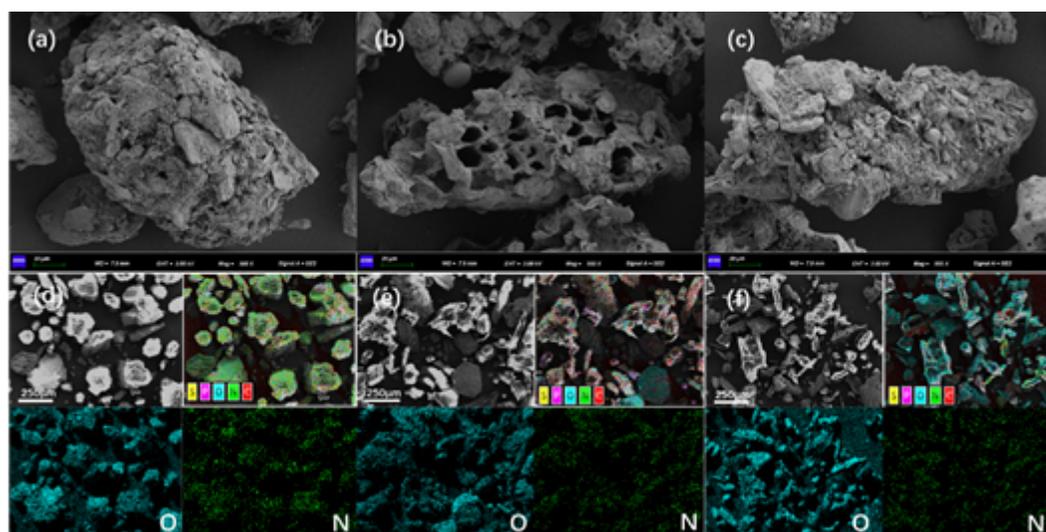


Figure 1

SEM images of organic fertilizers (HO (a), MO (b), SO (c)) and corresponding elemental distribution maps for HO (d), MO (e), SO (f)

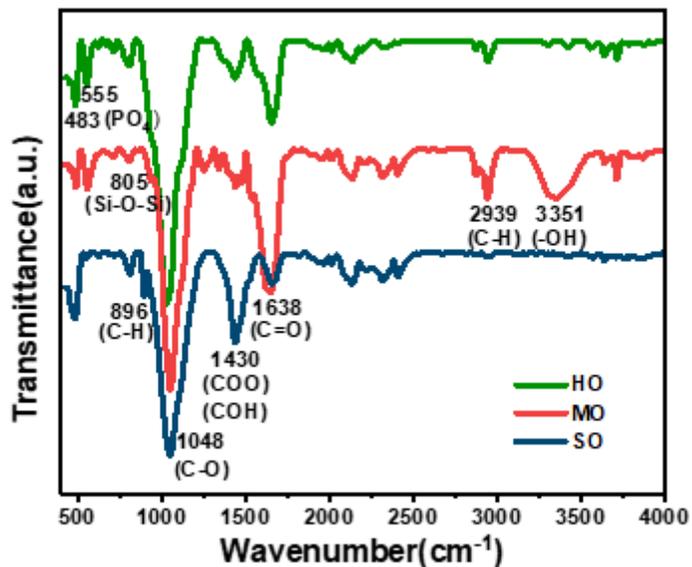


Figure 2

FTIR spectra of HO, MO and SO.

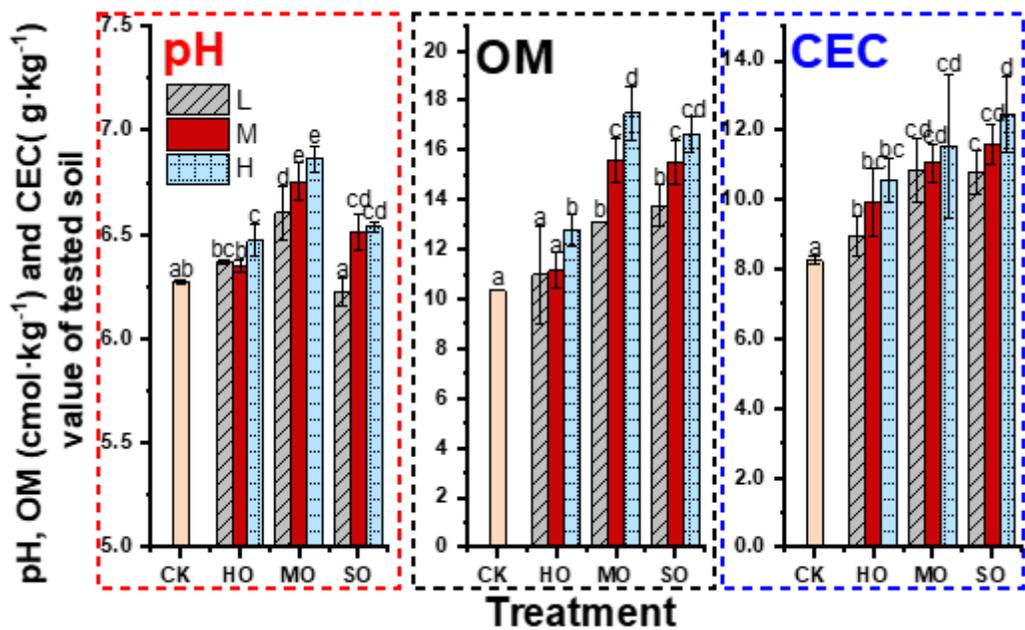


Figure 3

Effect of HO, MO and SO treatment on general chemical properties of soil.

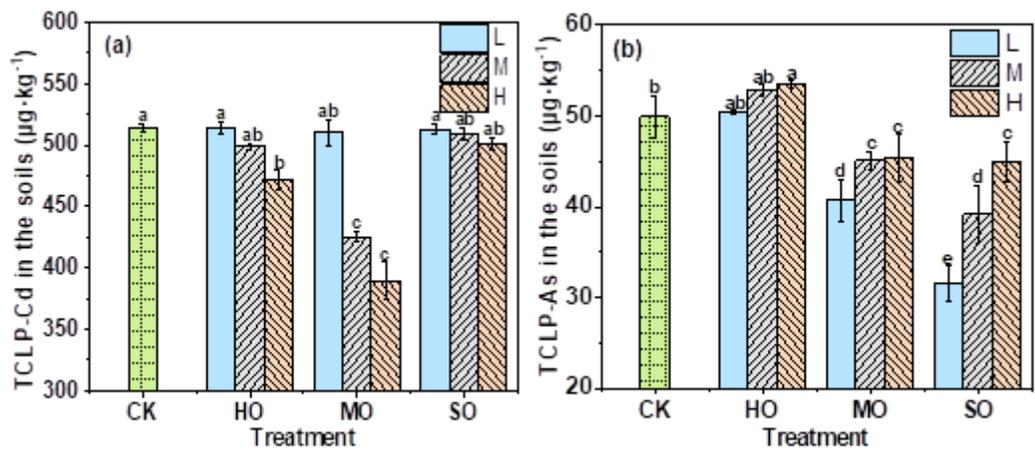


Figure 4

TCLP-Cd (a) and TCLP-As (b) in the soils treated by organic fertilizers.

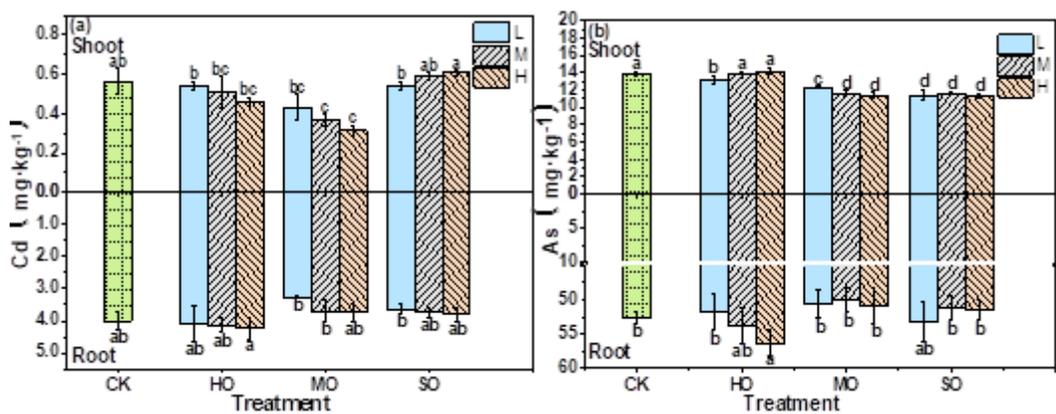


Figure 5

Cd (a) and As (b) concentrations in plants under different treatments

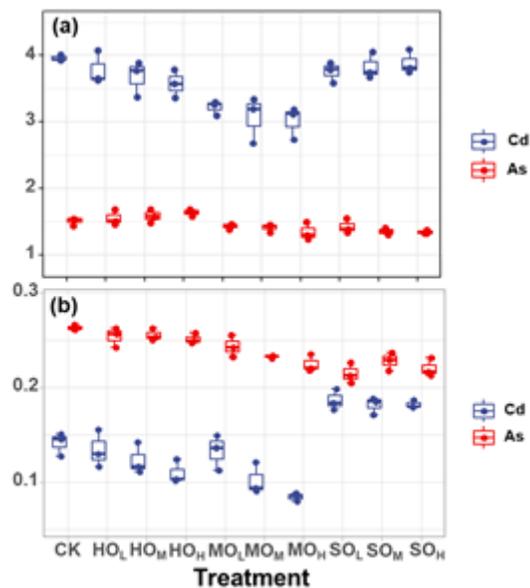


Figure 6

Bioaccumulation factor (BCF) (a) and transport factor (TF) (b) of Cd and As in rice

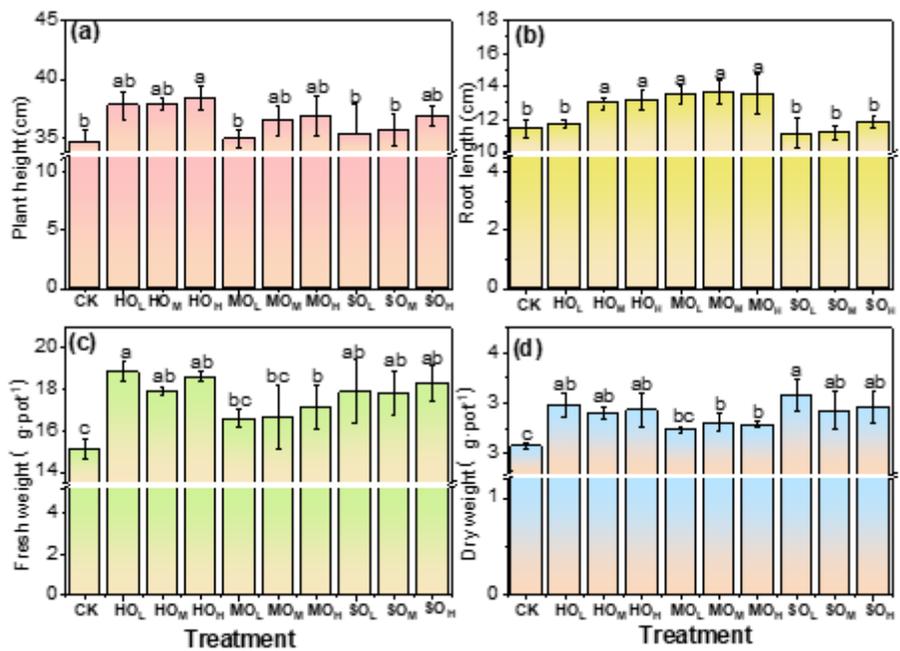


Figure 7

Effect of amendments on plant growth and biomass.

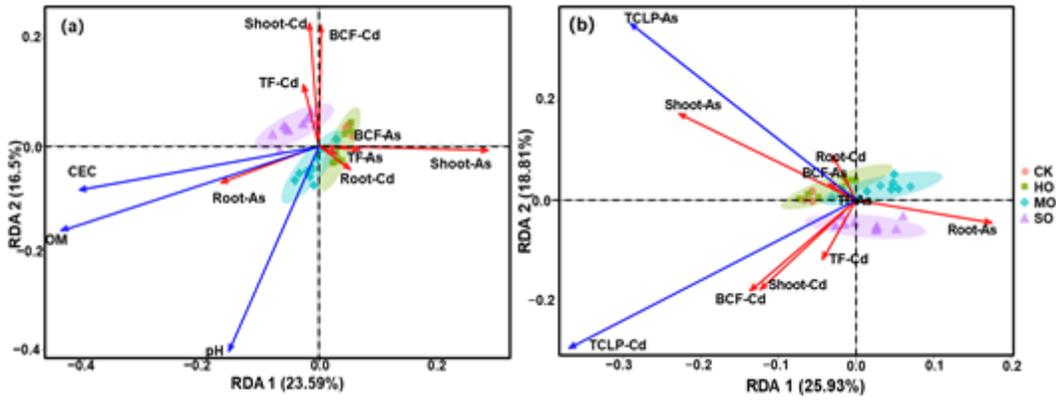


Figure 8

The links between Cd/As concentrations in rice (shoot and root) and accumulation factors and soil properties (a) and TCLP-Cd/As (b) shown by Redundancy analysis (RDA)

Supplementary Files

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