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Effects of combined amendments on crop yield and cadmium uptake in two cadmium contaminated soils under rice-wheat rotation

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ABSTRACT

Soil cadmium (Cd) contamination in China has become a serious concern due to its high toxicity to human health through food chains. A pot experiment was conducted to investigate the effects of hydrated lime (L), hydroxyapatite (H) and organic fertilizer (F) alone or in combination to remedy a mild (DY) and a moderate (YX) Cd contaminated agricultural soil under rice-wheat rotation. Results showed that crops grain yield and Cd concentration, soil pH, $CaCl_2$ extractable Cd and Cd speciation were markedly affected by the amendments. In both cropping seasons, hydrated lime and hydroxyapatite significantly immobilized soil Cd, and hydroxyapatite, organic fertilizer significantly increased grain yield. Hydrated lime mainly increased soil carbonates bound Cd fractions resulted from 16.7% to 36.2% and from 16.8% to 28.3%, and hydroxyapatite increased Fe/Mn oxides Cd fractions from 19.3% to 33.4% and from 31.4% to 42.1% in the DY and YX soils, respectively; while organic fertilizer slightly increased soil exchangeable and organic matter bound Cd fractions. Besides, combined amendments contain alkaline materials and organic materials have the potential to decrease grain Cd and increase grain yield simultaneously. Therefore, in view of the effects of amendments on grain yield and Cd concentration, the cost as well as the potential benefits expected, combined amendments like hydrated lime + organic fertilizer, hydrated lime + hydroxyapatite + organic fertilizer are recommended in practical application. Mechanisms of Cd immobilization affected by amendments are mainly attributed to the changes in soil Cd availability and crops root uptake rather than internal translocation in plants.

1. Introduction

Heavy metals contamination in soils is increasingly becoming an urgent problem in China. A recent nationwide survey has revealed that cadmium (Cd) is the most frequently detected heavy metal in soils, and 7% of the investigated sites are contaminated by Cd (Ministry of Environmental Protection P.R.C. and Ministry of Land and Resources P.R.C., 2014). Excessive accumulation of Cd in agricultural soils will lead to elevated Cd uptake in crops and inevitably pose risks to human health via food chains. Moreover, it is also noted that mild and moderate Cd contamination dominates among the contaminated agricultural soils, and thus it is possible to remediate these soils while maintaining crop production as usual (Hu et al., 2016; Zhao et al., 2015).

A number of remediation techniques for heavy metals contaminated agricultural soils have been explored, including soil replacement and turnover, chemical washing, phytoremediation, and chemical immobilization (Bolan et al., 2014; Zhao et al., 2015). However, some of the methods are not efficient in terms of time, cost or environmental compatibility. In situ chemical immobilization has recently been gaining prominence in the remediation of contaminated agricultural soils because of its cost-effectiveness, rapid implementation as well as its ability to be extended over large areas (Li and Xu, 2015; Sun et al., 2016; Zhao et al., 2015).

Common materials for chemical immobilization of heavy metals in soils include various inorganic and organic substances, such as hydrated lime, phosphorus-containing materials, biochar and organic residues. Hydrated lime is the oldest and most widely adopted immobilization amendment. The addition of lime will increase soil pH and decrease metals availability, moreover, it can be used as a co-amendment to reinforce the immobilization effect (Bolan et al., 2014; Lahori et al., 2017). Hydroxyapatite as one of the common phosphate minerals has demonstrated its high efficiency in heavy metals immobilization due to its moderate solubility between highly insoluble and highly soluble phosphate bearing materials such as phosphate rock and phosphate fertilizers, respectively (Mignardi et al., 2012; Smiciklas et al.,

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Table 1
Selected physical and chemical properties of the tested soils.

Parameters	D Y	Y X
Soil texture (%)		
Sand (2–0.05 mm)	30.60	11.24
Silt (0.05–0.002 mm)	50.88	67.24
Clay (< 0.002 mm)	18.52	21.52
pH	5.35	6.05
Cation exchange capacity (cmo kg^{-1})	9.15	18.45
Organic matter (g kg^{-1})	28.50	46.58
AN (mg kg^{-1})	135.98	172.73
AP (mg kg^{-1})	72.92	33.67
AK (mg kg^{-1})	260	120
Total Cd (mg kg^{-1})	0.73 ± 0.02	1.47 ± 0.12
Total Cu (mg kg^{-1})	55.84 ± 4.71	24.79 ± 1.30
Total Pb (mg kg^{-1})	78.23 ± 2.08	41.13 ± 1.89

DY and YX refers to soils collected from Dayu and Yixing County, respectively. Same as below.

2008). It is reported that apatite has a better sustainable effect on the immobilization of heavy metals than lime (Cui et al., 2015). Several organic residues (animal manures, biosolids, etc.) have been widely used for remedying heavy metals contaminated soils (Pardo et al., 2014a, 2014b; Sebastian and Prasad, 2014). These organic materials may not only modify the solubility and toxicity of heavy metals, but also can ameliorate the function of soil ecosystem. Nevertheless, there are reports that organic materials may increase the mobility of heavy metals, and the immobilizing effect depends on their characteristics (such as humification degree) and soil conditions (CEC, pH) (Bolan et al., 2014; Juang et al., 2012; Pardo et al., 2014a).

A successful immobilization remediation technique must maintain reasonably low bioavailability of heavy metals and also improve soil ecological function with the universality and long-term effect (Hu et al., 2016; Pardo et al., 2014b; Sun et al., 2016). Numerous amendments have been employed for the immobilization of Cd contaminated soils in the last few years, however, more works are still needed to seek amendments with cost-effective, large scale applicable, and environment friendly. It is well known that factors like soil type, irrigation regime and local climate will affect the effectiveness of heavy metals immobilization (Bolan et al., 2014; Sebastian and Prasad, 2014). Furthermore, different amendments have different abilities in immobilizing soil heavy metals, and the dosage of amendments used is one of the key factors in controlling the remediation efficiency (He et al., 2016). Bian et al. (2016) found that higher additions of calcium hydroxide, silicon slag and wheat straw biochar led to a higher soil pH and lower Cd availability. However, it was reported that excess usage of highly alkaline materials as amendments without fertility improvement will increase the risk of soil alkalinity, ultimately affecting the agricultural productivity (Cui et al., 2015; Roig et al., 2012). In view of the challenges, to develop inorganic-organic mixed or combined amendments by decreasing the amounts of the individual component may be a promising option, since the combination of different amendments have mutual compensation functions (Bolan et al., 2014; Zhou et al., 2014). A recent study indicated that the application of lime, slag, and bagasse alone or in combination significantly decreased the Cd content of rice plants and the mixture of lime, slag and bagasse had the most effective immobilization effect (He et al., 2017). Besides, other studies also demonstrated that combined amendments mixed by different inorganic materials could effectively reduce heavy metals accumulation in plants (Wu et al., 2016; Zhou et al., 2014). However, to date, very few studies are conducted to investigate the immobilization efficiency of combined amendments mixed by inorganic and organic materials in various mixing modes on Cd contaminated soils.

Therefore, a greenhouse pot experiment was conducted in a mild and a moderate Cd contaminated soils under rice-wheat rotation system. The objectives of present study were to investigate changes in crop yield and Cd concentration caused by applying hydrated lime, hydroxyapatite and organic fertilizer alone and in combination, and to explore their immobilization mechanisms by analysis of Cd species distribution in soil and Cd content in different plant parts.

2. Materials and methods

2.1. Soils and amendments characterization

Two Cd contaminated soils were collected from the plough layer (0–20 cm) of farmlands in Dayu county (DY), Jiangxi province (25°26′N, 114°22′E), and Yixing county (YX), Jiangsu province (31°15′N, 119°52′E) China, respectively. Soils were air dried, homogenized, and passed through a 2 mm sieve prior to use. The selected physical and chemical properties are listed in Table 1, and soils are categorized to a mild (DY) and a moderate (YX) Cd contaminated soil according to the Environmental Quality Standard for Soils of China (GB 15618-1995). Two inorganic materials (hydrated lime and hydroxyapatite) and one organic material (organic fertilizer) were selected as soil amendments. Hydrated lime (L, pH = 12.47) was purchased from a local market in Nanjing, China. Hydroxyapatite (H, 12 μm, pH = 6.47) was purchased from Nanjing Emperor Nano Material Co., Ltd. (Jiangsu, China). Organic fertilizer (F, pH = 6.75) was purchased from Nanjing Ningliang Bio Fertilizer Co., Ltd. (Jiangsu, China), and its water content, organic matter, N, P_2O_5, K_2O content were 11.6%, 48.3%, 4.0%, 0.7%, 3.1% (w/w), respectively. Total Cd concentrations were 0.46, 0.43 and 0.60 mg kg^{-1} in hydrated lime, hydroxyapatite and organic fertilizer, respectively.

2.2. Experimental design

Three materials as above mentioned were applied alone and in combination with various mixed modes at two application rates (the high dose was five folds of the low one). Application rates of a single

Table 2
Experimental design and cost of various treatments.

Treatments	Low dose	Cost[a] (USD$ ha^{-1})	Treatment	High dose	Cost (USD$ ha^{-1})
CK	–	–			
L1	2.23 t ha^{-1}	300	L2	11.15 t ha^{-1}	1500
H1	4.45 t ha^{-1}	15,000	H2	22.25 t ha^{-1}	75,000
F1	11.13 t ha^{-1}	2000	F2	55.65 t ha^{-1}	10,000
L1H1	1/2 (L1 + H1)	7650	L2H2	1/2 (L2 + H2)	38,250
L1F1	1/2 (L1 + F1)	1150	L2F2	1/2 (L2 + F2)	5750
H1F1	1/2 (H1 + F1)	8500	H2F2	1/2 (H2 + F2)	42,500
L1H1F1	1/3 (L1 + H1 + F1)	5767	L2H2F2	1/3 (L2 + H2 + F2)	28,835

CK: Control, L: Hydrated lime, H: Hydroxyapatite, F: Organic Fertilizer. The numerals 1 and 2 refers to the low and high application dosage, and the high dose was five folds of the low one.
[a] Estimated by market survey, including the cost of materials and operation.