

Enhancement of Cd solubility and bioavailability induced by straw incorporation in a Cd-polluted rice soil

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Abstract

Of the factors affecting migration and bioavailability of toxic metals in heavy metal contaminated soil, dissolved organic carbon (DOC) provides binding sites for metal cations and reduces the fixation and adsorption of heavy metals by the soil solid phase. Elevation of DOC level due to the direct incorporation of crop residues may lead to enhanced accumulation of toxic metals in crops grown in polluted farmland. In this study, an incubation experiment and a pot experiment were conducted respectively to investigate the effects of wheat straw incorporation on DOC level, cadmium availability, and Cd accumulation in rice plants, and to establish the relation between Cd solubility and DOC level. A Cd-contaminated rice soil was used and incorporated with different rates (0, 0.5 and 1%) of wheat straw in both experiments. Results showed that the change of Cd in soil solution was very similar to that of DOC level. Wheat straw addition significantly elevated Cd and DOC level in soil solution while NH_4NO_3 -extracted Cd was not affected. There existed a close linear correlation between soluble Cd and DOC level. Enhanced Cd accumulation in rice plants, grown in a Cd contaminated soil, induced by wheat straw incorporation was observed in this study.

Key Words

Cadmium, bio-availability, dissolved organic carbon, crop straw, rice soil

Introduction

The pollution of soil and agricultural farmland has received worldwide attention. In China, about one fifth of arable land has been polluted by heavy metals, due to acceleration of industrialization and urbanization, heavy input of chemical fertilizers and pesticides, and rapid development of transportation system (Chen, 1996; Gu *et al.*, 2003). However, the environmental risk of heavy metals in polluted soil largely depends on their mobility and availability which are affected by many factors and closely related to the composition of the solution (Bümmer *et al.*, 1986). Dissolved organic carbon (DOC) provides binding sites for metal cations and regulates the fixation and adsorption of heavy metals by soil solid phase. DOC in soil solution may affect the toxicity or bioavailability of heavy metals to plants (Inaba and Takenaka 2005; Hernández-Allica *et al.*, 2007). Rice provides a staple food source for over 60 percent of the population in China. Apart from other sources of heavy metal pollution, rice field may receive more heavy metals due mainly to the use of untreated or not well treated sewage water discharged from nearby industries as irrigation water (Wang, 1997). Cadmium (Cd) is one of the main pollutants in rice paddy soil near industrial areas. Cd is highly toxic to rice growth and development (Chien and Kao, 2000) and has strong interference with the uptake of other metal cations by rice plant (Liu *et al.*, 2003). Cd-contaminated milled rice (> 1mg Cd/kg) once appeared in the markets in many regions in China and became a potential threat to human health (Wang, 1997). In wheat-rice rotation systems, directly incorporating wheat straw into rice field is becoming an alternative way to replace open-field burning (Singh *et al.*, 2008). Our previous study indicated that wheat straw incorporation significantly increased DOC level in rice field (Lu *et al.*, 2006) and elevated the concentration of organic acids, an important source of DOC, in soil solution (Shan *et al.*, 2008). An earlier study showed that there existed a close link between Cd dissolution and DOC level in different soils (Chen and Chen 2002). The objective of our present work was to investigate the relationship between Cd availability and DOC level in a Cd-contaminated rice soil with different rates of wheat straw incorporated, and to clarify the question whether wheat straw incorporation may induce enhanced Cd accumulation in rice plant.

Methods

Soil and straw used

Cd-contaminated soil (top 20 cm) was sampled and air-dried at room temperature immediately after wheat harvest in a rice-wheat rotation system (31°17.6N, 119°53.7E) adjacent to Taihu Lake, China. The cropping system had been irrigated by untreated sewage water discharged from surrounding small industries for years and total Cd content in the sampled soil was 7.4 mg/kg. The soil was a moderately acid loam with pH 5.8, and clay, silt and sand content was 19%, 47 %and 34%, respectively. Other properties of the soil were: CEC

11.4 cmol/kg, total C 13.5 g/kg, total N 1.5 mg/kg, bicarbonate-extractable P 18 mg/kg and exchangeable K 0.09 cmol/kg. The straw used in this study was obtained from the matured wheat cultivar *Yangmai 5* (*Triticum aestivum L.*) which was grown in a neat field free from Cd contamination. The straw sample was oven-dried at 60 °C and cut into pieces (approximately 1cm in length) before use. The straw had a C/N ratio 82.4 and the contents of soluble sugar, cellulose, hemicellulose and lignin in the straw were 12.1%, 35.2%, 37.3% and 15.4%, respectively.

Incubation experiment

An incubation experiment with 3 duplicates was conducted in this study to investigate the response of DOC to straw incorporation and to understand the relation between Cd solubility and availability and DOC in flooded condition. 100 g soil (dried base) was put into a set of plastic beakers and three rates, 0%, 0.5% and 1%, of straw incorporation were implemented by adding 0, 0.5 and 1g wheat straw, respectively, into the beakers. Then 150 ml deionized water was added to each beaker (soil: water= 1:1.5) and the water layer was approximately 2 cm thick. After thoroughly mixed using glass rod, the open beakers were incubated at 30°C and the water layer was maintained by promptly adding deionized water to the beaker. At 1, 3, 5, 7, 10, 20, 40 and 60 d of incubation, the content in the beaker was moved to centrifuge tube and centrifuged at 4000 rpm for 20 min. The supernatant solution was filtered through a 0.45 µm membrane filter (Millex-HV, PVDF, Warsaw, Poland) for determination of DOC and Cd, while the centrifugal sediment was extracted using 1 mol/L NH₄NO₃ for Cd determination only.

Pot experiment

3 kg Cd-contaminated soil was mixed thoroughly with 0, 15 and 30 g wheat straw (straw incorporation rate was 0, 0.5 and 1%, respectively), and the mixture was put into a plastic pot (5L in volume). 3 rice (*Oryza Sativa L.*) seedlings, developed in a nursery bed for 20 d, for each pot was transplanted one day later after 4.5L solution containing 2g urea and 1g KH₂PO₄ as basal fertilizer was added to the mixture. The experiment duplicated 3 times. The rice plants were sampled at maturity stage and divided into root, straw, hull and milled rice. All the plant materials were oven-dried at 80°C for 48h and milled after dry weights were recorded. For Cd determination, milled samples were digested using a mixture of HNO₃/HClO₄ 85:15 (v/v).

Measurements

DOC was determined by a total carbon analyser (TOC-V CSN, Japan) and value of DOC was obtained by subtracting inorganic carbon (IC) from total carbon (TC) in the solution; Cd concentration was measured by an atomic absorption spectrometer (PEM2100, Germany).

Statistical analysis

Statistical analysis for the data obtained in this study was performed using SPSS (v.15.0, SPSS Inc. USA). Duncan's SSR-test was used to detect significant difference among the means at $p < 0.05$.

Results

DOC concentration in soil solution increased in the early stage of incubation and the peak concentration in the treatments without and with straw incorporation appeared at 3th and 5th d, respectively, after flooding (Figure 1). Then DOC concentration in all treatments declined gradually with incubation time. Straw incorporation significantly elevated DOC concentration in soil solution, and as shown in Figure 1, the peak concentration in treatments with 0.5% and 1% straw incorporation was approximately 2 and 3 times, respectively, higher than that in the treatment without straw incorporation. Much higher DOC concentration in the treatments with straw incorporation was maintained even at the end of incubation, compared to the treatment without straw incorporation (Figure 1).

The change pattern of Cd concentration in soil solution under different rates of straw incorporation (Figure 2) was very similar to that of DOC (Figure 1) and the peak concentration of Cd and DOC in soil solution occurred simultaneously. The response of Cd concentration to straw addition was also close to that of DOC. Straw incorporation significantly increased Cd concentration in soil solution and such effect was enhanced by higher rate of straw incorporated (Figure 2).

The similarity in change pattern with incubation time and response to straw incorporation indicated that Cd solubility, expressed by Cd concentration in soil solution in this study, might be closely associated with DOC level in the polluted soil. Statistical analysis showed that there existed a significant linear correlation

between Cd and DOC concentration (Figure 3). R-square value (R^2) of the fitted linear equation was 0.8865, which meant that approximately 90% variation of Cd solubility could be explained by the change of DOC level in Cd-contaminated soil. Based on the equation in Figure 3, 100 mg C increase of DOC would predict an increase of 36.9 μg Cd in soil solution.

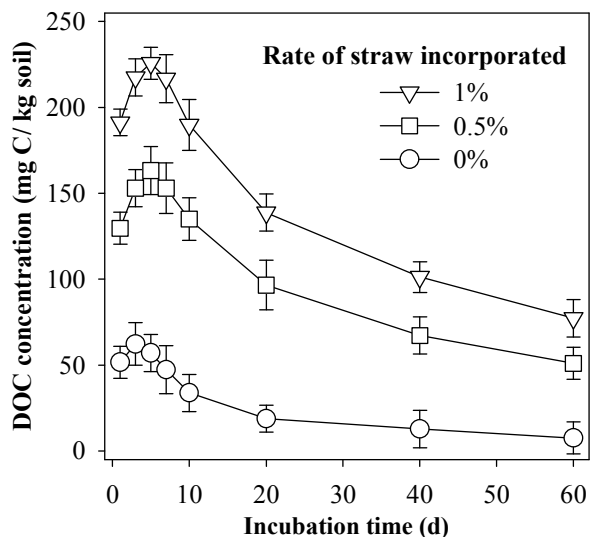


Figure 1. Change of DOC concentration in soil solution under different rates of straw incorporation. Vertical bars indicate standard errors.

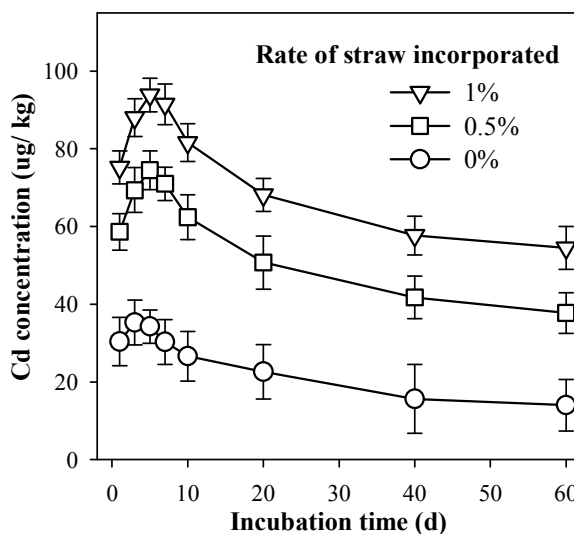


Figure 2. Change of Cd concentration in soil solution under different rates of straw incorporation. Standard errors are shown as vertical bars.

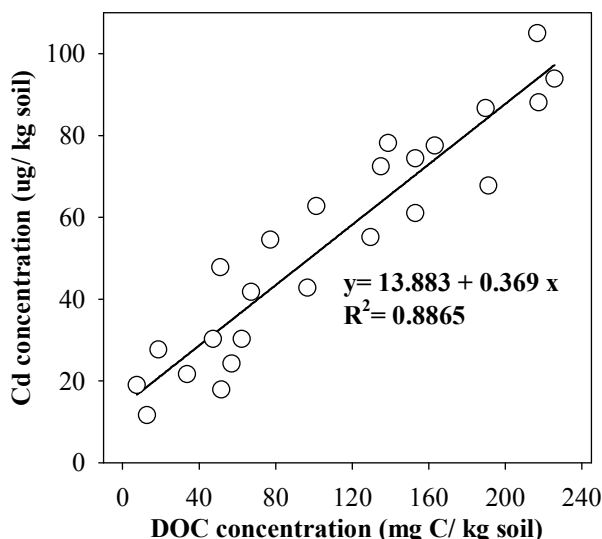


Figure 3. Correlation between Cd concentration (y) and DOC concentration (x) in soil solution. 24 data points in the figure represent the means calculated from 3 straw incorporation rates at 8 incubation times.

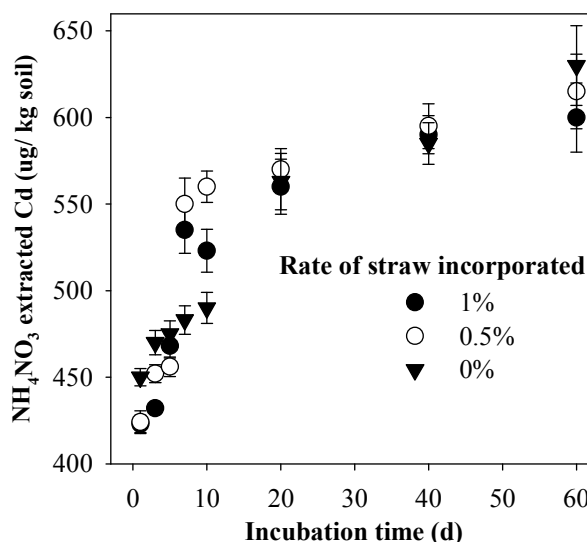


Figure 4. Change of NH_4NO_3 extracted Cd concentration in soil solution under different rates of straw incorporation. Vertical bars represent standard errors.

Cd extracted by 1 mol/L NH_4NO_3 tended to increase with the incubation time (Figure 4) and the tendency may partly attribute to the flooded soil condition. Unlike Cd in soil solution, however, NH_4NO_3 -extracted Cd did not apparently respond to straw incorporation (Figure 4).

The data obtained from pot experiment was shown in Table 1. Although a slight increase in biomass accumulation due to the beneficial effect of straw incorporation on soil fertility was observed, the difference in biomass accumulation between straw incorporation treatments was not statistically significant (Table 1), which indicated that enhanced Cd solubility by straw incorporation produced no detrimental influence on rice growth. However, Cd accumulation in both root and shoot of rice plant was significantly elevated by straw incorporation. Compared with the treatment without straw incorporation, Cd content in milled rice, straw, root and hull increased 382.4%, 279.9%, 279.3% and 35.5%, respectively, when 1% straw was incorporated into the polluted soil (Table 1). Since NH_4NO_3 -extracted Cd, did not respond to straw

incorporation (Figure 4), Cd in soil solution may contribute to the enhancement of Cd accumulation in rice plant induced by wheat straw incorporation. Of all plant parts tested, Cd accumulation in milled rice was most sensitive to straw incorporation while root had the highest Cd content (Table 1). Therefore, straw incorporation in Cd contaminated rice soil increased the risk of Cd into food chain through milled rice. In wheat–rice rotation systems in China, the incorporation rate of wheat straw seldom exceeds 5 t/ ha (approximately 0.5% of straw application in plow soil), which is lower than the rate in this study. However, high accumulation of Cd in rice plant induced by straw incorporation in Cd-contaminated soil may still occur due to uneven incorporation of the wheat straw in some regions lack of labour or relevant machinery.

Table 1. Effect of straw incorporation on biomass accumulation and Cd content in different parts of rice plant at maturity.

Rate of straw incorporated (%)	Biomass accumulation (g DW/pot)	Cd content (mg/ kg DW)			
		root	straw	hull	Milled rice
0	76.5a	0.405a	0.209 a	0.076 a	0.242 a
0.5	81.4a	0.985b (143.2)	0.557 b (166.5)	0.089 ab (17.1)	0.779 b (219.0)
1	78.3a	1.536c (279.3)	0.794 c (279.9)	0.103 b (35.5)	1.167 c (382.4)

Different letters in the same column indicate significant difference detected by SSR-test at $p < 0.05$. Biomass accumulation is the total dry weight (DW) of root, straw, hull and milled rice. The figure between brackets shows increase percentage over the treatment without straw incorporation.

Conclusion

Based on the results obtained in this study, we can conclude that wheat straw incorporation significantly enhanced Cd accumulation in rice plants in Cd-contaminated soil. This effect was induced by higher DOC level under wheat straw application which elevated Cd solubility and bioavailability. In heavy metal contaminated soil, direct incorporation of crop residue, especially in large amount, may not be recommended, to avoid hazardous accumulation in crop products.

Acknowledgement

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