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Cadmium dynamics in soil pore water and uptake by rice: Influences of soil-applied selenite with different water managements☆

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ABSTRACT

Cadmium (Cd) in rice grains is a potential threat to human health. This study investigated the effects of selenite fertilisation (0 mg kg^{-1}, 0.5 mg kg^{-1}, and 1.0 mg kg^{-1}) on soil solution Cd dynamics and rice uptake. Rice was grown in two Cd-contaminated soils in Jiangxi and Hunan Provinces under two different sets of conditions: aerobic and flooded. The experiments were conducted in pots. The plants were harvested at the seedling stage and at maturity to determine their Cd levels. Soil solutions were also extracted during the growing season to monitor Cd dynamics. The results showed that in the Jiangxi soil (pH 5.25), Cd concentrations in the soil solutions, seedlings, and mature rice plants were higher under aerobic than under flooded water management conditions. In the Hunan soil (pH 7.26), however, flooding decreased Cd levels in the rice seedlings but not in mature plants. Selenite additions to the Hunan soil decreased Cd concentrations in the soil solutions and in the mature rice plants. These effects were not observed for the solutions or the plants from Jiangxi soil amended with selenite. Relative to the control treatment, 0.5 mg kg^{-1} selenite decreased the rice grain Cd content by 45.2% and 67.7% under aerobic and flooding conditions, respectively. The results demonstrated that water management regimes affected rice Cd uptake more effectively in Jiangxi than in Hunan soil, whereas selenite addition was more effective in Hunan than in Jiangxi soil. Selenite addition was also more effective at reducing rice grain Cd levels when it was applied under flooding than under aerobic conditions.

1. Introduction

Cadmium (Cd) is a global and extremely toxic environmental contaminant (He et al., 2015). More than 7.0% of the agricultural soils in China contain Cd at levels exceeding the acceptable limit as defined by the Ministry of Environmental Protection (MEP), surpassing levels for all other heavy metals and metalloids measured (MEP and the Ministry of Land and Resources, 2014). Soil Cd is readily absorbed by plants, accumulates in their edible parts, and is a potential threat to human health (Rizwan et al., 2017; Templeton and Liu, 2010). Paddy rice (*Oryza sativa* L.) is consumed more than all other cereals in Southeast and East Asia. Unfortunately, rice is a major dietary Cd source because it accumulates this metal more efficiently than do other cereals. In a zinc-mineralised region of western Thailand, the daily Cd intake from rice grains is reported to be 21–84 μg week^{-1} kg^{-1} body weight (Simmons et al., 2009), while the provisional tolerable weekly Cd intake has been set to only 7 μg week^{-1} kg^{-1} body weight for adults (Joint FAO/WHO Expert Committee on Food Additives, 2004). The rice produced in certain areas of southern China (Hunan and Jiangsu provinces) also fails to meet the Chinese food standard limit of 0.2 mg Cd kg^{-1} and has caused widespread concern in recent years (Du et al., 2013; Fang et al., 2014; Qian et al., 2010; Williams et al., 2009). Therefore, effective measures are needed to reduce rice Cd levels.

Rice Cd accumulation is determined mainly by its soil bioavailability which, in turn, is affected by growing conditions, soil type (Sanchez-Camazano et al., 1998), pH (Sastre et al., 2006; Zeng et al., 2011), redox potential (Eh) (Bingham et al., 1976; Stroud et al., 2011) and organic matter in the rhizosphere (Han et al., 2006; Pandit et al., 2012). Current strategies are focussed on reducing soil Cd

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bioavailability as a means of reducing rice Cd levels and mitigating Cd exposure from rice. Lime, biochar, porous hydrated calcium silicate, and sepiolite applications decrease rice grain Cd accumulation by increasing soil pH (Bian et al., 2014; Shaheen and Rinklebe, 2015; Zhao and Saigusa, 2007; Zhu et al., 2010). There is a negative correlation between the bioavailability of heavy metals to plants and soil pH (Wang et al., 2006; Zeng et al., 2011). Soil Eh is closely related to rice field water management and effectively determines Cd solubility (Honma et al., 2016; Pan et al., 2016). Hu et al. (2013) found that the Cd content in rice harvested from flooded and conventionally treated paddy was lower than that in rice harvested from aerobic and intermittently drained soils. Micronutrient or macronutrient application can also reduce plant Cd accumulation. It has been recently reported that selenium (Se) amendments mitigate heavy metal and metalloid (Cd, As, Pb, Hg and Sb) accumulation and toxicity in various plants (Feng et al., 2013; Hu et al., 2014; Malik et al., 2012; Wang et al., 2014). Selenium is an essential micronutrient for human beings and animals and participates in antioxidation, antimutation, immunity responses, and other processes (Brown and Arthur, 2001). However, Se accumulation in rice grains is generally low. According to a recent global report, 75% of rice sampled had inadequate Se to meet the requirements for consumers (Williams et al., 2009). Therefore, Se soil amendments may reduce heavy metal levels in edible crop tissues, enhance plant Se accumulation, and augment human dietary Se intake.

Selenium may protect plants from the toxic effects of heavy metals by altering their localisation and speciation (Zhao et al., 2013), alleviating oxidative stress (Malik et al., 2012; Pedrero et al., 2008), rebuilding chloroplasts, and restoring cell membrane integrity (Filek et al., 2010). Selenium may also limit Cd uptake and accumulation in plants by reducing Cd bioavailability in soils (Badiello et al., 1996; Shanker et al., 1995). Wan et al. (2016) found that Se additions to the soil significantly reduced Cd in rice seedlings, mainly by reducing Cd translocation from roots to shoots under hydroponic conditions. In pot experiments conducted by Hu et al. (2014) and Huang et al. (2017), Se application reduced Cd in rice tissues but did not significantly influence root-to-shoot Cd translocation.

Selenium bioavailability is strongly affected by soil redox potential and pH (Mikkelsen et al., 1989). Under an intermediate redox potential, selenite is the predominant form of soil Se, while selenate prevails under aerobic and neutral to alkaline conditions (Elrashidi et al., 1987). Li et al. (2010) showed that Se levels in the grain, husk, and straw of rice grown under flooding conditions were higher than those in rice harvested from aerobic soils not being amended with Se. On the other hand, when selenite or selenate was applied, the aerobically grown rice accumulated more Se than that in rice grown under flooding conditions.

A major objective of our research was to determine the effectiveness of Se in regulating rice Cd uptake under various soil conditions as a means reducing Cd bioavailability. To this end, soils with different physicochemical properties, Cd levels, and differing water management regimes (aerobic and flooded) were tested. The aim, then, was to investigate the influences of Se addition on Cd accumulation in rice grown in two types of soil under different water management systems. Cadmium dynamics in the soil solution were also studied *in situ* to determine the impact of Se addition on heavy metal mobility under aerobic and flooding conditions.

2. Materials and methods

2.1. Pot experiment

Cadmium -contaminated topsoils (0–20 cm) were collected from paddy fields in Jiangxi and Hunan Provinces, China. The main physicochemical properties and total Cd content of the two soils are shown in Table 1. After air-drying and sieving to <4 mm, the soils were mixed with basal fertilisers (150 mg N kg^{-1} soil as $CO(NH_2)_2$, 30 mg P kg^{-1} soil as $Ca(H_2PO_4)_2 \cdot H_2O$, and 75.5 mg K kg^{-1} soil as KCl). Selenium in the form of Na_2SeO_3 (selenite) was blended into the soil at rates of 0 mg kg^{-1}, 0.5 mg kg^{-1}, and 1.0 mg kg^{-1}. The soils were either flooded (anaerobic) or aerobic. All treated soils were placed in plastic pots (diameter 20 cm; height 20 cm) either with or without holes in their bases. Each pot contained 2.5 kg of soil. Each treatment was replicated in three pots. Rice (*Oryza sativa* L. 'Zhunliangyou 608', a two-line hybrid indica rice cultivar, which is sensitive to Cd and Se stress) seeds were soaked in 30% H_2O_2 (v/v) solution for 15 min then thoroughly rinsed with distilled water (Hu et al., 2014; Huang et al., 2015). They were germinated on a pre-sterilised plastic net floating in deionised water at 25 °C for 7 d.

A soil pore-water sampling device (10 cm length, 2.5 mm o.d.; Rhizosphere Research Products, The Netherlands) was buried diagonally in each filled pot to collect the soil solutions. After 7 d equilibration, four pre-germinated rice seedlings were transplanted into each pot. Distilled water was then added to the pots with perforated bases. Moisture at 70% of the soil's water retention capacity was maintained in these (aerobic) treatments. Pots without holes were used in flooded treatments. They were filled and maintained with water up to a level of 3 cm above the soil surface (marked with graduated lines). The two water management regimes were maintained throughout the growing season through daily additions of distilled water. The pots were set randomly on a bench inside a glasshouse (14 h day length, 240–350 μmol $m^{-2} \cdot s^{-1}$ light intensity, 28 °C and 20 °C daytime and nighttime temperatures, respectively, and 60–70% relative humidity).

2.2. Sampling

Two plants per pot were removed at the growth stage of stem elongation (35 days after planting). The remaining two plants were harvested at grain maturity (150 days after planting). Stems were cut at 2 cm above the soil surface, rinsed with deionised water, and dried at 75 °C for 48 h. The samples were separated into leaf, stem, rachis, husk and unpolished rice grain. Soil pore water samples were extracted on days 2, 9, 24, 38, 82 and 148.

2.3. Cadmium concentration in soil solution

To each 5 mL soil solution aliquot was added 5 mL 5% HNO_3 (v/v) immediately after sample collection to prevent iron oxide/hydroxide precipitation. The total Cd concentrations in the soil solutions were determined using inductively coupled plasma mass spectrometry (ICP-MS, Model 7700ce, Agilent Technologies, USA). The pH values of the unacidified soil solutions were measured using a pH electrode (HI 98127, Hanna Instruments, Italy). The Eh of the soil solutions were determined immediately after sample collection

Table 1
Physico-chemical properties and total Cd contents of the two soils.

Soil property	Jiangxi	Hunan
pH (H_2O)	5.25	7.26
Proportion of clay mineral (%)	14.6	35.5
Organic matter (g kg^{-1})	21.64	28.13
Total N (g kg^{-1})	2.12	2.42
Total P (g kg^{-1})	0.39	0.87
Available P (mg kg^{-1})	11.94	15.78
Available K (mg kg^{-1})	75.25	115.29
Total Cd (mg kg^{-1})	0.45	5.12
$CaCl_2$-extractable Cd (mg kg^{-1})	0.10	0.02
Total Se (mgkg^{-1})	0.30	0.39