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Impact of Water Management on Arsenic and Cadmium Accumulation in Rice Grown Nearby Abandoned Mines in Korea

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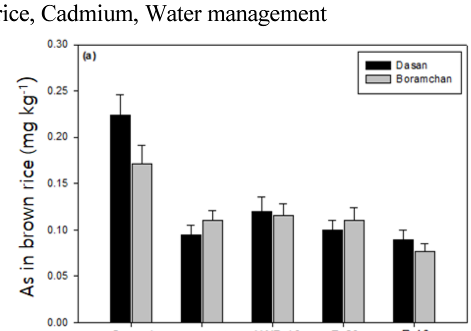
A B S T R A C T

Managing arsenic (As) and cadmium (Cd) together in rice (*Oryza sativa* L.) plants is challenging and different strategies are being developed for mitigating As and Cd loading into the rice grains. This study investigated the effect of water management on As and Cd accumulation in brown rice. A field plot experiment was conducted with five water management regimes [Flooded control, alternate wetting drying (AWD−60 and 40), and row (R-60 and R-40)] using two rice cultivars (Dasan and Boramchan). All the four treatments significantly reduced the concentration of As in brown rice compared to the flooded control, with R-40 treatment showing the least concentration. AWD and row treatments reduced As levels by 45-60% and by 32-55% in Dasan and Boramchan cultivars, respectively. However, increased Cd concentrations were noticed in both row and AWD treatments. The Dasan rice cultivar under the AWD-60 treatment reduced As without greatly increasing Cd concentration in brown rice, while also maintaining a competitive grain yield. The grain yields of both cultivars were influenced by different water regimes. While the flooded control showed the highest grain yield, between the cultivars, Boramchan showed an increase in grain yield under AWD-40 and R-40 treatments, and Dasan cultivar displayed higher grain yield in AWD-60 and R-60 treatments. AWD water management may be a promising strategy to reduce both As and Cd accumulation in rice grains, however, it depends on the selection of rice cultivars.

Keywords: Arsenic, Brown rice, Cadmium, Water management



Effect of water management on As concentrations in brown rice. AWD-Alternate wetting drying; R-Row.

Introduction

Heavy metal(loid) contamination in paddy soils is one of the most severe problems facing rice production and soil management in Asian countries. Rice (*Oryza sativa* L.) constitutes about 89% of the diet of people in Asian countries. In many East and South Asian countries including Bangladesh, Taiwan, China, Japan, and Korea, the accumulation of metal(loid)s, particularly arsenic (As) and cadmium (Cd), in rice ecosystems and its subsequent transfer to the human food chain is a major environmental issue. In Korea, rice is the most common crop grown on agricultural land. The cultivated land in Korea is around 21%, and of that 61% is paddy fields. Large areas of agricultural land, including paddy fields, have been contaminated by metal(loid)s including As and Cd through effluents from mine tailings and wastes generated by closed or abandoned mines, thus resulting in the uptake of metal(loid)s by rice plants, posing a significant public health risk to the local community (Yang et al., 2006; Kwon et al., 2013; Kunhikrishnan et al., 2015).

Managing low concentrations of As and Cd together in rice plants has always been a major issue and currently various strategies are being developed for reducing As and Cd loading into the rice grains (Jung et al., 2016; Lee et al., 2017; Yoo et al., 2017). Numerous studies have reported that water management affects As and Cd bioavailability in soils and their subsequent uptake by rice plants (Hu et al., 2013a, b; Linquist et al., 2015). When a paddy field is flooded and the soil has a low redox potential, any Cd present in the soil combines with sulfur (S) to form CdS which has a low solubility in water. Thus, flooding during the growing season, particularly during later stages of plant growth, can effectively reduce Cd concentrations in rice grains (Arao et al., 2009). In contrast, anaerobic conditions in paddy soil lead to the reduction in arsenate [As(V)] to arsenite [As(III)] which enhances the bioavailability of As to rice plants. Although aerobic rice cultivation results in a significant decline in As accumulation in rice, both Cd and As can occur together as contaminants in paddy fields, and they can accumulate simultaneously in rice plants (Xu et al., 2008; Williams et al., 2009). To help reduce water consumption during rice cultivation there has been considerable interest in expanding the aerobic cultivation practices employed in upland rice to lowland environments where anaerobic paddy cultivation is traditional. However, pest control issues and reduced yields associated with aerobic cultivation need to be addressed. One major recent progress in rice water management is the alternate wetting and drying (AWD) technique (Price et al., 2013). AWD combines the beneficial aspects of both aerobic and anaerobic cultivation including the reduction of greenhouse gas emissions and grain As levels in rice (Linquist et al., 2015). While there are studies demonstrating that different rice cultivars show different behaviors in relation to the uptake and accumulation of Cd and As, only few studies have considered As and Cd accumulation simultaneously in rice cultivars. Therefore, in this study, we investigated the effect of water management on As and Cd accumulation in brown rice from two rice cultivars grown in Korea.

Materials and Methods

Field experiment The field experiment was conducted in the year 2013. Arsenic- and Cd-contaminated paddy fields near a mining area in Seosan city, South Chungcheong province in Korea, were selected for the study. The soil pH ranged from 7.1 to 7.8. The soil organic matter contents ranged from 17.5 to 33.4 g kg^{-1} dry soil, with a mean value of 26.1 g kg^{-1} dry soil. The available phosphate (P_2O_5) was 132.0 mg kg^{-1} on the average, ranging from 25.2 to 143.9 mg kg^{-1}. Exchangeable cations varied in the range of 7.35-12.18 $cmol^+$ kg^{-1} for Ca, 0.17-0.55 $cmol^+$ kg^{-1} for K, 2.20-3.51 $cmol^+$ kg^{-1} for Mg, and 0.12-0.26 $cmol^+$ kg^{-1} for Na (Table 1). The total As concentration in Seosan plots was 128.1 mg kg^{-1}. The average 1 N HCl extractable As concentration was 22.39 mg kg^{-1}. The Seosan field was severely contaminated with Cd (average total and extractable Cd (0.1 N HCl) concentrations were 60.5 mg kg^{-1} and 10.29 mg kg^{-1}, respectively) (Table 2). Two rice cultivars, an Indica-Japonica hybrid (Dasan) and Japonica (Boramchan), grown in Korea, were used for the water management experiment. Five water management treatments were laid out in a randomized complete block design and replicated three times. Each plot was 1 m X 15 m in size. Fertilization was followed by the conventional method applying 4.5 kg 10 a^{-1} of urea (N), 4.5 kg 10 a^{-1} of fused phosphate (P_2O_5), and 4.0 kg 10 a^{-1} of Potassium chloride (K_2O). Treatments were : (i) Flood (continuously flooded control), (ii) AWD/60, (iii) AWD/40, (iv) row/60 (R-60) and (v) row/40 (R-40), where AWD represents alternate wetting and drying. In the flood treatment, water was maintained at 10 cm. For the AWD water treatments, the plots were irrigated to a flood depth of 10 cm and the water was allowed to decrease via evapotranspiration and percolation until soil moisture reached the critical moisture level (60 and 40% of saturated volumetric water) when the fields were re flooded. For the row treatments, rice plants were planted on beds and watering by furrows until soil in beds reached the critical moisture level (60% and 40% of field capacity).

Table 1. Selected soil properties of the experimental site.

Samples (n=50)	pH (H_2O) 1:5	EC (dS m^{-1})	Organic matter (g kg^{-1})	Av-P_2O_5 (mg kg^{-1})	Exchangeable cations ($cmol^+$ kg^{-1})			
					Ca	K	Mg	Na
Mean	7.4	0.220	26.1	70.0	9.57	0.25	2.88	0.14
Min	7.1	0.159	17.5	25.2	7.35	0.17	2.20	0.12
Max	7.8	0.294	33.4	143.9	12.18	0.33	3.51	0.26
2007†	5.8	-	24.0	132.0	4.70	0.29	1.30	-

†Average values for physicochemical properties of soils (n=2,110) collected from non-contaminated paddy fields in Korea (Kim et al., 2010).

Table 2. Total heavy metal(loid) concentrations in soils collected at the experimental site.

Samples (n=50)	Heavy metal(loid)s (mg kg^{-1})					
	As	Cd	Cu	Ni	Pb	Zn
Mean	128.1	20.36	109.4	35.0	2354.0	877.0
Min	47.9	6.19	66.5	30.4	898.2	792.2
Max	398.5	60.51	204.8	41.4	6615.1	887.8
2015†	4.41	0.25	13.2	13.6	21.3	54.1
Threshold value‡	25	4	150	100	200	300

†Average values of heavy metal(loid)s in non-contaminated paddy soils (n=82) collected nationwide (Kunhikrishnan et al., 2015).

‡Threshold values were designated by “Soil Environmental Conservation Law” (MOE, 2010).

Measurements The soil composite samples (n=50) were comprised of five sub-plots taken within a depth of 15 cm from the soil surface. The soil samples were air-dried, crushed, and passed through a 2 mm sieve. The soil pH and electrical conductivity (EC) were determined after end-over-end shaking of soil with water at a ratio of 1:5 for an hour and the solution was measured using a calibrated pH and conductivity meter (Orion, Thermo Scientific, USA). Organic matter and available P_2O_5 were determined by a wet oxidation and Lancaster method, respectively. The exchangeable cations, i.e. Ca, K, Mg, and Na, were measured using 1 N ammonium acetate at pH 7.0, and analyzed by inductively coupled plasma mass spectrometer (ICP-MS, Agilent technologies, 7500a). For the analysis of total heavy metal(loid) contents, soil samples (3 g) were digested using aqua regia at 30°C for 2h, and then extracted at 90°C for 150 min, by Kjeldatherm block digestion system (Gerhardt GmbH, Northants, UK). After cooling to ambient temperature, the digests were filtered through a 0.45- μm membrane filter, made up to a volume of 50 ml and analyzed for total metal(loid) concentrations using hydride generation inductively coupled plasma atomic emission spectrometer (HG-ICP-AES; Integra XL Dual, GBC, Melbourne, Australia). A standard reference material (SRM; contaminated soil BAM-U112a; certified by the BAM Federal Institute for Materials Research and Testing, Berlin, Germany) and a blank were included to validate the digestion operation.

Harvested rice samples (n=40) were air-dried to constant weight, husks were removed and pulverized using a homogenizer (Ace Homogenizer, Nihonseiki Kaisha Ltd, Tokyo, Japan), and stored until analysis. SRM rice flour [NIST 1568a]) and 0.5 g brown rice samples transferred into high pressured-polytetrafluoroethylene (PTFE) vessel were digested using 8 mL 70% HNO_3 and 1 mL H_2O_2 (Sigma,USA) using microwave digestion system (ETHOS, Milestone, Italy). After cooling at room temperature, extracts were filtered with 0.45 μm membrane filter, and adjusted to a final volume of 25 mL. Arsenic and Cd contents in brown rice were determined by HG-ICP-MS. The respective SRM accuracy values obtained for As and Cd were 0.29±0.05 and 0.019±0.001 mg kg^{-1} with certified values of 0.29±0.03 and 0.022±0.002 mg kg^{-1}, respectively. The extraction efficiency percent was 100.58±17.59% for As and 86.36±6.88% for Cd. All calculations and standard deviations between the replicates were done using the graphing software, SigmaPlot (version 10.0).

Results and Discussion

Compared to the flooded treatment, AWD and row treatments significantly reduced the concentration of As in brown rice with R-40 treatment showing the least concentration of As (Fig. 1a). AWD and row treatments reduced As levels by 45-60% and by 32-55% in Dasan and Boramchan cultivars, respectively. In the case of Cd, the trend was opposite; increased Cd concentrations were noticed in row and AWD treatments compared to the flooded treatment (Fig. 1b). Compared to the flooded control, Cd levels increased by 1.3-1.8 and 1.1-1.6 times in Dasan and Boramchan cultivars, respectively, with R-40 treatments showing a significant increase. The Dasan cultivar in AWD-60 water regime showed reduction in As without greatly increasing Cd concentration in brown rice (Fig. 1). Uptake of Cd and As has been shown to differ with rice cultivars (Hu et al., 2013a). With increasing irrigation from aerobic to flooded conditions, the As concentrations increased significantly in the straw, husk, and brown rice, whereas the Cd concentrations decreased (Hu et al., 2013a, b). However, intermittent and conventional treatments produced higher grain yields than the aerobic and flooded treatments. Li et al. (2009) suggested that maintaining aerobic conditions during either the vegetative or reproductive stage of rice growth decreased As accumulation in straw and grains significantly compared with rice grown under flooded conditions.

The grain yields were influenced by different water management practices in both the cultivars (Fig. 2). The flooded treatment displayed higher grain yield compared to AWD and row treatments. Between the cultivars, Boramchan cultivar showed an increase in grain yield under AWD-40 and R-40 treatments, while the Dasan cultivar displayed higher grain yield in AWD-60 and R-60 treatments. Yang et al. (2009) observed that alternate wetting and moderate soil drying reduces Cd in rice grains and increases grain yield. Linquist et al. (2015) noticed that the yields were reduced by <1-13% in AWD treatment compared to the flooded control treatment, but the grain As concentrations reduced by up to 64%. However, in a recent study, Das et al. (2016) noted that cultivating rice under AWD conditions as opposed to non-flooded and flooded conditions resulted in relatively low As levels in the rice grain, relatively high water productivity and a competitive grain yield.

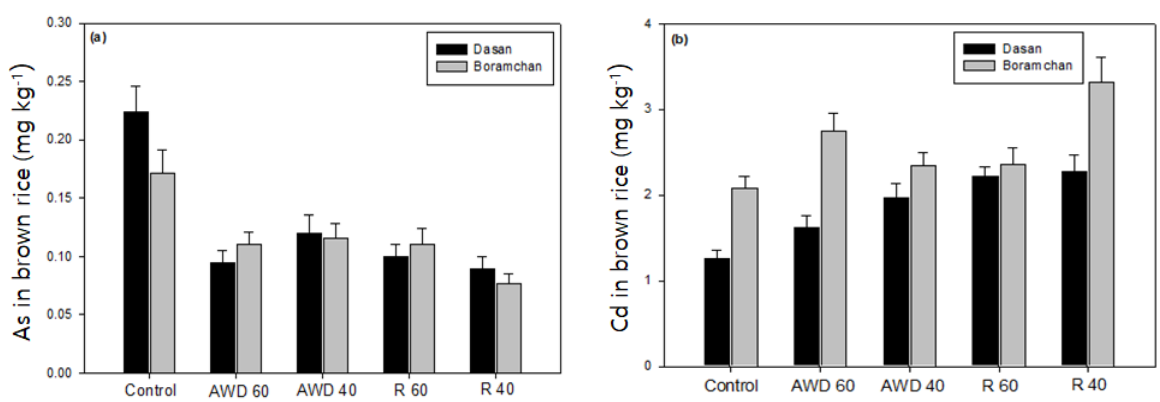


Fig. 1. Effect of water management on (a) arsenic (As) and (b) cadmium (Cd) concentrations in brown rice. AWD-Alternate wetting drying; R-Row.

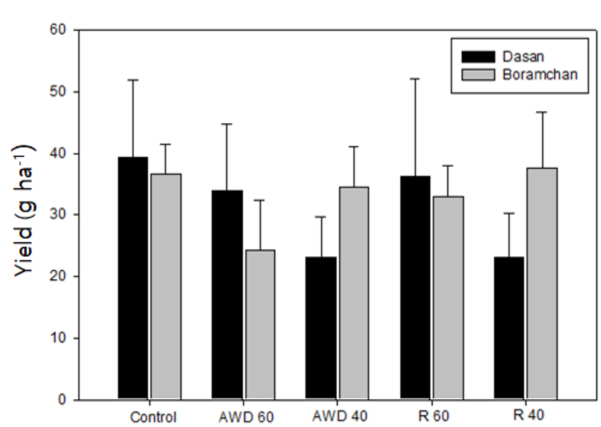


Fig. 2. Grain yields of rice cultivars as influenced by different water management regimes. AWD - Alternate wetting drying; R-Row.

Conclusion

Arsenic and Cd contamination threatens food security, safety and quality, as well as the long-term agricultural sustainability of rice crops. Managing low concentrations of As and Cd together in rice plants is challenging. In recent years, implementation of water-saving technologies in rice cultivation has received significant attention not only for saving substantial amounts of water but also for reducing greenhouse gas emissions and grain As levels in rice. Water management affects the bioavailability of As and Cd in soil and hence their accumulation in rice grains and grain yields. This study demonstrates that AWD water management offers a promising solution to mitigate As and Cd in rice grains, however, it depends on the selection of rice cultivars. Therefore, additional field studies using different upland and lowland rice cultivars under different water management practices are required to control both As and Cd in paddy soils and their uptake in rice grains.

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