Advance Journal of Food Science and Technology 5(9): 1244-1248, 2013
DOI:10.19026/ajfst.5.3090
ISSN: 2042-4868; e-ISSN: 2042-4876

Submitted: June 17, 2013 Accepted: June 25, 2013 Published: September 05, 2013

Research Article

Uptake and Bioaccumulation of Heavy Metals in Rice Plants as Affect by Water Saving Irrigation

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Abstract: To reveal the impact of Non-Flooding controlled Irrigation (NFI) on the bioavailability and bioaccumulation of metals (Cu, Pb, Cd and Cr) in rice fields, metals concentration in different organs of rice plant growing under both Flooding Irrigation (FI) and NFI were measured. It indicated that metals concentrations in root are always the highest one among all the plant organs and in the spike is the lowest. Compared with FI rice, NFI resulted in higher metal concentrations, bioaccumulation factors and metals uptakes of Cd, Cu and Pb. That might ascribed to the higher solubility and bioavailability of metals and the higher rice root absorbent ability under drying-wetting condition. But for Cr, NFI resulted in lower Cr concentration and uptakes in rice root than FI. It indicated that the Cr bound to the Fe and Mn oxides which were more stable under NFI condition may play a more important role in determining the bioavailability of Cr in paddy soil, but metals bound to organic matter which were more likely released may play a more important role for metals of Cu, Cd and Pb. When the soil is free from metals polluted, NFI can help to improve the availability of Cu as a micronutrient and reduce soil metals accumulation by drawing more metals out of the soil by plant uptakes. If the soil is metal polluted, NFI might result in the higher risk of food metals pollution in short-term. But long-term use of NFI will result in less metals accumulation in soil and finally resulted in reduced crop metals uptakes.

Keywords: Bioaccumulation, heavy metal, rice, uptake, water saving irrigation

INTRODUCTION

Heavy metals contamination has become a severe issue in agricultural production system around the world in the past few decades as a result of anthropogenic activities such as mining or industrial activities and the improper use of metal-enriched materials (Arao *et al.*, 2010; Wu and Zhang, 2010; Zheng and Zhang, 2011). The accumulation of metals in soil-plant system endangered the food security and people health. Rice is one of the most important cereal crops in monsoon Asian, which was also reported be confronted with metals pollution. The absorption and uptakes of metals by rice were determined simultaneously by the bioavailability of metals in soil and the rice root activity (Zheng and Zhang, 2011). The bioavailability of soil metals were always determined by the binding forms of metals in the soil (Zalidis *et al.*, 1999; Aydinalp and Marinova, 2003), which were associated with soil properties, including pH, cation exchange capacity, redox potentials (Eh) and contents of organic matter, clay minerals, calcium carbonate, Fe and Mn oxides (Kashem and Singh, 2001a, b; Kabra *et al.*, 2007; Usman, 2008). The absorption ability of rice roots are determined by soil aerobic condition, crop variety and soil mechanics conditions (Yoshida and Haseigawa, 1982; Iijima *et al.*, 1991; Kirk, 2003; Liu *et al.*, 2006, 2007; Adachi *et al.*, 2010; Mishra and Salokhe, 2011).

With the development of rice Water Saving Irrigation (WSI) technique, paddy soils were frequently subjected to multi-wetting-drying cycles and high Eh conditions (Mao, 2002; Bouman *et al.*, 2007; Mishra and Salokhe, 2011). Compared with the anaerobic saturated condition in traditional flooding rice field, which resulted in more stable or less liable fraction of metals in soil (Schwab and Lindsay, 1983; Patrick and Jugsujinda, 1992; Arao *et al.*, 2010), the wetting-drying and high Eh conditions in WSI fields led to change in the transformation and repartition of heavy metals in soil. At the same time, rice root growth was enhanced under WSI condition (Yang *et al.*, 2009; Liu *et al.*, 2010). Thus, wetting-drying cycle in flooding rice fields has been reported lead to change in both metals solubility and plant uptakes (Makino *et al.*, 2000; Zhang *et al.*, 2006; Liu *et al.*, 2010; Zheng and Zhang, 2011). But information on the bioaccumulation of metals in rice organs under WSI condition is still very little.

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In current research, with Non-Flooding controlled Irrigation (NFI) as a case of WSI technique, metals (Cu, Pb, Cd and Cr) uptakes and bioaccumulation were analyzed to reveal the influence of NFI on the bioavailability and bioaccumulation of metals in rice fields.

MATERIALS AND METHODS

The study was conducted in 2010 and 2011 in the rice fields at Kunshan irrigation and drainage experiment station (31° 15′ 15″ N, 120° 57′ 43″ E) in the Tai-lake region of China. The paddy soil is Stagnic Anthrosol, developed from alluvial deposits. The soil texture in the 0-20 cm is clay, with pH of 6.84 (soil: water, 1:2.5). Contents of organic matter, total nitrogen, total phosphorus and total potassium in 0-20 cm soil are 21.9, 1.03, 1.35 and 20.9 g/kg. The saturated water content (v/v) in 0-20, 0-30 and 0-40 cm soil layers are 54.4, 49.7 and 47.8%, respectively. The total Cu, Pb, Cd and Cr contents in 0-20 cm soil are 28.04, 15.69, 0.799 and 36.45 mg/kg. Those soil metals contents are less than the limit for soil pollution according to the Environmental quality standard for soils (State Environment Protection Administration of China, 1995), except for metal of Cd. The variety of rice is Japonica Rice NJ 46. It was transplanted with 13×25 cm hill spacing later June and harvested in later October. The same doses of fertilizers for each split were applied to each rice field, in agreement with the local conventional fertilizer application.

There were two irrigation treatments: Flooding Irrigation (FI) and NFI. A randomized complete block design was established with three replications in six plots (7×20 m). The ridges between plots were covered with plastic membranes which were inserted into the soil plough layer to a depth of 50 cm to avoid hydraulic exchange of water and nutrients between adjacent plots. The water management practice in both FI and NFI paddies were reported by Xu *et al.* (2013). Soil moisture during non-flooding period and water depth during flooding period were measured with three replicates for irrigation practice, by using Time-Domain Reflectometry equipment (TDR, Soil Moisture, USA) and vertical rulers fixed in the fields.

Plant samples were randomly taken from the plots at harvest and then divided into roots, sheaths, stems, leaves and spikes, before those were oven dried to a constant weight at 65°C. The dry weights were recorded and the dried subsamples of plant were ground to pass through a 1 mm sieve. Then dried crop samples (0.5 g) were digested in a polyvinyl-fluoride crucible with 4 mL of concentrated nitric acid (HNO_3). The Cu, Pb, Cd and Cr contents in the digested solution were measured using ICP-OES (Thermo ICAP 6000 duo, Thermo Scientific). Plant metals uptakes were calculated based on biomass and metals contents in each organ of the plants. The bioaccumulation factors were calculated as the ratios of metals concentrations in plant organs to the concentration in 0-20 cm paddy soils (Rezvani and Zaefarian, 2011).

RESULTS

Metals concentrations in plant organs: The metals concentrations in root are always the highest among all the plant organs and in the spike is the lowest (Table 1). For metals of Cd, Cu and Pb, NFI resulted in higher metal concentrations than FI in different organs of rice plant, but the different between NFI and FI treatments were mostly insignificant. For metal Cr, the concentrations in aboveground organs were almost the same between both irrigation treatments and FI resulted in higher Cr concentration than NFI in rice root.

Metal contents in spike are relevant to food security. According to the national standard for safety milled rice criteria (Ministry of Health of China, 2005), the Maximum Allowable Concentrations (MAC) of Cd, Pb and Cr are 0.20, 0.20 and 1.0 mg/kg, respectively. There was a certain metals pollution risk in rice for Cr and Pb, although the soil metals levels were safe except for Cd (State Environment Protection Administration of China, 1995). High risk in Cr and Pb pollutions for rice was also reported by Fu *et al.* (2008). But Cd level in spike is safe in current research, that might partially ascribed to change of binding forms of metals in soil under drying-wetting cycles condition. Assuming that the metals concentration in current research were determined in per weight of spike biomass (including null and rice) and the standards is mainly regarding to the polished rice, we cannot ensure the metals contents in polished rice is higher than the maximum level, because the metals in null always much higher than in polished rice (Cao and Hu, 2000; Fu *et al.*, 2008).

Plant metals uptakes: Metal uptakes in total and aboveground plant biomass were calculated and listed in Table 2. As a result of increased metals concentrations in different organs in NFI field, metals

Table 1: Metal concentrations in rice plant (unit: mg/kg)

Treatment		Root	Leaf	Sheath	Stem	Spike
2010						
Cd	FI	2.06a	0.38a	0.26a	0.27a	0.12a
	NFI	2.21a	0.43a	0.30a	0.33b	0.18b
Cr	FI	7.78a	2.66 a	3.07a	2.57a	2.40a*
	NFI	6.87b	2.62a	3.08a	2.61a	2.29a*
Cu	FI	2.69a	1.15a	1.07a	2.16a	0.89a
	NFI	3.09a	1.24a	1.23a	2.61b	0.92a
Pb	FI	12.90a	1.70a	2.47a	2.17a	0.45a*
	NFI	13.30a	1.87a	2.82a	2.33a	0.51a*
2011						
Cd	FI	2.00a	0.28a	0.20a	0.22a	0.11a
	NFI	2.08a	0.34a	0.23a	0.28b	0.15b
Cr	FI	5.23a	2.52a	2.81a	2.33a	1.70a*
	NFI	5.03a	2.50a	2.80a	2.33a	1.88a*
Cu	FI	2.95a	1.55a	1.45a	2.43a	0.65a
	NFI	3.40b	1.59a	1.53a	2.55a	0.75a
Pb	FI	10.80a	1.55a	2.15a	2.35a	0.30a*
	NFI	11.28a	1.83a	1.90a	2.25a	0.25a*

*: The metals contents higher than the maximum allowable concentrations, Different letter means significant different between NFI and FI treatments by t test

Table 2: Rice plant metal uptakes (unit: g/ha)

Treatment		Root	Aboveground	Total
2010				
Cd	FI	6.130a	4.100a	10.22a
	NFI	7.220a	5.300b	12.52a
Cr	FI	23.15a	44.94a	68.09a
	NFI	21.78a	48.05a	69.82a
Cu	FI	8.010a	20.32a	28.33a
	NFI	10.11b	23.92a	34.03b
Pb	FI	38.42a	26.31a	64.73a
	NFI	43.48b	31.64b	75.12b
2011				
Cd	FI	6.250a	3.130a	9.380a
	NFI	6.700a	4.090b	10.79a
Cr	FI	16.32a	39.60a	55.92a
	NFI	16.23a	42.75a	58.98a
Cu	FI	9.220a	23.27a	32.49a
	NFI	10.98b	25.15a	36.13b
Pb	FI	33.76a	22.48a	56.24a
	NFI	36.41a	23.06a	59.47a

Different letter means significant different between NFI and FI treatments by t test

Table 3: Bioaccumulation factors of metals

Treatment		Root	Leaf	Sheath	Stem	Spike
2010						
Cd	FI	2.578a	0.476a	0.325a	0.338a	0.150a
	NFI	2.766a	0.538a	0.375a	0.413b	0.225b
Cr	FI	0.213a	0.073a	0.084a	0.071a	0.066a
	NFI	0.188b	0.072a	0.084a	0.072a	0.063a
Cu	FI	0.096a	0.041a	0.038a	0.077a	0.032a
	NFI	0.110a	0.044a	0.044a	0.093b	0.033a
Pb	FI	0.822a	0.108a	0.157a	0.138a	0.029a
	NFI	0.848a	0.119a	0.180a	0.149a	0.033a
2011						
Cd	FI	2.503a	0.350a	0.250a	0.275a	0.138a
	NFI	2.603a	0.426a	0.288a	0.350b	0.188b
Cr	FI	0.143a	0.069a	0.077a	0.064a	0.047a
	NFI	0.138a	0.069a	0.077a	0.064a	0.052a
Cu	FI	0.105a	0.055a	0.052a	0.087a	0.023a
	NFI	0.121b	0.057a	0.055a	0.091a	0.027a
Pb	FI	0.688a	0.099a	0.137a	0.150a	0.019a
	NFI	0.719a	0.117a	0.121a	0.143a	0.016a

Different letter means significant different between NFI and FI treatments by t test

uptakes in NFI rice plant were mostly higher than in FI rice. The total uptakes of Cd, Cu and Pb were 2.30 and 5.70 and 10.39 g/ha higher in NFI field than in FI field in 2010 and 1.41, 3.64 and 3.23 g/ha higher in NFI field than in FI field in 2011. For the uptakes in root and aboveground organs of rice, uptakes of Cd, Cu and Pb were also higher in NFI fields than in FI field. But for metal of Cr, NFI resulted in fewer uptakes in root and more uptakes in aboveground organs. Root uptakes of Cr in NFI field were 1.37 and 0.09 g/ha lower than in FI in 2010 and 2011, uptakes of Cr in aboveground organs in NFI fields were 3.11 and 3.15 g/ha higher than in FI.

Bioaccumulation factors of metals: Bioaccumulation factors of metals in different rice plant organs under different irrigation treatment were listed in Table 3. It indicated root accumulated more metals and the spike accumulated fewer metals than other organs. Compared with rice under FI condition, rice under NFI irrigation accumulated more metals (Cd, Pb and Cu) in the most organs, although only a few comparison are significant at $p = 0.05$ level. But for metal Cr, FI resulted in higher Cr accumulation than NFI in rice root. That shows the same phenomena to the comparison of metals concentration in rice plant organs.

DISCUSSION

Why NFI resulted in higher uptakes and enrichment of metals (Cd, Pb and Cu) in rice plant organs than FI. That might ascribed to two main factors. The first is that the drying-wetting conditions led to higher solubility and bioavailability of metals in NFI fields. That was confirmed on different metals in soils and sediments (Kelderman and Osaman, 2007; Vandecasteele *et al.*, 2007; Zhang and Meng, 2008; Zheng and Zhang, 2011; Frohne *et al.*, 2011; Xu *et al.*, 2013). Another reason is that the rice root under water-saving irrigation was frequently reported with higher absorbent ability than rice under flooding condition (Yang *et al.*, 2009; Liu *et al.*, 2010). In current research, NFI rice root dehydrogenase activity measured by the TTC reduction method were 336.4, 181.3, 137.5, 77.2 and 59.6 ug/g/h in later tillering, jointing and booting, earing and sprouting and milk maturity stages, it was increased by 25.8-99.5% than in FI rice root.

But for metal Cr, it was different. That might ascribed to the different in the change of binding forms of metals in soils under the NFI condition. The drying-wetting cycles enhanced the transform of Fe and Mn from amorphous oxides to more crystalline forms which can immobilize trace metals (Zhang *et al.*, 2006; Tack *et al.*, 2006; Koopmans and Groenenberg, 2011) and consequently led to a stronger binding of the metals and an increase of metals binding with the Fe and Mn oxides. But at the same time, it also led to increase in soil dissolved organic matter which resulted in the release of metals which were bounded to sulfurs and organic matters (Arao *et al.*, 2010; Tang *et al.*, 2011; Koopmans and Groenenberg, 2011). That implies that the change of the transformation of metals Cr is different from other metals. The Cr bound to the Fe and Mn oxides may play a more important role in rice field, but metals bound to organic matter may play a more important role for metals of Cu, Cd and Pb.

Some of the metals are also micronutrients to crops, such as Cu and Zn, Some metals are toxic pollutant, such as Pb, Cd, Cr, As and Hg. In current research, NFI can help to improve the availability of Cu as a micronutrient. That means NFI may play an active role in improving micronutrient availability when the soil is free from Cu pollution. But long-term application of NFI might lead to soil Cu deficit. When the soil is metal polluted, NFI is help to reduce soil metals accumulation by drawing more metals out of the soil by plant uptakes, but might result in the higher risk of food metals pollution in short-term. If the plant is hyper-accumulation and not for food, which can be used in phytoremediation, NFI might be the suitable water management for phytoremediation of metal polluted paddy soil. And in long-term NFI will result in les metals accumulation in soil and finally resulted in reduced crop metals uptakes.

CONCLUSION

For metals of Cd, Cu and Pb, NFI resulted in higher metal concentrations and bioaccumulation factors than FI in different organs of rice plant. As a result, Cd, Cu and Pb uptakes in NFI rice plant were mostly higher than in FI rice. But NFI resulted in lower Cr concentration and uptakes in rice root than FI. The higher uptakes and enrichment of Cd, Pb and Cu in NFI rice plant might be ascribed to the higher solubility and bioavailability of metals and the higher rice root absorbent ability under drying-wetting condition. It also indicated that the Cr bound to the Fe and Mn oxides which were more stable under non-flooding condition may play a more important role in determining the bioavailability of Cr in paddy soil, but metals bound to organic matter which were more likely released may play a more important role for metals of Cu, Cd and Pb. When the soil is free from metals polluted, NFI can help to improve the availability of Cu as a micronutrient and reduce soil metals accumulation by drawing more metals out of the soil by plant uptakes. If the soil is metal polluted, NFI might result in the higher risk of food metals pollution in short-term. But long-term use of NFI will result in less metals accumulation in soil and finally resulted in reduced crop metals uptakes.

ACKNOWLEDGMENT

The research was financially supported by the National Natural Science Foundation of China (No. 50839002), State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (No. 2010585112) and Qinglan Project of Jiangsu Province.

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