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RESEARCH ARTICLE

Effects of chicken manure application on cadmium and arsenic accumulation in rice grains under different water conditions

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Abstract

Widespread contamination of agricultural soil with Cd and As has resulted in substantial transfer and accumulation of these toxicants in rice grains. In the present study, we investigated the effects of chicken manure application on Cd and As concentrations and As speciation in the rice grains grown under different water conditions by pot experiment. Under aerobic condition, the application of chicken manure increased soil pH and soil Eh during most of the growth period of rice. Consequently, the application of chicken manure has little effect on total Cd, slightly decreased total As and inorganic As of rice grains when applied at rate of 2.0%. Under intermittent irrigation condition, the application of chicken manure increased soil pH and decreased soil Eh during most of the growth period of rice. Thus, chicken manure decreased total Cd, As, and inorganic As of rice grains. Besides, there was increased reduction of Cd and As with increase in the amount of chicken manure applied. Under flooded condition, the application of chicken manure increased soil pH before heading but decreased soil pH after heading. The application of chicken manure dramatically decreased total and inorganic As in rice grains, and slightly decreased Cd of rice grains. There was increased reduction of total As concentration with the increase in the amount of chicken manure applied. Meanwhile, the inorganic As concentration was the lowest when the concentration of chicken manure was 1.0%.

Keywords Arsenic · As speciation · Cadmium · Chicken manure · Rice · Water management

Introduction

Exposure to toxic metals, particularly Cd and As, has become an increasingly recognized cause of illness worldwide (Honma et al. 2016; Meharg et al. 2013; Waqas et al. 2014; Zhao et al. 2015). Cd is a nephrotoxic heavy metal element that can readily accumulate in crops, leading to several diseases in livestock and human being (Hu et al. 2016; Khan et al. 2013). As, especially inorganic As (iAs), is a highly toxic human carcinogen that can cause lung and urinary tract cancer, cardiovascular disorders, and skin lesions (Honma et al. 2016). Rice (*Oryza sativa* L.), the staple food of more than half the global population, has been considered a major exposure pathway of Cd and As intake by humans (Liang et al. 2010; Mondal and Polya 2008; Tsukahara et al. 2003; Xu et al. 2008). Therefore, minimization of Cd and As concentrations in rice grains is an important health issue (Arao et al. 2009).

Among the agronomic management practices, water management has been recommended as one of the most effective ways to reduce bioavailability of Cd and As in paddy soils simultaneously and their subsequent uptake by rice plant (Arao et al. 2009; Rahaman et al. 2011; Hu et al. 2013). The predominant form of plant-available Cd is a metal ion, and its uptake is suppressed under flooded conditions. Ito and Iimura (1976) attributed the decrease in Cd uptake by rice plants to the formation of CdS when the soil has a low redox potential.

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However, drainage of paddy soils results in an oxidative condition that accelerates the conversion of CdS to soluble $CdSO_4$ (Bingham et al. 1976; Ito and Iimura 1976). Inahara et al. (2007) reported that maintaining flooded water conditions from 15 days before heading to 25 days after heading reduced the concentration of Cd in brown rice by 84% when compared with the concentration observed upon intermittent irrigation. As might be present in soil both as inorganic As (mainly arsenite As(III)) and methylated As species (mainly dimethylarsinic acid (DMA)) (Williams et al. 2006), and the predominant As species in the rice grains is iAs, which is generally considered more toxic than the methylated As species (Schoof et al. 1999). Besides, it has been established that anaerobic conditions enhance the bioavailability of As in paddy soils, ascribed to the reduction of arsenate to arsenite (Masscheleyn et al. 1991; Marin et al. 1993; Takahashi et al. 2004). Xu et al. (2008) reported that rice grain grown under flooded irrigation contained As species mostly in the form of DMA, whereas iAs accounted for the majority of total As under aerobic condition. Methylation of As might be a response to the increase in As uptake in rice grains when cultivation conditions change from aerobic to flooded. However, water management is known to affect the mobility and bioavailability of Cd and As to rice plants, and their subsequent accumulation in rice grains. Flooding condition increases the concentration of As in rice grains, whereas aerobic and intermittent treatments increase the concentration of Cd. Therefore, it might be difficult to maintain a low concentration of Cd and As in rice grains simultaneously by means of water management alone.

In situ remediation using soil amendment has been used for Cd- and As-contaminated paddy soils. It has been established that the application of silicon-based materials (Li et al. 2009; Seyfferth and Fendorf 2012), iron materials (Yamane 1989; Liu et al. 2004; Nath et al. 2014; Honma et al. 2016), and organic matters (Huang et al. 2012; Li et al. 2018) to paddy soils decreases As uptake in rice grains. Soil amendments employed for Cd immobilization include natural and modified additives, such as clay minerals (Yin et al. 2017; He et al. 2018), phosphorus materials (Sun et al. 2016; Wiggenhauser et al. 2019), and organic matters (Gao et al. 2018; Zhou et al. 2018). Among these amendments, organic manures are a promising, simple, natural material that can influence trace element mobility and toxicity. On one hand, CM might influence available Cd and As by changing soil pH. To the best of our knowledge, the adsorption of cationic elements increases with increase in pH, whereas the adsorption of arsenate (As(V)) exhibits an opposite trend. On the other hand, CM might suppress the bioavailability of Cd or As via complexing, adsorbing, and precipitating functions.

It has been reported that the application of chicken manure (CM) decreases Cd concentration in plants, and there is increased reduction with increasing amounts of CM applied (Yao et al. 2009; Huang et al. 2018). However, there are few reports on the effects of combined CM application and water management on Cd and As uptake by rice plants and As speciation in rice grains. The objectives of the present study were to investigate the simultaneous effects of water management and CM application on dissolved Cd and As concentrations in soils, Cd and As uptake by rice, and As speciation in rice grains, to identify the optimal water management methods and application ratio of CM for minimizing Cd and As concentrations simultaneously in rice grains.

Materials and methods

Characteristics of chicken manure and soil

Soil with natural Cd and As content was collected from the 0 to 20-cm layer in Chenzhou, Hunan, South China (112° 43′ 48″ N, 25° 43′ 48″ E) (Fig. 1). The soil samples passed through a 20-mesh sieve were used for physical and chemical analysis, and those passed through a 100-mesh sieve were used for the determination of Cd and As concentrations (Sun et al. 2016). The characteristics of the soil are presented in Table 1. CM was purchased from a local fertilizer market in Tianjin, China. The CM contained 44.1% organic matter, 3.42% total N, 0.89% total P, 2.04% total K, and 2.53% total S. The concentrations of total Cd and As in the CM, determined by inductively coupled plasma mass spectrometry (iCAP Q; Thermo Scientific, Waltham, MA, USA) after digestion with HNO_3 and $HClO_4$, were 4.7 and 18.4 mg kg^{-1}, respectively. The pH of CM measured at a soil-to-water ratio of 1:2.5 (w/v) with a pH meter (PB-10, Sartorius, Germany) was 6.47 (Yin et al. 2017).

Pot study setup

Pot experiments, with three replications each, were conducted in 2017 in a greenhouse at ambient temperatures (7–36 °C) under sunlight. All soil samples were air-dried, sieved (< 5 mm), and homogenized before the pot experiment. CM was air-dried, homogenized, and passed through 20-mesh sieve. A compound fertilizer, containing 3.87 g urea and 6.24 g monopotassium phosphate, was added to each pot by basal application (Xiao et al. 2015). During the growth stage, urea containing 0.2 g of N was top-dressed to each pot at the mid-tillering stage (40 days after transplanting). Contaminated soil (6 kg) was placed in plastic pots with an internal diameter of 24 cm and height of 34 cm, and the CM was blended into the contaminated soils at the ratio of 0.5%, 1.0%, and 2.0% (weight/weight), which were determined considering the remediation effect and economic benefit. A soil–water sampler (Rhizosphere Research Products B.V., Wageningen, the Netherlands) was buried at a depth of 15 cm in the middle

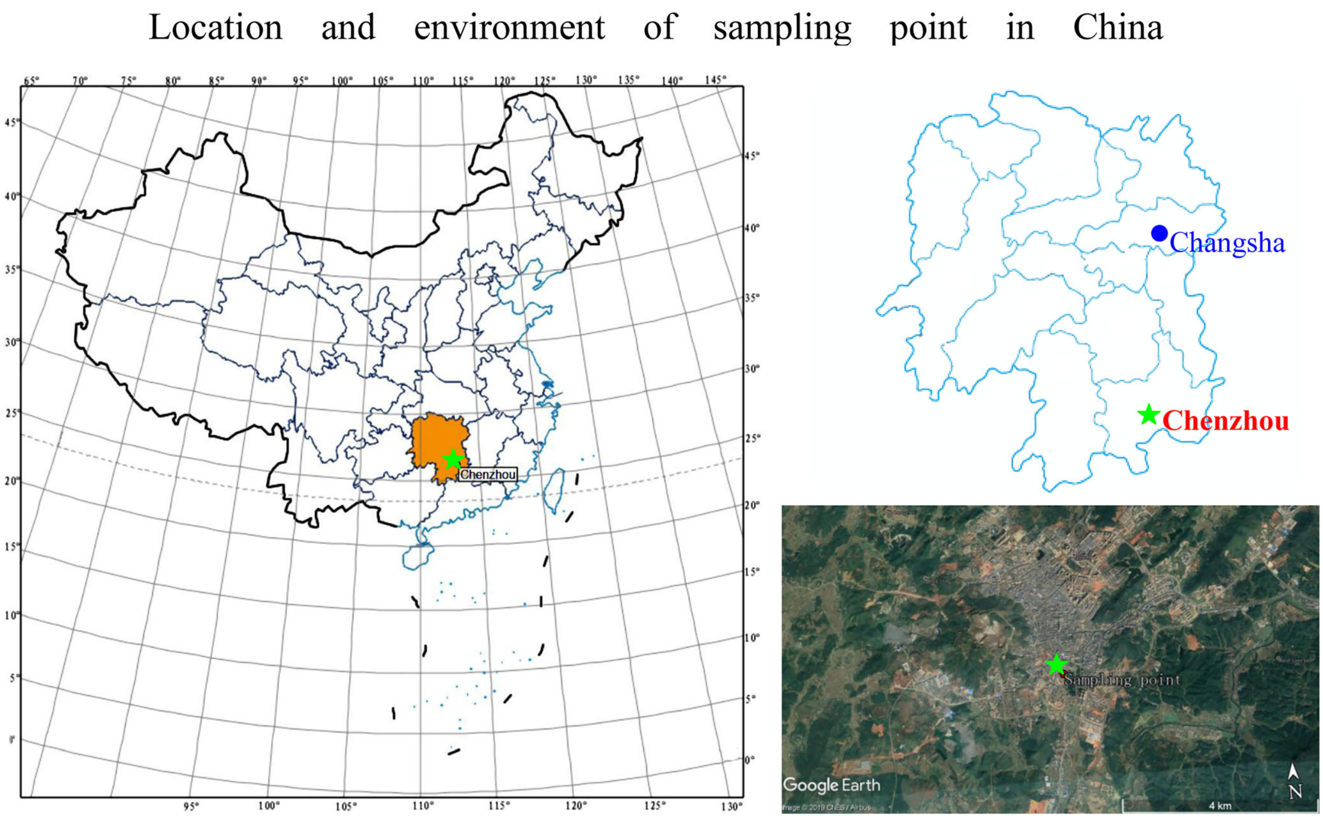

Fig. 1 Location of sampling point (green star) in Chenzhou, Huan province, China

of each pot for collecting soil solution. The soils were equilibrated for 1 month, maintaining approximately 75% of field water-holding capacity with tap water (without Cd).

Seedlings of rice (*Oryza sativa* L.) were germinated on perlite and transplanted on June 11, 2017. The rice plants were grown under uniform flooded conditions for 21 days before the water treatment. Thereafter, three different water managements were conducted, namely, flooded condition (2–3 cm water layer in the top soil throughout the growth period of rice plants), intermittent irrigation (repeated every 7-day with 3-day flooding followed by 4-day drainage), and aerobic condition (moisture was maintained in the top soil during the whole growth period of rice plants).

Table 1 Basic characteristics of soil

Properties	Value
pH (H_2O)	6.21
OM[a] (g kg^{-1})	34.6
Total N (mg kg^{-1})	42.9
Available P (mg kg^{-1})	9.3
Available K (mg kg^{-1})	182.7
CEC[b] (cmol kg^{-1})	25.3
Total Cd (mg kg^{-1})	2.5
Total As (mg kg^{-1})	11.0

[a] *OM* organic matter

[b] *CEC* cation exchange capacity

Sample preparation and analysis

Soil redox potential (Eh) was measured in situ using an ORP meter (Seven2Go Pro S8; Mettler-Toledo GmbH, Greifensee, Switzerland) with platinum electrodes (Redox, Switzerland) installed at a depth of 10 cm in each plot. The pH of soil solution was measured using a glass electrode (Expert Go-ISM, Switzerland). Meanwhile, the soil solution was sampled according to the method recommended by Arao et al. (2009) with minor modifications from early June to late September at intervals of 1–2 weeks to determine the concentrations of dissolved Cd and As.

To analyze the rice plants, two rice hills were selected for sampling at the maximum tiller number (July 12), heading (August 23), and maturing stages (October 11). Plant samples collected before maturity were separated into shoots and roots. After 135 days of growth, the plants were harvested, cut off at the rhizome junction, and separated into root, straw, rachis, husk, and rice grains. The rice grains were oven-dried at 75 °C and weighed immediately after removing the husk and unfilled grains. The plant samples and rice grains were ground to a fine powder, and the plant material remaining on the 1.85-mm sieve was used for further analysis.

Dried and powered rice plant samples (0.2500 ± 0.0005 g) were digested in 4:1 (v/v) $HNO_3/HClO_4$ (10 mL) using a block digester (Yin et al. 2017). The concentration of Cd and As in the digested samples and soil solutions was determined by inductively coupled plasma mass spectrometry (iCAP Q; Thermo Scientific, Waltham, MA, USA).

The concentrations of predominant As species in rice grains were determined according to the methods recommended by Baba et al. (2014) with minor modifications. The powdered sample of rice grain (1 g dry weight) was digested with 20 mL of 0.15 M HNO_3 on a thermostat at 90 °C for 2.5 h with regular shaking at every 30 min intervals. The solution obtained was centrifuged at 4000 rpm for 20 min and the supernatant was filtered through a sterilized 0.45-μm filter. Arsenic speciation in the rice grain was determined by HPLC (DIONEX Ultimate 3000, Thermo Scientific, Waltham, MA, USA) with ICP-MS (iCAP RQ, Thermo Scientific, Waltham, MA, USA). HPLC/ICP-MS analysis showed that the rice grain samples contained mostly As(III) and DMA.

Quality control

To monitor the accuracy and quality of chemical analyses, quality control measures were adopted using soil (GBW(E)-070009) and plant reference materials (GBW-10045 (GSB-23)) obtained from the Institute of Geophysical and Geochemical Exploration (IGGE, China). All reagent used in the experiment are guarantee reagent. Three reagent blanks and three standard reference materials were included in each batch of extraction, preparation, and analysis of every 40 samples. No Cd and As was detected in the reagent blanks (only HNO_3). The recovery rate was 95–101% and 91–101% for Cd and As of plants, respectively. The recovery rate was 90–100% and 90–110% for Cd and As of soil, respectively.

Statistical analyses

Statistical analyses were preformed using Excel 2010 and SAS 9.2 (SAS Inc., NC, USA). The mean values of the experimental parameters were compared using Student's *t* test at $p \leq 0.05$ (significant).

Results

Effects of CM on grain yield under different water management treatments

The application of CM had little effect on grain yield under aerobic condition. Under intermittent irrigation, the application of 2.0% CM marginally increased grain yield, but the application of 0.5% and 1.0% CM dramatically decreased grain yield. The application of CM significantly increased grain yield under flooded condition. Grain yield increased by 39.6%, 49.4%, and 48.4% upon applying 0.5%, 1.0%, and 2.0% CM, respectively (Table 2).

Soil pH, Eh, and the concentration of total dissolved Cd and As in soil solution

Figure 2 shows the effects of CM on total dissolved Cd and As concentrations in soil solution among different water management treatments. As shown in Fig. 1, the dissolved Cd concentration increased until the maximum tiller number stage, and then decreased till the fully matured period under the aerobic and intermittent irrigation conditions. While, dissolved Cd concentration throughout the growth period under flooded condition. Dissolved Cd decreased on Jul 10 as a consequence of top-dressing with urea at the mid-tillering stage. The dissolved Cd concentration was higher under aerobic condition than under intermittent irrigation condition. The concentration of dissolved Cd stayed well below 0.4 μg L^{-1} under the flooded condition in the control treatment. The application of CM significantly decreased the dissolved Cd concentration in soil solution under aerobic condition but increased Cd concentration under intermittent and flooded irrigation conditions.

The dissolved As concentrations in soil solution stayed well below 20 μg L^{-1} under aerobic and intermittent irrigation conditions after implementation of the water management practices, whereas it exceeded 100 μg L^{-1} under flooded condition. The application of CM increased dissolved As concentration in soil solution under aerobic and intermittent irrigation conditions, while it decreased dissolved As concentration under flooded condition. There was an increased reduction of dissolved As in soil solution with increased application of CM.

Figure 3 shows the effects of CM on soil pH and Eh under different water treatment throughout the growth period of rice. As shown in Fig. 3, soil pH and Eh were strongly affected by water management and the application of CM. The pH of soil increased initially, and then decreased till the heading stage, then increased again under different water conditions. The pH of soil was almost below 7.5 in the aerobic and intermittent irrigation conditions. The pH of soil was maintained at 7.5–8.0 under the flooded condition in control treatment after implementing the water management practice. The application of CM increased soil pH during most of the growth period under different water conditions, especially under the aerobic water condition. The pH of soil exceeded 7.5 with the application of CM under aerobic condition, and it

Table 2 Effects of chicken manure on grain yield under different water management treatments

Water management	Grain yield (g pot^{-1})			
	CK	CM1	CM2	CM3
Aerobic	25.4 ± 0.9 a	26.8 ± 0.4 a	27.5 ± 1.2 a	23.8 ± 0.5 a
Intermittent	27.8 ± 1.2 a	21.9 ± 0.2 b	21.8 ± 1.2 b	32.2 ± 0.9 a
Flooded	24.5 ± 1.1 b	34.2 ± 0.1 a	36.6 ± 0.1 a	36.35 ± 0.5 a

(a) CK, no chicken manure was applied, CM1, 0.5% (*w/w*, the same below) CM was applied to the pots; CM2, 1.0% CM was applied to the pots; CM3, 2.0% CM was applied to the pots. (b) The values with different letters in each set were significantly different at $p < 0.05$. Data are means ± SE ($n = 3$)

exceeded 8.0 under flooded condition. The application of 0.5% CM decreased soil pH, while 1.0% and 2.0% CM increased soil pH under intermittent irrigation.

The Eh of soil increased until the heading stage, and then decreased under different water conditions. The Eh of soil ranged from − 100 to − 250 mV under flooded irrigation. The Eh of soil dramatically increased under aerobic and intermittent irrigation conditions after implementation of water management practices. After the application of CM, soil Eh exceeded 200 mV during most of the time of vegetative growth stage and the whole reproductive growth stage under aerobic condition. The application of CM marginally decreased soil Eh during most of the growth period under intermittent irrigation conditions. But, the application of CM showed font-to-back effect on the Eh of soil under flooded irrigation conditions.

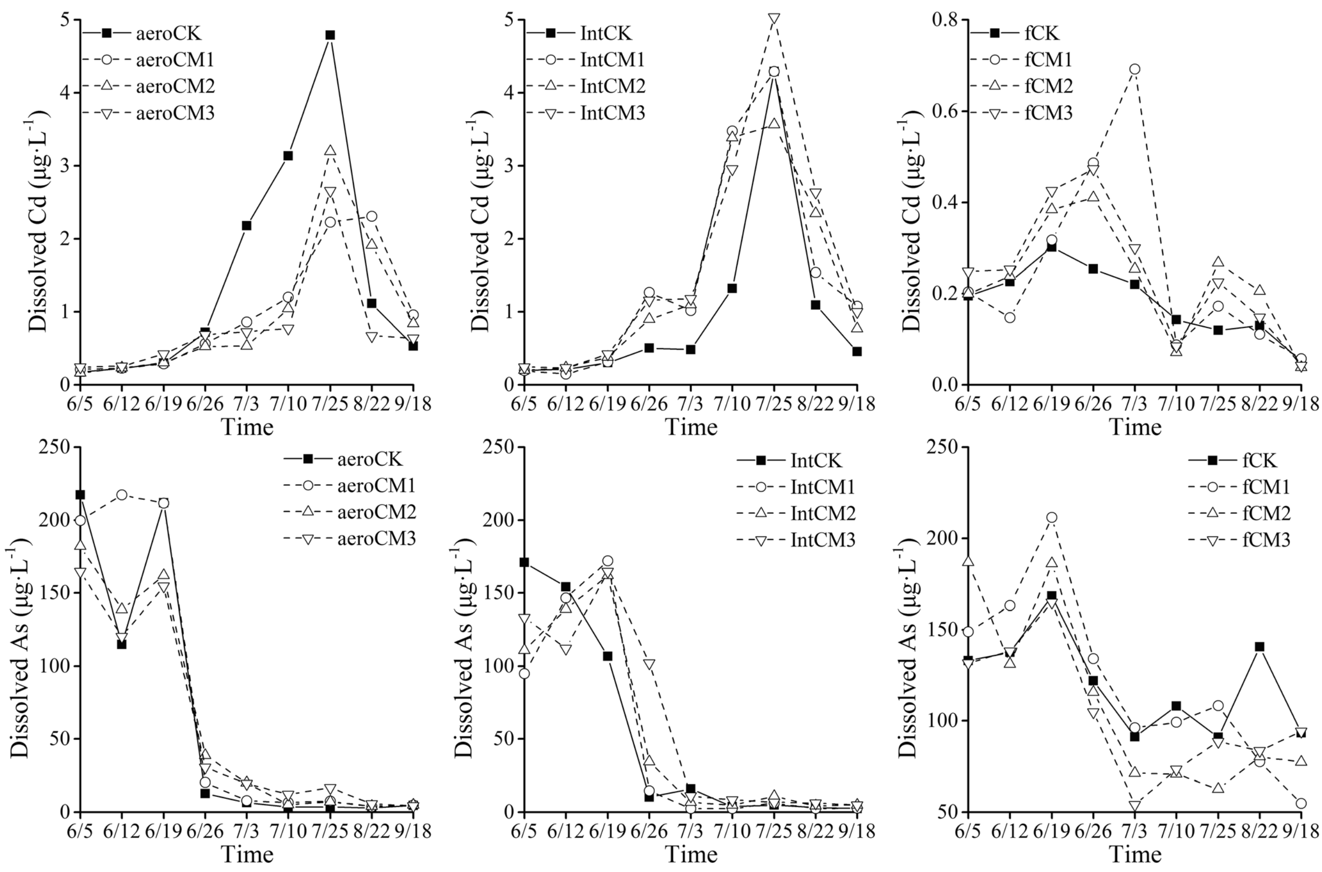

Fig. 2 Changes in dissolved Cd concentration and As concentration throughout the growth period of rice. aeroCK, the pots were maintained under aerobic condition during the growth period and had no chicken manure (CM) applied; aeroCM1, the pots were maintained under aerobic condition and had 0.5% CM applied; aeroCM2, the pots were maintained under aerobic condition and had 1.0% CM applied; aeroCM3, the pots were maintained under aerobic condition and had 2.0% CM applied; IntCK, the pots were intermittently irrigated and had no CM applied; IntCM1, the pots were intermittently irrigated and had 0.5% CM applied; IntCM2, the pots were intermittently irrigated and had 1.0% CM applied; IntCM3, the pots were intermittently irrigated and had 2.0% CM applied; fCK, the pots were flooded and had no CM applied; fCM1, the pots were flooded and had 0.5% CM applied; fCM2, the pots were flooded and had 1.0% CM applied; fCM2, the pots were flooded and had 2.0% CM applied

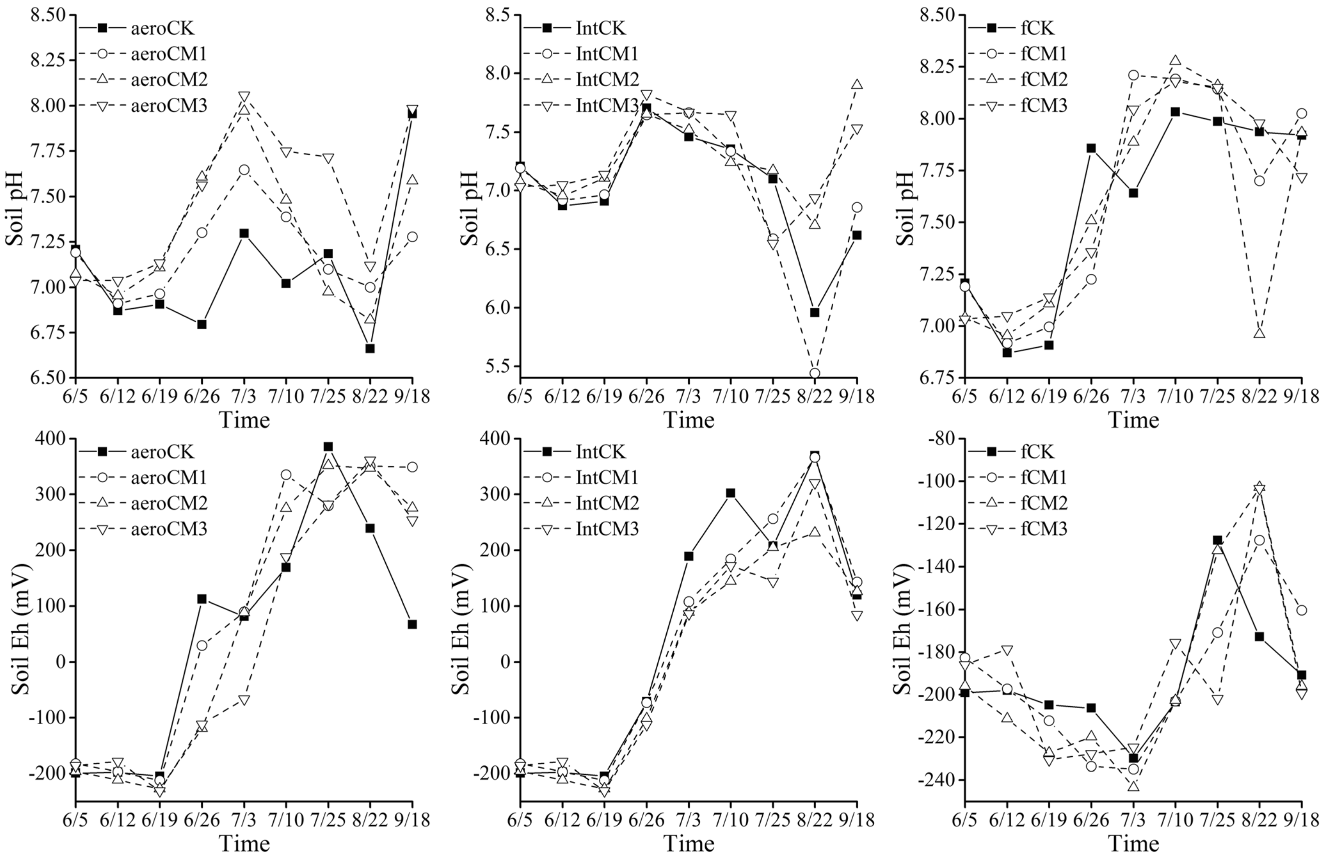

Fig. 3 Changes in soil pH and Eh throughout the growth period of rice. aeroCK, the pots were maintained under aerobic condition during the growth period and had no chicken manure (CM) applied; aeroCM1, the pots were maintained under aerobic condition and had 0.5% CM applied; aeroCM2, the pots were maintained under aerobic condition and had 1.0% CM applied; aeroCM3, the pots were maintained under aerobic condition and had 2.0% CM applied; IntCK, the pots were intermittently irrigated and had no chicken manure (CM) applied; IntCM1, the pots were intermittently irrigated and had 0.5% CM applied; IntCM2, the pots were intermittently irrigated and had 1.0% CM applied; IntCM3, the pots were intermittently irrigated and had 2.0% CM applied; fCK, the pots were flooded and had no chicken manure (CM) applied; fCM1, the pots were flooded and had 0.5% CM applied; fCM2, the pots were flooded and had 1.0% CM applied; fCM2, the pots were flooded and had 2.0% CM applied

Cd and As concentrations in shoots of rice plant during the growth period

As shown in Fig. 4, the concentration of Cd in shoots of rice plants significantly increased during the vegetative growth stage (Aug 23) and decreased during the reproductive growth stage under different water management treatments. This is because a large amount of Cd was transferred and accumulated in rice grains during the ripening and maturing stages. The application of CM significantly decreased the concentration of Cd in shoots under different water management treatments during the whole growth period. The application of CM was the most effective at the ratio of 1.0%, 2.0%, and 0.5% under aerobic, intermittent, and flooded conditions, respectively.

The concentration of As in shoots significantly decreased during the vegetative stage, but remarkably increased during the ripening and maturing stages under different water management treatments. The concentration of As was well below 3 mg kg^{-1} under aerobic and intermittent irrigation conditions. Under flooded condition, the concentration of As in shoots was particularly high during the tillering stage, and then decreased considerably during the heading and maturing stages (Aug 23). The application of CM considerably decreased the concentration of As in shoots throughout the rice growth period under different water management treatments. During the vegetative stage, the application of CM was the most effective at the ratio of 1.0%, 0.5%, and 2.0% under aerobic, intermittent, and flooded irrigation conditions, respectively.

Total As and Cd concentrations and As speciation in rice grains

Table 3 shows the combined effect of water management and the application of CM on Cd concentration and As speciation. As shown in Table 3, Cd content in rice grains was well above 1.0 mg kg^{-1} under aerobic and intermittent water conditions. Compared with aerobic and intermittent conditions, Cd content in rice grains decreased by 79.7–89.6% under flooded condition. The application of CM had little effect on the concentration of Cd under aerobic condition. Under intermittent

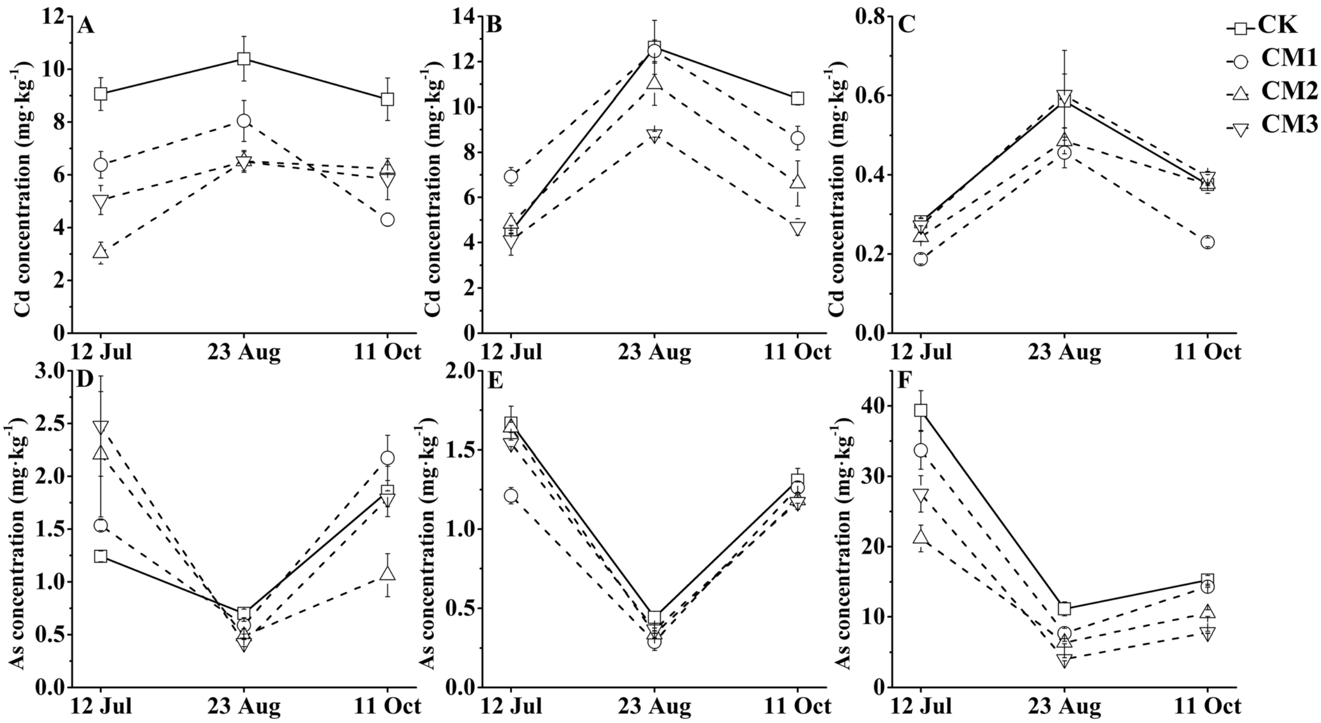

Fig. 4 Cd and As concentrations in shoots of rice plant under different treatments during the whole growth period. (a) A/D, The pots were maintained under aerobic condition during the growth period; B/E, the pots were intermittently irrigated; C/F, the pots were maintained under flooded condition. (b) CK, no chicken manure was applied to the pots; CM1, 0.5% CM was applied to the pots; CM2, 1.0% CM was applied to the pots; CM3, 2.0% CM was applied to the pots

irrigation condition, the application of 0.5%, 1.0%, and 2.0% CM decreased the concentration of Cd by 5.7%, 31.0%, and 48.0%, respectively. Under flooded condition, the application of 0.5%, 1.0%, and 2.0% CM decreased the concentration of Cd by 24.1%, 10.3%, and 17.2%, respectively.

The concentration of total As in rice grains under aerobic and intermittent irrigation conditions was well below 0.2 mg kg^{-1}, the standard for inorganic As proposed by Codex Alimentarius Commission. Flooded irrigation significantly increased the concentration of total As of rice grains. The application of CM decreased total As and there was increased reduction of total As with increased CM application under different water conditions. As reduction in rice grains upon 2.0% CM application reached 27.9%, 29.7%, and 48.7% under aerobic, intermittent, and flooded conditions, respectively.

Table 3 also shows the combined effects of water management and CM application on As speciation in rice grains. The main As species detected were As(III) and DMA(V). As(V) and Monomethyl arsenate (MMA) are not shown in the figure because they were all below the detection limit. The application of CM decreased As(III) under different water condition, and there was increased reduction with the increased application of CM. When the concentration of CM reached 2.0%, the application of CM significantly decreased As(III) under aerobic and intermittent irrigation conditions. While under flooded condition, the application of 0.5%, 1.0%, and 2.0% CM significantly decreased As(III) by 33.3%, 49.8%, and 48.8%, respectively.

Discussion

In the present study, there was only a marginal difference in grain yield under different water management conditions; however, the grain yield was higher under flooded and intermittent conditions than under aerobic irrigation. These results are consistent with those of Hu et al. (2013) and Sun et al. (2014). They reported that in all the rice cultivars examined, the grain yield of rice grown under intermittent condition was higher than that under aerobic and flooded irrigation conditions. The application of CM promoted rice growth under intermittent and flooded management conditions, but had little effect under aerobic condition.

This study investigated the changes in soil pH, Eh, and concentrations of dissolved Cd and As in soil solution throughout the growth period of rice plants. Soil pH continuously increased during the seedling stage and declined considerably after 2–3 weeks of vegetative growth under different water management conditions, which is consistent with the findings of Honma et al. (2016). This rhizosphere acidification likely occurred because of higher uptake cations, such as NH_4^+ and K^+, than that of anions (Maheshwari et al. 2012). Elevated concentration of dissolved Cd in the soil solution was observed as the pH decreased below 7.5 or 6.5 (Fig. 2). Javed et al. (2017) have also reported that the decrease in available Cd in the rhizosphere can be attributed to the increase in pH.

Table 3 As speciation and Cd concentrations in rice grains

Treatment		Total As (mg kg^{-1})	sum As (mg kg^{-1})	As(III) (mg kg^{-1})	DMA (mg kg^{-1})	Cd (mg kg^{-1})
Aerobic	CK	0.181 ± 0.005 a	0.176 (97)	0.157 ± 0.005 a	0.019 ± 0.002 a	1.70 ± 0.065 a
	CM1	0.165 ± 0.001 ab	0.153 (93)	0.133 ± 0.007 a	0.020 ± 0.003 a	1.63 ± 0.020 a
	CM2	0.144 ± 0.001 ab	0.145 (101)	0.131 ± 0.001 a	0.014 ± 0.002 a	1.53 ± 0.123 a
	CM3	0.130 ± 0.011 b	0.109 (84)	0.092 ± 0.006 b	0.017 ± 0.003 a	1.48 ± 0.039 a
Intermittent	CK	0.169 ± 0.009 a	0.140 (83)	0.127 ± 0.011 a	0.013 ± 0.003 b	2.29 ± 0.171 a
	CM1	0.160 ± 0.005 a	0.144 (90)	0.117 ± 0.006 ab	0.027 ± 0.001 a	2.16 ± 0.076 a
	CM2	0.129 ± 0.001 b	0.113 (88)	0.101 ± 0.005 ab	0.012 ± 0.002 b	1.58 ± 0.029 b
	CM3	0.119 ± 0.001 b	0.083 (70)	0.083 ± 0.001c	< 0.01	1.19 ± 0.094 c
Flooded	CK	0.801 ± 0.012 a	0.635 (79)	0.432 ± 0.034 a	0.203 ± 0.007 a	0.29 ± 0.001 a
	CM1	0.522 ± 0.052 b	0.451 (86)	0.288 ± 0.007 b	0.163 ± 0.017 a	0.22 ± 0.005 c
	CM2	0.485 ± 0.039 bc	0.402 (83)	0.217 ± 0.005 c	0.185 ± 0.009 a	0.26 ± 0.012 b
	CM3	0.411 ± 0.019 c	0.386 (94)	0.221 ± 0.013 c	0.165 ± 0.001 a	0.24 ± 0.009 bc

(a) CK, no chicken manure was applied, CM1, 0.5% (*w/w*, the same below) CM was applied to the pots; CM2, 1.0% CM was applied to the pots; CM3, 2.0% CM was applied to the pots. (b) Data are means ± SE ($n = 3$); sum As = As(III) + DMA(sum As/total As %). The values with different letters in each set were significantly different at $p < 0.05$

Soil Eh significantly increased throughout the whole growth period under aerobic and intermittent water management conditions. The concentration of dissolved Cd in the soil solution exhibited a continuous increase until the maximum tiller number stage under aerobic and intermittent conditions. This might be attributed to the significant increase in soil Eh. However, under flooded condition, soil Eh was well below − 180 mV during the seedling stage, and then increased till the end of the vegetative growth stage, showing a final increase during the reproductive growth stage. The concentration of Cd in soil solution was substantially low under flooded irrigation, in accordance with the findings of Arao et al. (2009). Increased concentration of dissolved As was observed as the Eh of soil decreased below − 100 or − 200 mV (Fig. 2). This is because the decrease in Eh below − 100 mV accelerated the release of As from ferrous(hydr)oxides (Honma et al. 2016). The concentration of As in the soil solution was 7–20 times higher under flooded condition than under aerobic and intermittent conditions. This is owing to the release of adsorbed or precipitated As from iron oxyhydroxides into the soil solution and the reduction of arsenate to arsenite, which easily release from the adsorptive surface of iron oxyhydroxides (Takahashi et al. 2004; Xu et al. 2008).

In this study, the application of CM increased soil pH remarkably throughout the growth period under aerobic condition. As a consequence, CM decreased Cd concentration in the soil solution throughout most of the growth period of rice plants. And, the concentration of Cd in rice grains slightly decreased under aerobic condition. Under intermittent irrigation condition, the application of 1.0% and 2.0% CM increased soil pH, but decreased soil Eh. Then, the content of dissolved Cd decreased throughout most of the growth period of rice plants. But, Cd concentration of rice grains decreased with the application of CM. However, the application of CM increased both soil pH and Eh under flooded water condition. As a result, the content of dissolved Cd upon CM application was higher than that under the control. Cd concentration of rice grains decreased upon CM application. It may have contributed to limiting the transfer of Cd from other plant parts to rice grains.

CM decreased total As uptake in rice grains under different water management conditions (Table 3) owing to the reduction of dissolved As in the soil solution throughout the growth period (Fig. 1). Rahaman et al. (2011) also found that the combined application of lathyrus, vermicompost, and poultry manure reduced As transport in plant parts. This is because organic matter released by compost or manure adsorbs As and reduces As concentration in soil–water-soluble exchangeable and carbonate fractions. Flooded treatment decreased the percent of As(III) in rice grains, but the concentration of As(III) remained higher than that in grains grown under aerobic condition. The results suggested that rice plants transferred DMA very efficiently into rice grains grown under flooded condition, in accordance with the findings of Raab et al. (2007). Arao et al. (2009) found that DMA accounted for 52% of the total As concentration in rice grains grown under flooded condition throughout the growth period. In this study, the concentration of As(III) reached the minimum level when the concentration of CM was 1.0%. When the amount of CM reached 2.0%, both the total As and As(III) concentrations in rice grains decreased by 48.7% under flooded condition. The results suggest that CM might have a great potential to reduce the concentration of both total As and inorganic As concentrations in rice grains.

The application of CM decreased the uptake of Cd and As by rice grains, and there was increased reduction of Cd uptake with the increase in the amount of CM applied. With respect to total As, there was increased reduction with the increase in the amount of CM applied. Chen et al. (2011) found that low quantities of OM enhance As accumulation but decrease Cd accumulation in rice grains, whereas the opposite trend was observed when high amounts of OM were added.

In conclusion, our study showed that with water management alone, it is difficult to simultaneously mitigate Cd and As concentrations in rice grains. The combined effect of flooded water condition and the application of CM might have a great potential to minimize the simultaneous uptake of Cd and As by rice grains. However, the application rate had a variable effects on the reduction of Cd and As uptake. Therefore, further research is needed to confirm the widely applicable ratio of CM for different soil types, weather conditions, and Cd and As concentrations in soils.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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