RESEARCH

Irrigation Practices on Rice Crop Production in Arsenic-Rich Paddy Soil

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ABSTRACT

Irrigation and water management are important cultivation practices, controlling rice crop production and regulating As concentration in both paddy fields and rice plants (*Oryza sativa* L.). This study investigated the impacts of various types of irrigation practices with As-contaminated groundwater on the extent of arsenic accumulation within rice plant parts during development and rice crop production at maturity. Three types of irrigation practices were applied to As-rich paddy fields: flooded irrigation, aerobic irrigation, and alternate wetting and drying irrigation (AWDI). The arsenic accumulation in various plant parts was monitored at 40, 54, 68, 82, 96, and 110 d after transplanting in the first (with 'Tainong 84') and the second (with 'Tainan 11') cropping seasons of 2013. Results show that the arsenic concentration in different parts of rice plants varied with growth stage and irrigation practices in both cropping seasons. There was a seasonal fluctuation of arsenic concentration within rice plants during plant development with flooded irrigation, which had the largest amount of irrigation input. Lower levels of As in rice were found in AWDI and aerobic irrigation than in flooded irrigation. Different irrigation practices can change the oxidation and reduction conditions of the paddy field, which lead to As release or absorption in the soil, thus influencing the uptake of As by plants.

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Abbreviations: As(III), trivalent arsenite; As(V), pentavalent arsenate; AWDI, alternate wetting and drying irrigation; DAT, days after transplanting; DMA, dimethylarsinate; DO, dissolved oxygen; EC, electrical conductivity; Eh, oxidation–reduction potential; MMA, monomethylarsonate; TDS, total dissolved solids.

ARSENIC-CONTAMINATED RICE and water are the major sources of As intake for Asians. In the Chianan Plain in southwestern Taiwan, naturally occurring As is plentiful in groundwater, on which rice cultivation depends for irrigation, particularly in the dry period when surface water from rivers, dams, ponds, and other resources in this area is limited. Because long-term irrigation of As-contaminated groundwater may cause an increase in the As concentration in agricultural soil and crop plants (Abedin et al., 2002a, 2002b; Rahman et al., 2007a, 2008), the Chianan Plain is considered as a high-risk region for growing rice.

Contamination of food and drinking water with hazardous substances is an issue of global concern (Kuramata et al., 2011). Among such substances, As is recognized as a Class 1 human carcinogen (IARC, 2004). Arsenic concentrations and speciation

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in soil water are strongly influenced by the redox conditions and water management in paddy fields (Roberts et al., 2011). In an anaerobic environment, such as in paddy soils, the inorganic trivalent arsenite [As(III)] has high mobility, and thus rice is more efficient than other cereal crops in assimilating As into its grains (Williams et al., 2007). Therefore, investigating the impacts of As-rich soil and As-contaminated irrigation water on As accumulation and metabolism in rice has drawn a lot of attention in recent years (Rahman et al., 2007b; Chou et al., 2014). Arsenite is present in paddy soils under flooded conditions as a result of As accumulation from irrigated groundwater, and this As can be taken up from soil, accumulating in roots and being transported to the shoots (stems plus leaf sheaths) and leaf blades of rice plants (Chou et al., 2014).

It has been reported that growing rice in a deficit irrigation environment reduces As uptake in various parts of plants, whereas a practical water management of the system must not significantly reduce grain yield (Sarkar et al., 2012). A management practice widely adopted for irrigated lowland rice, AWDI has been proven to reduce water consumption and greenhouse gas emissions while maintaining yields (Seckler, 1996; van de Hoek et al., 2001; Richards and Sander, 2014). The practice is defined by the periodic drying and reflooding of the rice field; irrigation water is applied a few days after the disappearance of ponded water. With alternating flooded and non-flooded conditions, grain yield is maintained while water use, greenhouse gas emissions, and As levels in rice are reduced (Linguist et al., 2015). In anaerobic soils, the reductive mobilization of As increases the phytoavailability and uptake of As in rice (Meharg and Zhao, 2012). According to Takahashi et al. (2004), arsenic in irrigation water is incorporated into Fe (hydr)oxide in soil during the nonflooded period, and it is quickly released from soil to water during the flooded period because of the reductive dissolution of the As-bearing Fe (hydr)oxide phase and reduction of As from pentavalent arsenate [As(V)] to As(III). Thus, flooded rice may contain high As concentration compared with that in other grain crops. However, more knowledge about the mobility of As within rice plants under the impacts of irrigation practices is required for the development of measures to reduce the As concentration in rice grain while maintaining normal production of rice. Arsenic concentrations and speciation in soil pore water of flooded paddy fields (or not flooded) are strongly influenced by bacterially induced dynamic biogeochemical processes (Masscheleyn et al., 1991; Garnier et al., 2010), as evidenced by the comparison between As release in poisoned and not poisoned medium (van Geen et al., 2006). During the rice growing period, the elevated As concentrations in soil pore water and their variations result from three main factors: (i) dynamic biogeochemical processes (leading to the reductive dissolution of

As-bearing hydroxides), (ii) the amount of As in soil that accumulates over years of irrigation practices, and (iii) the As concentration of irrigated water used to grow the rice (Abedin et al., 2002a; Khan et al., 2009; Garnier et al., 2010). Under aerobic conditions, only the first main factor (i) will be modified through the change of redox conditions (Xu et al., 2008).

Four species of As are commonly reported in rice grain: As(III), As(V), monomethylarsonate (MMA), and dimethylarsinate (DMA; Williams et al., 2005). Arsenic in groundwater is mainly inorganic, with arsenate comprising about 50% of the total As (Samanta et al., 1999). Inorganic As is generally more toxic than are methylated As compounds (Schoof et al., 1999). Peripheral vascular gangrene, also known as blackfoot disease (BFD), was first reported in Chianan Plain in southwestern Taiwan in the 1960s (Tseng et al., 1961). It was due to the consumption of deep well water with high As concentration (Tseng, 1977, 1985). Although As-contaminated groundwater is not used for drinking in Taiwan currently, it is still widely applied for irrigation purposes, including growing rice. However, few studies have examined the impacts of irrigation practices on rice production, As accumulation and its partitioning in rice plants, and As species in brown rice, collectively. The underlying mechanism how irrigation and water management control rice production and regulates As concentration in rice plants is still unclear. Arsenic toxicity in rice can be alleviated via the use of alternative irrigation sources, suitable agronomic practices, as well as appropriate irrigation practices.

This study investigated the impacts of irrigation practices on the As concentration in different parts of rice plants and grain production. The underlying mechanisms involved in regulating the uptake and mobilization of As in soil and within rice plant parts and possible strategies for minimizing As accumulation in rice are elucidated. Such information is required for the agricultural authority to formulate policies for enhancing water productivity and reducing the possible accumulation and distribution of As in rice plants.

MATERIALS AND METHODS

Experimental Layout

Field experiments were performed on an experimental farm (23°12'4.02" N, 120°10'50.7" E) in the Hsuehchia District of Tainan City in southwestern Taiwan. The area is situated at a subtropical latitude, where the weather is hot and humid in the wet season (April to September) with moderate temperature and low rainfall in the dry season (October to March). The experiments were conducted in the first (from February to June) and the second (from July to November) cropping seasons of 2013, a conventional two-crop system used locally. Since both cropping seasons occupy portions of dry and wet seasons, groundwater was used for rice irrigation in both cropping seasons. To provide various amounts of irrigation water and dissimilar levels of As in the paddy fields, three irrigation practices were employed.

Figure 1. Schematic diagram giving overview of all experiments and their roles in this study. AAS, atomic absorption spectroscopy; HG-AFS, hydride generation atomic fluorescence spectrometry; HPLC-ICP-MS, high performance liquid chromatography-inductively coupled plasma mass spectrometry.

To allow the establishment of a rice population, the irrigation practices were initially flooded and started 45 days after transplanting (DAT) until 10 d before the harvest. Both cultivars, Tainong 84 and Tainan 11, are japonica rice with different growth types and rice qualities. They are two popular cultivars grown locally, but Tainong 84 was planted in the first cropping season and Tainan 11 was grown in the second cropping season. In flooded irrigation, the paddy field was continuously irrigated to a depth of 5 to 10 cm above the surface of the soil. For AWDI, water was flooded to a depth of 5 to 10 cm above the soil surface after the disappearance of ponded water. For aerobic irrigation, water was applied to cover the paddy field to a depth of 5 to 10 cm when soil moisture tension reached 30 kPa at a depth of 15 cm (Fig. 1). Soil moisture tension was measured and monitored using soil tensiometers buried in the soil, two per plot, in conjunction with a water retention curve. Each irrigation practice had three replicated plots, with a plot area of 3 by 3 m and a planting density of 0.30 by 0.15 m (column × row). Plots were separated with isolation berms to avoid interference between plots. Three to four hills were sacrificed from each plot in every sampling to measure their growth traits, including plant height and fresh and dry weights of roots, leaf blades, and shoots. Changes in grain weights were monitored during the grain-filling stage, and grain production per unit area and 1000-grain weight were measured at the harvest. The weather conditions of the Hsuechia experimental site were automatically recorded from an automated weather station which was set up at the site. Between April and October 2013 the temperature and monthly rainfall were automatically recorded.

Sample Collection and Analysis

Arsenic Concentration in Irrigation Groundwater

Samples of irrigation groundwater in the experimental site were collected in the first and second cropping seasons from a shallow tube. The samples were collected on 11 April, 25 April, 9 May, 24 May, 20 June (at the harvest) in the first cropping season, and 14 August, 27 August, 10 September, 26 September, and 10 October (at the harvest). Sampled water was passed through a 0.45-μm filter, acidified with concentrated HNO₃ until pH < 2, and then stored in polyethylene bottles. The bottled samples were brought back to the Hydrogeology Laboratory of National Cheng Kung University, Tainan City, Taiwan, and stored in the dark at 4°C before analyses. The irrigation groundwater was analyzed for total As using an atomic absorption spectrophotometer (GF 5000, GBC Scientific Equipment Pty Ltd., Australia). The pH and oxidation-reduction potential (ORP or Eh) were measured using a portable pH/ORP/Temp meter (model TS-100, SUNTEX Instruments Co., Ltd., Kaohsiung, Taiwan). An AgCl₂ electrode was used to measure the Eh values, which were not corrected relative to the standard hydrogen electrode. The electrical conductivity (EC) and total dissolved solids (TDS) were measured by a handheld conductivity meter (Cond 330i, Wissenschaftlich-Technische Werkstätten GmbH & Co., Wellhelm, Germany), and dissolved oxygen (DO) was measured by a handheld DO meter (HI 9147, Hanna Instruments, Woonsocket, RI).

Arsenic Concentration in Soil

The soil samples irrigated with the As-contaminated groundwater were collected from the top soil layer (depth of 0 to 15 cm) in each plot, and were sealed in airtight polyethylene bags. The

soil samples were collected with a hand auger before the experiments (1 May and 1 July 2013). The soil samples were dried in a hot-air oven at 60°C until they reached a constant weight, and were then ground to powder, passed through a 2.0-mm-pore sieve, and stored in airtight polyethylene bags at room temperature. A modified procedure of Ruiz-Chancho et al. (2005) was adopted for As extraction. An aliquot of 0.1 g of soil was put into a clean conical flask and then 15 mL of extraction solvent (1 M phosphoric acid and 1 M vitamin C) was added to this. The ascorbic acid (vitamin C), with antioxidant properties, is used to dissociate the arsenic ions. The flasks were heated at 220°C for 30 min (heated to boiling; Ruiz-Chancho et al., 2005). After the solution had cooled down to room temperature, it was filtered through a 0.45-μm membrane, diluted to 25 mL with deionized water, and then analyzed with atomic fluorescence spectrometry (Millennium Excalibur System PS Analytical, UK).

Arsenic Concentration in Rice Plants

The rice plant samples were randomly sampled to monitor changes in As concentration in various plant parts at 40, 54, 68, 82, 96, and 110 DAT in both cropping seasons. These samples were brought back to the laboratory for further treatments. The rice plant samples were washed with tap water to remove soil and other substances, and then immersed into deionized water for several minutes. After drying in a hot-air oven at 70°C for 72 h, dry weights were measured. The dried rice plant samples were stored in airtight polyethylene bags at room temperature with proper labeling. Care was taken to avoid contamination during the measurement procedures. This analysis of the total As in rice plants is based on the work of Chou et al. (2014). Husks were removed from rice grains and then oven-dried at 70°C. The microwave method was employed to extract the As species from husks and the brown rice of rice grains. An aliquot of 0.2 g of rice powder was put into 50-mL polyethylene centrifuge tubes, to which 10 mL of 1% hydrochloric acid was added, and then left to stand overnight at room temperature. Samples were processed in a microwave (MARS, CEM, Matthews, NC) using a three-stage temperature ramping program. Each stage ramped up to the designated temperature over a 5-min period; that is, samples were maintained at 55°C for 10 min at Stage 1, at 75°C for 10 min at Stage 2, and at 95°C for 30 min at Stage 3. The samples were then cooled and centrifuged (6000 rpm) for 10 min, and filtered with a 0.45-μm membrane. The supernatant was kept at 4°C until analysis. The extracts were analyzed for As(III), As(V), MMA, and DMA using Agilent 7500a HPLC-ICP-MS (Sun et al., 2012).

Analytical Quality Control

All instruments were calibrated using matrix-matched standards. Three duplicates were analyzed for each sample, and the mean values were taken as representatives with an accuracy of 5% and a precision of 2%. For quality control, three certified reference materials (CRM) of 10010 Chinese rice flour samples were prepared to validate the analysis. Standard reference materials (SRM; item no. 2710) were obtained from the National Institute of Standard Materials and Technology, Gaithersburg, MD. The certified concentration value for As in NIST SRM 2710 is 610 ± 28 mg kg⁻¹. Arsenic recovery for individual samples ranged from 96 to 105%, with an average of 102 ± 3.5% (*n* = 10).

Table 1. Characteristics of groundwater (*n* = 11) collected at the Hsuechia experimental site (mean values were determined from 11 groundwater samples).

Parameter [†]	Value
pH	7.2 ± 0.1
EC, μS cm ⁻¹	2058 ± 123
TDS, mg L ⁻¹	985.6 ± 57.3
Salinity, ‰	0.9 ± 0.1
DO, mg L ⁻¹	0.9 ± 0.6
Eh, mV	-79 ± -16
As(III), μg L ⁻¹	90.1 ± 9.2
As(V), μg L ⁻¹	20.2 ± 4.1
Average total As, μg L ⁻¹	110.4 ± 10.2

[†] EC, electrical conductivity; TDS, total dissolved solids; DO, dissolved oxygen; Eh, oxidation-reduction potential.

RESULTS AND DISCUSSION

Characterization of Groundwater and Soil

At the Hsuechia experimental site, the maximum and minimum temperatures were recorded to be in the ranges of 31.4 to 35.7°C and 15.5 to 23.5°C, respectively, and the monthly rainfall was measured to be in the range of 0 to 813.2 mm mo⁻¹, with a total of 535 mm in the first cropping season and 920.1 mm in the second cropping season. The average total As in the groundwater at the studied site was 110.4 ± 10.2 μg L⁻¹ (Table 1), higher than the permissible limit (50 μg L⁻¹) for irrigation water recommended by the Environmental Protection Administration of Taiwan. Other characteristics of groundwater, including pH, EC, TDS, DO, and Eh, are listed in Table 1. From the ranges of these parameters, the aquifer was in moderate reducing conditions. With fairly low values of DO (<1 mg L⁻¹) and salinity (0.8 to 1‰), the groundwater used for irrigation could be considered as freshwater.

The soil of the experimental site is a sandy loam containing high percentages of sand and organic C, with a high cation exchange capacity (10 to 11 cmol kg⁻¹; Table 2). The range of As(V) concentration in soil was from 11.4 ± 1.3 to 13.1 ± 2.0 mg kg⁻¹, and that of As(III) was from 2.3 ± 0.1 to 3.0 ± 0.2 mg kg⁻¹. The total As concentration in soil ranged from 13.9 ± 1.8 to 16.1 ± 2.1 mg kg⁻¹ (Fig. 2). The concentrations of As(V) and As(III) in soil pore water of flooded paddy fields were 12.2 ± 0.1 mg L⁻¹ and 92.2 ± 1.6 mg L⁻¹, respectively, whereas those in non-flooded fields were 9.6 ± 0.5 mg L⁻¹ and 2.7 ± 0.3 mg L⁻¹, respectively. The concentration of As(III) in soil pore water of flooded paddy fields was 87% higher than that of As(V), and 97% higher than in nonflooded paddy fields. This indicates that more As(III) was released in soil pore water in flooded irrigation than in aerobic irrigation.

Arsenic Concentration in Rice Plant Parts

The As concentration in various parts (roots, shoots, and leaf blades) of rice plants collected at different growth stages (40, 54, 68, 82, 96, and 110 DAT) is plotted in Fig. 3

Table 2. Characteristics of soil (*n* = 7) collected at the Hsuehchia experimental site.

Plot [†]	pH	Clay	Sand	Silt	Organic C	Texture	CEC [‡]	As concentration
		g kg ⁻¹					cmol kg ⁻¹	mg kg ⁻¹
FI	7.1 ± 0.1	130 ± 10	710 ± 50	150 ± 10	13	sandy loam	10	13.9 ± 1.8
AI	7.1 ± 0.3	120 ± 10	720 ± 30	120 ± 10	12	sandy loam	11	16.1 ± 2.1
AWDI	7.2 ± 0.1	130 ± 20	710 ± 20	130 ± 20	14	sandy loam	10	14.1 ± 1.2

[†] FI, flooded irrigation; AI, aerobic irrigation; and AWDI, alternate wetting and drying irrigation.

[‡] CEC, cation exchange capacity.

Figure 2. The concentrations of two arsenic species measured in soil of the experimental site. Mean ± SE (*n* = 5). The values within each column followed by the same letter(s) are not significantly different at *P* < 0.05 by Fisher's LSD test. (A) Flooded irrigation plot. (B) Aerobic irrigation plot. (C) Alternate wetting and drying plot.

and 4. Results show that there was a seasonal fluctuation of As concentration in every part during plant development. In the vegetative tissues, generally the As concentration was in the order: roots > leaf blades ≥ shoots. At maturity, the As concentration was roughly in the order: roots > leaf blades ≥ shoots > husks > brown rice (Fig. 3–6). Uptaken As mostly accumulated in roots, with a small portion being transported to the aboveground plant parts. Moreover, the As concentration in flooded irrigation-treated plant parts was higher than that for the other two irrigation practices before the harvest, indicating that water-saving practices such as aerobic irrigation and AWDI resulted in lower accumulation of As within rice plants.

Similar results are reported by Marin et al. (1993), Rahman et al. (2004), and Bogdan and Schenk (2012). Other studies (Marin et al., 1993; Abedin et al., 2002a, 2002b; Meharg and Jardine, 2003; Rahman et al., 2007a, 2007b; Chou et al., 2014) pointed out that the partitioning of As within rice plants was in the order: roots > leaves > shoots regardless of the rice variety and cultivation method used in the experiments. Abedin et al. (2002a, 2002b) indicated that

Figure 3. Changes of arsenic concentration in various parts of rice plants: roots, shoots (stems plus leaf sheaths), and leaf blades, for different irrigation practices during the second cropping season of 2013. FI, flood irrigation; AI, aerobic irrigation; AWDI, alternate wetting and drying irrigation.

Figure 4. Changes of arsenic concentration in various parts of rice plants (i.e., roots, shoots [stem + leaf sheaths], and leaf blades) for different irrigation practices during the second cropping season of 2013. FI, flood irrigation; AI, aerobic irrigation; AWDI, alternate wetting and drying irrigation.

the concentration of As in rice straws could be up to 92 mg kg⁻¹ when rice plants were irrigated with As-contaminated water while the British statutory permissible limit for As in straw fed to cattle is 0.2 mg kg⁻¹ (Nicholson et al., 1999). They also showed that an increasing concentration of arsenate in irrigation water significantly decreased plant height, grain production, number of filled grains, grain weight, and root biomass, with the As concentration in roots, straws, and rice husks increasing substantially.

Figure 5. Effects of irrigation practices on arsenic speciation in (a) husks and (b) brown rice of rice plants grown in the first cropping season of 2013. Error bars represent mean $\pm$ SE. Values above each column followed by the same letter(s) are not significantly different according to Fisher's least significant difference test at $p < 0.05$. FI, flood irrigation; AI, aerobic irrigation; AWDI, alternate wetting and drying irrigation; DMA, dimethylarsinate.

In their experimental results, Bogdan and Schenk (2012) showed that, with As-rich irrigation water, flooded paddies provided abundant sources of As to the root zone, contributing to the higher As concentration in the roots. The present study obtained similar results, with roots, leaf blades, and shoots accumulating substantial As in both cropping seasons, particularly roots (Fig. 3 and 4). The As partitioning in the tissues of rice plants was observed to be 97 to 99% in roots, 2 to 3% in leaf blades and shoots, and 1 to 2% in grains (husks and brown rice; Fig. 5 and 6). This is consistent with a report by Rahman et al. (2007b), in which the As distribution in roots, straws, and grains was 96, 3, and 1%, respectively.

This study further indicated that the As concentration in roots decreased significantly in flooded irrigation-treated plants at the harvest. Since water was withheld for about 10

Figure 6. Effects of irrigation practices on arsenic speciation in (a) husks and (b) brown rice of rice plants grown in second cropping season of 2013. Error bars represent mean $\pm$ standard error. Values above each column followed by the same letter(s) are not significantly different according to Fisher's least significant difference test at $p < 0.05$. FI, flood irrigation; AI, aerobic irrigation; AWDI, alternate wetting and drying irrigation; DMA, dimethylarsinate.

d to aid the maturity of rice grains (normal local cultivation practice), the transpiration stream may be involved. In addition, the highest As concentration in the roots of flooded irrigation-treated plants occurred in the anthesis stage (around 68 DAT) in both cropping seasons (116.8 ± 8.9 mg kg⁻¹ and 108.8 ± 9.7 mg kg⁻¹, respectively), when total leaf area was maximal (data not shown). Results suggest a close link of the uptake and accumulation of As in roots with the mass transpiration stream, by which the available water in the root zone is actively absorbed. No such phenomenon was observed with aerobic irrigation and AWDI, for which soil moisture was insufficient to meet the water demand. Therefore, transpiration may be a mechanism that determines the uptake and partitioning of As in rice plants.

From the viewpoint of the functions of redox conditions in the soil, as reported by Zhao et al. (2010) and

Roberts et al. (2011), the reductive dissolution of As-bearing iron oxyhydroxides under a flooded irrigation environment may release more adsorbed As and thus increase the availability of free As ions in soil solution, increasing As uptake rate by rice plants relative to that for ADWI and aerobic irrigation. In this study, the Eh values of groundwater and soil under flooded irrigation at the Hsuehchia experimental site were -79 ± -16 mV (Table 1) and -54 ± -13 mV (data not shown), respectively, indicating that groundwater and soil were in reducing conditions. The oxidation and reduction conditions of a paddy field were changed by irrigation practices, which led to different concentrations of As in the soil solution for different irrigation treatments, thereby influencing the uptake of As by plants. It is worthwhile to mention that the rapid fluctuation of soil redox potential with AWDI might limit the available As in the soil solution, lowering the As concentration in rice plant parts.

The As in paddy soil goes through a number of transformation processes under the normal flooded condition, such as reduction, desorption, methylation, and volatilization, leading to profound changes in the As bioavailability to plants. The solubility and bioavailability of As are influenced by direct or indirect redox reactions. The As-bearing iron oxides or hydroxides under reduction conditions release As and other elements. A flooded paddy field can increase As bioavailability to rice plants.

Impact of Irrigation Practices on Arsenic Speciations in Husks and Brown Rice

At maturity, the As concentration in husks and brown rice were changed by the type of irrigation practices using As-contaminated groundwater in the two cropping seasons (Fig. 5 and 6). The As species in husks from rice plants treated with different irrigation practices in the first cropping season are shown in Fig. 5a. The As(V) level was higher than those of As(III) and DMA in husks in all irrigation practices in the first cropping season. The MMA concentration in husks and brown rice was not detectable (data not shown). Oparka and Gates (1984) reported that high As concentration in husks was due to the transpiration stream pulling As to the husks via the xylem channels in the vascular system. The As(III) level was higher than those of As(V) and DMA in brown rice under all irrigation practices in the first cropping season (Fig. 5b). A similar trend was found in the second cropping season, with As(V) being predominant in husks and As(III) being predominant in brown rice in all irrigation practices (Fig. 6a and 6b).

Geislinger et al. (2002) and Kuehnelt et al. (2000) found that methylated As, especially DMA, accounted for a considerable proportion of the total As in rice grain. Monomethylarsonate was not detected in rice grain. Nissen and Benson (1982) found that many plants were able to methylate inorganic As, particularly under the conditions of P deficiency. Such findings imply that applying P-rich

fertilizer to a paddy field could limit the methylation of inorganic As, leading to its reduction in the soil solution.

Li et al. (2006) and Lombi et al. (2009) showed that the As(III) complex forms in a large quantity with thiol peptides, and was controlled by the As(III) concentration in rice bran. In the present study, the concentration of As species in brown rice was in the order: As(III) > As(V) > DMA; that in husks was in the order: As(V) > As(III) > DMA. Li et al. (2009) found a considerable amount of organic As (e.g., DMA and MMA) in husks and brown rice, even though no organic As was detected in the soil solution. Similarly, the present study detected no DMA in paddy soil and found that As was methylated in the plants. The fractions of As(III), As(V), and DMA were 51 to 79, 16 to 31, and 5 to 18%, respectively, in brown rice, and 13 to 36, 61 to 83, and 3 to 5%, respectively, in husks (Fig. 5 and 6).

Results also show that the As concentration in husks and brown rice was the highest in flooded irrigation-treated plants (Fig. 5 and 6). The concentration levels of both As(III) and As(V) in brown rice with the flooded irrigation treatment were higher than those with the non-flooded irrigation practices, in which the concentration of As(III) was reduced by 43 to 62% and that of As(V) was reduced by 64 to 68%. Larger amounts of irrigation groundwater were used in flooded irrigation treatment than the aerobic irrigation and AWDI irrigation practices. Similar results were observed for the two tested rice cultivars. Somenahally et al. (2011) reported a 41% reduction in total grain As from rice grown on intermittently flooded fields relative to that from rice grown on flooded paddies. Sarkar et al. (2012) showed that the rapid fluctuation of reduced and oxidized environments in the rhizosphere soil was responsible for the significant decrease (25%) in As load of rice grains under intermittent ponding compared with that under continuous ponding.

Impact of Irrigation Practices on Grain Production and 1000-grain Weight

Grain production is known to be regulated by the amount of irrigation water. For the Tainong 84 japonica rice cultivar used in first cropping season, grain production and amount of irrigation water from flooded irrigation (750 ± 41 g m⁻² and 40.9 m³, respectively) plots were higher than those from aerobic irrigation (420 ± 32 g m⁻² and 18.5 m³, respectively) and AWDI (557 ± 38 g m⁻² and 26.5 m³, respectively) plots (Table 3). The effect of irrigation practices was significant ($p < 0.001$; data not shown) on grain production and 1000-grain weight. Similarly, grain production for Tainan 11 with flooded irrigation was 228 ± 21 g m⁻², higher than those obtained with aerobic irrigation (420 ± 32 g m⁻²) and AWDI (255 ± 25 g m⁻²). The 1000-grain weight for Tainong 84 was 26.9 g with flooded irrigation, 21.1 g with aerobic irrigation, and 23.9 g with AWDI. Similar results were obtained for Tainan 11. Accordingly,

Table 3. Amounts of irrigation water used, 1000-grain weights, and grain productions for rice ‘Tainong 84’ and ‘Tainan 11’ for different irrigation practices (flooded irrigation, aerobic irrigation, and alternate wetting and drying irrigation) grown in first and second cropping seasons (harvest) of 2013. Water use calculations do not include rainfall water.

Irrigation practice	Cropping season	Cultivar	Water used	1000-grain weight [†]	Grain production [‡]
			m ³	g	g m ⁻²
Flooded irrigation	1st	Tainong 84	40.9	26.9 ± 4.3	750 ± 41
	2nd	Tainan 11	14.5	26.7 ± 3.9	288 ± 21
Aerobic irrigation	1st	Tainong 84	18.5	21.1 ± 2.8	420 ± 32
	2nd	Tainan 11	16.0	24.7 ± 2.5	244 ± 24
Alternate wetting and drying irrigation	1st	Tainong 84	26.5	23.9 ± 2.1	557 ± 38
	2nd	Tainan 11	24.8	24.9 ± 2.9	255 ± 25

[†] 1000-grain weight was measured from the dry weight of 1000 rice grains at the harvest.

[‡] Grain production was measured from the rice grain weight per area of 9 m² at the harvest.

grain production and 1000-grain weight of both rice cultivars grown in the respective cropping seasons follow the order: flooded irrigation > AWDI > aerobic irrigation, with the difference between 8 and 43% (Table 3).

A reduced yield under insufficient irrigation was reported by Abbasi and Sepaskhah (2011) and Hayashi et al. (2006). Linquist et al. (2015) indicated that yields increased by 1 to 13% and water use efficiency improved by 18 to 63% for well-watered treatments relative to deficit irrigation plots. Hayashi et al. (2006) showed that the lower grain yield from nonflooded fields was due to a lower number of spikelets per panicle, a smaller percentage of filled grains, and/or a lower 1000-grain weight. In the present study, in addition to a lower plant height and plant biomass, both grain production per unit area and 1000-grain weight decreased significantly when non-flooded irrigation treatments (AWDI and aerobic irrigation) were used, implying that the rice grain production potential of rice can be regulated by the amount of irrigation water input to paddy fields.

CONCLUSIONS

This study investigated the impacts of irrigation practices with As-contaminated groundwater on the extent of As accumulation within rice plant parts during development and rice grain production at maturity. Results show that the As concentration in rice plants varied with irrigation practice and growth stage. Generally, the levels of As in roots, leaf blades, shoots, husks, and brown rice were elevated by flooded irrigation. The accumulation and partitioning of As in rice plants followed the order: roots > leaf blades ≥ shoots in the vegetative stages. Generally, rice plants grown under nonflooded irrigation practices had a lower As concentration as well as reduced grain production. Similar results were observed for the two tested

japonica rice cultivars (Tainong 84 and Tainan 11). The concentration levels of As species in brown rice were in the order: of As(III) > As(V) > DMA; those in husks were in the order: As(V) > As(III) > DMA. Irrigation with higher amounts of As-contaminated groundwater led to higher As concentration in both husks and brown rice at maturity in both cropping seasons, which may be due to the greater amounts of As-contaminated groundwater input to the paddy fields and the anaerobic conditions that favor the release of As into the soil solution, which is uptaken by roots. For flooded irrigation treatment conducted at the experimental site, the total As concentration in brown rice was less than 0.45 mg kg⁻¹ dry weight, yet exceeded the permissible limit (0.2 mg kg⁻¹ dry weight) set by the WHO. As a result, the type of irrigation practice should be taken into account to regulate the As concentration in rice plants, and control rice grain production. Arsenic in irrigation water is incorporated in Fe (hydr)oxide in soil during the nonflooded period, and it is quickly released from soil to water during the flooded period because of the reductive dissolution of the Fe (hydr)oxide phase and reduction of As from As(V) to As(III). Thus, flooded rice may contain high As concentrations compared with other grain crops. Water-saving irrigation practices can help conserve water resources and at the same time lower As concentration in rice. Bridging the gap between the volume of contaminated irrigation water and the levels of As within rice plants is the information required to set up a proper field practice for As-rich soils or fields irrigated with As-contaminated groundwater. This is a situation in which a difficult choice has to be made between rice production and As concentration level within rice plants through the adjustment of the amounts of As-contaminated irrigation water. However, this type of problem needs to be addressed by political decision rather than scientific results. In any case, this study provides decision-supporting evidence for the authority to make a policy decision.

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