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Effects of Water Management Practices on Reducing Arsenic Toxicity in Rice: A Glass House Study

M. Rafiqul Islam*, Sohel Rana, M. Jahiruddin and Shofiqul Islam

Department of Soil Science, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh
*corresponding author Email: mrislam58@bau.edu.bd, Cell No: +8801711985414

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Some paddy soils in Bangladesh are contaminated with arsenic (As) due to irrigation of As-laden groundwater, which lead to elevated As in rice grains thus created a health hazard for the local communities. A pot experiment was carried out at the glass house of Bangladesh Agricultural University, Mymensingh during January-May 2009 using calcareous soil elevated with arsenic (22.5 mg kg^{-1}) to find out an option of water management that will reduce the arsenic toxicity to rice plants. The rice variety tested was the BRRI dhan29. Three levels of arsenic was added @ 0, 10 and 20 mg As kg^{-1} to the soil with three water management options i.e. continuous 5 cm standing water, alternate wetting and drying (AWD) and continuous saturation level. Arsenic contamination reduced plant height, tillering, panicle length, grain panicle^{-1}, 1000-grain weight, grain and straw yields. The grain yield of rice was reduced by 40% for 10 mg kg^{-1} As treatment and 82% due to 20 mg kg^{-1} As treatment. AWD irrigation treatment significantly increased plant height, panicle length and grains panicle^{-1} which ultimately increased grain and straw yields of rice over two other water management methods. The toxicity of arsenic contamination to rice was greatly reduced due to AWD water management compared to other water management options.

Key words: Rice, arsenic toxicity, water management, AWD

INTRODUCTION

In Bangladesh, As-contaminated water extracted through shallow tube-wells is widely used to irrigate rice crops during the dry season (Saha and Ali, 2007), which has resulted in elevated As concentrations in soils and rice grains (Islam *et al.*, 2007, Islam et al. 2012, Norton *et al*., 2014), and significant yield losses due to As phytotoxicity (Khan *et al.*, 2009; Panaullah *et al.*, 2009). Water management techniques may also prove to be highly effective in combating the problem of excessive accumulation of As in rice. Rice grown under flooded conditions was found to accumulate much more As than that grown under aerobic condition. Growing rice aerobically during the entire rice growth duration resulted in the least As accumulation in rice straw and grain significantly compared with rice grown under flooded conditions (Li *et al.*, 2009). A comparison between the impacts of using flooded versus intermittent flooding in which the soil was periodically allowed to dry on availability of arsenic showed that under flooded conditions, the soil lacked oxygen, and this resulted in the release of iron and arsenic into the soil solution, making them more available for plant uptake (Hua *et al.*, 2011).

They concluded that the combination of water management practices that allow periodic aeration of the soil and use of cultivars that are low accumulators of arsenic can reduce arsenic in the grain. Another report stated that anaerobic water management is the main reason for the enhanced As uptake in rice (Talukder *et al.*, 2012). Irrigation practices also change microbial communities in flooded rice fields (Somenahally *et al.*, 2011a). Field that was maintained under a permanent flood had high concentrations of iron-reducing bacteria which results increase solubility of both iron and As, and therefore more available for uptake by the plant, as compared to soil that was only intermittently flooded.

In a paddy field in Bangladesh irrigated intermittently, the As concentration in the soil pore water from the plough layer remained relatively low during the grain filling stage, corresponding to the oxic conditions observed in the soil layer (Roberts *et al.*, 2011). In another field study in Bangladesh, the site employing intermittent irrigation (not strictly AWD) produced lower grain As than the other site under continuously flooded conditions (Stroud *et al.*, 2011). A recent field study at Stuttgart, Arkansas, USA showed that grain contained 41% lower As in intermittently flooded paddy than in continuously flooded paddy (Somenahally *et al.*, 2011b). There is a 13% increase in grain yield over the conventional cultivation method and, importantly, As concentrations in grain and straw are decreased by 62% and 86%, respectively (Talukder *et al.*, 2011). The farmers' of Bangladesh keep the paddy fields flooded for the cultivation of winter season rice. The concept of alternate wetting and drying (AWD) technique for water management has been advocated by the BRRI to cut down the amount of water for rice cultivation with some yield benefit as well (Sattar et al. , 2009). By this method the soils are kept aerobic during some period of growth of rice plants. Under aerobic condition, the native arsenate may be less available to plants and thus the toxic effects of arsenic to rice may be reduced. Keeping this in view, a pot experiment was carried out on an arsenic contaminated soil from Faridpur to find out an option of water management that will reduce the arsenic toxicity to widely grown BRRI dhan29 rice.

MATERIALS AND METHODS

A pot culture experiment was conducted at the glass house of Bangladesh Agricultural University, Mymensingh during January-May 2009 using a silty clay calcareous soil collected from arsenic contaminated paddy fields. The physico-chemical properties of the soil to which As was spiked at different concentrations are presented in Table 1. An amount of 7 kg soil was taken in a series of pots. The diameter of the pot was 43 cm and height was 40 cm. The rice variety tested was the BRRI dhan29. Three levels of arsenic was added @ 0, 10 and 20 mg As kg^{-1} from $Na_2HAsO_4.7H_2O$ to the soil with three water management options i.e. Continuous 5 cm Standing Water (CSW), Alternate Wetting and Drying (AWD) and Saturation Condition (SC). Under continuous saturation condition, the bottom of plastic bucket was perforated and placed on galvanized iron tray with 10 cm water. Under alternate wetting and drying (AWD) treatment, 5 cm water was added and allowed to dry until cracking was observed. Water was then added up to 5 cm depth; this process was continued up to grain maturity stage. Forty five days old healthy seedlings were transplanted in the pots on 27 January 2010. In each pot, two hills were placed in an equal distance and each hill consists of two seedlings. After transplanting all the pots were kept with continuous standing water (5 cm) for 15 days. Then different water management practices were imposed. Each pot had received 100 mg N, 40 mg K and 25 mg S kg^{-1} soil from urea, MoP and gypsum, respectively. The crop was harvested in different dates at maturity. The yield and yield contributing characters of rice variety under different treatments were recorded. Grain and straw samples were oven dried at 65ºC until constant weight. Rice grain and straw samples were digested with concentrated HNO_3 and 30% H_2O_2. Total As in the digest was determined by flow injection hydride generation atomic absorption spectrophotometer (HG-AAS) with UNICAM model 969 and MHS-10 hydride generator assembly using matrix-matching standard. All the plant data were statistically analyzed following F test and Duncan's Multiple Range Test (DMRT).

RESULTS AND DISCUSSION

Effective tillers pot^{-1}

The number of effective tillers pot^{-1} of BRRI dhan29 was significantly decreased by the addition of different levels of As to soil (Table 2). The highest number of effective tillers pot^{-1} of 21.44 was found when arsenic was not added and was statistically superior to other levels of As application. Addition of each increasing level of As significantly decreased the number of effective tillers pot^{-1}. Different water management practices exerted significant variation in effective tillers pot^{-1} of rice (Table 2). Alternate wetting and drying condition and continuous standing water recorded the identical number of effective tillers pot^{-1}. The lowest number of effective tillers pot^{-1} was found when plants were grown under saturated condition. At a particular water management practice, the number of effective tillers pot^{-1} decreased with increasing levels of As addition to soil (Table 3). Besides, there was significant variation among the water management practices at a particular level of As level. There was no effective tiller under saturated condition when 20 mg kg^{-1}

Table 1. Physico-chemical properties of initial soil to which As was spiked at different concentrations

Soil properties	Value
Soil texture	Silty clay
Soil pH	7.84
Total N (%)	0.12%
Organic matter (%)	2.32%
Available P (mg kg^{-1})	12.2
Available K (cmol kg^{-1})	0.12
Available S (mg kg^{-1})	16.3
Total As (mg kg^{-1})	22.5

Table 2. Main effects of added As and water management practices on yield and yield contributing characters of BRRI dhan29 rice

Factors	Effective tillers (no.)	Plant height (cm)	Filled grains $panicle^{-1}$ (no.)	1000 grain weight (g)	Grain yield (g pot^{-1})	Straw yield (g pot^{-1})
Added As (mg kg^{-1})						
0	21.44a	65.78a	61.44a	19.06a	24.82a	26.12a
10	13.56b	53.56b	40.44b	17.87a	14.62b	17.11b
20	7.33c	43.11c	20.78c	10.29b	4.54c	11.14c
SE(±)	0.633	1.900	2.937	0.370	1.060	0.332
CV (%)	9.47	8.52	7.55	7.06	9.89	5.49
Water management options						
CSW	16.56a	51.22b	42.67b	17.16a	15.12b	17.50b
SC	8.00b	42.33c	18.78c	12.23b	7.48c	16.42b
AWD	17.78a	68.89a	61.22a	17.82a	21.39a	20.46a
SE(±)	0.633	1.900	2.937	0.370	1.060	0.332
CV (%)	9.47	8.52	7.55	7.06	9.89	5.49

In a column, the figure(s) having common letters do not differ significantly at 5% level of probability. CSW = Continuous Standing Water; SC = Saturated Condition; AWD=Alternate Wetting and Drying.

As was added to soil. Alternate wetting and drying (AWD) and continuous standing water (CSW) had identical effective tillers at all levels of As addition.

Plant height

Addition of As to soil considerably affected the plant height of BRRI dhan29 (Table 2). The tallest plant of 65.78 cm was recorded in the pot without As contamination while the shortest plant of 43.11 cm was recorded when the soil received 20 mg kg^{-1} As. All the three levels of As were statistically different from each other for plant height. Alternate wetting and drying technique had significantly tallest plants compared to other two methods of water management practices. Plants grown under saturated soil moisture condition resulted in the shortest plants (Table 2). A significant interaction effect was noted between different levels of As contamination and different water management practices on plant height of rice (Table 3). The tallest plant (76.33 cm) was observed in alternate wetting drying condition without any

Table 3 Interaction effects of added As and water management practices on yield and yield contributing characters of BRRI dhan29 rice

Added As (mg kg^{-1})	**Water management**	**Effective tillers (no.)**	**Plant height (cm)**	**Filled grains panicle^{-1} (no.)**	**1000 grain weight (g)**	**Grain yield (g pot^{-1})**	**Straw yield (g pot^{-1})**
0	CSW	22.67a	63.67b	61.67b	19.63a	26.50a	25.73b
0	SC	15.67b	57.33bc	38.33c	18.73ab	17.07b	23.90b
0	AWD	26.00a	76.33a	84.33a	18.80ab	30.90a	28.73a
10	CSW	16.00b	49.67cd	40.67c	17.63ab	13.80bc	16.50d
10	SC	8.33c	43.33d	18.00d	17.97ab	5.37de	16.10d
10	AWD	16.33b	67.67ab	62.67b	18.00ab	24.70a	18.73c
20	CSW	11.00c	40.33d	25.67cd	14.20c	5.07de	10.27f
20	SC	0.00d	26.33e	0.00e	0.00d	0.00e	9.27f
20	AWD	11.00c	62.67b	36.67c	16.67b	8.57cd	13.90e
SE(±)		0.633	1.900	2.937	0.370	1.060	0.332
CV (%)		9.47	8.52	7.55	7.06	9.89	5.49

In a column, the figure(s) having common letters do not differ significantly at 5% level of probability.

As addition which was statistically similar to As_{10} × alternate wetting drying (67.67 cm). The shortest plant (26.33 cm) was observed under saturation water management practice having 20 mg kg^{-1} As added to soil.

Filled grains panicle^{-1}

The number of filled grains panicle^{-1} of rice significantly decreased by addition of As to soil. The highest number of filled grains panicle^{-1} recorded in 0 mg kg^{-1} As was 61.44 and the lowest number of filled grains panicle^{-1} recorded in 20 mg kg^{-1} As was 20.78 (Table 2). Different water management practices resulted in marked variation on the number of filled grains panicle^{-1} of BRRI dhan29. All the three water management practices differed significantly from each other for filled grains panicle^{-1}. The interaction effect of different levels of As addition and water management practices had significant effect on filled grains panicle^{-1} (Table 3). All the three water management practices differed significantly from each other when no As or 10 mg kg-^{1} As was added to soil. There was no filled grain in panicle when grown under saturated condition with 20 mg kg^{-1} added As. Continuous standing water and alternate wetting and drying recorded the identical number of filled grains panicle^{-1} when 20 mg kg^{-1} As was added to soil.

1000-grain weight

Thousand-grain weight of BRRI dhan29 decreased with increase in As doses. The 1000- grain weights due to 0 and 10 mg kg^{-1}As treatment were statistically identical. Different water management practices had significant effect on 1000-grain weight of BRRI dhan29 (Table 2). The 1000-grain weights of alternate wetting and drying and continuous standing water were statistically identical and superior to that found under saturated soil moisture condition. A significant interaction effect was observed between different levels of As addition and water management practices on 1000-grain weight of rice (Table 3). Thousand grain weights recorded in all water management treatments under 0 and 10 mg kg^{-1} added As were statistically identical. There was no grain formation under saturated soil moisture condition with 20 mg kg^{-1} added As and hence there was no 1000-grain weight. The 1000-grain weight of continuous standing water at 20 mg kg^{-1} added As were lower compared to grain weight obtained with alternate wetting and drying condition at 20 mg kg^{-1} added As.

Grain yield

Effective management strategies are required to reduce As accumulation in rice grain under As contaminated soils and irrigation water. Grain yield of BRRI Dhan29 was significantly decreased due to addition of 10 mg kg^{-1} As to soil compared to that without any As addition (Table 2). The addition of 20 mg kg^{-1} As to soil further significantly decreased the grain yield. Different water management practices had significant effect on grain yield of rice (Table 2). All the three water management practices differed significantly from each other for grain yield. The highest grain yield of 21.39 g pot^{-1} was observed when grown under AWD and was significantly superior to other two water management practices. The second highest grain yield was obtained under CSW condition. Plants grown under SC recorded the lowest grain yield. The interaction effect between different levels of As addition and water management practices on grain yield of BRRI dhan29 was statistically significant (Table 3). The grain yields obtained under different water management practices in As control pots were much higher compared to the As treated pots. The highest grain yield was obtained under alternate wetting and drying condition in As control pot. There was no grain formation under saturated soil condition with 20 mg kg^{-1} As added pot. Arsenic toxicity to rice was reduced when grown under alternate wetting drying condition compared to other two methods of water management. There are some reports of rice grain yield reduction under conventional method compared to permanent raised bed culture (Panaullah *et al.*, 2009; Talukder *et al.*, 2011). The toxicity was more when plants were grown under moisture saturated condition. In As control pots, the grain yields obtained under alternate wetting and drying and continuous standing water condition were statistically identical but superior to that found under water saturated soil condition. When BRRI dhan29 plants were grown with 10 mg kg^{-1} As added condition, all the three water management practices produced statistically different grain yields. Alternate wetting and drying and continuous standing water practices with 20 mg kg^{-1} added As produced identical grain yields but such yield was much lower compared to those observed in As control pots. The reduction in grain yield was also associated with a decrease in the number of effective tillers and filled grains per panicle (data presented in Tables 2 and 3).

Straw yield

Like grain yield, the straw yield of BRRI dhan29 was also significantly decreased by the application of different doses of As to soil (Table 2). The highest straw yield (20.46 g pot^{-1}) found under alternate wetting and drying condition and was statistically superior to other water management practices. The straw yields obtained under continuous standing water and water saturated conditions produced identical straw yields. Different levels of As addition and water management practices had significant interaction effect on straw yield of BRRI dhan29 (Table 3). Alternate wetting drying practice of water management recorded significantly highest straw yield at all levels of As additions compared to other two water management practices. The water management practices like continuous standing water and water saturated condition produced identical straw yields at all levels of As addition. There was no grain formation in pots treated with 20 mg kg^{-1} As and grown under water saturated condition but there was some straw yield in the same treatment. It appears that vegetative portion of rice is less sensitive to As toxicity compared to reproductive stage. The highest yield (28.73 g pot^{-1}) was found alternate wetting and drying without any As added in soil and the lowest straw yield (9.27 g pot^{-1}) was found under water saturation condition with 20 mg kg^{-1} As added.

Arsenic accumulation in rice grain

Data indicated that As concentration in grain of BRRI dhan29 rice was significantly increased by different levels of As addition to soil (Table 4). Arsenic concentration in grain in As control treatment was 0.47 mg kg^{-1} and that in treatments receiving 10 or 20 mg kg^{-1} As were 0.58 and 1.04 mg kg^{-1}, respectively. Arsenic accumulation in grain significantly varied with the different water management practices. The highest As concentration in grain was observed when plants were grown under continuous standing water (0.94 mg kg^{-1}) followed by water saturated condition and alternate wetting drying condition. There was a significant interaction effect among the arsenic rates and different water management practices on grain arsenic concentration (Table 5). At a particular water management practice, the concentration of increased with increase in levels of As addition to soil. Besides, there was a significant variation in grain As concentration among the water management practices at a particular level of As level. Alternate wetting and drying practice of water management showed the lowest grain As concentration compared to other management practices at all levels of As addition to soil. Grain As concentration ranged from 0.37 mg kg^{-1} when plants were grown without any As addition under alternate wetting and drying condition to 1.52 mg kg^{-1} in soil treated with 20 mg kg^{-1} As and under continuous standing water condition. Therefore, growing rice AWD condition may be an effective way to mitigate As accumulation in rice grain without yield penalties, which is in agreement with the findings of Xu *et al.* (2008) and Talukder *et al.* (2011).

Table 4. Main effects of added As and water management practices on grain and straw As concentration of BRRI dhan29 rice

Factors	Grain-As (mg kg^{-1})	Straw-As (mg kg^{-1})
Added As (mg kg^{-1})		
0	0.47b	6.40c
10	0.58b	8.17b
20	1.04a	11.36a
SE(±)	0.056	0.460
CV (%)	8.19	8.96
Water management options		
CSW	0.94a	12.23a
SC	0.65b	7.95b
AWD	0.50b	5.75c
SE(±)	0.06	0.46
CV (%)	8.19	8.96

In a column, the figure(s) having common letters do not differ significantly at 5% level of probability.

Table 5. Interaction effects of added As and water management practices on As concentration in rice grain and straw of BRRI dhan29 rice

Added As (mg kg^{-1})	Water management	Grain-As (mg kg^{-1})	Straw-As (mg kg^{-1})
0	CSW	0.60cd	10.61bc
0	SC	0.45cd	4.92e
0	AWD	0.37d	3.66e
10	CSW	0.72bc	12.58ab
10	SC	0.54cd	7.30d
10	AWD	0.48cd	4.64e
20	CSW	1.52a	13.50a
20	SC	0.0 e	11.63ab
20	AWD	0.64cd	8.94cd
	SE(±)	0.06	0.46
	CV (%)	9.47	8.96

In a column, the figure(s) having common letters do not differ significantly at 5% level of probability.

Arsenic accumulation in rice straw

Arsenic concentration in straw of BRRI dhan29 rice was significantly affected by the addition of 10 and 20 mg kg^{-1} As to soil (Table 4). Arsenic concentration in straw of arsenic control treatment was 6.40 mg kg^{-1} and that in treatments receiving 10 and 20 mg kg^{-1}As were 8.17 and 11.36 mg kg^{-1}, respectively. The different water management practices showed significant variation in As concentration in straw (Table 4). All the three water management practices differed significantly with respect to As concentration in straw. The highest As concentration in straw was observed when plants were grown under continuous standing water (12.23 mg kg^{-1}) followed by water saturated condition (7.95 mg kg^{-1}) and alternate wetting and drying condition (5.75 mg kg^{-1}). There was also a significant interaction effect between the different levels of As addition and different water management practices on As concentration in straw (Table 5). The straw As concentration ranged from 3.66

mg kg^{-1} obtained from alternate wetting and drying condition in As control pot to 13.5 mg kg^{-1} in continuous standing water condition with 20 pm As addition. There was about 3-fold increase in straw As concentration under continuous standing water condition compared to alternate wetting and drying condition when plants were grown with 0 and 10 mg kg^{-1} added As to soil. When soil was added with 20 mg kg^{-1} As, the straw As concentration increased by about 50% under continuous standing water compared to that of alternate wetting and drying condition.

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