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Arsenic Management in Contaminated Irrigation Water for Rice Cultivation

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ABSTRACT

Arsenic (As) contaminated irrigation water (groundwater) is a threat to irrigated rice cultivation. Studies were conducted during three consecutive Boro seasons (fully dependent on irrigation) at highly As contaminated areas in Bangladesh to determine a suitable water management practice to reduce As accumulation in rice. In this study, two water management techniques were evaluated: 1) alternate wetting and drying (AWD) and continuous standing water (CSW) with surface (25 µg L^{-1} As); and 2) groundwater (419 µg L^{-1} As). A high yielding rice variety, BRRI dhan28, was grown. Results showed that the yield obtained by two management techniques were almost similar, except in CSW with groundwater application where significant yield reduction was observed. Significantly lower As content was found in the straw (77.23%) and rice grain (38.14%) of AWD with groundwater and CSW (straw 70.41% and 26.36%) with surface water application compared to CSW with ground water application. Among the water management practices, AWD with groundwater application showed similar benefit to CSW with surface water irrigation. Thus, alternate wetting and drying (AWD) with groundwater or surface water irrigation with CSW can be advocated as an appropriate agronomic practice for rice cultivated in As contaminated soils of Bangladesh.

Keywords: Arsenic mitigation, water management, alternate wetting and drying, continuous standing water

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INTRODUCTION

Rice is the main food crop in Bangladesh. Some of this rice is cultivated on areas contaminated with As. This As comes from irrigation water extracted from underground. Arsenic contaminated irrigation water remains a threat to rice cultivation in Bangladesh and such water adds As to rice soils in Bangladesh, India and some other countries in the South and Southeast Asia (Smith et al., 2000). The added As through irrigation water for 10-20 years or more accumulates in the topsoil gradually, and the amounts now appear to be reaching levels that are toxic (>10.0 mg kg^{-1}) to rice growth (Brammer, 2007). It is reported that As level has gone up to 1.8 mg kg^{-1} in rice grain in some parts of the highly As contaminated areas (Mehrag & Rahman, 2003).

In many countries including Bangladesh, the statutory permissible limit for rice grain is only 1.0 mg of As kg^{-1} dry weight (Khan et al., 2010), but as in grains obtained from As contaminated areas is above the permissible level. A recent study showed that As concentration in the rice straw has reached the level of 92 mg kg^{-1} in Bangladesh (Abedin et al., 2002), whereas the statutory level for As in rice straw is only 0.2 mg kg^{-1} (Nicholson et al., 1999). Arsenic contamination in rice is not only affecting human health, but also drastically reduces grain yield. It is proven that As significantly reduces plant height, effective tiller number, straw weight and results in less rice grain yield (Wang, 2006). Arsenic is one of the most global toxicants that is transferred to human body via the food chain.

Arsenic speciation in the soil environment is dynamic. Inorganic species of arsenite (As-III) and arsenate (As-V) are mostly taken up by the rice plant. However, oxidised condition arsenate and waterlogged condition arsenite are the dominant forms of As. It is proven that As uptake by rice root is influenced by the presence of dominant species in the soil solution, root morphology and the presence of Fe, P and Si (Abedin et al., 2002; Lauren et al., 2003). Arsenite appears to be the main As species that is transported from the root cortical cells to the xylem vessels and its accounts for 60-100% of the total As. It was also found that arsenite accumulation is higher under flooded conditions than non-flooded areas (Li et al., 2009).

The application of As contaminated water increases the level of As in the soils when anaerobic condition occurs. From the previous studies, it has been reported that 85–95% of total As in rice was found under flooded conditions such as wetland rice. Moreover, it was observed that As concentration in soils, groundwater and plants is above the acceptable limits (>1.0 mg of As kg^{-1}). This circumstance poses a severe threat to human and livestock health, and highlights the need for more studies (Hossain, 2006).

There are 150 species of As bearing minerals in nature, namely, As sulfide or realgar (As_2S_2), As tri-sulfide or orpiment (As_2S_3) and arsenopyrite. According to Fazal et al. (2001), in Bangladesh, arsenopyrite has been recognised as the major source of As pollution. The original sources of As exists as both sulfide and oxide minerals. Furthermore, the oxidation of pyrite from these sources during sediment transport would have released soluble arsenic and sulfate (Karim et al*.,* 1997; BGS, 2000).

Application of irrigation water from different sources having different levels of As and different water management techniques may affect its uptake from soil by the rice plant. Rice grown under flooded conditions is found to accumulate much more As than that grown under aerobic conditions. Roberts et al. (2011) found at the early growth stages, As porewater concentrations reached up to 500 µg L^{-1} and were dominated by arsenite, while in the later part of the season, soil conditions became toxic and porewater concentration was only 150 µg L^{-1} of arsenate. Based on these findings, two water management techniques [alternate wetting and drying (AWD) and continuous standing water (CSW)] with two sources of water (groundwater 419 µg L^{-1} As and less contaminated surface/pond water, 25 µg L^{-1} As) were tested in this study to mitigate As contamination in soils as well as in rice plant.

MATERIALS AND METHODS

Location

The experiment was conducted at the Bangladesh Rice Research Institute (BRRI) farm Bhanga, Faridpur, during three consecutive Boro seasons (Boro 2011, 2012, 2013). The experimental soil contained OC (%) 1.74, pH 6.5, total N (%) 0.17, available P 9 mg kg^{-1}, K 0.56 $cmol_{(+)}$ kg^{-1} soil, S 29 mg kg^{-1}, Zn= 0.9 mg kg^{-1} and 12.7 mg kg^{-1} of As with sandy clay loam in texture. In Bangladesh, Boro season is considered as a dry season (from November to April) and rice is cultivated mainly with ground irrigation water. The experimental location was at BRRI regional station at Bhanga, Faridpur (23^{o}23ʾ20.49'' N and 89^{o}59ʾ27.07ʺE).

Planting

The popular high yielding rice variety BRRI dhan28 was grown in this study. Thirty-day-old rice seedlings were transplanted (20 cm × 20 cm) in the research plots. The fertilisers applied were N, P, K, S and Zn at 115-20-60-12-3 kg ha^{-1} from urea, triple super phosphate (TSP), muriate of potash (MOP), gypsum and zinc sulfate, respectively. Each plot size was 4 m × 4 m and the distance between plants was one meter. There were two water sources and two cultivation methods. The experimental design was Randomized Complete Block Design (RCBD) with three replications. Rice plant was harvested at maturity. The experiment was repeated for three successive seasons.

Water Management

Two water management techniques (AWD and CSW) were maintained with two sources of water, namely, groundwater and surface water containing 419 µg L^{-1} and 25 µg L^{-1} As, respectively. Irrigation water was continuously applied during the first 2 weeks in all the research plots. However, after 2 weeks, AWD plots received irrigation water and kept up to 15 cm depth from the soil surface for the period of panicle initiation to maturity in all the plots.

Determination of As in Soil and Water

Samples were dried and processed before digestion and total As content was determined by digesting the soil, paddy and straw samples with tri-acid mixture (HNO_3:$HClO_4$:H_2SO_4, 5:2:1) until it became whitish or clear (Rahman et al*.,* 2007).

Sample Preparation and Digestion

Rice samples were sun-dried soil sampled and ground. About 1.0 g ground samples were taken separately into digestion tube and 10 mL of 69% concentrated nitric acid and 70% of perchloric acid mixture at the ratio of 5:3 were added. The samples were left to react overnight in a chemical hood, and then heated in a block digester (M-24 plazas/ samples, JP Selecta, Spain) at 160ºC for two hours, and later it was increased to 300ºC for about 4-5 hours until colourless clear watery fluid appeared. Tubes were gently shaken several times to facilitate destruction of all the carbonaceous material. This digestion converts all arsenicals to inorganic arsenic for FI-HG-AAS determination. Tubes were removed from the digestion block, cooled, diluted to 50 mL adding Millipore water, filtered through filter paper and stored in 50 mL plastic bottles.

Clean and oven-dried rice straw samples were ground and digested as described by Wang et al. (2006) with some modifications. About 0.45 - 0.50g ground rice straw sample was taken after further drying at 60ºC to constant weight. It was taken separately into digestion tube and 7 mL of 69% concentrated nitric acid was then added. Similar procedures were followed as before.

Detection of Arsenic

The digest was cooled and then filtered, and the volume was finally made up to 50 mL. Concentrations of As in digested samples were determined using atomic absorption spectrophotometer (AAS), model PG – 990, equipped with a computer with atomic absorption (AA) Win software (PG Instruments Ltd., UK), as described by Samanta et al. (1999). Briefly, the samples were spiked with standards at different concentrations. Arsenic in the sample was calculated using the following formula:

$$\text{As concentration} = \frac{\text{As in sample solution } (\mu L) \times \text{mL of sample}}{\text{Sample weight (g)} \times 1000}$$

Statistical Analysis

The analysis of variance (ANOVA) was done and Duncan's multiple range test (DMRT) was used for mean comparisons of the treatment at 5% level of probability. Pearson correlation coefficients among the parameters were also determined.

RESULTS

As Concentration in the Paddy Soils

The concentration of As in the soils varied due to different water management practices (Table 1). It was observed that higher As concentration (11.6-13.9 mg kg^{-1}) was recorded in the first Boro (2011) compared to that of the following season for both water management practices. In the CSW system, comparatively high As values were obtained in the first season of Boro 2011 compared to AWD, whereas similar values were observed for the remaining seasons. Among the water sources, irrigation with surface water resulted in lower As concentrations than the groundwater. This was due to the surface water containing lower As compared to that of the groundwater. In Bangladesh, it is known that arsenopyrite ($FeAsS_2$) occurs in some of the sediments in its floodplains, especially a few meters below the surface. When wells are dug in those areas, mineral is disintegrated and oxidised, releasing As into the water.

As Uptake in Straw and Grain of Paddy

The present study showed that significantly higher As content was found in the straw and rice grain of the CSW compared to that of the AWD technique (Table 2). Additionally, higher concentrations of As were found in the rice straw for both of the water management practices. However,

Table 1
Arsenic contents in the soils at harvest

Methods of irrigation	Source	Soil As (µg kg^{-1}) (post-harvest)		
		Boro 2011	Boro 2012	Boro 2013
CSW	surface water	13.9	9.91	10.38
	ground water	13.9	10.47	10.70
AWD	surface water	11.6	9.2	9.28
	ground water	12.9	11.22	10.80
	LSD $_{(5\%)}$	3.18	1.49	2.89
	CV %	12.2	8.5	14.1

AWD = alternate wetting and drying, CSW = continuous standing water
Initial soil As =12.7 mg kg^{-1}, STW water As=419 µg kg^{-1}, Pond water As =25 µg kg^{-1}

Table 2
Arsenic contents (mg kg^{-1}) in the straw and paddy

Methods of irrigation	Source	Boro 2011		Boro 2012		Boro 2013	
		Straw	Paddy	Straw	Paddy	Straw	Paddy
		--------------------------- mg kg^{-1} ---------------------------					
CSW	surface water	1.79	0.48	0.52	0.35	1.07	0.46
	ground water	3.43	0.52	0.85	0.46	1.48	0.65
AWD	surface water	1.55	0.34	0.39	0.29	0.70	0.45
	ground water	1.73	0.40	0.67	0.37	0.85	0.41
	LSD $_{(5\%)}$	0.61	0.61	0.35	0.08	1.17	0.14
	CV %	14.4	14.4	33.2	12.7	57.4	14.1

AWD = alternate wetting and drying, CSW = continuous standing water the concentrations of As were higher in the first (Boro 2011) compared to that of the following two seasons.

Among the water sources, groundwater showed higher As values during the planting period compared to those of surface water. The trend of the As uptake by the rice plant was found to follow the order of straw > grain. Higher As concentration observed in the CSW system might be due to rice plant growing under water saturated soil conditions through the entire life period in which more As was mobilised and absorbed into the rice plant. On the other hand, in the AWD system, part of the growth phase was under dry condition with plenty of oxygen around the root system that helps to form Fe plaque. The actual As in bulk was locked in the soils and did not get into the plants to such an extent as for rice cultivated under CSW condition.

In the present study, CSW agronomic practice using surface water showed less As accumulation in the paddy and post-harvest soils. Approximately 77.23 and 38.14% of straw and grain As reduction, respectively, were found in AWD with groundwater irrigation which was closer to CSW with surface water treatment, where 70.41% in straw and 26.36% in grain As reductions were observed compared to CSW with groundwater irrigation.

The addition of As with irrigation water severely affected the rice tillers number, panicle length and grain yield significantly ($p \leq 0.05$). The maximum plant height and straw yield was observed at lower As concentrations. However, the lowest tillers number, panicles number, panicle length and grain yield were found in control treatment.

Grain Yield

The effects of different water management practices on the grain yield during the three consecutive years differed (Figure 1). For Boro 2011, the grain yield of BRRI dhan28 differed significantly among the treatments. Maximum grain yield was observed in the AWD treatment irrigated with groundwater (8.28 t ha^{-1}), followed by (8.21 t ha^{-1}) continuous standing water irrigated with surface water treatments (Figure 1a). Unlike grain yield, grain As content was not affected by the water management practices. Grain As content of BRRI dhan28 ranged from 0.17 to 0.26 mg kg^{-1} and was much lower than the permissible limit of 1 mg kg^{-1}.

The study showed that the grain yield was significantly decreased by the As concentration present in the groundwater used for the CSW, although it was not the case for surface water used in the AWD irrigation system. It was observed that Boro 2012 showed lower grain yield than that of the other seasons (Figure 1b and Figure 1c). Among all seasons, a decrease in yield was found in the CWS planting seasons irrigated with groundwater (Boro 2011-2013). Post-harvest soils As concentration was increased by the continuous standing water condition. In the AWD system, such an increase was not observed in soil whereas surface water irrigation system showed a decreasing tendency of As in the soil. However, more As content in both straw and grain was found in the CSW system than the AWD

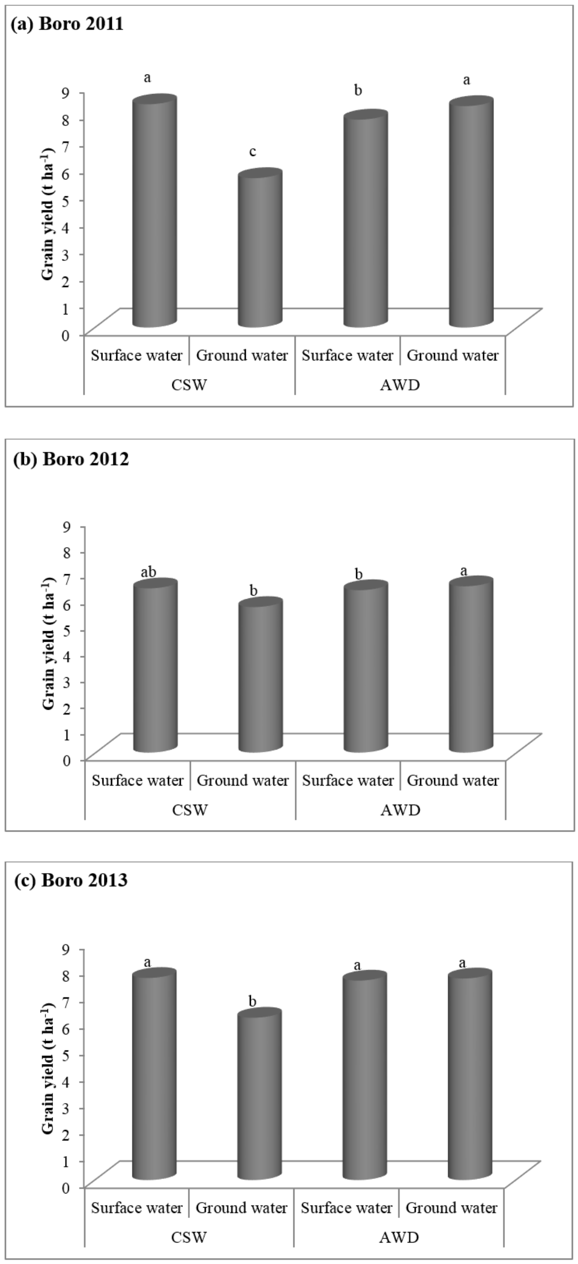

Figure 1. Effects of arsenic contaminated irrigation water on the rice yield (a) Boro 2011, (b) Boro 2012 & (c) Boro 2013

(AWD = alternate wetting and drying, CSW = continuous standing water) system, yet these values were lower in both irrigation systems irrespective of different As contents in the irrigation water. The grain yield of BRRI dhan28 significantly decreased under continuous standing water system (CSW) irrigated with groundwater which might be due to continuous standing of arsenic contaminated groundwater. Furthermore, the As concentrations in either irrigation water or as soil-applied rice reduced yield significantly.

DISCUSSION

Arsenic contaminated irrigation water used for the paddy cultivation increased As concentration in the cropland. Simultaneously, the As accumulated in the soil becomes hazardous to the plants. A similar finding has also been reported by Roberts et al. (2007). Flooded conditions in the paddy soils lead to As mobilisation that enhances its bioavailability to the rice plant (Takahashi et al., 2004; Xu et al., 2008). Similar findings were also reported by Ahmed et al. (2011) that As in grain was higher in the Boro than the Aman season, which was nearly twice as high. Hence, the seasonal differences in grain As concentration could be caused by irrigation of Boro rice with As contaminated groundwater. On the other hand, reduced condition in the soils releases iron oxides that increase inorganic arsenic content. Furthermore, even the flooding (monsoon) is unable to prevent the As accumulation in rice soils. Farmers usually practice intermittent irrigation which temporally limits As release into porewater during rice growth (Roberts et al., 2012). Li et al. (2009) proved that there was a rapid rise in As concentration in water as Eh dropped below 200 mV. Rice plant mostly takes arsenite, which is the dominant species under flooded conditions. Arsenate, rather than arsenite, is the main species that could adsorb on Fe-oxide root precipitates (Liu et al., 2006) and that is a positive factor as arsenate adsorption will be higher than that of arsenite in lower pH environment of rice rhizosphere (Dixit & Hering, 2003). Under oxidised state and also due to root respiration, iron plaque forms in the rhizosphere result in the oxidation of ferrous to ferric ion that precipitates as Fe hydroxides on the root surface. Fe hydroxides have a strong adsorptive capacity for arsenate making it unavailable for rice plant uptake (Chen et al., 2005). The presence of P also influences As uptake by rice plant and As concentration in rice shoot has been found to significantly reduce under low P condition (Sun, 2008).

Furthermore, it is clearly shown that soil becomes highly contaminated with As due to the excessive use of arsenic rich groundwater for irrigation (Bhattacharya et al., 2009). According to the findings of BGS (2000), groundwater As problem occurs because of three factors: 1) a source of As (As is present in the aquifer sediments); 2) mobilisation (As is released from the sediments to the groundwater); and 3) transport (As is flushed in the natural groundwater circulation).

The mobilisation of As into groundwater is mainly due to arsenopyrite oxidation and oxy-hydroxide reduction (Zheng et al., 2004). These As contaminants in the vadose zone in to the soil may be due to long-term source of groundwater contamination and these require remedy evaluations. Most remediation for the vadose zone needs to be made in part based on projected impacts to groundwater of the soil (Truex & Carroll, 2013). Due to the lowering of water table, the oxidation of arsenopyrite in the vadose zone releases As and this As can be adsorbed on Fe hydroxide during the subsequent recharge period; the reduction of Fe hydroxide releases As into groundwater. Moreover, the extent of formation of Fe-oxide that may precipitate on rice roots and in soil rhizosphere is one of the important factors leading to adsorption of As from soil solution (Hossain et al*.,* 2009) and can reduce As uptake by rice (Mei et al., 2009).

Lauren and Duxbury (2005) and Li et al. (2009) suggested cultivating non-flooded cereal crops in Boro season in As contaminated areas. It is known that As contamination in soil hampers rice plant growth and yield, although trace amount is required for plant growth (Khan et al*.,* 2010). Rice grown on As contaminated soils suffers from a disease called stripped head that decreases crop yield. Similar findings were reported by Dilday (2000), whereby the presence of soil contamination with As caused yield reduction in rice. There is no doubt that irrigating rice fields with groundwater enhances food security in Bangladesh. Nonetheless, the presence of high As concentrations in the groundwater limits its use for rice cultivation. To a certain extent, the hazard of using groundwater for irrigating rice fields can be reduced via special management practice proposed by this study. The accumulation of As and Cd in rice grains in opposite trends was affected by both water management and rice cultivar. Hence, the safe rice in relation to As and Cd may be possible through balancing water management and rice cultivar based on the severity of soil pollution (Hu et al*.,* 2013).

CONCLUSION

Contamination of As in groundwater is a threat for rice cultivation in Bangladesh. In this study, different water management techniques were evaluated for As uptake and accumulation in soil and plant. The results of the three years of field study demonstrated that AWD with groundwater irrigation system or irrigation with surface water could reduce As accumulation in the rice plant and soil. Hence, alternate wetting and drying (AWD) with groundwater or surface water irrigation with CSW can be advocated as an appropriate agronomic practice for rice cultivated in As contaminated soils of Bangladesh.

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