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Effect of water management, arsenic and phosphorus levels on rice in a high-arsenic soil–water system: II. Arsenic uptake

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ABSTRACT

Rice consumption is one of the major pathways for As intake in populations that depend on a rice diet in several countries of South and South-east Asia. Pot experiments were undertaken to investigate the effects of water management (WM), arsenic (As) contaminated soil-water and Phosphorus (P) rates on As uptake in rice plants. There were 18 treatments comprising of three each of As rates (0, 20 and 40 mg kg^{-1} soil) and *P* rates (0, 12.5 and 25 mg kg^{-1} soil) and two WM (aerobic and anaerobic) strategies on winter (boro var. BRRI dhan 29) and monsoon (aman var. BRRI dhan 32) rice at the Wheat Research Center (WRC), Nashipur, Dinajpur, Bangladesh. Arsenic concentrations in rice grain and straw increased significantly (**$P \leq 0.01$) with the increasing As rates in the soil. Arsenic availability in soil pore-water solution was less (58%) under aerobic WM (redox potential-Eh = +135 to +138 mV; pH—6.50 at 24.3 °C) as compared to anaerobic WM (flooded: Eh = −41 to −76 mV; pH-6.43 at 23 °C). The highest total grain As content 2.23 ± 0.12 mg kg^{-1} and 0.623 ± 0.006 mg kg^{-1} was found in T_6 ($P_{12.5}As_{40}$-anaerobic) and T_9 ($P_{25}As_{40}$-anaerobic) in BRRI dhan 29 and BRRI dhan 32, respectively, which was significantly higher (41–45%) than in the same As and P treatments for pots under aerobic WM. The As content in rice straw (up to 24.7 ± 0.49 ppm in BRRI dhan 29, 17.3 ± 0.49 mg kg^{-1} in BRRI dhan 32 with the highest As level) suggested that As can more easily be translocated to the shoots under anaerobic conditions than aerobic condition. BRRI dhan 29 was more sensitive to As than BRRI dhan 32. Under aerobic WM, P soil amendments reduced As uptake by rice plants. The study demonstrated that aerobic water management along with optimum P amendment and selection of arsenic inefficient rice varieties are appropriate options that can be applied to minimize As accumulation in rice which can reduce effects on human and cattle health risk as well as soil contamination.

1. Introduction

Rice (*Oryza sativa* L) is by far the most important cereal grown in Bangladesh. Per capita cereal consumption is 150.4 kg year^{-1} of which rice is 91% (Alam et al., 2002). High As concentrations in soil and the use of irrigation water with high As levels may lead to elevated concentrations of As in cereals, vegetables and other agricultural products in As affected areas of Bangladesh (Alam et al., 2003a, b; Williams et al., 2006). Khan et al. (2009) found that increasing arsenic concentrations of both soil and irrigation water resulted significantly increased As concentrations in both rice grain and straw. Khan et al. (2010) also found that addition of As either in irrigation water or in soil decreased grain yields by 21–74% in *boro* rice and 8 to 80% in aman rice. Human exposure to As is mainly through the intake of drinking water and foods, such as rice grains, that contain elevated amounts of As (Duxbury and Panaullah, 2007). Arsenic-contaminated rice could aggravate human health risk because it is consumed in large quantities especially in Asian countries (FAO, 2002).

Rice growing in the anaerobic situation was found to score the highest amount of As among all grain crops (Marin et al., 1993). Boro rice is exposed to As caused by both soil and irrigation water, whereas the aman rice is exposed to As through the natural soil As in addition to the build up of As over time due to use of contaminated irrigation water (Duxbury and Panaullah, 2007). Duxbury and Panaullah also assessed that As accumulation in soils could be increased at the rate of 1 mg kg^{-1} crop^{-1} through the use of 1.5 m of irrigation water containing 0.13 mg As L^{-1}, resulting in no net loss of As from the soil environment, it has a

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strong residual effects on following crops (Khan et al., 2010). Dittmar et al. (2010) also found that annually there was an estimated 4.4 ± 0.4 kg ha^{-1} a^{-1} As deposited through irrigation water. In the top 40 cm soil, the mean As accumulation over three years were recorded to 2.4 ± 0.4 kg ha^{-1} a^{-1}, implying that there was an average loss of As is 2.0 kg ha^{-1} a^{-1}. Arsenic contaminated groundwater has caused As accumulation in soils as high as 83 mg As kg^{-1} soil (Ullah, 1998).

The As content of lowland paddy-rice grain is generally much higher than that of upland rice or other cereal crops (Schoof et al., 1999; Williams et al., 2007) because of the high availability of soil As under anaerobic (lowland, flooded) conditions as compared to upland (aerobic) rice. The global normal range of As concentration in rice is 0.08–0.20 mg kg^{-1} (Zavala and Duxbury, 2008). But, rice grains contained As as high as 1.835 mg of As kg^{-1} have been found in Bangladesh (Meharg and Rahman, 2003). For a Bangladeshi adult, the average per day intake of As from As contaminated rice can be nearly 100 mg As (400 g dry wt $\times$ 0.25 mg As kg^{-1}), which is 5 times higher when compared to 20 mg As intake from consumption of 2 L of water at WHO recommendation (10 mg As L^{-1}) (Panaullah et al., 2009).

The presence of high As concentrations in agricultural soils and the use of As contaminated irrigation water may affect the movement of As in soil and its accumulation by rice (Abedin et al., 2002a). Arsenic dynamics and uptake by rice is impacted by complex soil variables and environmental and management factors. Different soils can behave differently. Two factors that have received considerable attention are water management and soil phosphate to mitigate arsenic phyto-toxicity and its uptake by rice plants. Hossain et al. (2009) observed that Fe-oxide plaque formation on the root surface has reduced As toxicity effects in a flooded-rice culture and thereby resulted in increased grain yields and reduced grain-As accumulation. On the other hand, the effect of applied phosphate was opposite. Growing rice in an aerobic situations where As is adsorbed on oxidized Fe surfaces and renders it largely unavailable to uptake by the rice plant (Lauren and Duxbury, 2005; Duxbury and Panaullah, 2007). Arsenic may also be present as arsenate where uptake is interrupted by phosphate (Abedin et al., 2002b), whereas arsenite is found in flooded anaerobic soils and can be readily taken up by plant cells allowing its passage into the plant parts (Meharg and Jardine, 2003) and which is not affected by phosphate (Abedin et al., 2002b; Creger and Peryea, 1994). So, from the above discussion it has come out that As uptake by rice plants parts would have a distinct negative impact on quality and profitability of rice products.

Water Management (WM) includes two systems: keeping the amount of irrigation water applied to just attain soil moisture near saturation (aerobic) vs. flooded anaerobic conditions. Understanding such effects of WM and P amendment and their interactions under As contaminated soil is critical to minimize As uptake by the rice plants. Therefore, the objectives of the present study were to: (1) investigate the impacts of water management on arsenic uptake by the rice plants, and (2) determine the influences of P amendment on As uptake under different WM regimes.

2. Materials and methods

The high yielding boro (BRRI dhan 29), and aman (BRRI dhan 32) rice, were grown in plastic pots at the Wheat Research Center, Nashipur (25°38′ N, 88°41′ E, and 38.2 m asl), Dinajpur, Bangladesh. Both are popular rice varieties widely used in Bangladesh (Khan et al., 2010). Soil used in the pots was extracted from a typical field in Dinajpur. Soil was Non-calcareous Brown Floodplain soil according to the Bangladesh soil classification system (FAO-UNDP, 1988), sandy loam and acidic in nature (Tables 1 and 2). The soils were analyzed for selected physical and chemical characteristics before initiation of the experiment. The physico-chemical properties of the pot soil are presented in Tables 1 and 2.

Treatments consisted of three levels each of As (0, 20 and 40 mg of As kg^{-1} soil) and P (0, 12.5 and 25 mg of P kg^{-1} soil) and two WM levels; flooded (anaerobic) and near saturated conditions (aerobic) conditions. There were eighteen treatment combinations in the experiment. The design was completely randomized and each treatment was replicated three times.

Table 1
The physical properties of the pot soil.

Physical properties of soil	Value (%)
Sand (2–0.05 mm)	60
Silt (0.05–0.002)	18
Clay (< 0.002 mm)	22
Soil texture class	Sandy loam
Moisture	20.5

Table 2
The chemical properties of the pot soil.

Chemical properties of soil	Value
pH (1: 2) soil: water	5.5
Organic carbon (%)	0.25
Exchangeable potassium (meq/100 g soil)	0.23
Exchangeable calcium (meq/100 g soil)	2.35
Exchangeable magnesium (meq/100 g soil)	0.70
Total N	0.064
Available phosphorus (mg kg^{-1})	7.31
Available sulphur (mg kg^{-1})	1.09
Available zinc (mg kg^{-1})	0.53
Available iron (mg kg^{-1})	23.24
Available *boron* (mg kg^{-1})	0.23
Arsenic (mg kg^{-1})	10.00

2.1. Pot preparation

An amount of 5 and 3 kg soil was taken in each of 5 and 3 l plastic pots for BRRI dhan 29 and BRRI dhan 32, respectively. The heights of the 3 and 5 l pots were 14.1 cm and 18.6 cm and diameters were 14.4 and 18.9 cm, respectively. There were altogether 54 pots for both BRRI dhan 29 and BRRI dhan 32. For aerobic WM (near saturation), pots were placed into a plastic bowl 6.5 cm deep. Each pot had five holes to create an opportunity for removal of excess water or uptake by the plant as and when necessary. On the other hand, under anaerobic (flooded) WM, there were no holes in the pots to remove the excess irrigation water to create a flooded situation.

2.2. Fertilizer application

2.2.1. Transplanted BRRI dhan 29

The total amount of P, potassium (60 mg K kg^{-1} soil), sulphur (12.6 mg S kg^{-1} soil) and zinc (3.6 mg Zn kg^{-1} soil) for each pot were calculated and added as a solution of triple super phosphate, murate of potash, gypsum and zinc sulphate (monohydrate), respectively in distilled water and was applied once before transplanting the rice seedlings during final pot preparation. After fertilization, irrigation with distilled water was applied to the pot to bring the soil up to saturation. Arsenic was applied as a solution of $Na_2HAsO_4.7H_2O$ (24% As) in distilled water in concentrations of 0, 20 and 40 mg As kg^{-1} soil at one day after transplanting. The total amount of nitrogen (124 mg N kg^{-1} soil) was supplied as a solution of urea in distilled water and applied in three equal splits at 15, 45 and 55 day after transplanting (DAT).

2.2.2. Transplanted BRRI dhan 32

The total amount of P (0, 12.5 and 25 mg kg^{-1} soil) from triple super phosphate, potassium (35 mg K kg^{-1} soil) from murate of potash, sulphur (12.6 mg S kg^{-1} soil) from gypsum and zinc (3.6 mg Zn kg^{-1} soil) from zinc sulphate (monohydrate) for each pot were calculated and mixed in distilled water and applied once before transplantation of the rice seedlings during final pot preparation. After fertilization, the pots were irrigated with distilled water to bring the soil up to saturation. Arsenate was applied as a solution of $Na_2HAsO_4.7\ H_2O$ (24% As) in distilled water in concentrations of 0, 20 and 40 mg As kg^{-1} soil at one day after transplanting. The total amount of nitrogen (70 mg N kg^{-1} soil) as a solution urea in distilled water was applied in three equal splits at 15, 30 and 45 DAT.

2.3. Seedling transplanting

Two 35-day old seedlings per pot were transplanted into the plastic pots and grown to maturity inside a clear polyethylene tent house. The overall temperature