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# Influence of Soil Arsenic in Rice and its Mitigation Through Water Management

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**ABSTRACT**

Arsenic (As) contamination in rice (*Oryza sativa* L.) has become a global concern as a potential dietary risk to human health. In order to elucidate the effect of soil As contamination on rice and its management through water regimes, we analyzed two water management practices viz. alternate wetting and drying (AWD) and continuous flooding (CF) in combination with different concentration of As (0, 20 and 40 mg kg$^{-1}$) using BRRI dhan47 rice variety. Pots were filled with 10 kg soil with background soil As 3.73 mg kg$^{-1}$. Results showed that As contamination significantly reduced growth and yield of rice. The grain and straw arsenic concentrations were 0.55 and 17.31 mg kg$^{-1}$, respectively in soil treated with As 40 mg kg$^{-1}$ while 0.18 mg kg$^{-1}$ grain As and 2.41 mg kg$^{-1}$ straw As were found in As 0 mg kg$^{-1}$ treatment. The AWD technique significantly reduced grain As concentration by 14% compared to CF with significant increase in grain yield. Straw As concentration, grain As uptake, and total As uptake were also significantly reduced by AWD practice. Thus, AWD rice cultivation can be a potential and sustainable technology to mitigate arsenic problem in rice in As-contaminated areas.



## Introduction

Arsenic (As) contamination in paddy soils is one of the most serious problems facing rice production in Asian countries. In Bangladesh, out of 64 districts, 61 districts are reported to have considerable levels of As in groundwater (BGS, 2001). Use of As contaminated groundwater in irrigation has resulted in an accumulation of As in soils and elevated uptake of As by crops (Meharg and Rahman, 2003; Norra *et al.*, 2005). Rice is an efficient crop in As uptake compared to other cereals (Bhattacharya *et al.*, 2009; Su *et al.*, 2009). Higher As concentration up to 1.8 mg kg$^{-1}$ in grain has been reported in some Bangladeshi rice cultivated in As-contaminated areas (Meharg and Rahman, 2003). Consumption of As-contaminated rice in large quantities could aggravate human health risk especially in Asian countries (FAO, 2002). Studies that examined rice intake stratified by water concentrations of arsenic found evidence of increasing trends in cardiovascular disease risk, skin lesions, and squamous cell skin cancers and bladder cancer associated with higher rice consumption (Karagas *et al.*, 2019). So, it is very important to reduce the As concentration in rice grain.

Some recent water saving rice cultures like aerobic rice culture and alternate wetting and drying (AWD) irrigation have shown the potentials in reducing As mobilization in porewater and finally reduce As uptake by rice (Roberts *et al.*, 2011). AWD is a water management system where rice fields are not kept continuously flooded but are allowed to dry intermittently during the rice growing stage. Around 15-30% of water inputs can be saved (Belder *et al.*, 2005) in this system and it has also been found effective in reducing greenhouse gas emission (Chidthaisong *et al.*, 2017) compared with continuous flooding (CF) system. Several studies also reported that AWD significantly reduce As uptake in rice (Talukder *et al.*, 2012; Linquist *et al.*, 2015; Islam *et al.*, 2017) compared to CF. In continuous flooded condition, reductive dissolution of As containing iron oxyhydroxides (FeOOH) releases arsenic due to reduction of iron (II) accompanied with reduction of arsenate (AsV) to arsenite (AsIII) which leads to arsenic mobilization and enhances bioavailability to rice (Hossain *et al.*, 2012). In oxic condition, arsenate (AsV) predominates and is adsorbed strongly to soil minerals such as iron (oxyhydro) oxides and thus limiting its movement to soil solution (Meharg, 2004; Williams *et*

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*al.*, 2007; Yamaguchi *et al.*, 2014). BRRI dhan47 was released by Bangladesh Rice Research Institute (BRRI) as a salt tolerant variety which also showed to some extent tolerance to As (Islam *et al.*, 2017). Performance of BRRI dhan47 in As contaminated soil in combination with AWD management is not that much clear. AWD technique combined with this variety might be a promising means of mitigating As in rice. Therefore, the present study was designed to find out the effect of soil As contamination in BRRI dhan47 and its mitigation through AWD irrigation.

## Materials and Methods

### *Experimental site, soil and treatments*

A pot experiment was carried out in the net house of the Department of Soil Science, Bangladesh Agricultural University (BAU), Mymensingh which belongs to the same environment of BAU farm (AEZ 9). The soil was silt loam with pH 6.28, organic matter content 1.12%, total N 0.152%, available P 11.08 ppm, exchangeable K 0.053 me% and available S 9.83 ppm and total arsenic 3.73 mg $kg^{-1}$. The experiment was laid out in a Completely Randomized Design (CRD) with three arsenic levels (0, 20 and 40 mg $kg^{-1}$ soil) in interaction with two water regimes such as CF (Continuous flooding) and AWD (alternate wetting and drying). All the treatment combinations were replicated three times. Eighteen (3×2×3) plastic pots were prepared with 10 kg soil in each pot. Arsenic was added with the soil in the form of sodium arsenite ($NaAsO_2$) following the experimental design at 10 days before transplanting of rice seedlings and thoroughly mixed for homogenization.

### *Fertilizer application and water management*

Recommended doses of fertilizers viz. triple superphosphate (TSP) for phosphorus, muriate of potash (MoP) for potassium, gypsum for sulphur and zinc oxide for zinc, were applied as basal dose before transplanting and puddled to give a complete mix. Urea was applied at 7, 27 and 55 days after transplanting in three equal splits (Hossain *et al.*, 2008). Forty-five (45) days old seedlings of BRRI dhan47 were transplanted and water (3-5 cm) was maintained at the beginning in each pot for plant establishment. After two weeks, AWD cycle was initiated in the assigned pots and irrigation was done when hair cracking was observed on soil surface due to water scarcity and continued up to the panicle initiation stage. Other intercultural operations were done as and when necessary.

### *Harvesting*

The crop was harvested at full maturity and data on growth and yield parameters like plant height, number of effective tillers $pot^{-1}$, panicle length, filled grains $panicle^{-1}$, unfilled grains $panicle^{-1}$, 100 grain weight, grain yield and straw yield were recorded.

### *As determination in rice grain and straw*

#### Sample preparation and digestion

The grain samples were collected, cleaned and dehusked whereas the straw samples were cleaned and chopped into 5mm pieces. Grain and straw samples were oven dried, powdered in the ball mill (Retsch Planetary Ball Mill PM100) and digested to analyze total arsenic concentrations. Digestion tubes were washed, soaked in acid bath containing 5% $HNO_3$ for 6 hrs and finally rinsed with deionized water. After drying the tubes, 0.3 g grain and 0.2 g straw samples were taken for digestion in the different tubes. Five mL trace element grade $HNO_3$ (nitric acid 65%, suprapur) was added to the samples and was allowed to stand overnight for pre-digestion. The following day, 2mL $H_2O_2$ was added and kept for 30 minutes to reduce effervescent bubbles and tubes were heated in the block digester raising a temperature upto 120°C. After 4-5 hrs, heating was stopped when the content of the digestion tube was colorless.

#### As concentration detection

The digest was cooled, diluted to 30mL with Milli-Q water. Arsenic content in the plant sample digest was determined by graphite furnace atomic absorption spectrophotometer (ZA3000 Series Polarized Zeeman).

### *Data analysis*

The analysis of variance (ANOVA) for various plant parameters and grain and straw arsenic concentrations were done following Two-way analysis of variance (TW-ANOVA) using General Linear Model (GLM) and the means were compared using Tukey method at 95% Confidence level in Minitab 18 statistical package (State College, PA).

## Results and Discussion

### *Effect of soil arsenic, water management and their interaction on rice growth*

Plant height (cm), number of effective tillers $pot^{-1}$, panicle length (cm), filled grains $panicle^{-1}$, unfilled grains $panicle^{-1}$ and 100 grain weight (g) were significantly affected by arsenic contamination in soil (Table 1). Plant height was significantly reduced at As 40 mg $kg^{-1}$ treated soil (62.81 cm) and As 20 mg $kg^{-1}$ treated soil (74.74 cm) compared to control (80.16). Soil contaminated with As 40 mg $kg^{-1}$ and As 20 mg $kg^{-1}$ showed statistically similar effect on plant height. Number of effective tillers $pot^{-1}$ was significantly reduced by 16.67% and 45% at As 20 mg $kg^{-1}$ and As 40 mg $kg^{-1}$ treated soil, respectively. Panicle length was reduced with increased As levels and the shortest panicle (20.06 cm) was recorded at As 40 mg $kg^{-}$

[1] followed by As 20 mg $kg^{-1}$ treated soil (22.32 cm) and control (24.40 cm). Number of filled grains $panicle^{-1}$ was reduced by 12% and 27% at 20 mg $kg^{-1}$ and 40 mg $kg^{-1}$ soil added arsenic, respectively compared to control. Number of unfilled grains $panicle^{-1}$ was increased with increasing As stress in soil. The lowest number of unfilled grains was found at control which was increased at As 20 mg $kg^{-1}$ and As 40 mg $kg^{-1}$ treatment. 100 grain weight was also decreased by 7% and 10% at 20 mg $kg^{-1}$ and 40 mg $kg^{-1}$ soil added As, respectively. Shah *et al.* (2014) reported a similar outcome that plant height, tiller number per pot, filled spikelet production were reduced with increasing As levels in soil. Negative effects of As on growth and yield parameters were also reported by several studies (Abedin *et al.*, 2002; Azad *et al.*, 2012; Hu *et al.*, 2013). *Wang et al.* (2006) reported that plant height and effective tiller number reduces significantly due to As contamination which results in less rice grain yield.

Effect of water management and soil arsenic contamination × water management was insignificant on plant height, number of effective tillers $pot^{-1}$ and number of unfilled grains $panicle^{-1}$ whereas AWD water management significantly increased panicle length, number of filled grains $panicle^{-1}$ and 100 grain weight compared to CF (Table 1). The interaction effect of soil arsenic contamination and water management was also significant on number of filled grains $panicle^{-1}$. Shah *et al.* (2014) also reported higher number of spikelets per pots and less sterility under aerobic condition compared to CF.

### *Effect of soil arsenic, water management and their interaction on grain and straw yield*

Grain yield and straw yield (g $pot^{-1}$) of BRRI dhan47 were significantly affected by arsenic contamination ($p=0.000$) in soil (Table 2). Grain yield was reduced by 46% and 177% at As 20 mg $kg^{-1}$ and As 40 mg $kg^{-1}$, respectively compared to control. The highest straw yield was found in control treatment (23.41 g $pot^{-1}$) which was significantly decreased at As 20 mg $kg^{-1}$ (17.64 g $pot^{-1}$) and As 40 mg $kg^{-1}$ treated soil (14.80 g $pot^{-1}$). As 20 mg $kg^{-1}$ and As 40 mg $kg^{-1}$ showed statistically similar effect. Panaullah *et al.* (2009) reported similar results that grain yield and straw yield were reduced by increased arsenic levels in soil. Negative effect of As contamination on grain yield was also reported by Islam *et al.* (2004). Decreased rice growth and grain yield in paddy soils of Bangladesh containing >13 mg As $kg^{-1}$ was also reported by Khan *et al.* (2010). Water management ($p=0.012$) and arsenic contamination × water management ($p= 0.047$) also significantly affected grain yield which was insignificant in case of straw yield (Table 2). The AWD system increased grain yield by 3% and 9% than CF at 20 mg $kg^{-1}$ and 40 mg $kg^{-1}$ soil As, respectively. In AWD system, production of increased number of filled and weightier grains is the main driving force leading to higher yield irrespective of little increase in grain arsenic concentration (Zhao *et al.*, 2010). Several studies found 12 to 18% increase (Talukder *et al.*, 2011; Liu *et al.*, 2013) in grain yield with AWD irrigation practice.

### *Effect of soil arsenic, water management and their interaction on grain and straw arsenic concentrations*

Grain and straw As concentration was significantly affected by soil arsenic contamination ($p=0.000$) (Table 2). The highest grain and straw arsenic concentrations (0.55 mg $kg^{-1}$ and 17.31 mg $kg^{-1}$, respectively) were found in As 40 mg $kg^{-1}$ treatment whereas 0.42 mg $kg^{-1}$ grain As and 7.37 mg $kg^{-1}$ straw As were found at As 20 mg $kg^{-1}$ treatment. The lowest grain and straw arsenic was found in control pots. Increased arsenic accumulation in different plant parts was reported by Wang *et al.* (2006) and Hu *et al.* (2013). Abedin *et al.* (2002) also found increased grain and straw arsenic concentrations with higher As contamination in irrigation water. Water management also significantly affected arsenic concentrations in grain ($p=0.019$) and straw ($p=0.049$) (Table 2). AWD system reduces 14% grain arsenic compared to CF system. Straw As concentration was significantly lower in AWD practice (8.49 mg $kg^{-1}$) than CF (9.97 mg $kg^{-1}$). The interaction effect of soil arsenic contamination and water management was not significant over grain and straw As concentration (Table 2). Several studies reported that compared to CF, AWD lowers arsenic concentration in rice grain (Linquist *et al.*, 2015; Norton *et al.*, 2016; Islam *et al.*, 2017). Xu *et al*. (2008) and Takahashi *et al*. (2004) demonstrated that flooded paddy soil enhances soil As mobilization and As bioavailability for plant. Roberts *et al.* (2011) found that continuously flooded irrigation environment facilitates the reductive dissolution of As-bearing iron oxyhydroxides which increase the availability of free As ions in soil solution and increasing As uptake rate by rice plants relative to that for AWD irrigation. In our study, grain arsenic concentration had significant negative relationship with grain yield (Fig. 1). Duan *et al.* (2017) also reported significant negative relationship between grain arsenic concentration and grain yield.

### *Effect of soil arsenic, water management and their interaction on grain, straw and total arsenic uptake*

Soil arsenic contamination significantly affected grain ($p=0.001$), straw ($p=0.000$) and total As uptake ($p=0.000$) of BRRI dhan47 (Table 3). The highest grain As uptake (5.89 µg) was found at As 20 mg $kg^{-1}$ followed by As 40 mg $kg^{-1}$ (4.08 µg) and control (3.69 µg). The effect of soil As contamination on straw and total As uptake showed the following trend: As 40 mg $kg^{-1}$> As 20 mg $kg^{-1}$> As 0 mg $kg^{-1}$.

Table 1. Growth performance of rice (cv. BRRI dhan47) under different soil arsenic concentrations and irrigation water management

| Treatments | Plant height (cm) | Effective tillers pot$^{-1}$ (No.) | Panicle length (cm) | Filled grains panicle$^{-1}$ (No.) | Unfilled grains panicle$^{-1}$ (No.) | 100 grain weight (g) |
|---|---|---|---|---|---|---|
| $T_1$ | 80.16±1.83a | 15.00±0.41a | 24.40±0.26a | 72.08±0.94a | 39.04±0.38c | 1.92±0.03a |
| $T_2$ | 74.74±1.36a | 12.50±0.29b | 22.32±0.42b | 63.53±0.25b | 46.27±0.62b | 1.79±0.03b |
| $T_3$ | 62.81±2.65b | 8.25±0.25c | 20.06±0.14c | 52.85±0.57c | 52.59±0.37a | 1.72±0.01c |
| *p value* | *0.003* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* |
| $I_1$ | 71.11±3.01 | 11.67± 1.23 | 21.90±0.79b | 62.20±3.42b | 45.72±2.42 | 1.78±0.03b |
| $I_2$ | 74.03±4.00 | 12.17±1.30 | 22.62±0.83a | 63.43±3.66a | 46.21±2.58 | 1.83±0.05a |
| *p value* | *0.271* | *0.228* | *0.034* | *0.025* | *0.419* | *0.039* |
| $T_1I_1$ | 77.13±1.07 | 14.5±0.50 | 24.10±0.04 | 70.55±0.45b | 39.23±0.77 | 1.87±0.02 |
| $T_2I_1$ | 73.57±2.35 | 12.5±0.50 | 21.75±0.46 | 63.95±0.05c | 45.60±0.91 | 1.76±0.03 |
| $T_3I_1$ | 62.63±3.87 | 8.0±0.00 | 19.86±0.15 | 52.10±0.90d | 52.33±0.79 | 1.72±0.01 |
| $T_1I_2$ | 83.18±0.82 | 15.50±0.50 | 24.71±0.48 | 73.60±0.70a | 38.85±0.45 | 1.96±0.02 |
| $T_2I_2$ | 75.90±1.68 | 12.5±0.50 | 22.90±0.40 | 63.10±0.10c | 46.94±0.76 | 1.82±0.03 |
| $T_3I_2$ | 63.00±5.20 | 8.5±0.50 | 20.26±0.14 | 53.60±0.20d | 52.84±0.28 | 1.71±0.02 |
| *p value* | *0.642* | *0.579* | *0.529* | *0.024* | *0.503* | *0.182* |
| *CV (%)* | *11.58* | *24.91* | *8.66* | *13.21* | *12.71* | *5.27* |

Table 2. Yield and arsenic concentration of rice under different soil arsenic concentrations and irrigation water management

| Treatments/ Interactions | Grain yield (g pot$^{-1}$) | Straw yield (g pot$^{-1}$) | As concentration grain (mg kg$^{-1}$) | As concentration straw (mg kg$^{-1}$) |
|---|---|---|---|---|
| $T_1$ | 20.75±1.01a | 23.41±1.25a | 0.18±0.02c | 2.41±0.47c |
| $T_2$ | 14.20±0.23b | 17.64±1.00b | 0.42±0.03b | 7.37±0.68b |
| $T_3$ | 7.49±0.25c | 14.80±0.37b | 0.55±0.02c | 17.31±0.65a |
| *p value* | *0.000* | *0.000* | *0.000* | *0.000* |
| $I_1$ | 13.45±2.2b | 18.11±1.49 | 0.41±0.07a | 9.97±2.96a |
| $I_2$ | 14.85±2.67a | 19.12±1.97 | 0.35±0.07b | 8.49±2.86b |
| *p value* | *0.012* | *0.382* | *0.019* | *0.049* |
| $T_1I_1$ | 19.15±0.75b | 22.67±0.27 | 0.22±0.02 | 3.08 ±0.52 |
| $T_2I_1$ | 14.02±0.32c | 16.25±1.33 | 0.46±0.02 | 8.00±0.88 |
| $T_3I_1$ | 7.81±0.07d | 15.42±0.08 | 0.56±0.05 | 18.83±0.49 |
| $T_1I_2$ | 22.35±0.65a | 24.16±2.86 | 0.14±0.02 | 1.74±0.38 |
| $T_2I_2$ | 14.38±0.38c | 19.03±0.57 | 0.37±0.00 | 6.75±1.10 |
| $T_3I_2$ | 7.17±0.41d | 14.18±0.22 | 0.53±0.01 | 17.00±0.77 |
| *p value* | *0.047* | *0.361* | *0.515* | *0.914* |
| *CV (%)* | *40.74* | *22.12* | *42.94* | *74.10* |

Table 3. Arsenic uptake in grain and straw of rice (cv. BRRI dhan47) under different soil arsenic concentrations and irrigation water management

| Treatments/ Interactions | Arsenic uptake in grain (µg) | Arsenic uptake in straw (µg) | Total arsenic uptake (µg) |
|---|---|---|---|
| $T_1$ | 3.69±0.30b | 56.34±10.6c | 213.27±53.5c |
| $T_2$ | 5.89±0.37a | 128.89±10.2b | 758.92±72.4b |
| $T_3$ | 4.08±0.18b | 265.69±15.8a | 1077.87±53.7a |
| *p value* | *0.001* | *0.000* | *0.000* |
| $I_1$ | 4.87±0.52a | 162.86±41.9 | 761.63±163a |
| $I_2$ | 4.23±0.40b | 137.75±37.2 | 605.08±162b |
| *p value* | *0.035* | *0.076* | *0.033* |
| $T_1I_1$ | 4.17±0.19 | 69.66±11.0 | 292.38±58.90 |
| $T_2I_1$ | 6.44±0.46 | 128.71±3.54 | 831.06±81.5 |
| $T_3I_1$ | 4.01±0.32 | 290.22±8.89 | 1161.45±57.0 |
| $T_1I_2$ | 3.21±0.27 | 43.03±14.2 | 134.16±34.1 |
| $T_2I_2$ | 5.34±0.09 | 129.06±24.8 | 686.79±120 |
| $T_3I_2$ | 4.14±0.29 | 241.16±14.6 | 994.29±10.2 |
| *p value* | *0.148* | *0.300* | *0.986* |
| *CV (%)* | *25.02* | *62.15* | *56.87* |

$T_1$: 0 mg kg$^{-1}$ As, $T_2$: 20 mg kg$^{-1}$ As, $T_3$: 40 mg kg$^{-1}$ As;$I_1$: Continuous Flooding (CF), $I_2$: Alternate wetting and drying (AWD). (Figures in a column having common letters do not differ significantly at 5% level of significance) *p*= Probability; SE (±) = Standard error of means, CV= Coefficient of variation.

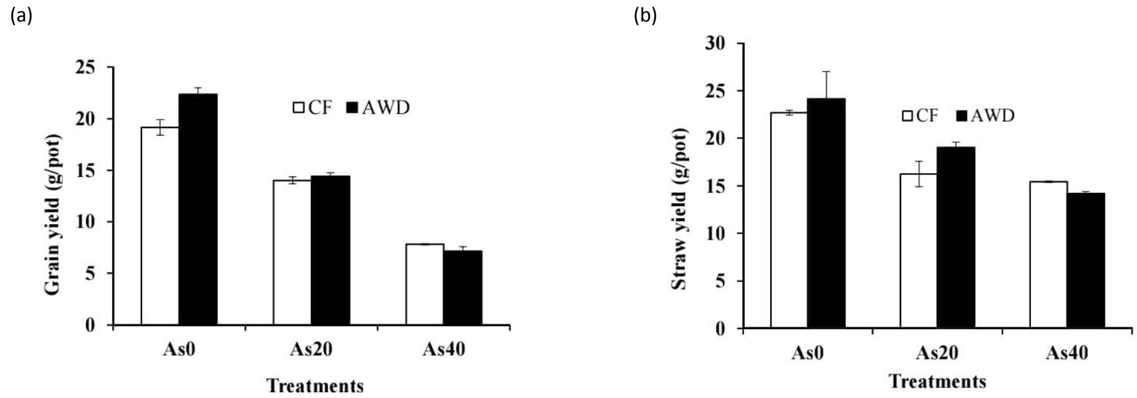


Figure 1. Grain and straw yield of rice (BRRI dhan47) under different soil arsenic concentrations and irrigation water management

As uptake in grain and total As uptake was significantly reduced in AWD system whereas reduction in straw As uptake was not statistically significant compared to CF. The effect of arsenic contamination × water management was not significant. Arsenic uptake in rice follows different mechanisms. Arsenite (AsIII) and arsenate (AsV) are the two mostly available inorganic forms of arsenic in soil. Arsenate availability increases under AWD condition while arsenite availability increases under CF (Norton *et al.*, 2013). In rice, arsenate is taken up through phosphate transporters while arsenite is taken up via the Lsi1 silicon transporters (Ma *et al.*, 2008). Very high silicon content in rice supports the high arsenite uptake in rice through silicon transporter (Ma and Yamaji, 2006) leading to higher arsenic accumulation under flooded condition compared to AWD condition (Norton *et al.*, 2013).

## Conclusion

In this study we investigated the effect of different levels of soil As contamination on rice (BRRI dhan47) and its management through irrigation practices. Our results revealed that rice growth and yield was significantly affected by soil arsenic contamination and AWD irrigation practice significantly increased rice yield compared to CF practice. Grain As concentration and uptake was significantly lower in AWD treatment as non-flooded condition did not facilitate As availability and mobilization compared to flooding management. Thus in high As-contaminated areas of Bangladesh, AWD irrigation can be practiced to minimize As concentration and uptake for betterment of rice yield compared to CF.

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## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

## References

Abedin, M.J., Cresser, M.S., Meharg, A.A., Feldmann, J. and Cotter-Howells, J. 2002. Arsenic accumulation and metabolism in rice (Oryza sativa L.). *Environmental Science & Technology,* 36: 962–968. https://doi.org/10.1021/es0101678

Azad, M.A.K., Mondal, A.H.M.F.K., Hossain, M.I. and Moniruzzaman, M. 2012. Effect of Arsenic Amended Irrigation Water on Growth and Yield of BR-11 Rice (Oryza sativa L.) Grown in Open Field Gangetic Soil Condition in Rajshahi. *Journal of Environmental Science and Natural Resources,* 5: 55-59. https://doi.org/10.3329/jesnr.v5i1.11553

Belder, P., Spiertz, J.H.J., Bouman, B.A.M., G., Lu, G. and Tuong, T.P. 2005. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crop Research,* 93: 169–185. https://doi.org/10.1016/j.fcr.2004.09.022

BGS and DPHE, 2001. Arsenic contamination of groundwater in Bangladesh (four volumes). British Geological Survey. www.bgs.ac.uk/Arsenic/Bangladesh

Bhattacharya, P., Samal, A.C., Majumdar, J. and Santra, S.C. 2009. Transfer of arsenic fromgroundwater and paddy soil to rice plant (Oryza sativa L.): a micro level study in West Bengal, India. *World Journal of Agricultural Sciences,* 5: 425–431.

Chidthaisong, A., Cha-un, N., Rossopa, B., Buddaboon, C., Sriphirom, P., Towprayoon, S., Tokida, T., Padre, A. and Minamikawa, K. 2017. Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand. *Soil Science and Plant Nutrition,* 64: 1-8. https://doi.org/10.1080/00380768.2017.1399044

Duan, G., Shao, G., Tang, G., Chen, H., Wang, B., Tang, Z., Yang, Y., Liu, Y. and Zhao, F.J. 2017. Genotypic and Environmental Variations in Grain Cadmium and Arsenic Concentrations among a Panel of High Yielding Rice Cultivars. *Rice,* 10: 9. https://doi.org/10.1186/s12284-017-0149-2

FAO (Food and Agriculture Organization). 2002. Rice Information, vol. 3. FAO, Rome, Italy.

Hossain, M., Islam, M.R., Jahiruddin, M., Abedin, A., Islam, S. and Meharg, A.A. 2008. Effects of Arsenic Contaminated Irrigation Water on Growth, Yield, and Nutrient Concentration in Rice. *Communications in Soil Science and Plant Analysis,* 39: 302-313. https://doi.org/10.1080/00103620701759335

Hossain, M., Williams, P.N., Mestrot, A., Norton, G.J., Deacon, C.M. and Meharg, A.A. 2012. Spatial Heterogeneity and Kinetic Regulation of Arsenic Dynamics in Mangrove Sediments: The

Sundarbans, Bangladesh. *Environmental Science & Technology,* 46: 8645-8652. https://doi.org/10.1021/es301328r

Hu, P., Huang, J., Ouyang, Y., Wu, L., Song, J., Wang, S., Li, Z., Han, C., Zhou, L., Huang, Y., Luo, Y. and Christie, P. 2013. Water management affects arsenic and cadmium accumulation in different rice cultivars. *Environmental Geochemistry and Health,* 35: 767–778. https://doi.org/10.1007/s10653-013-9533-z

Islam, M.R., Jahiruddin, M. and Islam, S. 2004. Effects of irrigation water arsenic in the rice-rice cropping system. On line Journal of Biological Science, 4: 542-546.

Islam, S., Rahman, M.M., Islam, M.R. and Naidu, R. 2017. Effect of irrigation and genotypes towards reduction in arsenic load in rice. *Science of the Total Environment,* 609: 311-318. http://dx.doi.org/10.1016/j.scitotenv.2017.07.111

Karagas, M.R., Punshon, T., Davis, M., Bulka, C.M., Slaughter, F., Karalis, D., Argos, M. and Ahsan H. 2019. Rice Intake and Emerging Concerns on Arsenic in Rice: a Review of the Human Evidence and Methodologic Challenges. *Current environmental health reports,* 6: 361–372. https://doi.org/10.1007/s40572-019-00249-1

Khan, M.A., Islam, M.R., Panaullah, G.M., Duxbury, J.M., Jahiruddin, M. and Loeppert, R.H. 2010. Accumulation of arsenic in soil and rice under wetland condition in Bangladesh. *Plant and Soil,* 333: 263–274. https://doi.org/10.1007/s11104-010-0340-3

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., da Rosa, E.F.F. and van Kessel, C. 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology,* 21: 407–417.

Liu, L., Chen, T., Wang, Z., Zhang, H., Yang, J. and Zhang, J. 2013. Combination of site-specific nitrogen management and alternate wetting and drying irrigation increases grain yield and nitrogen and water use efficiency in super rice. *Field Crop Research,* 154: 226–235. https://doi.org/10.1016/j.fcr.2013.08.016

Ma, J.F. and Yamaji, N. 2006. Silicon uptake and accumulation in higher plants. Trends in *Plant Science,* 11: 392–397. https://doi.org/10.1016/j.tplants.2006.06.007

Ma, J.F.,Yamaji, N., Mitani, N., Xu, X.Y., Su, Y.H., McGrath, S.P. and Zhao, F.J. 2008. Transporters of arsenite in rice and their role in arsenic accumulation in rice grain. *Proceedings of the National Academy of Sciences,* 105: 9931–9935. https://doi.org/10.1073/pnas.0802361105

Meharg, A.A. 2004. Arsenic in rice – understanding a new disaster for South-East Asia. *Trends in Plant Science,* 9: 415–417. https://doi.org/10.1016/j.tplants.2004.07.002

Meharg, A.A. and Rahman, M. 2003. Arsenic contamination of Bangladesh paddy field soils: implications for rice contribution to arsenic consumption. *Environmental Science & Technology,* 7: 229-234. https://doi.org/10.1021/es0259842

Norra, S., Aggrawala, P., Wagner, F., Berner, Z., Chandrasekharam, D. and Stuben, D. 2005. Impact of irrigation with As rich groundwater on soil and crops: a geochemical case study in Malda District, West Bengal. *Applied Geochemistry,* 20: 1890-1906. https://doi.org/10.1016/j.apgeochem.2005.04.019

Norton, G.J., Adomako, E.E., Deacon, C.M., Carey, A.M., Price, A.H. and Meharg, A.A. 2013. Effect of organic matter amendment, arsenic amendment and water management regime on rice grain arsenic species. *Environmental Pollution,* 177: 38–47. https://doi.org/10.1016/j.envpol.2013.01.049

Norton, G.J., Travis, T.J., Douglas, A., Price, A.H., Hossain, M. and Islam, M.R. 2016. Utilizing genetic variation and water management for cultivating low grain arsenic rice. Arsenic Research and Global Sustainability: Proceedings of the Sixth International Congress on Arsenic in the Environment, June 19-23, Stockholm, Sweden.

Panaullah, G.M., Alam, T., Hossain, M.B., Loeppert, R.H., Lauren, J.G., Meisner, C. A., Ahmed, Z.U. and Duxbury, J.M. 2009. Arsenic toxicity to rice (Oryza sativa L.) in Bangladesh. *Plant and Soil,* 317: 31-39.

Roberts, L.C., Hug, S.J., Voegelin, A., Dittmar, J. and Kretzschmar, R. 2011. Arsenic dynamics in porewater of an intermittently irrigated paddy field in Bangladesh. *Environmental Science & Technology,* 45: 971-976. https://doi.org/10.1021/es102882q

Shah, A.L., Naher, U.A., Hasan, Z., Panhwar, Q.A. and Radziah, O. 2014. Influence of Arsenic on Rice Growth and its Mitigation with Different Water Management Techniques. *Asian Journal of Crop Science,* 6: 373-382. https://doi.org/10.3923/ajcs.2014.373.382

Su, Y.H., McGrath, S.P. and Zhao, F.J. 2009. Rice is more efficient in arsenite uptake and translocation than wheat and barley. *Plant Soil,* 328: 27–34. https://doi.org/10.1007/s11104-009-0074-2

Takahashi, Y., Minamikawa R., Hattori, K.H., Kurishima, K., Kihou, N. and Yuita, K. 2004. Arsenic behavior in paddy fields during the cycle of flooded and non-flooded periods. *Environmental Science & Technology,* 38:1038–1044.

Talukder, A.S.M.H.M., Meisner, C.A., Sarkar, M.A.R. and Islam, M.S. 2011. Effect of water management, tillage options and phosphorus status on arsenic uptake in rice. *Ecotoxicology and Environmental Safety,* 74: 834-839.

Talukder, A.S.M.H.M., Meisner, C.A., Sarkar, M.A.R., Islam, M.S., Sayre, K.D., Duxbury, J.M. and Lauren, J.G. 2012. Effect of water management, arsenic and phosphorus levels on rice in a high-arsenic soil-water system: II. Arsenic uptake. *Ecotoxicology and Environmental Safety,* 80: 145-151. https://doi.org/10.1016/j.ecoenv.2012.02.020

Wang, S. and Mulligan, C.N. 2006. Occurrence of arsenic contamination in Canada: Sources, behavior, and distribution. *Science of the Total Environment,* 366: 701–721. https://doi.org/10.1016/j.scitotenv.2005.09.005

Williams, P.N., Villada, A., Deacon, C., Raab, A., Figuerola, J., Green, A.J., Feldmann, J. and Meharg A.A. 2007. Greatly enhanced arsenic shoot assimilation in rice leads to elevated grain levels compared to wheat and barley. *Environmental Science & Technology,* 41: 6854–6859. https://doi.org/10.1021/es070627i

Xu, X.Y., McGrath, S.P., Meharg, A.A. and Zhao, F.J. 2008. Growing rice aerobically markedly decreases arsenic accumulation. *Environmental Science & Technology,* 42: 5574-5579. https://doi.org/10.1021/es800324u

Yamaguchi, N., Ohkura, T., Takahashi, Y., Maejima, Y. and Arao, T. 2014. Arsenic distribution and speciation near rice roots influenced by iron plaques and redox conditions of the soil matrix. *Environmental Science & Technology,* 48: 1549–1556. https://doi.org/10.1021/es402739a

Zhao, F.J., McGrath, S.P. and Meharg, A.A. 2010. Arsenic as a Food Chain Contaminant: Mechanisms of Plant Uptake and Metabolism and Mitigation Strategies. *Annual review of plant biology,* 61: 535-59. https://doi.org/10.1146/annurev-arplant-042809-112152