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Alternate wetting and drying decreases arsenic content and increases yield of rice grown in organic matter amended soil

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Abstract

Organic matter (OM) shows a critical role in mobilization and uptake of arsenic (As) by rice, and water management practice can mitigate this problem. However, very few research highlighted the impact of management of water on rice as influenced by OM amendment. Therefore, this study has evaluated the changes in As mobilization in paddy soil under different OM amendment and water management practices. Here, rice was grown to maturity in a two-factorial pot experiment comprising two different water management practices [continuous flooding (CF) and alternate wetting drying (AWD)] and eight combinations of As and OM amendment [comprising two As treatments (0 and 20 ppm) and four OM amendments (0, 0.25%, 0.5% and 5.0% w/w)]. Application of OM in As contaminated soil caused a significant increase in As accumulation in rice, and exhibited decreased growth and yield of rice. However, the results showed that rice growth and yield was significantly higher under AWD practice compared to CF. Arsenic concentration in rice was the lowest in As and OM control pots (44.67 µg/kg in AWD and 62.13 µg/kg in CF), and higher in As treated pots. Moreover, As concentration in rice grain increased with increasing levels of OM amendment. The As concentration in rice grain (168.44 µg/kg in AWD and 183.85 µg/kg in CF) was significantly higher in As treated pots with 0.5% OM amendment compared to other treatment combinations. Application of 5% OM in As contaminated soil did not produce any grains due to extreme toxicity. Thus, As accumulation in rice can be decreased by AWD water management technique without compromising yield. The findings suggest that applying OM in paddy soils with high soil As content should be done with caution.

Keywords: Arsenic mobilization, water management, organic matter amendment, rice.

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Introduction

Abiotic stresses such as extreme of salt, water logging and scarcity, and heavy metals (HM) are serious environmental treat to agriculture (Rhaman et al., 2022). Groundwater and sediment contamination by arsenic (As) is regarded as a significant environmental problem worldwide. In Bangladesh, however as in other parts of the Asian subcontinent soil As contamination is one of the most important problems (Mondal et al., 2020). Arsenic is particularly hazardous to most plant species at greater concentrations due to its interference with plant physiological processes, suppression of seedling growth, decrease in root development, and As induced phytotoxicity (Abbas et al., 2018; Zhang et al., 2021; Sharma et al., 2021). As a consequence, it is critical to examine the detrimental influence of As on plant growth, particularly in paddy soil, because it is a major issue in rice production using conventional water management approaches.

Rice is one of the dominant as well as staple food in many Asian countries, including Bangladesh (Rhaman et al., 2016; Mondal et al., 2020). However, rice production is severely affected by different environmental constrains. Especially, rice in particular is problem because rice is generally grown in submerged soil, and it causes a significant increase in As accumulation in rice grains due to the increasing bioavailability and mobility

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of As in wetland soils (Upadhyay et al., 2019). Although the rice production under continuous flooded condition is productive, it is also associated with high water consumption, methane emission and As accumulation in rice (Zhao et al., 2010). Thus, development of sustainable agronomic practice to decrease the As accumulation in rice is crucial.

Arsenic accumulation in rice can be decreased by adopting efficient water management approaches, which can contribute to decrease the As mobility in soils (Harine et al., 2021). It has been reported that mobilization and bioavailability of As was increased by continuous flooding in the rice field and further enhances the accumulation of As in grain and straw. On the contrary, As accumulation was decreased by alternate wetting and drying (AWD) in rice field (Murugaiyan et al., 2021). The IRRI experts have promoted the idea of the AWD approach for water management to decrease water requirement for rice growing with some yield benefits as well (Mubeen et al., 2022). This technique keeps the soils oxygenated for a while and thus reduce the formation of greenhouse gases. Some reports have shown the potentials of water saving rice cultures like aerobic rice culture (Harine et al., 2021; Mubeen et al., 2022), and intermittent irrigation (Roberts et al., 2011) in reducing As mobilization in pore water and finally reduced As uptake by rice. However, anaerobic condition in paddy soil leads to As mobilization and, therefore, As uptake by rice could increase.

Applying organic matter (OM) to soil is considered as a beneficial practice, because it serves as a source of nitrogen, phosphorus, and other nutrients (Abbas et al., 2020). However, OM is important for the mobilization of soil As in paddy field and addition of OM in soil may increase the amount of As released into the paddy pore fluids and the amount of As assimilated by rice plants (Hossain et al., 2021). Furthermore, decreased water management techniques has been introduced in Bangladesh, such as Alternate Wetting and Drying (AWD), which may also alters As mobilization in paddy soil. Hence, it is important to test the mobilization of As under AWD system with OM amendment in paddy soil. Arsenic contamination of groundwater is a big issue everywhere, but direct interactions of As and OM under different water management practices requires further investigation. Therefore, this research was undertaken to assess the effectiveness of water management to alter As mobilization in paddy soil and increase yield of rice under OM amendment.

Material and Methods

Soil samples were collected from the Soil Science field laboratory of Bangladesh Agricultural University using an auger at 0–15 cm depth of soil. The unwanted materials such as plant debris were removed from the collected soil samples. Soils were air-dried, sieved (≤2 mm), and thoroughly blended with hand. The characteristics of the collected soil samples are presented in Table 1. The non-draining pots (405 mm in diameter and 385 mm in height) were filled with 10kg of soil. The most popular rice (*Oryza sativa*) variety of Bangladesh (BRRI dhan28) was grown to maturity in the plant growth facility of the department.

Table 1. Morphological, physical and chemical properties of the initial soil samples

Morphological characteristics			
AEZ (Agroecological zone)	Old Brahmaputra Floodplain (AEZ 9)		
General Soil Type	Non calcareous dark grey floodplain soil		
Parent Material	Old Brahmaputra river borne deposits		
Physical characteristics			
Textural class	Silty loam [sand (13.3 %), silt (64.7 %) and clay (22 %)]		
Chemical characteristics			
Organic Matter (%)	2.03	Available P (ppm)	11.58
pH	6.50	Available K (meq/100g soil)	0.10
EC (µS/cm)	51.50	Available S (ppm)	9.00
Available N (%)	0.13	Total As (ppm)	3.74

Mechanical analysis of soil was done by hydrometer method (Bouyoucos, 1926). Soil pH was measured with the help of a glass electrode pH meter, the soil-water ratio being maintained at 1: 2.5 (Jackson, 1962). Electrical conductivity of the soil was measured by the EC meter (soil: water= 1:5). Organic carbon in soil was determined volumetrically by wet oxidation method (Walkley and Black, 1934). Total N content of soil was estimated following the micro-Kjeldahl method (Bremner and Mulvaney, 1982). Available P was extracted from the soil with 0.5 M $NaHCO_3$ solutions (Olsen, 1954). Exchangeable potassium was determined on 1N NH_4OAc (pH 7.0) extract of the soil by using flame photometer (Najafi-Ghiri et al., 2021). Available S content of soil was determined by extracting the soil with $CaCl_2$ (0.15%) solution as described by Sarap et al. (2020).

Experimental design and approach

The two-factorial experiment consisted of two water managements (continuous flooding and AWD) and eight treatment combinations of As and OM amendments (As_0 OM_0, As_0 $OM_{0.25\,\%}$, As_0 $OM_{0.5\,\%}$, As_0 $OM_{5\,\%}$, $As_{20\,ppm}$ OM_0, $As_{20\,ppm}$ $OM_{0.25\,\%}$, $As_{20\,ppm}$ $OM_{0.5\,\%}$ and $As_{20\,ppm}$ $OM_{5\,\%}$) and was replicated three times using completely randomised design (CRD). Arsenic was added from analytical grade sodium arsenate @ 0 and 20 mg As/kg soil, while the OM (N: 1.07%, P: 0.57%, K:0.54%, S:0.32%) was added @ 0, 0.25, 0.5 and 5.0 % (w/w) during pot preparation. Each pot received 0.65 g N from urea, 0.375 g P from TSP, 0.24 g K from MoP and 0.42 g S from gypsum, based on the fertilizer recommendation guide 2018. Except for N, all fertilizers were applied during final pot preparation. Urea was applied in three equal splits i.e., during pot preparation, 36 and 51 days after transplanting. Seventeen days healthy seedlings were transplanted in the pots. Three hills, each made up of two seedlings, were planted in each pot at an equal distance apart. All the pots were continuously submerged in water (4–6 cm) for 12 days following transplanting. Then, new water management techniques were introduced. In case of water management, 4–6 cm continuous standing water height was maintained in continuous flooding condition (CF). Under AWD condition, six cm water was added, and soil water was monitored using AWD pipes. Further irrigation was done when water level went 15 cm below the soil surface; this process was continued up to grain filling stage. Weeding and loosening of soils around the rice hills were done as and when necessary. The harvesting was conducted at maximum maturity stage on same day and time.

Data recorded

The data were collected from all the plants grown in each pot for all the yield contributing characteristic such as plant height, panicle length, number of filled and unfilled grains, number of effective and ineffective tillers pot^{-1} and 100-grains weight. Following harvesting, both grain and straw yield of rice were recorded and stored for chemical analysis. The samples were dried at 60 °C in an oven for 48 hours, and then grinded homogenously for determining the As concentration in by rice grain and straw samples. About 0.5 g of sub sample was transferred in the digestion tube with 5 mL HNO3 and 2.5 mL H2O2, and allowed to stand overnight (Jahan et al., 2021). Then, the tubes containing the samples were subjected to digestion and heated slowly up to159°C for two hours, and allowed to cool. Again, the digestion tubes was heated up to 162°C, and continued until it looks colorless. The plant digest was run through the Atomic Absorption Spectrophotometer (AAS) using the graphite furnace atomizer (Model: Shimadzu AA-7000) to determine the As concentration in rice.

Statistical analysis

The data were analyzed statistically using two-way analysis of variance (ANOVA) and the significant ($p \leq 0.05$) difference among the treatments were determined by Tukey's test in Minitab17 statistical software.

Results

Effect of OM and As treatment on growth of rice under AWD and CF condition

Plant height, panicle length and number of filled grains per panicle varied significantly depending on water management practices and treatment combinations of As and OM amendment, with the interaction being non-significant (Table 2). The results exhibited that AWD practice was associated with at least 1.1-fold increase in the yield contributing characters in comparison to CF. Nevertheless, these parameters varied insignificantly with the addition of OM in soil in absence of As. When the plants were exposed to 20 ppm As, the above mentioned yield contributing parameters decreased significantly with the increasing OM content (Table 2).

Table 2. Effect of organic matter (OM) amendment and arsenic (As) treatment combinations on growth parameters of Boro rice (cv. BRRI dhan28) under continuous flooding (CF) and alternate wetting and drying (AWD) conditions.

Treatments		Plant height (cm)	Panicle Length (cm)	Effective Tiller/Hill	Ineffective Tiller/Hill	No. of filled grains/panicle	No. of unfilled grains/panicle	100 grain weight (g)
Water (W)	CF	56.59 b	18.49 b	16	1.54	42.20 b	29.84	1.43
	AWD	60.85 a	19.73 a	17	1.83	56.00 a	31.80	1.54
	P value	*0.002*	*0.02*	*0.17 (ns)*	*0.41 (ns)*	*0.000*	*0.42 (ns)*	*0.33 (ns)*
Treatment (T)	T_1: As_0 OM_0	67.09 a	21.60 a	24 a	1.00 b	62.00 ab	39.00 a	2.00 a
	T_2: As_0 $OM_{0.25}$	68.43 a	21.86 a	21 ab	0.33 b	63.00 a	38.00 ab	2.00 a
	T_3: As_0 $OM_{0.5}$	68.60 a	21.71 a	20 bc	0.50 b	74.00 a	29.00 ab	2.00 a
	T_4: As_0 $OM_{5.0}$	68.56 a	21.21 ab	21 ab	0.17 b	73.00 a	26.00 ab	2.00 a
	T_5: As_{20} OM_0	58.60 b	19.48 ab	17 cd	0.50 b	46.00 bc	35.00 ab	2.00 a
	T_6: As_{20} $OM_{0.25}$	54.70 b	18.27 b	14 d	1.00 b	36.00 c	33.00 ab	1.44 a
	T_7: As_{20} $OM_{0.5}$	54.98 b	18.03 b	14 d	0.00 b	39.00 c	25.00 ab	2.00 a
	T_8: As_{20} $OM_{5.0}$	28.78 c	10.74 c	1 e	10.00 a	0.00 d	21.00 b	0.33 b
	P value	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.010*	*0.000*
W×T	*P* value	*0.21 (ns)*	*0.69 (ns)*	*0.22 (ns)*	*0.32 (ns)*	*0.15 (ns)*	*0.09 (ns)*	*0.30 (ns)*

Here, arsenic as As@ 0 and 20 mg/kg soil while organic matter as OM@ 0, 0.25, 0.5 and 5.0 % (w/w). Water management alternate wetting and drying as AWD and continuous flooding as CF.

Number of effective and ineffective tillers per hill, number of filled grains per panicle and 100-grain weight were significantly influenced by the treatment combinations of As and OM amendment only, with the water management practices and interactions being non-significant (Table 2). When the plants were exposed to 20 ppm As, these parameters decreased significantly with the increasing OM content. Whereas, the number of ineffective tillers per hill was the lowest when the plants were exposed to T_8 treatment ($As_{20\ ppm}$ $OM_{5\ \%}$).

Effect of OM and As treatment on grain and straw yield of rice under AWD and CF condition

Grain yield varied significantly by water management practices, treatments, and their interactions (Table 3). The grain yield of rice exhibited significant increase under AWD condition compared to the CF condition. The results showed that grain yield varied insignificantly when the plants are exposed to different levels of OM in absence of As. When the plants were exposed to 20 ppm As, the grain yield decreased with the increasing soil OM amendment, and no grain yield was obtained when the soil was amended with 5 % OM. The highest grain yield was obtained in T_4 (As_0 $OM_{5\,\%}$) treatment under AWD condition and the lowest grain yield was obtained in T_6 ($As_{20\,ppm}$ $OM_{0.25\,\%}$) treatment under CF condition and no grain yield was obtained in T_8 ($As_{20\,ppm}$ $OM_{5\,\%}$) treatment in interaction with both CF and AWD condition (Table 3).

Table 3. Effect of organic matter (OM) amendment and arsenic (As) treatment combinations on growth parameters of Boro rice (cv. BRRI dhan28) under continuous flooding (CF) and alternate wetting and drying (AWD) conditions.

Treatments		Grain yield (g/pot)		Straw yield (g/pot)	
Water (W)	W_1: CF	13.48	b	12.23	a
	W_2 :AWD	17.12	a	13.25	a
	P value	*0.006*		*0.147*	
Treatment (T)	T_1: As_0 OM_0	20.82	a	19.90	a
	T_2: As_0 $OM_{0.25}$	21.76	a	17.35	a
	T_3: As_0 $OM_{0.5}$	24.65	a	17.44	a
	T_4: As_0 $OM_{5.0}$	25.85	a	17.23	a
	T_5: As_{20} OM_0	12.15	b	11.85	b
	T_6: As_{20} $OM_{0.25}$	9.11	b	8.74	b
	T_7: As_{20} $OM_{0.5}$	8.10	b	7.92	b
	T_8: As_{20} $OM_{5.0}$	0.00	c	1.50	c
	P value	*0.000*		*0.000*	
Water (W)× Treatment (T)	$W_1 \times T_1$(CF×As0 OM0)	24.55	ab	21.24	a
	$W_1 \times T_2$(CF×As0 OM0.25)	20.95	abcd	16.93	abc
	$W_1 \times T_3$(CF×As0 OM0.5)	19.60	abcd	15.51	abcd
	$W_1 \times T_4$(CF×As0 OM5.0)	23.25	ab	18.56	ab
	$W_1 \times T_5$(CF×As20 OM0)	9.50	defg	10.70	cde
	$W_1 \times T_6$(CF×As20 OM0.25)	4.05	fg	6.41	efg
	$W_1 \times T_7$(CF×As20 OM0.5)	5.95	efg	7.13	efg
	$W_1 \times T_8$(CF×As20 OM5.0)	0.00	g	1.36	g
	$W_2 \times T_1$(AWD×As0 OM0)	17.10	abcde	18.56	ab
	$W_2 \times T_2$(AWD×As0 OM0.25)	22.57	abc	17.76	abc
	$W_2 \times T_3$(AWD×As0 OM0.5)	29.72	a	19.38	ab
	$W_2 \times T_4$(AWD×As0 OM5.0)	28.44	a	15.89	abcd
	$W_2 \times T_5$(AWD×As20 OM0)	14.80	bcdef	13.01	bcde
	$W_2 \times T_6$(AWD×As20 OM0.25)	14.16	bcdef	11.10	cde
	$W_2 \times T_7$(AWD×As20 OM0.5)	10.20	cdefg	8.71	def
	$W_2 \times T_8$(AWD×As20 OM5.0)	0.00	g	1.64	fg
	P value (Water × Treatment)	*0.025*		*0.048*	

Here, arsenic as As@ 0 and 20 mg/kg soil while organic matter as OM@ 0, 0.25, 0.5 and 5.0 % (w/w). Water management alternate wetting and drying as AWD and continuous flooding as CF.

Straw yield varied significantly by the treatments and the interaction of water management and treatments, with the water management practices being non-significant (Table 3). There was no significant difference in straw yield when the plants are exposed to different levels of OM in absence of As. On the other hand, the straw yield decreased at 20 ppm As concentration due to the addition of OM. The highest straw yield was obtained when both OM and As were absent and the lowest straw yield was obtained when the plants were exposed to 20ppm As concentration with 5 % OM amendment. The highest straw yield was obtained in T_1 (As_0 OM_0) treatment, and the lowest straw yield was obtained in T_8 ($As_{20\,ppm}$ $OM_{5\,\%}$) treatment both under AWD and CF condition (Table 3).

Effect of OM and As treatment on As concentration in grains under AWD and CF condition

Arsenic concentration in rice grains varied significantly depending on water management practices and treatment combinations of As and OM amendment (Figure 1). Arsenic concentration was 8.3% higher in CF condition than AWD condition even at the lowest level of OM amendment. Arsenic concentration in rice grains was the lowest in absence As and OM amendment both under AWD and CF conditions. The As concentration in rice grains increased with the increasing OM amendment, even in absence of As under AWD and CF conditions. The highest amount (168.44 μg/kg) of As was absorbed when the soil was amended with 0.5 % OM and the application rate of As in soil was 20 ppm under CF condition (Figure 1).

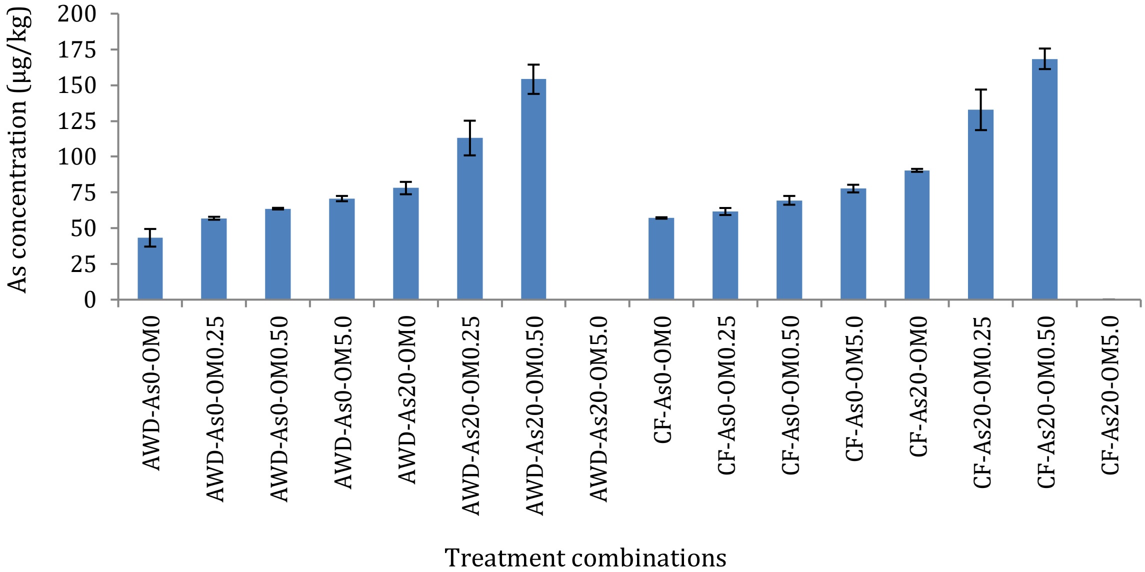

Figure 1. Effect of organic matter (OM) amendment and arsenic (As) treatment combinations on arsenic concentration in grains of Boro rice (cv. BRRI dhan28) under continuous flooding (CF) and alternate wetting and drying (AWD) conditions ($p <.005$). Arsenic as As@ 0 and 20 mg/kg soil while organic matter as OM@ 0, 0.25, 0.5 and 5.0 % (w/w). Water management alternate wetting and drying as AWD and continuous flooding as CF.

Discussion

It is evident that changes in As biogeochemistry in soil is dependent on the OM status of soil (Xiao et al., 2021). Here, we evaluated the changes in As mobilization in paddy soil under different OM and water management techniques. Based on the present study, As mobility in soil is likely to be increased by applying OM to soil. For examples, applying 5 % (w/w) OM to soil significantly increased As concentration in rice grains both under AWD and CF conditions. The result is also in covenant with Kumarathilaka et al. 2018, who also described that oxidation and reduction of As varies with the added dissolved organic matter (DOM) in soil because of it's potential to mobilize As in soil. Thus, it is evident that OM contributes to enhance As release in soils by accelerating the dissolution of Fe (III) minerals and enhances As concentrations in paddy soils under irrigated condition. Alternate wetting and drying practice contributes to enhanced rice growth and yield compared to CF condition in As contaminated soils. The results from previous research has also highlighted that bioavailability As in soil depends on the soil moisture and irrigation intervals (Harine et al., 2021). Anaerobic conditions promote As mobilization in soil, As severely reduced rice growth and yield under CF conditions (Honma et al., 2016). On the other hand, the soil is getting wet and dry sporadically, and the paddy soil is getting prolonged aerobic period being re-irrigated under AWD condition. This might decreased the mobilization of As in paddy soil, which ultimately lead to minimum accumulation of As in rice grain and straw samples due to the extended drying period in AWD systems (Harine et al., 2021).

We observed that the application of As to soil decreased rice growth, and the water management practice was likely to change the As concentration in rice grain. Arsenic content is more spontaneous in grain sample under CF condition than AWD condition. For example, As concentration was 1.1-fold higher under CF condition compared to AWD condition, when the soil was amended with 0.5 % OM and the application rate of As in soil was 20 ppm (Figure 1). The findings are similar with the results of Wang et al. (2019) and Li et al. (2019), who found that As uptake is much greater in CF compared to AWD condition. The accumulation of As in rice grains increases under anaerobic conditions because of the increase in As mobilization through reductive dissolution of iron oxyhydroxides and reduction of arsenate to arsenite (Jahan et al., 2021). On the other hand, As accumulation in rice grains was significantly lower under AWD water management practice compared to CF condition, which might occur due to maintaining intermittent wetting and drying condition in paddy field.

In conclusion, application of OM in soil contributed to increase As mobilization and decreased rice growth and yield. Water management practices including AWD condition and OM amendment increase the concentration of As in rice grain. However, it is necessary to validate the present findings under field condition.

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