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Translocation of Soil Arsenic towards Accumulation in Rice: Magnitude of Water Management to Minimize Health Risk

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Citation: Jahan, I.; Abedin, M.A.; Islam, M.R.; Hossain, M.; Hoque, T.S.; Quadir, Q.F.; Hossain, M.I.; Gaber, A.; Althobaiti, Y.S.; Rahman, M.M. Translocation of Soil Arsenic towards Accumulation in Rice: Magnitude of Water Management to Minimize Health Risk. *Water* **2021**, *13*, 2816. https://doi.org/10.3390/w13202816

Academic Editor: Dongmei Zhou

Received: 3 September 2021
Accepted: 7 October 2021
Published: 10 October 2021

Abstract: Globally, the risk of arsenic (As) contamination in soil and rice is well documented across the globe. In Bangladesh, drinking water and rice are two major exposure pathways of As to humans. Therefore, the efficiency of recent technologies to reduce rice As and associated human health risks still need to be deeply investigated. In this direction, a pot experiment was performed to investigate the impact of soil As and agronomic irrigation management on rice (cv. BRRI dhan28) growth, yield, As accumulation, and finally, health risks to humans from consuming rice. Treatment combinations were made with three levels of As (0, 20, and 40 mg kg^{-1}) having two irrigation procedures, including alternate wetting and drying (AWD) and traditional continuous flooding (CF). According to the findings, As pollution in the soil lowered the yield contributing features and rice yield, including panicle length, filled grains per panicle, sterile grains per panicle, 1000-grain weight, grain yield, and straw yield. AWD water management significantly improved the growth performance and productivity of rice. Grain yield was increased by 13% in AWD compared to CF. Rice grain and straw As concentrations were increased to 0.56 mg kg^{-1} and 15.10 mg kg^{-1}, respectively, in soil with 40 mg kg^{-1} As and CF water management. AWD treatment significantly reduced grain and straw As contents by 16% and 28%, respectively. Increased grain, straw, and total As uptake was noticed with higher soil As concentrations. The study also found that rising soil As raised non-carcinogenic risks (HQ > 1) and carcinogenic risks (CR > 1.010–4) while AWD lowered health risks compared to CF. Thus, rice farming using AWD irrigation could be a viable and long-term solution for reducing As contamination in rice and associated human health hazards.

Keywords: arsenic; rice; water management; rice yield; arsenic accumulation; non-cancer; cancer risks

1. Introduction

Arsenic (As) is one of the most dangerous global environmental toxins, posing a threat to 200 million people globally [1]. The main contributors of As intake for Asians are drinking water contaminated with As and rice grown in As-prone hotspots. Bangladesh has 144 million people who rely on groundwater [2,3], with 80% of the extracted groundwater being used for irrigation [3]. Groundwater is contaminated by high levels of As and other hazardous elements, which are mainly caused by natural processes and anthropogenic activities [2]. Groundwater contamination has been documented in 59 districts of Bangladesh out of 64 districts having As concentration greater than 10 μg L^{-1}, the World Health Organization's (WHO) interim recommendation threshold for As [4]. Iqbal et al. [5] studied Bangladeshi groundwater quality and discovered that most deep tube wells had higher water quality than shallow tube wells due to lower amounts of pollutants, particularly As in deep tube wells compared to shallow tube wells. Drinking As contaminated groundwater and using groundwater for irrigation exposes Bangladeshis to As toxicity [6]. About 3.86 million hectares of land are irrigated with groundwater, primarily for paddy rice farming [7]. Since water-logging environments in rice fields promote As mobilization, resulting in increased bioavailability of As to rice, which makes paddy rice more susceptible to contamination than other cereal crops [8–10]. Groundwater irrigation has increased arsenic in rice grains due to arsenic deposition in paddy soils. In As-endemic parts of Bihar, India, a recent study found that As exposure through food exceeded that from drinking water [11]. The average As concentration in rice straw was 22 times that of rice grain [12]. Tainted straw poses a risk to animals, particularly cattle, and human health through contaminated beef and milk [13].

Several arsenic removal technologies have been tested so far for groundwater As remediation [14,15]. Groundwater As remediation by nanofiltration using two types of membranes led to lower than 10 μg L^{-1} arsenic concentration in the permeate with arsenic contents ranging from 59 to 118 μg L^{-1} [16]. Different agronomic practices may potentially be used as mitigation strategies to minimize bioavailability of As in soil, water-saving rice culture is one of them As [17]. The amount of As ingested is reduced when less water is used. Water-saving rice cultures like aerobic rice culture and intermittent irrigation reduce As mobilization in porewater and finally reduce As uptake by rice [18]. According to the report, alternative wet and dry irrigation (AWD) can save 15–30% of water input for rice cultivation when compared to continuous flooding (CF) [19]. AWD water management significantly reduced As concentration (up to 64%) and uptake in rice [10,20,21] compared to CF. Traditional water supply and intermittent water supply at different intervals were found to cause significant differences in rice grain As concentrations [22]. Shrivastava et al. [23] conducted a four-year field study in India and found that using a combined aerobic and anaerobic irrigation method improved rice productivity while lowering As mobility and concentration in grains. Redox potential, reductive dissolution of iron (Fe) and manganese (Mn) oxides, pH, biological activity, and adsorption-desorption processes are all important determinants in soil arsenic speciation and dynamics [23,24]. The ability of rice roots to absorb water is influenced by soil moisture, crop variety, and soil mechanics [25]. In CF conditions, reductive dissolution of As containing iron oxyhydroxides (FeOOH) releases As due to reduction of iron (II) accompanied with reduction of arsenate, As (V) to arsenite, As (III) facilitate enhanced mobility of As [26].

In Asian countries, per capita rice consumption can reach 0.5 kg (dry weight) each day [27,28]. Inorganic As has also been identified in high concentrations in rice-based products used by newborns and small children, who are particularly more susceptible to the negative consequences of As ingestion [29,30]. As a result, rice is a significant contributor of As exposure for humans, particularly for individuals who eat rice-based diets on the Asian subcontinent [28,31]. Rice consumption is a substantial risk factor for cancer, especially for people who eat a rice-based diet [21,32]. Recent studies have linked As exposure from rice to risks of hypertension and cancer in As-affected populations in Bihar, England, and Wales [33,34] and Beijing [35]. Influence of CF and AWD on rice As uptake in soils with 20 and 40 mg kg^{-1} As is already found in the literature. However, field levels studies focusing on health risk analysis from rice with different water management and soil As contaminations are very limited. Consequently, the present research was designed to evaluate how water management combined with soil As pollution affected growth, yield, and As uptake in a widely grown rice variety (BRRI dhan28) and analyze the dangers to human health.

2. Materials and Methods

2.1. Site Description and Soil Properties

Using soils taken from paddy fields of Soil Science Field Laboratory, Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh, a pot culture experiment was conducted in the net house (average temperature 24 °C and relative humidity 60%), which belongs to the same environment of BAU farm (AEZ 9). The experimental site has a subtropical humid environment with high temperatures and reasonably substantial rainfall, as well as cold temperatures during the rabi season (October–March), and is made up of Non-calcareous Dark Grey Floodplain soil (Aeric Haplaquept in the U.S. Soil Taxonomy) [36]. Initial soil samples were analyzed for physical and chemical features, and the results are shown in Table 1. BRRI dhan28, a popular rice cultivar in Bangladesh, was tested in this experiment.

Table 1. Physicochemical properties of soil with their methods of determination.

Soil Properties	Values	Method of Determination
Soil texture	Silt loam	Hydrometer method [37]
% Sand	21	
% Silt	62	
% Clay	17	
Soil pH	6.3	Glass electrode pH meter method [38]
Soil organic matter (%)	1.2	Wet oxidation method [39]
Soil total nitrogen content (mg kg^{-1})	1320	micro-Kjeldahl method [40]
Soil available phosphorus content (mg kg^{-1})	9.31	Olsen method [41]
Soil exchangeable potassium content (meq %)	0.07	NH_4OAc (1 N) extraction method [42]
Soil available sulphur content (mg kg^{-1})	13.16	$CaCl_2$ turbidity method [43]
Soil total As content (mg kg^{-1}) (Background As)	3.73	AAS (Graphite Furnace) method [6]

2.2. Treatments and Experimental Design

The experiment was set up in a completely randomized design (CRD) with two factors, that is soil As levels (T1 = 0, T2 = 20, and T3 = 40 mg kg^{-1} soil) and water regimes (I1 = CF and I2 = AWD). A total of six treatment combinations were formed in this experiment which was replicated thrice. The main effect of As contamination (T) and water regimes (I) and the effect of their interaction (T × I) were analyzed and represented in Tables 2–4. AWD and CF details were already provided [44].

2.3. Pot Preparation and Fertilizer Application

Each plastic pot (15 L) received a total of 10 kg soil, and eighteen (3 × 2 × 3) plastic pots were constructed. In the form of sodium arsenite ($NaAsO_2$), As was added with the soil 10 days before transplanting following the experimental design. Added As was thoroughly mixed for homogenization and for preparing representative natural As contamination. Recommended doses of fertilizers viz. triple superphosphate for phosphorus, muriate of potash for potassium, gypsum for sulfur, and zinc oxide for zinc were applied during final pot preparation using the BARC fertilizer recommendation guide [45] and puddled to give a complete mixture. At 7, 27, and 55 days after transplanting the seedlings, the recommended dose of urea was administered in three equal splits [6].

2.4. Transplanting of Seedlings and Water Management

Thirty-five (35) day old BRRI dhan28 seedlings were transplanted, with 3–5 cm water maintained in each pot for the first two weeks for seedling establishment. After two weeks, irrigation was done in the AWD pots when hair-like cracking appeared in soil due to water scarcity, and the system continued up to the panicle initiation stage. On the other hand, CF condition was maintained in the other pots. Other multicultural operations were carried out when needed. The crop was harvested when it was fully mature, and data on growth and yield factors was collected.

2.5. Determination of As Concentration

The grain and straw samples were collected, cleaned, and chopped into 5 mm pieces for straw and dehusked for grains, oven-dried, powdered in the Ball Mill (Retsch Planetary Ball Mill PM100), and digested. Digestion tubes were washed carefully, soaked in an acid bath containing 5% HNO_3 for 6 hrs., and finally rinsed with deionized water. After drying the tubes in the oven, 0.3 g of powdered grain and 0.2 g of straw samples were taken into labeled 100 mL digestion tubes. The As content in grain and straw samples was tested using the method reported by Hossain et al. [6]. Each tube received five milliliters of Sigma Trace element grade 65 percent nitric acid (HNO_3, suprapure) and was allowed to stand overnight for pre-digestion. In the case of a blank, the tube was also filled with the same amount of nitric acid. The following day, 2 mL of Analar 30% hydrogen peroxide (H_2O_2) was added and kept for 30 min to reduce effervescent bubbles, and tubes were heated in the block digester (VELP, Rome, Italy) at 120 °C. When the content of the digestion tube was colorless and white fume was observed in the digestion tubes, digestion was completed. The digest was cooled and diluted to 30 mL with deionized water. To transfer the entire digest of each sample into a plastic bottle (50 mL) and check for element loss, the digestion tubes were carefully rinsed multiple times with deionized water. Each plastic container was filled with deionized water until it reached its ultimate weight (50 g), and the weights were meticulously recorded to determine the dilution factor. Arsenic content in the plant sample digest was determined by ZA3000 Series Polarized Zeeman Atomic Absorption Spectrometer (AAS, Graphite Furnace). The detailed description and other operating conditions of AAS were given in our previous publication [46].

2.6. Determination of As Uptake

By using the following formula, As uptake was calculated:

$$\text{As uptakepot}^{-1}\ (\mu\text{g pot}^{-1}) = \text{As concentration in rice grain}\ (\mu\text{g kg}^{-1}) \times \text{Grain yield (kg pot}^{-1})$$

2.7. Health Risk Estimation from As Exposure

The possible health effects from As contamination through rice consumption were examined using the following equations to calculate average daily intake (ADI), hazard quotient (HQ), and cancer risk (CR) [47–51].

$$ADI = \frac{C_{As \times IR}}{BW} \quad (1)$$

$$HQ = \frac{ADI}{R_f D} \quad (2)$$

$$CR = ADI \times CSF \quad (3)$$

where,

ADI = Estimated daily intake of As (mg d^{-1}) per BM (kg)

CAs = Concentration of inorganic As in rice (mg kg^{-1}) (73% of total As in raw rice can be considered as inorganic As) [47]

IR = Ingestion rate of rice for adult (0.432 kg d^{-1}) [51]

BW = Body weight (70 kg) [48]

$R_f D$ = Oral reference dose (0.3×10^{-3} mg kg^{-1} daily for As) suggested by USEPA [50].

CSF = Cancer slope factor (1.5 mg kg^{-1} per day) [48,49]

HQ > 1 denotes considerable detrimental human health impacts due to the presence of a certain element in the diet in the case of non-carcinogenic risk. In contrast, according to various reports, *HQ* 0 denotes no significant risk [52–55]. In terms of carcinogenic risk, *CR* values between 1.0×10^{-6} and 1.0×10^{-4} are generally regarded as tolerable. A *CR* value of greater than 1.0×10^{-4} is regarded as unsatisfactory in terms of major health effects, while a *CR* value of less than 1.0×10^{-6} is not considered to have substantial health effects [50].

2.8. Quality Control of the Data

Rice flour's Standard Reference Material (SRM 1568b) was analyzed to check the analytical data in this study, and the recovery rate was 91 ± 5% (n = 4).

2.9. Data Analysis

The analysis of variance (ANOVA) for diverse rice variety, grain, and straw plant parameters. In the Minitab 18 statistical package, a two-way analysis of variance (TW-ANOVA) was performed using the general linear model (GLM), and the means were compared using Tukey's procedure at the 95 percent confidence level (State College, Harrisburg, PA, USA).

3. Results

3.1. Effect of soil As, Water Management and Their Interaction on Growth Parameters of BRRI dhan28

To determine the effect of soil As, associated irrigation management, and their interactions on the growth of rice cv. BRRI dhan28, a number of rice growth parameters were recorded, including plant height (cm), panicle length (cm), number of filled per grains panicle, number of sterile grains per panicle, and 1000-grain weight (g) (Table 2).

Table 2. Growth performance of boro rice (BRRI dhan28) under different soil As concentrations and irrigation water management.

Treatments/ Interactions		Plant Height (cm)	Panicle Length (cm)	Filled Grain per Panicle (No.)	Sterile Grain per Panicle (No.)	1000-Grain Weight (g)
T	T_1	71.11 ± 1.88	22.47 ± 0.47 [a]	68.86 ± 0.59 [a]	14.11 ± 0.37 [b]	19.37 ± 1.16 [a]
	T_2	68.33 ± 1.60	20.53 ± 0.25 [b]	61.81 ± 0.73 [b]	26.84 ± 3.95 [a]	17.08 ± 0.59 [b]
	T_3	65.91 ± 3.40	18.06 ± 0.63 [c]	56.58 ± 1.35 [c]	30.68 ± 2.77 [a]	14.69 ± 0.43 [c]
	p value	0.341	0.001	0.000	0.002	0.000
I	I_1	68.66 ± 0.78	19.99 ± 0.96	60.96 ± 2.48 [b]	24.91 ± 3.77	15.99 ± 0.58 [b]
	I_2	68.24 ± 2.87	20.71 ± 0.77	63.87 ± 2.05 [a]	22.85 ± 3.84	18.11 ± 1.20 [a]
	p value	0.877	0.157	0.001	0.387	0.004
T × I	T_1I_1	67.92 ± 0.69	22.03 ± 0.80	67.86 ± 0.15	14.62 ± 0.09 [b]	17.42 ± 0.23
	T_2I_1	68.83 ± 0.47	20.82 ± 0.44	60.66 ± 0.66	32.86 ± 4.57 [a]	16.21 ± 0.09
	T_3I_1	69.25 ± 2.75	17.14 ± 0.24	54.36 ± 0.86	27.25 ± 4.25 [ab]	14.34 ± 0.32
	T_1I_2	74.30 ± 0.58	22.92 ± 0.54	69.86 ± 0.21	13.60 ± 0.52 [b]	21.33 ± 0.63
	T_2I_2	67.84 ± 3.84	20.24 ± 0.13	62.95 ± 0.35	20.82 ± 0.62 [ab]	17.95 ± 0.75
	T_3I_2	62.57 ± 6.27	18.99 ± 0.78	58.81 ± 0.58	34.12 ± 2.12 [a]	15.05 ± 0.88
	p value	0.209	0.162	0.114	0.035	0.071

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). Averaged values within a column, succeeded by different small letters ([a], [b], [c]), differ significantly between different treatments at $p < 0.05$ significance level. p indicates probability level; SE (±) indicates standard error of means.

Plant height was unaffected by soil As × water management. However, plant height was influenced solely by soil As. The tallest plant (71.11 cm) was discovered in control pots (T1), whereas the smallest plant (65.91 cm) was found in soil treated with As 40 mg kg^{-1} (T3), indicating that higher soil As levels had a negative impact on plant height. Plants in the constantly flooded water management system were taller (68.66 cm) than those in the AWD system (68.24 cm), but the difference was not statistically significant (p = 0.877). Panicle length was significantly influenced (p = 0.001) by As contamination in soil. The longest panicle (22.47 ± 0.47 cm) was found in the non-contaminated pot (T1), while the shortest panicle (18.06 ± 0.63 cm) was recorded in T3 (40 mg kg^{-1} soil As). Water management and the interplay of As pollution and water management did not affect panicle length. The number of filled grains per panicle was significantly affected ($p < 0.001$) by As exposure in the soil. Control pots had the maximum number of full grains panicle^{-1} (68.86 ± 0.59), which was reduced to 61.81 ± 0.73 and 56.58 ± 1.35 when 20 mg kg^{-1} and 40 mg kg^{-1} As in soil were used, respectively. The number of filled grains per panicle was significantly affected by water management. Under AWD practice (63.87 ± 2.05), the number of filled grains panicle^{-1} was larger than in constantly flooded conditions (60.96 ± 2.48). The maximum number of filled grains per panicle (69.86 ± 0.21) was obtained in T1I2 (As0 AWD), even though the interaction impact of As contamination and water management on the number of filled grains per panicle was not statistically significant. Arsenic pollution in soil reduced the number of sterile grains panicle^{-1} considerably ($p = 0.002$). The soil containing 40 mg kg^{-1} As (T3) had the maximum number of sterile grains per panicle (30.68 ± 2.77), whereas the lowest number of sterile grains panicle^{-1} was detected in control pots (T1). The number of sterile grains per panicle was unaffected by water management. The interaction effect of As treatment and water management in soil was significant ($p = 0.035$) in producing sterile grains. The number of sterile grains panicle^{-1} was the highest (34.12 ± 2.12) in 40 mg kg^{-1} As in soil under AWD irrigation, the number was 2.5 times lower in (13.60 ± 0.52) in control pots (T1). The 1000-grain weight was significantly affected ($p < 0.001$) by As contamination in soil. The highest 1000-grain weight (1.73 ± 0.65 g) was recorded in T1 (control), and the lowest value (14.69 ± 0.43) was found in T3 (soil As 40 mg kg^{-1}). Water management caused significant variation ($p = 0.004$) on 1000-grain weight. The AWD water management produced a higher 1000-grain weight (18.11 ± 1.20 g) than CF (15.99 ± 0.58 g). The interaction effect of soil As and water management was not significant ($p = 0.071$) on 1000-grain weight.

3.2. Effect of Soil As, Water Management and Their Interaction on Grain and Straw Yield of BRRI dhan28

Grain yield of rice cv. BRRI dhan28 was significantly ($p < 0.001$) affected by As contamination in soil. Grain yield decreased with increasing As contamination in soil (Table 3).

Table 3. Yield and As concentration of rice under different soil As concentrations and irrigation water management.

Treatments/ Interactions		Grain Yield (g pot^{-1})	Straw Yield (g pot^{-1})	As Concentration in Grain (mg kg^{-1})	As Concentration in Straw (mg kg^{-1})
T	T_1	17.60 ± 0.83 [a]	24.70 ± 0.94 [a]	0.24 ± 0.01 [c]	2.66 ± 0.68 [c]
	T_2	13.20 ± 0.59 [b]	18.67 ± 1.02 [b]	0.39 ± 0.03 [b]	7.55 ± 0.89 [b]
	T_3	9.55 ± 0.36 [c]	12.95 ± 0.46 [c]	0.56 ± 0.02 [a]	15.10 ± 1.15 [a]
	p value	<0.001	<0.001	<0.001	<0.001
I	I_1	12.6 ± 1.40 [b]	17.59 ± 2.03 [b]	0.43 ± 0.06 [a]	10.18 ± 2.62 [a]
	I_2	14.3 ± 1.59 [a]	19.95 ± 2.32 [a]	0.36 ± 0.06 [b]	7.29 ± 2.34 [b]
	p value	0.017	0.009	0.000	0.001
T × I	T_1I_1	16.55 ± 0.25	23.17 ± 0.71	0.26 ± 0.02	3.74 ± 0.63
	T_2I_1	12.30 ± 0.70	17.30 ± 1.30	0.44 ± 0.02	8.99 ± 0.32
	T_3I_1	8.95 ± 0.05	12.30 ± 0.55	0.59 ± 0.01	17.83 ± 0.94
	T_1I_2	18.65 ± 1.35	26.23 ± 0.30	0.22 ± 0.01	1.59 ± 0.25
	T_2I_2	14.10 ± 0.10	20.03 ± 0.88	0.34 ± 0.01	6.11 ± 0.77
	T_3I_2	10.15 ± 0.25	13.60 ± 0.40	0.52 ± 0.01	14.17 ± 0.58
	p value	0.781	0.513	0.065	0.524

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). Averaged values within a column, succeeded by different small letters (a, b, c), differ significantly between different treatments at $p < 0.05$ significance level. p indicates probability level; SE (±) indicates standard error of means.

The highest grain yield (17.60 ± 0.83 g pot^{-1}) was found in T1 (control), which was reduced to 13.20 ± 0.59 g pot^{-1} and 9.55 ± 0.36 g pot^{-1} in T2 (20 mg kg^{-1} soil As) and T3 (40 mg kg^{-1} soil As), respectively. A significant grain yield difference ($p = 0.017$) was recorded between I1 (AWD) and I2 (CF) water management practices (Table 3). The AWD irrigation management increased the grain yield by 13% compared with CF. Interaction of soil As contamination and water management had no significant effect (p = 0.781) on rice grain yield. However, the highest grain yield (18.65 ± 1.35 g pot^{-1}) was found in the control treatment with AWD water management. Grain yield was 10.15 ± 0.25 g pot^{-1} in AWD and 8.95 ± 0.05 g pot^{-1} in CF at the highest As (40 mg kg^{-1}) contamination in soil (Table 3).

Significant variation (p < 0.001) was observed in straw yield due to different levels of As contamination in soil (Table 3). The highest straw yield (24.70 ± 0.94 g pot^{-1}) was found in control pots, while the lowest (12.95 ± 0.46 g pot^{-1}) straw yield was found in the pots having the highest soil As contamination (40 mg kg^{-1}). Water management had a significant effect (p = 0.009) on the straw yield of rice. When compared to CF irrigation, the AWD irrigation approach enhanced straw output by 13%. The interaction effect of soil As contamination and water regimes were not significant on straw yield (p = 0.513). The straw yield was 12.30 ± 0.55 g pot^{-1} in CF practice which was increased to 13.60 ± 0.40 g pot^{-1} in AWD practice at 40 mg kg^{-1} soil As contamination.

3.3. Effect of Soil As, Water Management and Their Interaction on As Accumulation in Rice Grain and Straw

Grain As content was significantly affected (p < 0.001) by As contamination in soil (Figure 1; Table 3). The highest grain As (0.56 ± 0.02 mg kg^{-1}) was found in T3 (40 mg kg^{-1} soil As), which was higher than the grain As (0.39 ± 0.03 mg kg^{-1}) from T2 (20 mg kg^{-1} soil As) while the lowest grain As (0.24 ± 0.01 mg kg^{-1}) was found in the control treatment (0 mg kg^{-1} soil As). Water management revealed a significant effect (p < 0.001) on grain As concentration. The AWD irrigation system reduced grain As concentration by 16% compared to the CF system. Interaction of soil As and water regimes exerted no significant effect (p = 0.065) on grain As concentration. In 40 mg kg^{-1} soil As, grain As concentration was 0.59 ± 0.01 mg kg$^{-1,}$ which was reduced to 0.52 ± 0.01 mg kg^{-1} in AWD treatment.

Straw As concentration was also significantly affected (p < 0.001) by As contamination in soil (Figure 1; Table 3). The highest straw As (15.10 ± 1.15 mg kg^{-1}) was recorded in the pots having 40 mg kg^{-1} soil As, which was 2-fold higher and significant over 20 mg kg^{-1} soil As (7.55 ± 0.89 mg kg^{-1} As) and control treatment (0 mg kg^{-1} soil As). Water management made significant variation (p = 0.001) in straw As content. The AWD system significantly reduced straw As content by 28% compared with CF. Soil As contamination x water management did not produce significant variation (p = 0.524) in the straw As content of rice. The lowest straw As (1.59 ± 0.25 mg kg^{-1}) was obtained under AWD treatment followed by CF (3.74 ± 0.63 mg kg^{-1}) under background soil As while the highest straw As (17.83 ± 0.94 mg kg^{-1} As) was recorded under 40 mg kg^{-1} As contamination in soil under CF irrigation system which was decreased to (14.17 ± 0.58 mg kg^{-1} As) in AWD system.

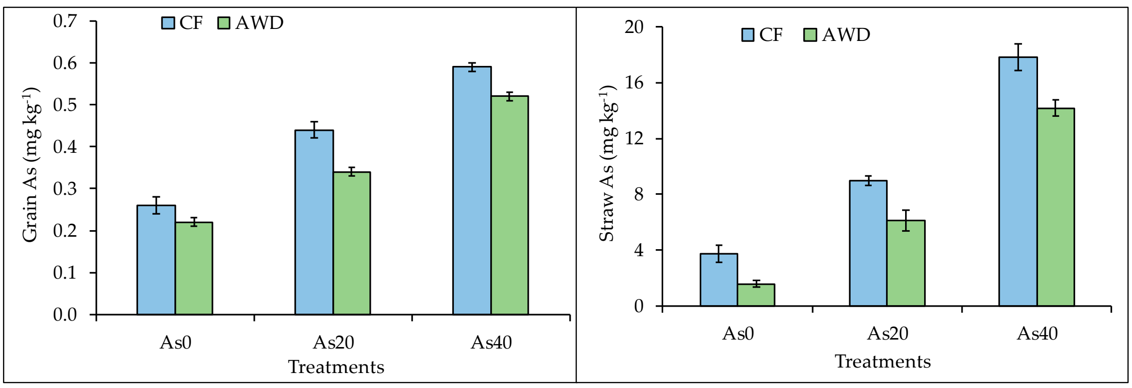

Figure 1. Grain and straw As concentrations of rice (cv. BRRI dhan28) under different soil As concentrations (0 mg kg^{-1} As, 20 mg kg^{-1} As, 40 mg kg^{-1} As) and irrigation water management (CF = continuous flooding, AWD = alternate wetting and drying).

3.4. Effect of Soil As, Water Management and Their Interaction on Grain, Straw and Total As Uptake by BRRI dhan28

Arsenic uptake in grain was significantly affected (p < 0.001) by As contamination in soil (Table 4).

Table 4. Grain, straw, and total As uptake of rice (cv. BRRI dhan28) under different soil As concentrations and irrigation water management.

Treatments/Interactions		Arsenic Uptake in Grain ($\mu g\ pot^{-1}$)	Arsenic Uptake in Straw ($\mu g\ pot^{-1}$)	Total As Uptake ($\mu g\ pot^{-1}$)
T	T_1	4.10 ± 0.13^{b}	63.89 ± 14.0^{c}	68.00 ± 14.1^{c}
	T_2	5.06 ± 0.20^{b}	138.73 ± 12.8^{b}	143.80 ± 12.9^{b}
	T_3	5.28 ± 0.08^{a}	206.09 ± 11.8^{a}	211.37 ± 11.8^{a}
	p value	<0.001	<0.001	<0.001
I	I_1	4.98 ± 0.25^{a}	153.96 ± 25.6^{a}	158.94 ± 25.8^{a}
	I_2	4.65 ± 0.24^{b}	118.51 ± 27.7^{b}	123.16 ± 28.0^{b}
	p value	0.032	0.016	0.015
T × I	T_1I_1	4.22 ± 0.19	86.28 ± 12.0	90.49 ± 11.8
	T_2I_1	5.39 ± 0.06	155.85 ± 17.1	161.25 ± 17.1
	T_3I_1	5.33 ± 0.07	219.76 ± 21.3	225.09 ± 21.2
	T_1I_2	4.00 ± 0.20	41.50 ± 5.95	45.51 ± 5.75
	T_2I_2	4.72 ± 0.10	121.62 ± 9.94	126.34 ± 9.84
	T_3I_2	5.23 ± 0.18	192.41 ± 2.15	197.64 ± 1.97
	p value	0.189	0.806	0.802

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). Averaged values within a column, succeeded by different small letters (a, b, c), differ significantly between different treatments at $p < 0.05$ significance level. *p* indicates probability level; SE (±) indicates standard error of means.

Arsenic uptake by grain was increased with increasing soil As concentrations. The lowest grain As uptake (4.10 ± 0.13 µg pot^{-1}) was observed in treatment T1 (control), which was relatively higher at 20 mg kg^{-1} soil As contamination (T2) (5.06 ± 0.20 µg pot^{-1}), and the highest uptake was recorded in soil treated with 40 mg kg^{-1} soil As (T3) (5.28 ± 0.08 µg pot^{-1}). Water management significantly influenced ($p = 0.032$) grain As uptake. Grain As uptake was found 7% lower under AWD than CF condition (Table 3). Soil As contamination × water management had no significant effect ($p = 0.189$) on grain As uptake. At highest soil As contamination (40 mg kg^{-1} soil As), grain As uptake was lower in AWD condition (5.23 ± 0.18 µg pot^{-1}) than CF system (5.33 ± 0.07 µg pot^{-1}).

Arsenic contamination in the soil had a significant effect ($p < 0.001$) on straw As uptake of rice (Table 4). Straw As uptake was the maximum (206.09 ± 11.8 µg pot^{-1}) in 40 mg kg^{-1} As contaminated soil which was significant over 20 mg kg^{-1} As contamination (138.73 ± 12.8 µg pot^{-1}). Straw As uptake in the non-contaminated pots was 63.89 ± 14.0 µg pot^{-1}. Straw As uptake was also significantly affected ($p = 0.016$) by water management in paddy soil. In the AWD system, straw As uptake was reduced to 118.51 ± 27.7 µg pot$^{-1,}$ which was 153.96 ± 25.6 µg pot^{-1} under the CF system. The interaction effect of As contamination in soil and water management was not significant ($p = 0.806$) on straw As uptake. The straw As uptake was 192.41 ± 2.15 µg pot^{-1} and 219.76 ± 21.3 µg pot^{-1} in CF and AWD irrigation systems, respectively, at 40 mg kg^{-1} As contamination in soil.

A strong statistical significance ($p < 0.001$) was observed in total As (grain + straw) uptake when rice was grown in contaminated soils (Table 4). Total As uptake followed an increasing trend with increasing As concentration in soil. The highest total As uptake (211.37 ± 11.8 µg pot^{-1}) was recorded in 40 mg kg^{-1} As contaminated soil, which was significant over 20 mg kg^{-1} As contaminated soil (143.80 ± 12.9 µg pot^{-1}) and over non-contaminated control pots (68.00 ± 14.1 µg pot^{-1}). AWD water management also significantly ($p = 0.015$) reduced total As uptake. Total As uptake was 158.94 ± 25.8 µg pot^{-1} under CF, which was decreased at 123.16 ± 28.0 µg pot^{-1} under AWD. The interaction of soil As contamination and water regimes displayed no significant influence (p = 0.802) on total As uptake.

3.5. Exposure and Cancer Risk Assessment

From inorganic rice grain As concentrations of BRRI dhan28, different health risk assessment indices such as ADI, HQ, and CR were calculated and presented in Table 5. Increased ADI was found with increased grain As content, and comparatively lower ADI was recorded with AWD water management (1.62×10^{-3} mg kg^{-1} bw) compared with CF (1.94×10^{-3} mg kg^{-1} bw). Interaction between As contamination and water management demonstrated that the lowest ADI value was found at no As added in soil under AWD water management. The HQ value was changed with different soil As concentrations and water management. Considering soil As contamination, the highest HQ (8.41) was observed at 40 mg kg^{-1} soil As and decreased at 20 mg kg^{-1} soil As (5.86) and control pots (3.60). Considering soil As and water management, the highest HQ (8.86) was found at 40 mg kg^{-1} soil As with CF practice. In case of all treatments and their combinations in this study, As level exceeded the acceptable limit of HQ (>1) which could aggravate adverse health effects. The CR values were also calculated in the present study. The CR values were affected greatly under different As levels and water management. It was observed that CR value was increasing with increased soil As content, and lower CR value was found under AWD water management in all soil As levels (2.43×10^{-3}) compared to CF (2.91×10^{-3}). Considering the interaction between soil As and water management, the lowest CR value (1.49×10^{-3}) was observed in control treatment combined with AWD water management.

Table 5. Average daily intake of inorganic As from rice consumption and human health risk assessment.

Treatments	Grain As Concentration (mg kg^{-1})	Inorganic Grain As Concentration (mg kg^{-1})	ADI $\times 10^{-3}$	HQ	CR*10^{-3}
T1	0.24	0.18	1.08	3.60	1.62
T2	0.39	0.28	1.76	5.86	2.64
T3	0.56	0.41	2.52	8.41	3.78
I1	0.43	0.31	1.94	6.46	2.91
I2	0.36	0.26	1.62	5.41	2.43
T_1I_1	0.26	0.19	1.17	3.90	1.76
T_2I_1	0.44	0.32	1.98	6.61	2.97
T_3I_1	0.59	0.43	2.66	8.86	3.99
T_1I_2	0.22	0.16	0.99	3.30	1.49
T_2I_2	0.34	0.25	1.53	5.11	2.30
T_3I_2	0.52	0.38	2.34	7.81	3.51

T_1: 0 mg/kg As, T_2: 20 mg/kg As, T_3: 40 mg/kg As; I_1: continuous flooding (CF), I_2: alternate wetting and drying (AWD). ADI, estimated daily intake of As (mg d^{-1}) per B_M (kg); HQ, hazard quotient; CR, cancer risk.

4. Discussion

The impacts of several water regimes, AWD and CF, at different soil As levels and associated human health risks were investigated in this study. Boro rice (BRRI dhan28), a common cultivar in Bangladesh, was tested for soil As contamination in combination with water management. The AWD system has also been shown to be beneficial in terms of decreasing As levels in rice [56]. Soil As had a clear negative effect on the yield and yield contributing features of BRRI dhan28 in this investigation. Except for plant height, As pollution in the soil affected all yield metrics and yield, including panicle length, number of filled grains panicle^{-1}, number of sterile grains panicle^{-1}, 1000-grain weight, grain, and straw yield. Grain and straw yields of rice were also affected by increased As levels in the soil. When compared to the control (background soil As only; 3.73 mg kg^{-1}), grain yield was reduced by 25% and 46% at 20 and 40 mg kg^{-1} soil As, respectively, while straw yield was reduced by 24% and 48% at the same two soil As levels. With increasing As concentrations, Azad et al. [57] showed a reduction in tiller number, panicle length, and grain production. At As 40 mg kg^{-1} soil, Shah et al. [58] found lower plant height, tiller number, full grains, grain, and straw yield in BRRI dhan 28. Islam et al. [59] observed a negative relationship between As application and grain production, agreeing with our findings. Arsenate (As V) and arsenite (As III) are two dominant inorganic As species in soil solution. Arsenate is frequently taken up by plant roots with phosphate metabolism and disrupts phosphate-dependent aspects of metabolism. When plants are exposed to As, reactive oxygen species induce lipid peroxidation, which causes plant death [60]. Increased As accumulation also reduces chlorophyll content of the rice plants, the extent of reduction varying slightly among different varieties. This results in a reduction in the rate of photosynthesis, leading to a reduction in root and shoot growth and grain yield [61]. Grain yield was increased by 13% under the AWD water management system compared to CF. Increased number of filled and weightier grains production in AWD system are the main driving forces leading to higher yield under AWD system irrespective of little increase in grain As concentration [62]. Islam et al. [63] reported a 7% to 38% increase in grain yield under AWD water management in different local and high yielding rice cultivars of Bangladesh. Liu et al. [64] reported a 12% to 15% increase in grain yield in AWD water management. Several studies also reported a declining trend of grain yield in AWD practice [20,65].

Straw and grain As levels in the soil grew, so did As accumulation. Various studies have revealed higher As accumulation in various plant sections in response to increasing soil and irrigation water [63,66,67]. In this experiment, the AWD system dramatically reduced grain As concentration by As buildup and uptake compared to the CF system. When the redox potential of the soil is reduced in flooded conditions, it allows the reductive dissolution of iron oxyhydroxides, resulting in a rise in As (III) concentration in the soil solution [59]. Flooding decreases the redox potential of the soil, resulting in increased As concentration in the soil solution. At higher soil redox levels (~500 mV), arsenic solubility is low, while at low redox levels (−200 mV) and it increases thirteen-fold as compared to 500 mV [24]. There is always a tradeoff between both inorganic species under dry and flooded conditions. As is always highly reduced and mobile under flooded conditions and taken up by rice leading to high As concentration. In rice, arsenite is absorbed by the Lsi1 transporters [68], but arsenate is absorbed via the phosphate transporters (OsPT1) [69]. Very high silicon content in rice is also responsible for the high arsenite uptake in rice via silicon transporters [70] under flooded conditions compared to non-flooded AWD conditions [71]. In this study, the greatest grain As concentration was 0.24 mg kg^{-1} in the control treatment (0 mg kg^{-1} extra soil As; 3.73 mg kg^{-1} baseline soil As only). Norton et al. [72] discovered almost identical rice grain As concentrations in the same soil at Mymensingh, Bangladesh, where we collected soil for this experiment, in field research with several rice cultivars, including BRRI dhan28. Norton et al. [73] also found AWD effectively lowered As in rice across all cultivars on average, by 15.4% in grain and by 27.0% in shoot As in the same experimental site of Bangladesh. Linquist et al. [20] showed a 64% decrease in grain As under extreme AWD. Islam et al. [30] reported a 17% to 35% reduction in grain As concentration under AWD irrigation practice in different rice genotypes.

In this study, the non-carcinogenic risks in terms of HQ value exceeded the safe level (HQ > 1) [74] in all soil As levels, water management, and their interactions. It was observed that HQ was lower in AWD management than CF in all soil As contaminations. Similarly, Rahman et al. [75] reported that HQ value from food composites intake existed between 1.0 to 20, higher than the threshold level. Islam et al. [21] also found that the HQ values varied from 1.20 to 4.70 from rice consumption. In the case of CR estimation, increased CR values were found in soil with higher As levels, and AWD water management reduced CR values in all treatments compared to CF. The allowed value of CR is 1.0×10^{-4}, but the regulation tolerance limit of CR ranges from 1.0×10^{-6} to 1.0×10^{-4} [76]. The highest CR value found in this investigation was 3.99×10^{-3}, indicating that 39.9 per 10,000 people exposed to As are at risk of cancer. The CR value obtained in this study (1.49–3.99×10^{-3}) as a result of rice intake was significantly greater than that of Islam et al. [14], who recorded a

CR value of (0.76–2.12) × 10^{-3} per 10,000 exposed people, but much lower than the results reported in Iran (45–55 × 10^{-2} per 10,000 exposed people) [77].

5. Conclusions

This study evaluated yield and yield components and As uptake, which is based on accumulation x yield. The soil used in this study was from a paddy field where rice was grown for the last 20 years. Our findings demonstrate the impact of water management on As uptake by rice with a corresponding health risk assessment. This study found that increasing As concentration in soil substantially impacts rice growth, yield contributing features, and yield. With rising As content in the soil, greater As accumulation in rice plant parts was also discovered. In As-contaminated soil, grain, straw, and total As uptake all rose. Compared to CF, the AWD technology considerably reduced As level and accumulation in rice plant parts while increasing yield. Increasing HQ values with increased soil As indicates significant human health risks from As exposure and AWD system reduces both HQ and CR compared to CF. As a result, the AWD system may be used to lower As toxicity in rice and the danger of As exposure to humans without compromising grain output. However, more research on boro rice water management strategies in As-contaminated hotspots of the country and other rice dominating regions of the world with high soil As is required before complete recommendations can be made. Future research should also include other common varieties that repel As and appropriate water management. As the percentage of inorganic As, bioaccessibility, and cooking rice had significantly impacted As retention/removal, health risk estimation should be considered.

Author Contributions: Conceptualization, M.A.A., M.R.I. and M.H.; methodology, I.J., M.A.A., M.R.I., M.H. and T.S.H.; software, I.J., M.H. and Q.F.Q.; validation, M.A.A., M.R.I., M.H. and T.S.H.; formal analysis, I.J., M.A.A., M.R.I., M.H. and Q.F.Q.; investigation, I.J., M.A.A., M.R.I., M.H. and T.S.H.; resources, M.A.A., M.R.I. and M.H.; data curation, I.J., M.A.A., M.R.I., M.H., T.S.H. and A.G.; writing—original draft preparation, I.J., M.R.I. and M.H.; writing—review and editing, I.J., M.A.A., M.R.I.; M.H., T.S.H., Q.F.Q., M.I.H., A.G.; Y.S.A. and M.M.R.; visualization, I.J., M.R.I. and M.H.; supervision, M.A.A. and M.R.I.; project administration, M.A.A., M.R.I. and M.H.; funding acquisition, M.A.A., M.R.I., Y.S.A. and M.M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Taif University Researches Supporting Project number (TURSP 2020/78), Taif University, Taif, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support this study will be shared upon reasonable request to the corresponding author.

Acknowledgments: The authors extend their appreciation to the Taif University Researches Supporting Project number (TURSP 2020/78), Taif University, Taif, Saudi Arabia. The first author acknowledges the support of the NST Fellowship (2017-18) from the Ministry of Science and Technology, Government of the People's Republic of Bangladesh.

Conflicts of Interest: The authors declare that they have no conflict of interest to publish this manuscript.

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