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Risk Assessment of Arsenic Toxicity Through Groundwater-Soil-Rice System in Maldah District, Bengal Delta Basin, India

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Abstract

Arsenic (As), a toxic trace element, is of great environmental concern due to its presence in soil, water, plant, animal and human continuum. Its high toxicity and increased appearance in the biosphere have triggered public concern. The present study measured As concentrations in soil, groundwater and rice plant samples of five selected blocks of Maldah district, West Bengal, India. Soil, irrigation water and rice plant samples were collected from the fields of the selected study areas. The results revealed the presence of As in higher concentrations than the maximum permissible limit of As in irrigation water (0.1 mg L^{-1} by FAO, 2010) in groundwater of Manikchak (0.553 ± 0.17 mg L^{-1}), Kaliachak III (0.528 ± 0.20 mg L^{-1}), and Kaliachak II (0.449 ± 0.15 mg L^{-1}), Kaliachak I (0.207 ± 0.19 mg L^{-1}). The soil As was also found higher in those four blocks. The As content in rice grain of the study area was positively correlated ($r = 0.896$**, $p < 0.001$) with As content in irrigation water. The data of consumption of rice per day in the survey were used for the measurement of average daily intake, Hazard quotient (HQ) and Incremental Life time Cancer Risk. Kaliachak III, Manikchak and Kaliachak II showed HQ greater than 1, indicating the possibility of non-carcinogenic health hazard due to As exposure to the local residents. The study emphasized the severity of As problem in remote areas of West Bengal where people consume As tainted rice due to lack of awareness about the As associated health issues.

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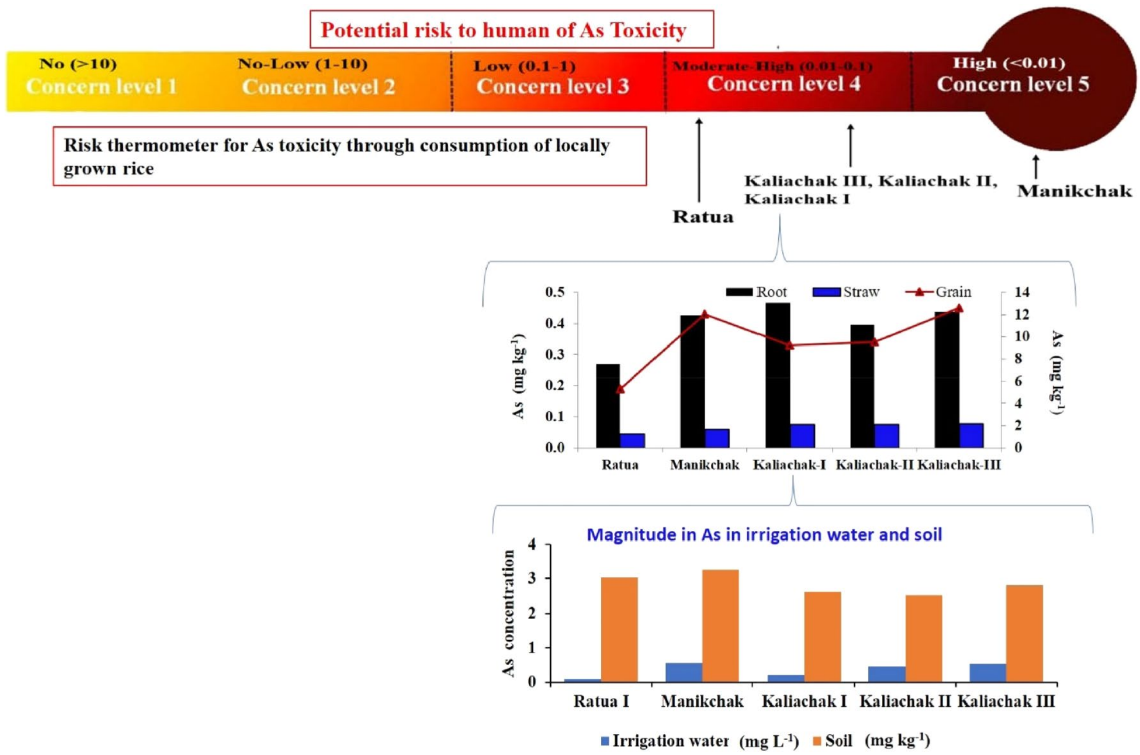
Graphic Abstract



The problem of arsenic (As) contamination in irrigation water and accumulation in edible plant parts is one of the most alarming factors, which poses a health risk to over 200 million people across the world (Shaji et al. 2020; Mochizuki 2019; Nurchi et al. 2020). The first report of high As levels in groundwater was made in West Bengal, India, in 1978 (Shaji et al. 2020). The districts of Maldah, Murshidabad, Nadia, North 24 Parganas, and South 24 Parganas on the eastern bank of the Bhagirathi River, as well as Howrah, Hooghly, and Burdwan on the western side, are the most affected in West Bengal. In south and southeast Asian nations, As-contaminated groundwater is utilized not just for drinking but also for agricultural irrigation, notably for paddy (*Oryza sativa* L.) (Samal et al. 2021; Khanam et al. 2020). Arsenic polluted groundwater has been widely utilized to irrigate paddy rice in India, especially during the rabi season. According to a number of recent studies, rice, vegetables and other food crops grown and irrigated with As-contaminated groundwater are another important source of As exposure, which turned this region into a true health emergency (Biswas et al. 2020; Upadhyay et al. 2019; Abedin et al. 2002). This is the primary cause of concern about the amount of As in food, as it is linked to carcinogenicity and a variety of other negative health effects. In human, common symptoms of chronic As toxicity are pigmentation and keratosis (Guha Mazumder and Dasgupta 2010). Other problems caused by arsenicosis include weakness, chronic respiratory disease, peripheral neuropathy, liver fibrosis, genotoxic effects, cardiovascular diseases, peripheral vascular disease, conjunctivitis, cardiovascular diseases, gangrene and skin cancer, pre-malignant skin lesions, bladder and lung cancer (Guha Mazumder and Dasgupta 2010; Samal et al. 2013). The permissible limit of As in irrigation water was 0.1 mg L^{-1} (FAO, 2010) and in polished rice (inorganic As) 0.20 mg kg^{-1} (FAO, 2014), respectively.

In West Bengal, rice is grown traditionally in the monsoon season (July–October) as 'aman or *kharif* rice' and during the winter season (January-April) as '*boro* or summer rice'. The aman rice is usually rainfed, whereas the boro rice is mostly irrigated with groundwater. During our investigation, we interviewed farmers of the study area and learnt that, for the past few decades, they have been irrigating their rice fields with As-contaminated groundwater, particularly during the winter season, when there has been little rainfall, resulting in more As contamination in soil and rice plants. Thus, to minimize the knowledge gap about As contamination and determine the potential health threat for local residents, the need was felt to investigate the level of As in different varieties of rice grown using groundwater-based irrigation.

Materials and Methods

Study Area

Maldah district is situated in the Ganges–Brahmaputra–Meghna flood and delta plain, between the Latitude and Longitude of 24^0 40′20″ N to 25^0 32′08″ N and 88^0 28′10″ E to 87^0 45′50″ E, respectively. The present study was confined to five blocks (Kaliachak I; Kaliachak II; Kaliachak III; Manikchak and Ratua I) of the district. The total population of the studied blocks is more than 1.5 million (86.4% rural population) (Census report, 2011). The area is under hot and humid climate with annual average rainfall of about 1500 mm, and maximum and minimum monthly temperature of 35.8 ± 2.0°C and 9.5 ± 2.0°C, respectively. The soil of the district is of light textured broadly classified as Old alluvium, Vindhyan alluvial and Ganga alluvial with plain surface (average elevation 17 m) (Saadat and Gupta 2016). The study area is comprising quaternary sediments deposited by the Ganga-Pagla-Bhagirathi-Mahananda river system situated just adjacent to the west of Bangladesh, where elevated As levels have been reported (Golui et al. 2017). Agricultural practice is the major occupation of the residents in this area, where shallow and/or deep tube wells are the main sources of irrigation water (Khanam, 2021).

Sample Collection

From each block, 20 locations were selected using a handheld GPS (Garmin GPS 12) for collection of irrigation water, soil and rice plants. As a part of present investigation, 20 samples each of soil, irrigation water and rice plants were collected from same location from each of five selected blocks during the *rabi* season. Water samples were collected directly from irrigation sources used for irrigating the rice field.

Processing and Analysis of Samples

The collected soil samples were dried in a shade on the clean paper, ground in wooden mortar and sieved through 2 mm nylon sieve. The soil samples were analyzed for physicochemical properties such as mechanical analysis (Piper 1966), pH (Jackson 1973), EC (Jackson 1973), organic carbon (Walkley and Black 1934) and available As (Schmidt et al. 2004) by standard methods. The collected water samples were kept in 50 mL sized brown polyethylene bottles with 2–3 drops of diluted HCl (AR grade) in it ($pH < 2$) to preserve the sample for long use (Mccleskey et al. 2004). The samples were filtered through Whatman filter paper 1 and ready for analysis of total As content by standard method. The fresh plants were washed with clean and As free deionized distilled water to remove dust and other adhering substances. Then, the washed plants samples were dried in the hot air oven at 60 °C temperatures till constant weight is achieved. On drying at 60 °C in an oven for 48 h, the samples were ground with the help of a stainless-steel mini-grinder and stored properly for determining nutrient/pollutant concentration.

Sample Digestion and Instrumental Measurement

Digestion of the rice and soil samples for As analysis was carried out employing the method used by Rahman et al. (2007) with concentrated HNO_3. After proper digestion, the digests were diluted, filtered, and stored in polyethylene bottles for future use. Arsenic in the samples was measured with hydride generation atomic absorption spectrometry (HS-AAS). For hydride generation, analytical standard sodium borohydride (3%; Merck), sodium hydroxide (2.5%; Merck) and hydrochloric acid (6 M; Merck) were used. The concentrations detected in all the samples analyzed were above the instrumental limits of detection (0.2 ppb). All glassware and plastic bottles were washed by deionized-distilled water and dried. The precision of the analysis was always checked by certified standard reference materials (SRMs) (NIST, USA) such as 1568a (rice flour). The analytical results indicated that the observed values were very close to the certified values. Quality control tests were also performed by analyzing triplicates and calculating recovery of spiked digested samples following Rahman et al. (2007).

Indices for Arsenic Transfer and Risk Assessment

Bioaccumulation Factor (BAF)

The BAF is the ratio of the concentration of As in the plant parts to that in the corresponding soil (Arumugam et al. 2018). It was calculated by the equation:

$$BAF\ root = \frac{Concentration\ of\ As\ in\ riceroot}{Concentration\ of\ As\ in\ soil}$$

$$BAF\ straw = \frac{Concentration\ of\ As\ in\ rice\ straw}{Concentration\ of\ As\ in\ soil}$$

$$BAF\ grain = \frac{Concentration\ of\ As\ in\ rice\ grain}{Concentration\ of\ As\ in\ soil}$$

Translocation Factor (TF)

The TF was calculated to determine relative translocation of As from roots to other parts (shoot or grain) of rice plant as follows (Arumugam et al. 2018):

$$TF\ root\ to\ shoot\ (TFr - s) = \frac{Concentration\ o\ fAs\ in\ rice\ shoot}{Concentration\ of\ As\ in\ rice\ root}$$

$$TF\ shoot\ to\ grain\ (TFs - g) = \frac{Concentration\ of\ As\ in\ rice\ grain}{Concentration\ of\ As\ in\ rice\ shoot}$$

Average Daily Intake (ADI)

Ingestion exposure to As from rice was estimated by calculating average daily intake (ADI) using the following equation; the values were then used to calculate non-carcinogenic risk.

$$ADI = \frac{CiAsXIR}{BW} \times \frac{EFxED}{AT}$$

where ADI represents average daily intake of As (μg day^{-1}), CiAs is the concentration of inorganic As [μg kg^{-1}, taking 86% of total as inorganic (Halder et al. 2014)], IR is the ingestion rate (kg day^{-1}); BW is body weight (kg), EF is the exposure frequency (d yr^{-1}), ED is the exposure duration (yr) and AT is the averaging time (day) (US EPA, 2011).

Hazard Quotient (HQ)

The hazard quotient (HQ) was calculated to estimate chronic-toxic risk using the equation:

HQ = $\frac{ADI}{Rfd}$, where Rfd is the reference dose 0.3 μg kg^{-1}d^{-1} (US EPA, 2011).

Incremental Lifetime Cancer Risk (ILCR)

The Incremental Lifetime Cancer Risk (ILCR) associated with ingestion exposure was calculated using the following equation: ILCR = ADI x SF; where ADI is average daily intake of As (μg kg^{-1} bw day^{-1}) and SF is the slope factor of As (per mg kg^{-1} day^{-1}). SF value employed in this study was 1.5 (per mg kg^{-1} day^{-1}) (US EPA, 2011).

Risk Thermometer

Arsenic toxicity exposure level was assessed through risk thermometer taking into consideration the As intake value calculated from the daily consumption of rice. Assessment of risk factor was performed based on As concentration of polished rice, cooking water, and cooked rice prepared through different methods. According to the Swedish National Food Agency, risk thermometer is known for demonstrating new protocol on risk characterization (Sand et al. 2015). The risk thermometer mainly estimates the exposure to a toxic material in food which is compared with the material's health-based reference value (Tolerable Daily Intake, TDI). The different exposure levels to the populations through the ingestion of rice of different cultivars were determined using the following equation as mentioned in other studies (Chowdhury et al. 2020; Sand et al. 2015).

$$\textbf{SAMOE (Severity Adjusted Margin of Exposure)} = \textbf{TDI} / \left(\textbf{AF}_{\textbf{BMR}} * \textbf{AF} * \textbf{SF} * \textbf{E}\right)$$

where TDI (Tolerable Daily Intake) = 3.0 μg kg^{-1} bw^{-1} day^{-1} value for intake of inorganic As (WHO 2011). AF_{BMR} = Non-linear relation in dose range (1/10; BMR—Benchmark response).AF (Assessment factors) = A factor 10 (conservative assessment) (Sand et al. 2015).SF (Severity factor) = 100 (For cancer, the most severe category).E = Different exposure factor.

Result and Discussion

Initial Properties of Soil and Irrigation Water of the Study Area

Soil pH of the blocks of Maldah ranged from 6.45 ± 0.663 to 6.88 ± 0.277. Irrigation water was slightly alkaline to neutral in reaction (7.3 ± 0.003- 7.9 ± 0.061). Organic carbon status of the study area was medium to high (Table 1) ranged from 0.57 ± 0.172% to 1.12 ± 0.129%. Data presented (Table1) showed that the pH and EC of the water varied from 6.4 ± 0.012 to 7.9 ± 0.061 and 0.45 ± 0.09 (dS m^{-1}) to 1.2 ± 0.05 (dS m^{-1}), respectively. Results, therefore, showed that irrigation water of the study area mostly non-saline in nature and neutral to slightly alkaline in reaction. Arsenic mobility in the paddy soil environment is controlled by different factors such as redox potential (Eh), pH, organic carbon status, phosphate (PO_4), iron (Fe) oxides, manganese (Mn), and microbial species (Upadhyay et al., 2019). Thus, the change in these controlling factors under different conditions is important to understand the As dynamics in paddy soil environment.

Spatial distribution of Arsenic in Irrigation Water

Table 2 summarizes the results of our investigation on As contamination of irrigation water in the selected blocks. The percentages of water samples with > 0.05 mg L^{-1} As were

Table 1 Initial properties of irrigation water and soil of selected blocks of Maldah district of West Bengal

Blocks ($n=20$)	Irrigation water				Soil					
	pH		EC (dS m^{-1})		pH		EC (dS m^{-1})		Organic carbon (%)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Ratua I	7.5 ± 0.017	7.02–7.78	1.2 ± 0.05	0.53–1.45	6.68 ± 0.666	6.12–7.34	0.19 ± 0.008	0.15–0.22	1.02 ± 0.107	0.82–1.23
Manikchak	6.8 ± 0.01	7.35–7.02	0.96 ± 0.04	0.34–1.12	6.88 ± 0.277	6.38–7.29	0.28 ± 0.015	0.17–0.37	0.96 ± 0.161	0.67–1.28
Kaliachak I	7.3 ± 0.003	6.98–7.42	0.71 ± 0.1	0.34–0.89	6.65 ± 0.267	6.34–7.25	0.19 ± 0.022	0.11–0.27	0.98 ± 0.165	0.56–1.13
Kaliachak II	7.9 ± 0.061	7.02–8.19	0.53 ± 0.09	0.46–0.76	6.45 ± 0.663	6.22–6.98	0.14 ± 0.029	0.11–0.21	1.12 ± 0.129	0.89–1.31
Kaliachak III	6.4 ± 0.012	6.28–7.01	0.45 ± 0.09	0.31–0.51	6.67 ± 0.468	6.41–7.07	0.32 ± 0.036	0.24–0.41	0.97 ± 0.172	0.56–1.16

Table 2 Concentrations of arsenic in irrigation water (mg L^{-1}) and soil (mg kg^{-1}) in the five blocks of Maldah district

Block ($n=20$)	Irrigation water		Available soil As		Total soil As	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Ratua I	0.093 ± 0.10	0.01–0.48	3.03 ± 0.03	0.50–5.90	7.38 ± 1.14	4.11–13.40
Manikchak	0.553 ± 0.17	0.02–0.79	3.24 ± 0.81	1.18–4.98	14.27 ± 2.19	7.02–18.01
Kaliachak I	0.207 ± 0.19	0.01–0.48	2.64 ± 0.02	0.94–4.13	13.6 ± 1.42	5.03–18.98
Kaliachak II	0.449 ± 0.15	0.01–0.52	2.54 ± 0.97	0.94–4.19	13.8 ± 3.20	6.10–17.60
Kaliachak III	0.528 ± 0.20	0.03–0.74	2.81 ± 0.28	0.28–4.22	15.9 ± 1.40	7.89–18.21

high in Manikchak, Kaliachak III, Kaliachak II, Kaliachak I, and Ratua I, corresponding to 70%, 65%, 65%, 60%, and 45 percent, respectively. The mean concentration of As in irrigation water was 0.553 ± 0.17 mg L^{-1}, 0.528 ± 0.20 mg L^{-1}, 0.449 ± 0.15 mg L^{-1}, 0.207 ± 0.19 mg L^{-1} and 0.093 ± 0.10 mg L^{-1} for Manikchak, Kaliachak III, Kaliachak II, Kaliachak I and Ratua I, respectively. Our results also corroborated well with the study by Rahman et al. (2013); they showed the As contamination level in water was in the order of Manikchak (0.851 mg L^{-1}) > Kaliachak II (0.793 mg L^{-1}) > Ratua I (0.746 mg L^{-1}) > Kaliachak III (0.682 mg L^{-1}) > Kaliachak I (0.623 mg L^{-1}) (Table 2). In contrary to the previous studies, Ratua I showed less As contamination in irrigation water with mean concentration of 0.093 mg L^{-1}. In a previous study by Golui et al. (2017), the As contamination level in irrigation water was found in the order of 0.57 mg L^{-1} (Kaliachak III, $n=4$) and 0.48 mg L^{-1} (Kaliachak II, $n=5$) in Maldah. The high concentration of As in irrigation water in these areas is mainly due to its regional geomorphic setup. Geomorphologically, the area comprises active flood plain, older flood plain and the oldest flood plain. The recent flood plain deposits of district, however, recorded high concentration of groundwater As.

Spatial distribution of Arsenic in Soil

The concentrations of As in the 20 agricultural soils collected from each of the five blocks followed the order of Manikchak (3.24 ± 0.808 mg kg^{-1}) > Ratua (3.03 ± 0.03 mg kg^{-1}) > Kaliachak III (2.81 ± 0.283 mg kg^{-1}) > Kaliachak II (2.54 ± 0.973 mg kg^{-1}) > Kaliachak I (2.64 ± 0.0216 mg kg^{-1}) (Table 2). However, the total As concentration of the selected blocks ranged from 7.38 ± 1.14 to 15.9 ± 1.40 mg kg^{-1} (Table 2). Bhattacharya et al. (2010) also reported that the total soil As concentration of Nadia district, which was considered as one of worst As affected area in West Bengal, was varied from 4.60–0.013 to 9.72 ± 0.108 mg kg^{-1}. Purkait and Mukherjee (2008) reported that high accumulation of As is common in this alluvial track of the Bengal Basin, owing to Himalayan erosion, supplying immature sediments with low surface loadings of FeOOH on mineral, which may release As into soil–water system by changing redox state of aquifer during heavy pumping of groundwater for agricultural purposes.

Arsenic Profiling in Different Plant Parts of Rice

Rice is being grown in flooded (reduced) conditions, which has significant influence on As bioavailability in soil, enabling rice to become more efficient at assimilating As into grain than the dry land cereal crops (Chowdhary et al. 2020). Arsenic content in rice roots depends on bioavailable soil As, Fe concentration in soil solution, volume of absorbing roots, redox conditions in the root-zone, Fe plaque formation on root surface and abundance of As transporters in roots. Deposition of Fe plaque on root surface is most important factor to reduce As uptake in plants. The anoxic environment (under flooding condition) leads to dissolution of Fe(oxy)hydroxides and release Fe^{+2}; these swarm of Fe^{+2} precipitated on rice root as Fe plaque (Samal et al. 2021;

Kumarathilaka et al. 2018). This Fe plaque has strong binding affinity for As^{+3} and restricts its entry inside the plant. Kaliachak I has the highest root As (13.03 ± 8.08 mg kg^{-1}), followed by Kaliachak III (12.22 ± 5.81 mg kg^{-1}) (Table 3). The levels of As contamination in rice grain varied from 0.028–0.79 mg kg^{-1} among the blocks. The As contamination level in rice grain followed the order of Kaliachak III (0.45 mg kg^{-1}) > Manikchak (0.43 mg kg^{-1}) > Kaliachak III (0.34 mg kg^{-1}) > Kaliachak II (0.34 mg kg^{-1}) > Kaliachak I (0.33 mg kg^{-1}) > Ratua I (0.23 mg kg^{-1}). In a previous report, Rahman et al. (2007) showed As concentration in rice grain collected from Maldah district was 0.429 mg kg^{-1}. Bhattacharya et al. (2010) reported in their study that the grain As concentration was varied from 0.23 ± 0.009 to 0.54 ± 0.002 mg kg^{-1} grown in As hot spot area (Nadia) of West Bengal. The result of the current study and previously reported work showed that the plants grown in As-rich soil and irrigated with As-contaminated water deposited As in the tissues (Hussain et al. 2021).

Irrespective of blocks As accumulation in the grain was generally low as compared to root and straw. The amount of As in the grain collected from all of the blocks did not exceed the permissible limit by FSSAI (2011) (1.1 mg kg^{-1}). However, it may contribute to significant exposure to a person having rice-based subsistence diet (Mawia et al. 2021).

Spatial Distribution Map of Arsenic in Irrigation Water and Soil of Maldah

Interpolated maps of irrigation water and soil As prepared using Kriging method and validated with semivariogram model (exponential) are presented in Figs. 1a–e, 2a–e. In case of irrigation water in Manikchak, most of the area came under dark color which meant to be extremely affected (0.5–1.0 mg L^{-1}) category. As concentration in water was not uniform across the study region in Kaliachak III, Kaliachak II and Kaliachak I, but rather occurred in patches spread over the study area. In Ratua I, however, more than 80% of the region was classified as moderately affected (0.051–0.10 mg L^{-1}). Thematic maps of soil As for Manikchak, Kaliachak III, Kaliachak II and Kaliachak I showed high spatial variability even at short distances (Fig. 1 b, c, d, e). However, the Ratua I block map (Fig. 1a) had a lighter color, indicating a lower level of As in the soil (2.51–5.0 mg kg^{-1} class) throughout the block.

Relationships Between as Contents of Rice Plants, Irrigation Water and Soil Parameters

The results of correlation analysis between As concentrations in irrigation water, soil and in different parts (root, straw and grain) of the rice plant cultivated in the five blocks of the district are presented in Fig. 3a-d. The data showed a significant positive correlation among As concentrations in irrigation water, soil, root and grain. Continued irrigation using high As water gradually enhances As loading in soil; it further increases As accumulation in different parts of plant (Shrivastava et al. 2017; Chowdhury et al. 2020).

The bioavailability of As in rice is influenced by a number of physical and chemical factors in the soil and/or irrigation water. Table 4 summarizes the correlation coefficients (r) between As concentrations in different parts (root, straw, husk, and grain) of the rice plant and selected soil properties (pH and organic carbon). Organic carbon showed negative correlation with As accumulation in soil and rice plant parts. In this study, the As content of soil had a positive correlation with soil pH. As concentration of rice grain and straw, on the other hand, is unaffected by soil pH.

Bioaccumulation Factor (BAF)

In order to reflect As transfer from soil to straw and grain in rice in different blocks of Maldah district, BAF for both straw and grain was calculated for each sample and summarized in Table 4. BAF soil to root followed the order of Manikchak (3.11) = Ratua I (3.11) > Kaliachak I (2.55) > Kaliachak III (1.68) > Kaliachak II (1.49). Among the blocks, BAF values for straw were found to be higher in Kaliachak I (0.4), but BAF values for straw (BAFstraw) were comparatively lower in Manikchak (0.19). The BAF for grain (BAFgrain) in Ratua I, Manikchak, Kaliachak I, Kaliachak II and Kaliachak III, as shown in Table 4, was 0.05, 0.05, 0.07, 0.05 and 0.06, respectively. Manikchak block has the lowest BAF in both straw and grain. It suggests that Manikchak block soil has a high absorptive capacity, limiting As access

Table 3 Concentrations of arsenic (mg kg^{-1}) in different of rice plant in the five blocks of Maldah district

Block (*n* = 20)	Root		Shoot		Grain (husked)	Grain (dehusked)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Mean ± SD	Range
Ratua I	7.56 ± 3.88	3.1–15.14	1.25 ± 1.50	0.15–4.32	0.63 ± 0.13	0.19 ± 0.029	0.03–0.59
Manikchak	11.93 ± 7.34	2.82–24.01	1.68 ± 0.97	0.30–3.38	1.03 ± 0.20	0.43 ± 0.022	0.08–0.79
Kaliachak I	13.03 ± 8.08	3.03–25.98	2.08 ± 0.46	1.14–2.91	0.98 ± 0.19	0.33 ± 0.010	0.20–0.52
Kaliachak II	11.06 ± 6.29	3.10–26.61	2.10 ± 0.93	0.52–3.98	1.09 ± 0.31	0.34 ± 0.010	0.12–0.48

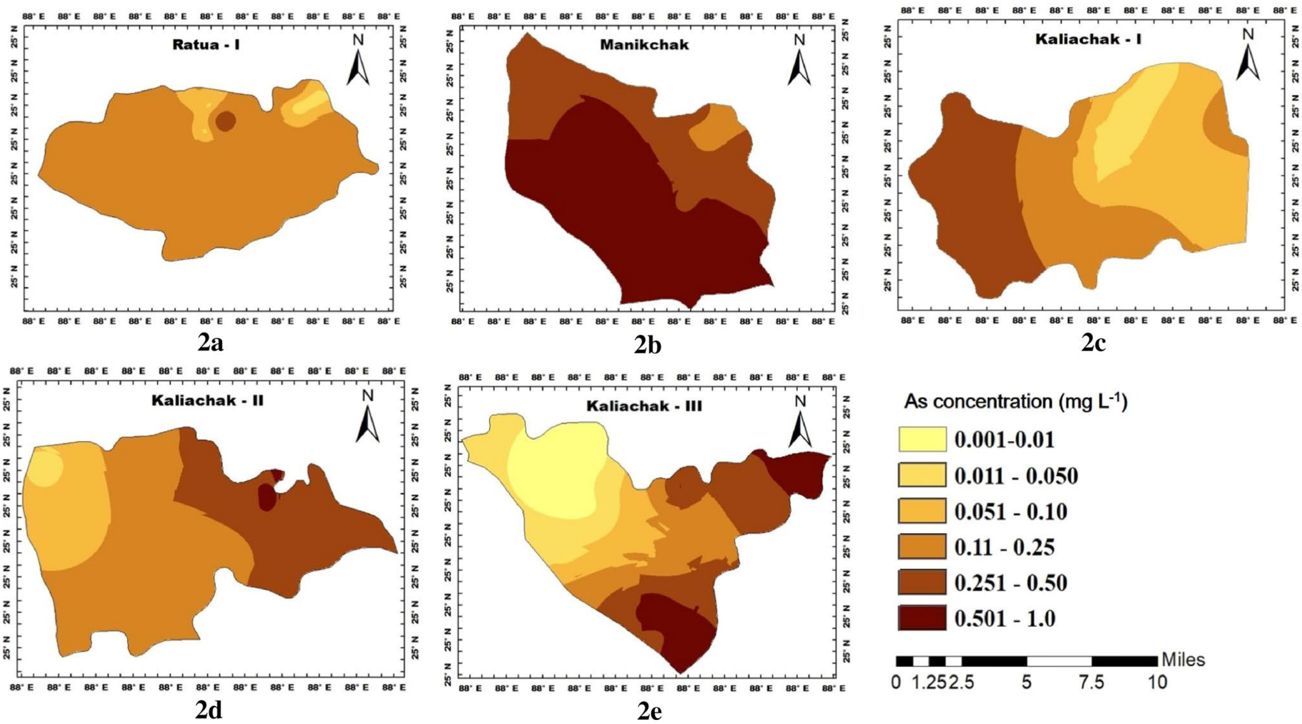


Fig. 1 **a-e** Spatial distribution Maps showing As of irrigation water (mg L^{-1}) of different blocks of Maldah district

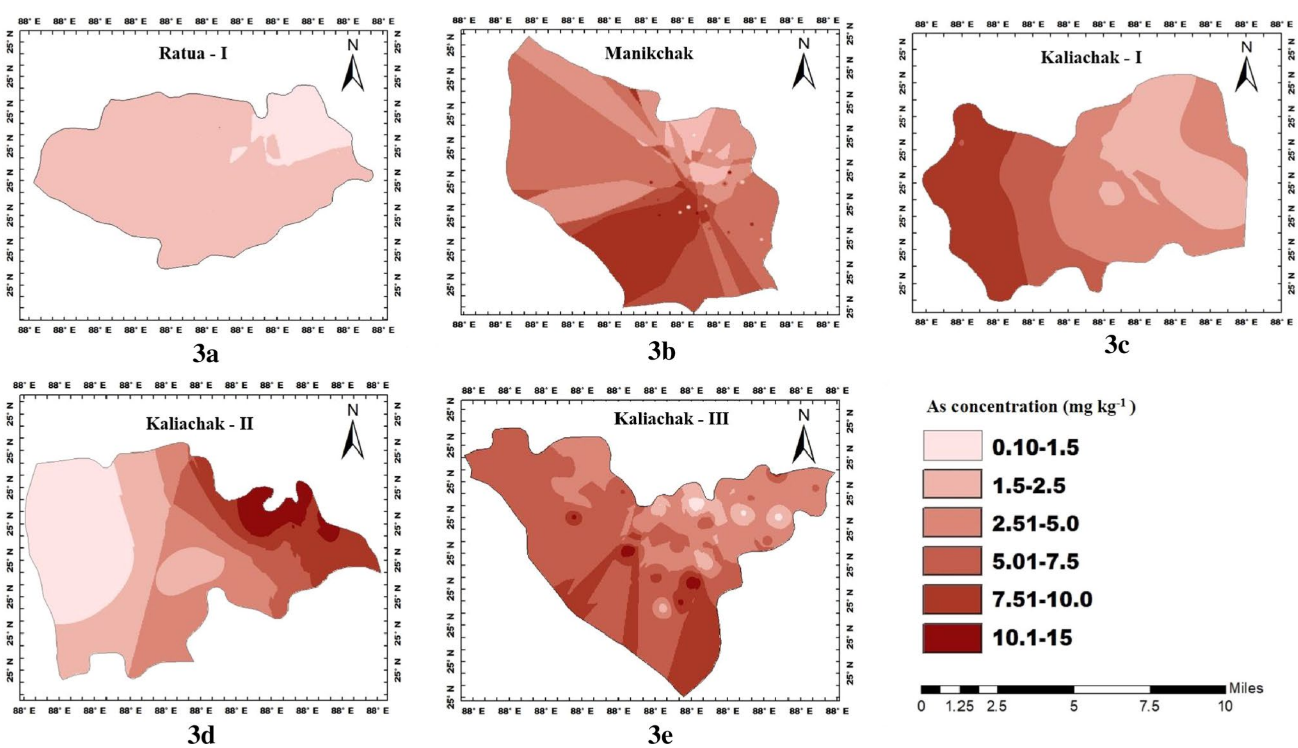


Fig. 2 **a-e** Spatial distribution Maps showing soil As (mg kg^{-1}) of different blocks of Maldah district

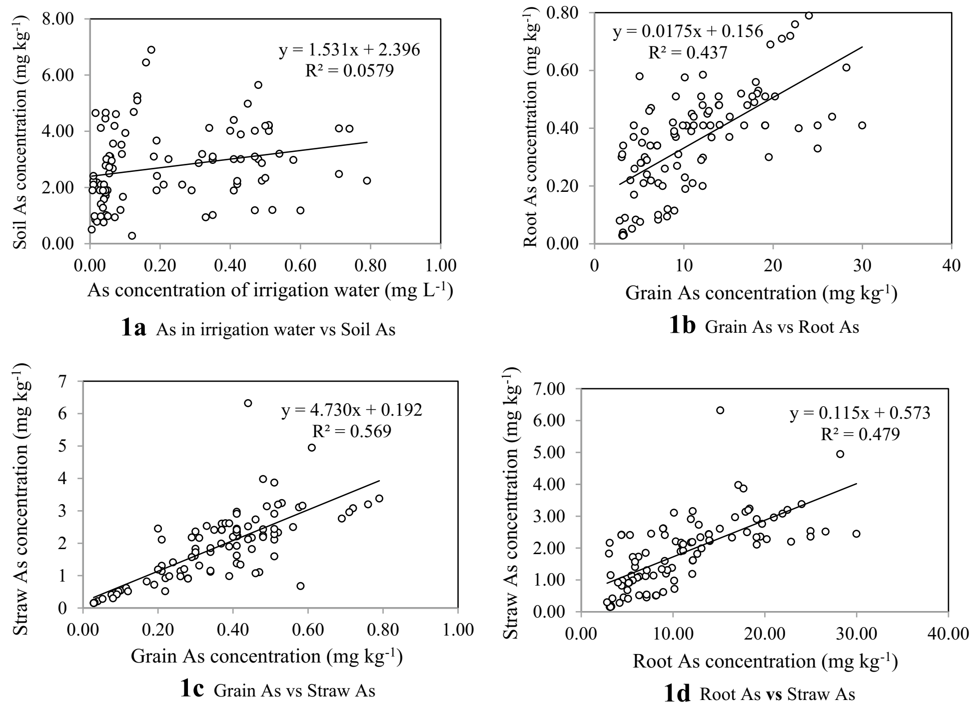


Fig. 3 a-d Interrelationship in-between As concentration of different plant parts of rice at maturity

to the plant. The findings of the present study were in good accord with a previous experiment by Singh et al. (2011). They found that BAF in grain was low (0.04), despite significant As contamination in the soil. It is worth noting that BAF factor for straw and grain in all blocks is less than 1.

Translocation Factor of Soil, Root and Straw

The calculated TF from root to straw and straw to grain for the studied blocks is presented in Table 4. However, maximum $TF_{r\text{-}s}$ values were seen in Kaliachak II (0.26) and minimum were in Ratua I (0.12) blocks. $TF_{s\text{-}g}$ was in the following order: Manikchak (0.27) > Kaliachak III (0.25) > Kaliachak II (0.19) > Ratua I (0.18) > Kaliachak I (0.16).

Hazard Quotient (HQ) and Incremental Lifetime Cancer Risk (ILCR)

The hazardous quotient was calculated for all the selected blocks to evaluate the potential risk of As from contaminated rice intake on human health. Results confirmed that HQ value from consumption of rice was 1.36 ± 0.236 in Kaliachak III and 1.28 ± 0.673 in Manikchak. Likewise, the HQ in Kaliachak II, Kaliachak I and Ratua I was 1.01 ± 0.293, 1.0 ± 0.304 and 0.58 ± 0.586, respectively (Fig. 4). Furthermore, the ILCR value of As, obtained by multiplying ADI and cancer slope factor, was 0.43×10^{-3}—0.81×10^{-3}, 0.34×10^{-3}—0.49×10^{-3}, 0.31×10^{-3} -0.45×10^{-3}, 0.11×10^{-3} -0.26×10^{-3} and 0.43–0.78×10^{-3} for consumers of rice from Kaliachak III, Kaliachak II, Kaliachak II, Ratua I and

Table 4 Bioaccumulation factor (BAF) and Translocation factor (TF) of arsenic in the rice varieties cultivated in the five blocks of Maldah district

Block (*n* = 20)	Bioaccumulation factor (BAF)			Translocation factor (TF)	
	soil to root	soil to straw	soil to grain	root to straw	straw to grain
Ratua I	3.11	0.34	0.05	0.12	0.18
Manikchak	3.11	0.19	0.05	0.15	0.27
Kaliachak I	2.55	0.40	0.07	0.21	0.16
Kaliachak II	1.49	0.30	0.05	0.26	0.19
Kaliachak III	1.68	0.31	0.06	0.18	0.25
Mean ± SD	2.3 ± 0.77	0.30 ± 0.07	0.56 ± 0.008	0.184 ± 0.05	0.21 ± 0.04
Range	1.49–3.11	0.19–0.40	0.05–0.07	0.120.26	0.16–0.27

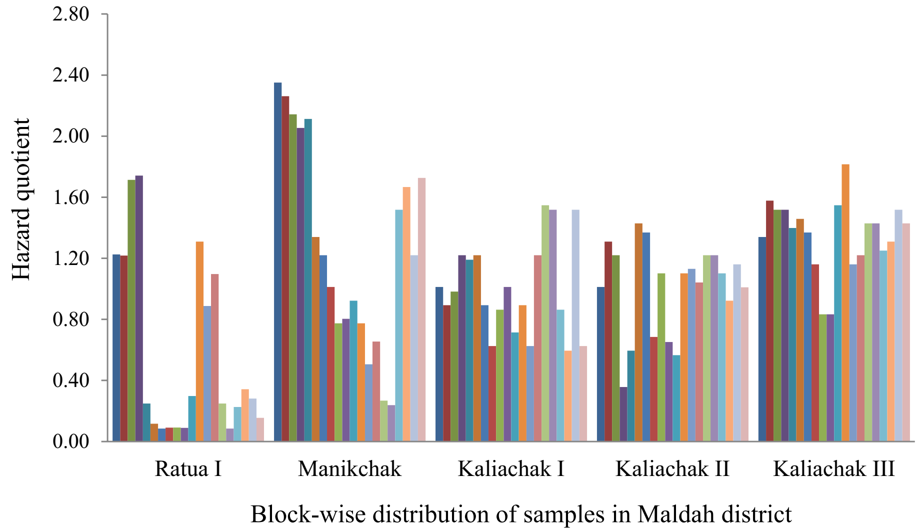


Fig. 4 Block wise distribution of hazard coefficient in Maldah district

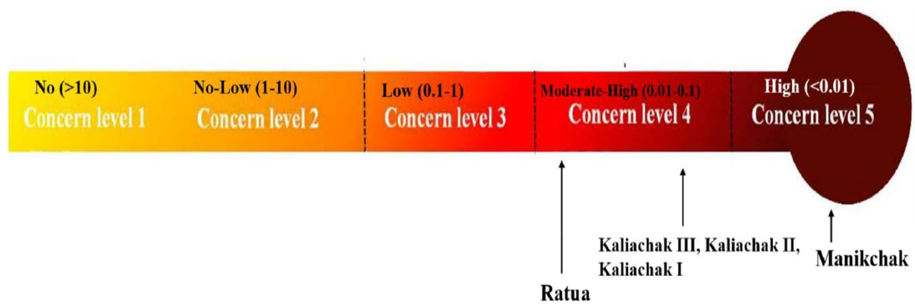


Fig. 5 Risk thermometer scale showing the class of arsenic toxicity in selected blocks through consumption of locally grown rice

Manikchak, respectively (supplementary Table 1). If the HQ is more than 1, there is a chance of adverse health effects. According to the findings of our study, Manikchak, Kaliachak III, Kaliachak II, and Kaliachak blocks may pose a non-carcinogenic health risk. Golui et al. (2017) conducted an epidemiology study in Maldah district, finding that As-contaminated drinking water and a rice diet posed a risk to the population. The range of HQ values from their study showed that in many cases, HQ for rice grain cultivated in the selected farmer fields surpassed 1.0.

Risk Thermometer for as Toxicity

Supplementary Table 1 and Fig. 5 show the 'Risk thermometer' and the calculated Severity Adjusted Margin of Exposure (SAMOE) value for As toxicity of different rice cultivars cooked in contaminated and non-contaminated water. According to this thermometer, consumption of locally grown rice from the selected block showed separate concern levels of risk from class 4 to class 5 depending on its As concentration. The Manikchak block showed concern level with highest risk (class 5), whereas for Kaliachak III, Kaliachak II and Kaliachak I showed moderate to high risk (class 4), Although Ratua I is in class 4, its SAMOE value is higher than the other three blocks in this group. Thus, Ratua I is considered to be comparatively at lower risk.

Conclusion

In the present study, spatial distribution of As in soil and groundwater was investigated in details in selected blocks of Maldah districts of West Bengal. However, spatially georeferenced database of As of all the districts of West Bengal is highly anticipated to assess the toxicity problem from all the other parts of the state. High variability of As content in irrigation water and soil was observed in Maldah. Manikchak recorded the highest soil and irrigation water contamination. Grain As content found highest in Kaliachak III. Ratua 1 recorded lowest As in irrigation water, soil and grain. The use of As-contaminated groundwater for irrigation resulted in elevated As levels in top soils, posing a risk of the As accumulation in locally grown rice and subsequent entry into the food chain . Therefore, rice has been identified as a potentially important route of As exposure in the study area. Remediation aimed at reducing human exposure to rice As in West Bengal should gradually be focused.

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Authors' Contributions RK had done the field experiments and the laboratory analyses. GCH conceptualized the study and finalized the methodologies. PGPSK had done statistical analysis of the data. RK and PGPSK prepared the first draft. All authors subsequently added their inputs and improved the MS. GCH had done the overall supervision of the entire research study, manuscript revisions and corrections.

Declarations

Conflict of interest The authors declare that they do not have any conflict of interest.

Consent to Participate All authors informed consent to participate in this paper.

Consent to Publish All authors informed consent to publish this paper.

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