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From Irrigation Water to Rice Grain: Arsenic Transfer, Accumulation and Human Health Risk in North 24-Parganas, West Bengal, India

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Abstract

Arsenic (As) is a toxic metalloid widely distributed in rocks, soils, water, sediments, and the atmosphere. Arsenic is distributed from different sources into air, water and soil and finds its way into the human system through direct inhalation or by contamination of food and consumer products. The World Health Organization (WHO) recommended the guideline value of 10 µg L^{-1} (0.01 mg L^{-1}) of As in drinking water. This study aims to quantify arsenic (As) concentrations in irrigation water, soil, and different rice plant part samples from intensively cultivated four selected blocks of North 24- Parganas district, West Bengal, India. Irrigation water, soil, and rice plant samples were collected from the fields of selected blocks. This study showed that As content in irrigation water of Basirhat-I (0.46 mg L^{-1}) > Bongaon (0.37 mg L^{-1}) > Deganga (0.30 mg L^{-1})> Gaighata (0.26 mg L^{-1}) surpassed the permissible maximum limit. Arsenic content in soil for these blocks also showed high value. Among the four blocks Basirhat-I (3.09 mg kg^{-1}) showed highest Available As. The daily intake of rice (0.4 kg day^{-1}) used for the measurement of average daily intake, hazard quotient (HQ) and incremental life time cancer risk. Though the all the blocks are showing HQ> 1, highest HQ was in Basirhat-I which indicating the non-carcinogenic hazard due the exposure of As. This huge As exposure among local people is mainly due to not having the proper mindfulness and technical support to beat the threat.

***Keywords*:** Arsenic, Irrigation water, Hazard Quotient, Rice grain

Introduction

One of the most concerning issues is the accumulation of Arsenic (As) in edible plant parts and contamination of irrigation water, which endangers the health of more than 200 million people worldwide (Shaji *et al.*, 2020). Groundwater As contamination remains one of the most persistent public health concerns in the Bengal Delta, and North 24-Parganas continues to stand out as one of the worst-affected districts within this belt. Situated in the Lower Ganga Plain (LGP), the district's shallow aquifers are drawn from Holocene alluvial sediments that are naturally rich in As-bearing minerals, and the reductive dissolution of iron oxides under anoxic conditions has steadily released As into the groundwater used by millions of residents for drinking, cooking, and irrigation (Paul & Das, 2021).

The scale of the problem in North 24-Parganas was documented in detail by Rahman *et al.* (2003), whose seven-year survey of more than 48,000 hand tube-wells found that nearly 30% exceeded the Indian national standard permissible limit of 50 μg L^{-1}, while over half crossed the WHO-recommended threshold of 10 μg L^{-1}. Their work also showed that arsenic-related skin lesions and other clinical symptoms had already appeared across a large share of the district's blocks, pointing to long-term chronic exposure rather than an isolated event. Later assessments confirmed that the contamination is not confined to drinking water alone; irrigation with As-loaded groundwater has allowed the element to move into the food chain, with elevated concentrations reported in soil, rice grain, and locally grown vegetables (Singh *et al.*, 2024).

Despite decades of monitoring, the spatial pattern of contamination of As in North 24-Parganas is far from uniform. Blocks such as Deganga, Habra I and II, Amdanga, Barasat, and Basirhat-I have repeatedly been flagged as high-risk zones, largely because of shallow aquifer depth, poor recharge conditions, and dense population pressure on a limited number of safe water sources (Paul & Das, 2021). Groundwater quality assessments conducted in Habra Block II further revealed that a substantial proportion of sampled tube-wells failed to meet Indian drinking water standards for As, alongside high iron content, underscoring that As rarely occurs as an isolated contaminant in this terrain (Mondal *et al.*, 2021).

The significances for public health are considerable. Long-term consumption of As-contaminated water has been linked to skin lesions, respiratory illness, and elevated cancer risk among exposed populations, and biological monitoring of hair, nail, and urine samples from affected villages has consistently shown As levels well above normal ranges (Giri & Banerjee, 2024). More recent health-risk evaluations confirm that the danger has not diminished with time; rather, it has diversified, with dietary exposure through contaminated rice and vegetables now recognised as a meaningful added pathway, particularly for populations who may not be aware that their food, and not just their drinking water, carries risk (Rokonuzzaman *et al.*, 2022). The present study seeks to contribute to this understanding of block-level investigation of As distribution in North 24-Parganas by examining As contamination in the district in light of recent hydrogeological and health-risk evidence, with the aim of informing more targeted mitigation and safe water planning at the local level.

Materials and Methods

Study area

West Bengal's North 24 Parganas district lies roughly between latitudes 22°11′N and 23°15′N and longitudes 88°20'E and 89°05'E. The district is identified as one of the state's areas afflicted by arsenic (As) and is a part of the lower Gangetic alluvial plain.

North-24-Parganas is located in the Bhagirathi-Hooghly river sub-basin in the southeast of the state. It borders the districts of Satkhira and Jessore in Bangladesh, both of which are severely afflicted by As. For this study, four blocks from the North 24 Parganas district- Bongaon, Basirhat-I, Deganga and Gaighata - were chosen. In Gaighata block specifically, a detailed survey found arsenic above the WHO guideline value in every one of the 107 surveyed mouzas, with roughly 40% of tubewells exceeding the Indian permissible limit of 50 µg L^{-1} (Roychowdhury, 2010). Water-quality-index research covering Deganga and Gaighata found that around 91% and 85% of water samples from these two blocks, respectively, were unfit for consumption (Majumder *et al.*, 2024). The study area's primary source of income is agriculture, which is practiced year-round using groundwater as the primary irrigation source. This region is irrigated with shallow tube well pumps, and research in Deganga block estimated that thousands of As-laden irrigation tube wells deposit several tons of arsenic onto agricultural land each year, with the majority of tested irrigation wells exceeding 10 µg L^{-1} (Chakraborti *et al.*, 2018).

Sample Collection

Using a handheld GPS (Garmin GPS 12), 25 locations were chosen from each block to collect soil, rice plants, and irrigation water samples. 25 samples of soil, irrigation water, and rice plants were taken from the same location in each of four chosen blocks throughout the rabi season as part of the current study. Water samples were taken straight from the irrigation sources that were used to irrigate the rice field.

Sample processing and analysis

The collected soil samples were dried in a shade on the clean paper, mashed in wooden mortar and sieved through 2 mm nylon sieve. The soil samples were examined for physicochemical parameters such as mechanical analysis (Piper, 1966), p^H (Jackson, 1973), EC (Jackson, 1973), organic carbon (Walkley and Black, 1934) and available As (Schmidt *et al.* 2004) by standard procedures. The collected irrigation water samples were kept in 50 mL sized brown polyethylene bottles with 2-3 drops of diluted HCl (AR grade) in it ($p^H < 2$) to preserve the sample for long term use (Mccleskey *et al.*, 2004). The samples were filtered through Whatman filter paper 1 and prepare for analysis of total As concentration by standard method. The plant

samples were rinsed with clean and As free deionised distilled water to eliminate dust and other adhering contaminants. Following a 48-hour drying period at 60°C in an oven, the samples were ground using a stainless-steel mini-grinder and appropriately kept to determine the concentration of nutrients and pollutants.

Digestion of samples and Instrument Measurements

The procedure utilised by Rahman *et al.* (2007) with concentrated HNO_3 was employed to digest the rice and soil samples for As determination. Following adequate digestion, the digested samples were filtered, diluted and kept in plastic bottles for later use. Hydride generation atomic absorption spectrometry (Perkin Elemer PinAAcle 900F AAS) was used to detect the amount of As in the samples. Analytical standards sodium borohydride (3%; Merck), sodium hydroxide (2.5%; Merck), and hydrochloric acid (6 M; Merck) were utilised for hydride production. All of the samples that were examined had concentrations that were higher than the 0.2 ppb analytical limits of detection. After being cleaned with deionised distilled water, all glassware and plastic bottles were dried.

Risk Assessment and Arsenic Transfer Indices

Translocation factor (TF)

Translocation Factor (TF) was calculated to determine relative translocation of As from root to other parts (root, shoot, or grain) of the plant species as follows:

$$\text{TF root to shoot} = \frac{\text{Concentration of As in plant straw}}{\text{Concentration of As in plant root}}$$

$$\text{TF shoot to grain} = \frac{\text{Concentration of As in plant grain}}{\text{Concentration of As in plant straw}}$$

Bioaccumulation factor (BAF)

Bioaccumulation factor is the ratio of the concentration of the element in the plant parts to that in the corresponding soil. It was calculated by the equation-

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

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

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

Average Daily Intake (ADI)

The average daily intake (ADI) of As from rice was calculated using the following formula to estimate ingestion exposure; the results were then utilised to determine and then was used to calculate both cancer and non-cancer risk.

$$\mathrm{ADI} = \frac{\mathrm{CiAs} \times \mathrm{IR}}{\mathrm{BW}} \times \frac{\mathrm{EF} \times \mathrm{ED}}{\mathrm{AT}}$$

Where,

ADI represents average daily intake of Arsenic (μg kg^{-1} bw day^{-1}), CiAs is the concentration of inorganic As [μg kg^{-1}, taking 90% of the total as inorganic (Rahman and Hasegawa 2011)], IR is the ingestion rate (0.4 kg day^{-1}); bw is body weight (60 kg), EF is the exposure frequency (365 day $year^{-1}$), ED is the exposure duration (70 years), AT is the average lifetime (25,550 day) (Khanam *et al.*, 2023) and BCF is the bio-accessibility factor [taking 97% of As in cooked rice as bio-accessible to human (Signes Pastor *et al.*, 2008)].

Hazard quotient (HQ)

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

$$\mathrm{HQ} = \left(\frac{\mathrm{ADI}}{\mathrm{Rfd}}\right) \times \mathrm{RBA}$$

Where, Rfd is the reference dose 0.3 μg kg^{-1} day^{-1} (IRIS, 2013), ADI is the average daily intake of As (μg kg^{-1} bw day^{-1}) and RBA is the relative bioavailability factor (60%) (Khanam *et al.*, 2023).

Incremental Lifetime Cancer Risk (ILCR)

The Incremental Lifetime Cancer Risk (ILCR) connected 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 used in this study was 1.5 (per mg kg^{-1} day^{-1}) (US EPA, 2011).

Result and Discussion

Initial soil and irrigation Water Characteristics of Study Area

Across the four selected blocks, both irrigation water and soil showed a near-neutral to mildly alkaline p^H, generally ranging between 6.9 and 7.7, with Basirhat-I recording the highest values in both media (irrigation water p^H-7.54; soil p^H-7.69) and Gaighata the lowest (soil p^H-6.92). A near-neutral to alkaline pH range is broadly consistent with the geochemical conditions reported for shallow aquifers in North 24-Parganas, where such conditions favour the reductive dissolution of iron oxides and the subsequent release of As into groundwater (Bhowmick *et al.*, 2018). Irrigation water EC was highest in Bongaon (0.95 dS m^{-1}) and lowest in Gaighata (0.65 dS m^{-1}). Similar EC variability has been reported in the neighbouring Chakdaha block, where fluctuating conductivity levels in irrigation water were linked to differences in As mobility between agricultural plots (Shrivastava *et al.*, 2014). Organic carbon (OC) content in soil was highest in Gaighata (1.03%), and lowest in Basirhat-I (0.69%) (Table 1), which had the highest p^H and EC among the four blocks. This inverse pattern is obvious, since organic matter often plays a role in binding or mobilising As in soil. Comparable work on West Bengal's arsenic-affected agricultural soils has shown that higher OC content tends to enhance As bioavailability by promoting microbially driven reductive dissolution, meaning that blocks like Gaighata, despite lower salinity, may still carry elevated As-mobilisation risk on account of their OC load (Singh & Srivastava, 2020).

Spatial distribution of Arsenic in Soil and Irrigation Water

Available As concentrations ranged from 2.28 to 3.09 mg kg^{-1}. Basirhat-I recorded the highest Available As content, followed by Deganga and Bongaon, while Gaighata exhibited the lowest concentration. Total As concentrations varied from 21.69 to 25.63 mg kg^{-1}, with the highest value observed in Deganga and the lowest in Gaighata. The elevated Total As levels across all blocks indicate substantial As accumulation in agricultural soils. A study evaluating As contamination in four villages of Nadia and North 24 Parganas districts- specifically Chamta and Byaspur villages of North 24 Parganas found soil As concentrations of 46.17 to 66.00 mg kg^{-1}, groundwater As of 35.00 to 186.00 µg L^{-1}, and rice grain As of 0.017 to 1.27 µg g^{-1} (Singh *et al.*, 2024).

As concentrations in irrigation water ranged from 0.26 to 0.46 mg L^{-1}. Basirhat-I showed the highest irrigation water As concentration (0.46 mg L^{-1}), followed by Bongaon (0.37 mg L^{-1}), whereas Gaighata and Deganga recorded comparatively lower values (Table 2). All irrigation

water samples contained As concentrations far exceeding the WHO guideline value of 0.01 mg L^{-1}, suggesting groundwater irrigation as a major source of As input into agricultural soils. The consistently high concentrations of As in both irrigation water and soils indicate widespread contamination. The elevated As levels, coupled with intensive groundwater irrigation practices, may enhance As accumulation in the soil-plant system and increase the risk of its transfer to rice crops. Similar findings were reported by Paul *et al.* (2021), who identified Deganga, Habra-I, Amdanga, Basirhat, and Barasat blocks of North 24 Parganas as highly vulnerable to As contamination. Their study demonstrated that extensive use of shallow tube wells for irrigation introduces considerable amounts of As into agricultural soils, with annual deposition reaching approximately 5.02 kg ha^{-1}. The deposited As is further redistributed during the monsoon season, influencing key soil properties such as p^H, OC content, and micronutrient dynamics, thereby affecting the overall soil environment in these As-affected regions.

Arsenic profiling in different parts of rice plants under North 24-Parganas district

Arsenic profiling in rice plants from different blocks of North 24 Parganas district revealed substantial accumulation in all plant parts, with the highest concentrations consistently observed in roots, followed by straw, and grains. This indicates that rice roots serve as the primary site of As accumulation, while only a portion of the absorbed As is translocated to aerial tissues and grains. Among the studied blocks, Deganga recorded the highest root As concentration (14.97 mg kg^{-1}), followed by Gaighata (14.01 mg kg^{-1}), whereas Bongaon showed the lowest value (7.79 mg kg^{-1}). Straw As concentrations varied from 2.06 mg kg^{-1} in Bongaon to 2.23 mg kg^{-1} in Gaighata. Arsenic concentration in rice grains ranged from 0.42 mg kg^{-1} in Gaighata to 0.59 mg kg^{-1} in Basirhat-I (Table 3). The comparatively higher grain As concentration in Basirhat-I suggests greater As translocation from vegetative tissues to the edible portion of the crop (Fig.). The overall pattern of As accumulation followed the order: Root> Straw > Grain. The elevated As concentrations in roots and vegetative tissues reflect the influence of As-contaminated irrigation water and soils in the study area. Although grain As concentrations were lower than those in other plant parts, their presence is a matter of concern because rice is a staple food crop. These findings indicate a potential risk of As entry into the food chain and highlight the need for regular monitoring and appropriate management practices in the rice-growing areas of North 24 Parganas district. Similar results were reported by Bhattacharya *et al.* (2013), who observed significant variation in As accumulation among rice varieties cultivated in West Bengal, indicating the influence of genotype on As uptake and distribution. Arsenic content in rice root is influenced by the bioavailability As in soil. Fe

plaque formation on the root surface, the amount of As transporters in roots, the volume of absorbing roots, the redox conditions in the root zone, and the concentration of Fe in soil solution. The most significant element in lowering As uptake in plants is the deposition of Fe plaque on the root surface. Fe^{2+} is released when Fe(oxy)hydroxides dissolve in an anoxic environment (during flooding); this swarm of Fe^{2+} precipitates on rice roots as Fe plaque (Samal *et al.*, 2021).

Spatial distribution map of arsenic in soil and irrigation water of North 24 pargana

The spatial distribution maps of As content in soil and irrigation water of different blocks of the district using Kriging method are presented in Fig. 1 a-d and Fig. 2 a-d. The thematic map of Deganga and Gaighata blocks for soil As content came under class 2.50-5.00 mg kg^{-1}. In case of Bongaon block mostly (almost 40% area) came under the category 5.00-7.50 mg kg^{-1} followed by the class 1.50-2.50 mg kg^{-1}. Whereas, Basirhat-I came under class 5.00-7.50 mg kg^{-1}, followed by the class 2.50-5.00 mg kg^{-1}. Arsenic concentration was never uniform all over the selected blocks rather found in spots over the study area. For As in irrigation water, Deganga block mostly came under moderately affected (0.25-0.50 mg L^{-1}) category. Gaighata block came mostly under 0.15-0.30 mg L^{-1} category followed by 0.30-0.50 mg L^{-1} category. Basirhat-I showed huge variability of As content in irrigation water from highly (0.50-1.50 mg L^{-1}) to less (0.05-0.10 mg L^{-1}) affected class. Bongaon showed As in irrigation water mostly under class 0.30-0.38 mg L^{-1}.

Inter-relationship between As content in soil and different parts of rice plant in blocks of North 24 Parganas district

Fig. 3a-c shows the results of a correlation analysis between As concentrations in soil, and several portions (grain, straw, and root) of the rice plant grown in the four blocks of North 24 Parganas district. Arsenic content in soil, grain, and root was found significant positive correlation. Arsenic loading in the soil is progressively improved by continuous irrigation with high As water, which also increases As accumulation in various plant parts (Chowdhury *et al.* 2020).

West Bengal's agricultural soils are showing worrying levels of arsenic contamination. The region's reliance on intensive rice farming, with two harvests per year, means the soil undergoes constant irrigation cycles and frequent shifts in its physical and chemical condition. These irrigation patterns and the resulting changes in soil chemistry are closely tied to microbial activity in the soil, and researchers have pointed to this microbial-chemical interaction as a key

reason behind the elevated As levels found in West Bengal's soils (Majumdar *et al.*, 2021). Arsenic buildup in soil and irrigation water was negatively correlated with OC. In the present study, As concentrations in soil and irrigation water showed a positive correlation with soil pH. Similar findings have been reported, where increasing soil pH was associated with greater concentrations of mobile and bioavailable As fractions (Shen *et al.*, 2019).

Translocation factor of Straw, Root and Soil

The calculated Translocated factor (TF) from straw to grain for the four studied blocks is presented in Table 5. TF values (straw to grain) followed order Basirhat-I (0.28)> Deganga (0.26)> Bongaon (0.22)> Gaighata (0.20). However, highest TF values (root to straw) were seen in Bongaon (0.26) and Basirhat-I (0.21) followed by Gaighata (0.16) then Deganga (0.14) block.

Bioaccumulation factor

BAF for both straw and grain were computed for each sample and summed to show the transfer from soil to root, straw and grain in rice in several blocks of the North 24 Parganas district in Table 4. BAF for soil to root followed the order of Gaighata (9.36)>Deganga (5.59)> Basirhat-I (3.38) > Bongaon (3.23). Among the selected blocks, BAF value for straw was highest in Gaighata (1.53) and lowest in Basirhat-I (0.69). BAF for soil to grain in Bongaon, Basirhat-I, Deganga and Gaighata, as shown in Table 4, was 0.16, 0.19, 0.20 and 0.28, respectively. It implies that high absorptive capacity of Basirhat-I block soil, limiting As access to the plant. The findings of the present study were in good accord with a previous experiment by Singh *et al.* (2024). It is important to note that the BAF values for soil to grain in all blocks are less than 1.

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

To measure the possible risk of As from contaminated rice consumption on human health, the hazardous quotient was computed for each of the chosen blocks. Results established that value of HQ from intake of rice was 4.40 ± 2.30 in Bongaon, 6.04 ± 2.30 Basirhat-I, 5.34 ± 0.89 in Deganga and 4.31 ± 1.12 in Gaighata (Fig. 4). HQ value higher than 1 possess the possibility of threat to health. The range of HQ values surpassed 1 for the rice grain in the present study. Whereas, the ILCR value was acquired by multiplying ADI and cancer slope factor. ILCR value for As was 0.128×10^{-3} – 7.41×10^{-3}, 2.40×10^{-3} – 9.04×10^{-3}, 2.56×10^{-3}- 5.00×10^{-3} and 1.74×10^{-3} -4.60×10^{-3} respectively in the people who consumed rice collected from Bongaon, Basirhat-

I, Deganga and Gaighata blocks. These results are in accordance with studies by Khanam *et al.*, 2021.

Conclusions

This investigation looked closely at how As is distributed across soil and groundwater in the selected blocks of North 24 Parganas district, West Bengal. That said, a properly geo-referenced As database covering every district in the state would go a long way toward understanding how serious this contamination problem is elsewhere too. Within North 24 Parganas itself, As levels in both irrigation water and soil varied quite a bit from one block to another. Basirhat-I showed the highest contamination of As in both soil and irrigation water. When it came to As reaching the grain, Basirhat-I was the worst affected. Gaighata, on the other hand, consistently showed the lowest As levels across water, soil, and grain respectively but not in the other parts of rice. This indicates a clear path of contamination: farmers irrigating their fields with As contaminated groundwater end up pushing As into the topsoil, and from there it makes its way into the rice being grown, ultimately entering the food chain. This makes rice a major, and often overlooked, pathway through which people in this region are exposed to As. Ensuring a safe water supply should be a top priority for the government to address right away. The kriging maps can help to identify which locations should be prioritized for intervention, agreeing communities to be served through drinking water network wells and ensuring access to safe water. Running a focused well-testing campaign would help reassure residents to switch from high-As wells to low-As ones, reducing their exposure to contaminated water.

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Author Contributions

Nafisa: Writing—review & editing, Investigation, Methodology, Data curation, Writing—original draft; Sidhu Murmu: Conceptualization and supervision, Investigation, Data curation, validation, resources and writing – review and editing; Abir Choudhury: writing – review and editing and visualization, Samayita Basu: Writing—review & editing, Avinaba Maji: Writing—review & editing, Data curation, Formal analysis, Sushanta Saha: writing – review and editing. Kanu Murmu: writing – review and editing.

Declaration of competing interest

The authors have no financial and non-financial interest to disclose.

Data Availability

The corresponding authors can provide the data on request.

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