



Arsenic contamination of rainfed versus irrigated rice[☆]

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ABSTRACT

Arsenic (As) contamination of rice remains a major human health issue in Asia. Most research has been on irrigated rice. However much of the projected increase in global rice demand over coming decades must be met by rainfed lowland systems, for which As relations are poorly understood. We present the most comprehensive survey to date of As in rice in farmers' fields across Bangladesh, covering both irrigated and rainfed systems. We collected rice grain and soil at 943 sites in the three rice growing seasons: irrigated Boro, rainfed Aus, and longer-duration rainfed Aman. Grain As concentrations increased in the order Aman < Boro < Aus with 2, 25 and 41 % of the sites exceeding permitted thresholds, respectively. The greater concentration in Aus than Boro challenges the accepted wisdom that contaminated irrigation water is the main source of As. The main growth and grain filling periods, when most As is taken up, coincide in Aus with the peak of the monsoon rains, suggesting a link between rainfall and high grain As. We suggest this is due to stronger soil reducing conditions and hence As solubility during peak rainfall. We discuss implications for rainfed lowland rice across Asia and mitigation options.

1. Introduction

Rice and drinking water are the largest dietary sources of arsenic (As), which is a non-threshold Group 1 carcinogen (Wang et al., 2025). Arsenic contamination is particularly problematic in rice because its solubility – and consequently its plant availability – increases sharply under reducing conditions in anoxic rice paddies, and soluble inorganic As species are readily taken up by rice roots and transferred to the grain (Zhao and Wang, 2020; Leavitt et al., 2025). It is particularly problematic in rice in Asia firstly because of the extent of contamination of soils and irrigation waters with As from both geogenic and industrial sources (Zhao and Wang, 2020; Hou et al., 2025); and secondly because of the huge quantities of rice consumed: median consumption of white rice in South Asia exceeds 600 g per person per day, which is 30 times that in Europe (Bhavadharini et al., 2020). The main source of As in rice in Asia was thought to be irrigation water pumped from shallow sediments contaminated with geogenic As, with the As gradually accumulating in the soil over time (Meharg and Rahman, 2003; Dittmar et al., 2010). Areas with geogenic contamination particularly include the

major river deltas of South and Southeast Asia receiving water and sediment from the Himalayas (Nickson et al., 1998; Fendorf et al., 2010; Podgorski and Berg, 2020). The sediment contains As-rich iron oxyhydroxides formed upstream from base-metal sulfides, and As is released into soil and groundwater in microbially-mediated reductive dissolution reactions, driven by labile organic matter (Nickson et al., 1998). Recently attention has also focused on atmospheric deposition of As from industrial sources, particularly in southern China (Meharg and Meharg, 2021; Hou et al., 2025).

Past research has largely focused on irrigated rice. As far as we know, there have been no large-scale studies on As in rainfed lowland rice; that is, rice grown in level to gently sloping, banded fields that are flooded for at least part of the growing season. A third of the global harvested rice area is rainfed lowland (GRiSP, 2013; Yuan et al., 2021). Much of the projected 15 % increase in global rice demand over the coming decades, driven by population growth and economic development (GRiSP, 2016; Kruseman et al., 2020), must be met from rainfed lowland systems (Yuan et al., 2021). Rainfed rice grown in soils contaminated with geogenic or anthropogenic sources of As, or both, may be just as at

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risk of contamination as irrigated rice, depending on redox conditions and As solubility at key times during crop growth and grain filling. Further, rainfed rice might be more vulnerable to contamination by wet deposition in rainfall at key growth stages. Other factors that may increase the solubility of As in soils and hence uptake by rainfed as well as irrigated rice include rising temperature with climate change (Muehe et al., 2019), rising temperature in interaction with elevated atmospheric CO₂ (Wang et al., 2025) and increased salinity due to groundwater depletion and saltwater intrusion (Zhi et al., 2022).

Much of the research on As in rice has been carried out in Bangladesh, where there are three lowland rice systems with differing water regimes, facilitating a comparison of As behaviour under rainfed and irrigated conditions. These are the irrigated dry-season 'Boro' crop; the rainfed short-duration 'Aus' crop, planted and harvested during the height of the monsoon season; and the rainfed long-duration 'Aman' crop, planted during the monsoon but then grown on residual soil moisture and harvested well into the dry season when the soil is aerobic (Al Mamun et al., 2021). Contamination of the Boro crop with As is much worse than that of Aman, pointing to irrigation water as the source of As (Williams et al., 2006; Islam et al., 2012). But differences in rainfall, soil hydrology and redox conditions, particularly during the main growth and grain-filling periods when As is accumulated in the crop and grain, will mean large differences between Aman and Aus. As far as we are aware, no studies have compared the three seasons. We here present the largest survey to date of As in rice grain and soil in farmers' fields across Bangladesh in the irrigated and rainfed growing seasons. We analyse the results in terms of the seasonal differences in rainfall and water regime, soil properties, irrigation waters and rice genotypes.

2. Methods

2.1. Farm survey

Rice grain and soil samples were collected from 943 sites across Bangladesh in the three rice growing seasons of 2018 (Fig. S1, Table S1). We implemented a stratified sampling design to account for the heterogeneous distribution of geogenic and anthropogenic factors influencing As contamination across Bangladesh's rice-growing environments. The design incorporated differences in groundwater As concentration, geological formation and potential industrial contamination, as well as farming practices. The study was part of a broader survey of heavy metal contamination (with findings on cadmium and other metals to be published separately), which also influenced site selection. Preliminary sampling in the Boro (137 sites) and Aman (200 sites) seasons in 2017 informed subsequent site selection, with stratification across eight key categories: high As groundwater, high Cd groundwater, brick kilns, textile industry, Pleistocene terraces, flooding, urban expansion and canal irrigation. The preliminary study also revealed elevated grain As in the north-west and north-east regions (contrary to previously published findings which focused on central and southern Bangladesh), and that was also incorporated in the sampling design.

Locations of industrial activities were obtained from remotely sensed imagery, land-use data and a survey of garment factories by NYU Stern School of Business (Labowitz and Baumann-Pauly, 2017). Approximately 8,000 brick-kiln point locations were determined using band ratios from Sentinel-2 imagery to produce a density map of kilns. Areas of high density were identified, and sites of interest selected.

The data collected are summarised in Table S2. Grain samples of approximately 50 g were collected either from plants in individual fields during the harvest stage, or from recently harvested grain retained in individual farmer households. In the latter case, the specific field or fields harvested were identified for the concomitant soil sampling. In-field sampling was done by randomly cutting 3–4 hills of rice from the middle of the field and bulking the threshed grain for each field. Grain

samples were subsequently air-dried, unfilled grains discarded and filled grains de-hulled using a Mi JLGJ-45 hulling machine.

Soil samples were collected at the same time as grain sampling from drained fields. Soil samples were collected between individual hills of rice. Five samples were collected from the field in a 5-point lazy-W shape from 0 to 10–15 cm depth using a Dutch auger. The samples were mixed in different buckets, discarding large plant fragments, and then approximately 100–250 g of soil was collected per bucket. The samples were subsequently air dried and sieved to <2 mm, discarding large plant fragments.

A structured questionnaire was adapted from an existing rice monitoring survey (Yamano, 2017) and used to gather data from the farmer at each site on such variables as sowing and harvest dates, input use, water and fertilizer management, rice varieties, irrigation sources, land topography and potential contamination sources (Table S2). Enumerators were trained in survey methods, and interviews were implemented using the KoBoCollect data collection tool (<https://www.kobotoolbox.org/>).

2.2. Plant and soil analysis

The de-hulled (but unpolished) grain samples were milled to a fine powder in a planetary ball mill (Fritsch P6, Gerhardt UK Ltd, Brackley) and digested in a mixture of nitric acid and hydrogen peroxide in a microwave digester (Anton Paar Multiwave 3000) (Wu et al., 1997; Meharg et al., 2013). The resulting digests were analysed for total As by inductively coupled plasma mass spectrometry (ICP-MS; PerkinElmer NexION 350, Boston, MA, USA). A certified rice flour reference material (CRM NIST-1568b) and reagent blanks were digested and analysed with each batch of samples.

Arsenic in rice grain is primarily in the carcinogenic inorganic form with a proportion in less-toxic organic forms (on average 20–30 % for rice produced in Bangladesh) (Zhao and Wang, 2020). As a non-threshold carcinogen, there is no safe threshold for As concentration. Based on rice consumption in European diets (which is at least an order of magnitude less than in Asian diets – GriSP, 2013), the European Commission's permitted threshold for inorganic As is 0.25 mg kg⁻¹ in brown rice (i.e. dehulled but not polished), 0.15 mg kg⁻¹ in non-parboiled polished white rice, and 0.1 mg kg⁻¹ in rice destined for food for infants and young children (EU, 2023). For the purposes of this study, we take 0.25 mg kg⁻¹ as an approximate reference threshold for total As in the grain.

Soil samples were analysed for per centage clay, silt and sand using the laser diffraction method, organic C by DUMAS dry combustion, pH at 1:2.5 in H₂O, and total As, Cd, Ca, Mg, Fe, Zn, K, P and other metals by extraction in aqua regia and analysis by ICP-OES. Subsets of soil were analysed for crystalline and amorphous Fe oxide content by citrate dithionite and ammonium oxalate extraction, respectively, with analysis by ICP-OES.

2.3. Additional data

The ancillary datasets used are summarised in Table S2. Ground water As levels were mapped using data from the DPHE/BGS survey (Kinniburgh and Smedley, 2001). Inverse distance weighting interpolation with 15 nearest neighbours was used to estimate ground water As at all sample sites. Data on climate, hydrology, soil characteristics, agricultural practices and natural resources in shapefiles (<http://maps.barcapps.gov.bd/>) from BARC (Bangladesh Agricultural Research Council) was used. Data from these shapefiles were extracted for each sample site location. Soil maps were purchased from SRDI (Soil Resource Development Institute) and soil data, such as flooding land type and drainage class, were extracted for each sample location.

Estimates of crop phenology at each site were obtained using the rice crop model ORYZA (Li et al., 2017) with planting and harvest dates collected from the farmer surveys and weather data from the nearest of

the 37 district weather stations in the Bangladesh Meteorological Department network (<http://live.bmd.gov.bd/>). The Oryza model estimates the timing and duration of rice growth stages, as well as final biomass and grain yield, assuming water, nutrients, pests and diseases are non-limiting. Four developmental stages are distinguished: basic vegetative phase, photoperiod-sensitive phase, panicle formation, and grain-filling (Li et al., 2020).

2.4. Data analysis

Statistical analyses were made using the R statistical environment (Version 4.0.3, R Core Team, 2020) and Netica software (Version 6.06, Norsys Software Corp., Vancouver, BC, Canada). We carried out Principal Component Analysis (PCA) using the R factoextra package (Version 1.0.7, Kassambara and Mundt, 2020). Due to the large number of variables and the presence of discontinuous data (e.g., rice varieties, drainage classes), exhaustive application of conventional statistical techniques was impractical. We therefore used Bayesian Belief Networks (BBNs) to model complex variable relationships. Continuous variables

were discretized into four equal-frequency categories prior to analysis. We used the conditional probability tables to construct heat maps visualizing relationships between important variables. See Supplementary data for detailed BBN methodology.

3. Results and discussion

3.1. Seasonal weather patterns

Fig. 1 shows the alignment of the three cropping seasons with the seasonal weather patterns during the sampling year. The irrigated Boro crop is planted in January mid dry season, when monthly solar radiation (not shown) and therefore yield potential are greatest, and it is harvested mid rainy season in June/July. Whereas the short duration Aus crop is planted following the early rains in March and harvested towards the end of the rains in September. The long-duration Aman crop is planted in May/June and harvested in December several weeks after the main rains when the soil is dry.

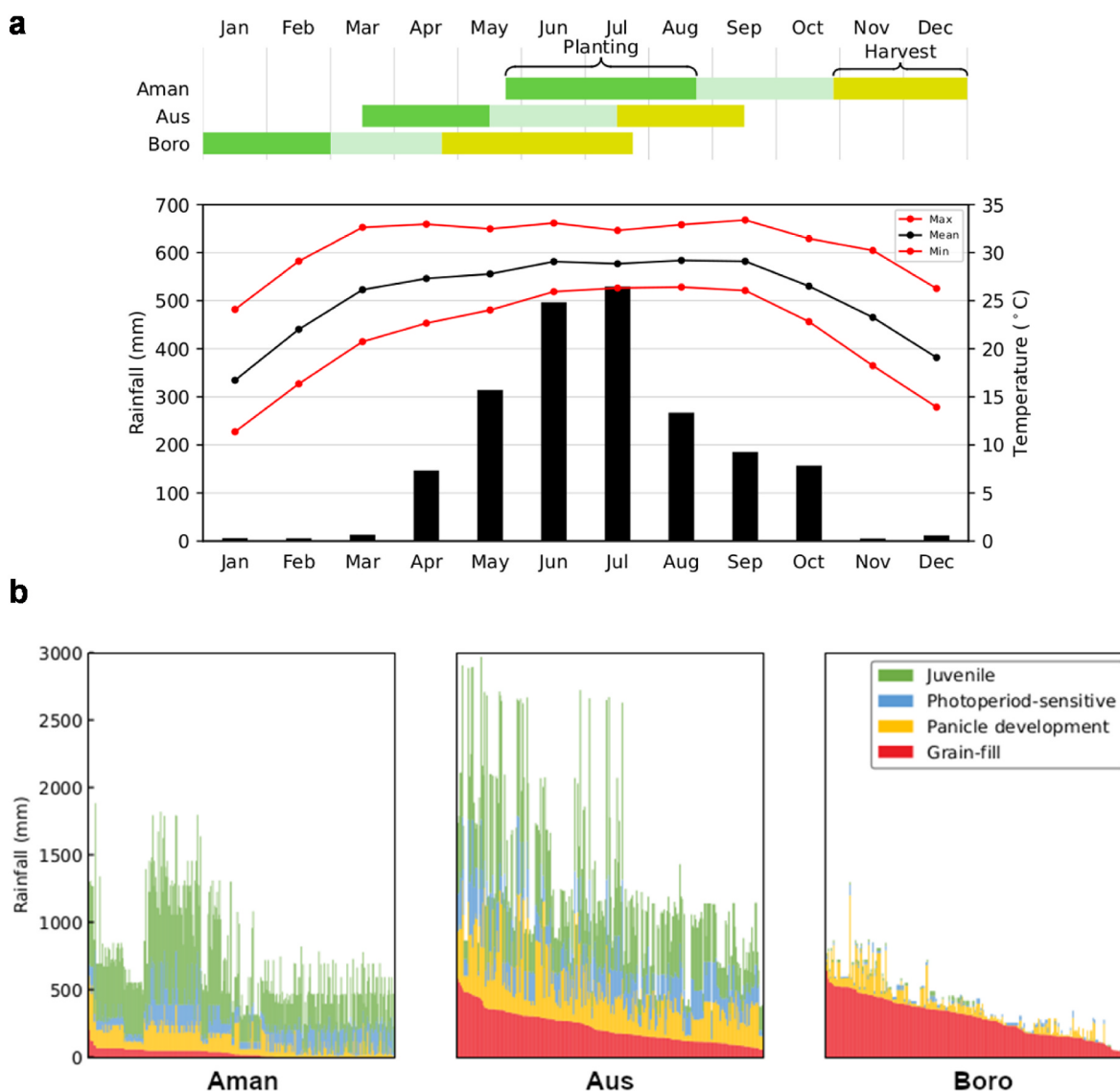


Fig. 1. a Average monthly minimum, mean and maximum temperatures and average monthly rainfall across Bangladesh in 2018, aligned with planting and harvest dates of the three cropping seasons. b Stacked bar charts showing total precipitation at each sample location for each season in 2018, divided into growth stages and reordered by precipitation during grain-filling. Growth stages were calculated from planting and harvest dates and local weather using the ORYZA model (Methods).

3.2. Grain As and rice season

Grain As concentrations increased in the order Aman (mean 0.07 mg kg^{-1} , $n = 350$) $\ll$ Boro (0.18 mg kg^{-1} , $n = 299$) $<$ Aus (0.23 mg kg^{-1} , $n = 290$) with similar distributions of concentrations in Boro and Aus but positively offset for Aus (Fig. 2a). According to the EU permitted threshold of 0.25 mg kg^{-1} (Methods), 2, 41 and 25 % of sites in the Aman, Aus and Boro seasons, respectively, had grain As exceeding the permitted limit. The finding that grain As concentrations were greater in Boro than Aman rice, consistent with use of contaminated irrigation water in Boro, is not new (Duxbury et al., 2003; Williams et al., 2006; Islam et al., 2012). Our more striking result is the greater As concentration in rainfed Aus rice than either Boro or Aman. Aus grain yields are typically below Boro yields (typically 2–3 vs 3.5–4.5 t ha^{-1} – Al Mamun et al., 2021), but growing seasons are 3–4 weeks shorter. So the greater grain As concentration also implies a more rapid uptake of As into the grain.

The alignment of the main rice growth and grain filling periods in Aus rice with the peak of the monsoon rains (Fig. 1) suggests a direct link between rainfall and high grain As. The PCA results (Fig. 3) and BBN results (Table S3) confirm that grain As in Aus rice was linked to variables related to rainfall and land flooding. Heat maps for high and low levels of grain As associated with rainfall amounts at different growth stages (Fig. 4) show that, for Aman rice, there is a low probability of high grain As given high or very-high rainfall, whereas for Aus and Boro, greater rainfall during grain-filling is linked to high levels of grain As, although this is less pronounced for Boro rice. Equivalent heat maps for grain As relationships with soil As (Fig. S2) show no clear relationships for Boro – in fact, curiously, low grain As coincides with high soil As – but in Aus there is some relation between high grain As and higher soil As. We offer the following possible reasons for these observations.

First, the solubility of As in submerged rice soils depends on reductive dissolution reactions that result in (a) dissolution of solid phases on which inorganic As species are sorbed, and (b) transformation of As(V) species into the more soluble As(III) species, which are also taken up by rice roots and transferred to the shoots and grain more readily than As (V) (Yamaguchi et al., 2014; Zhao and Wang, 2020). The degree of reductive dissolution depends on soil redox conditions driven by the level of flooding and inputs of organic substrates from crop residues,

sediments and rhizodeposition (Kirk, 2004). Hence the most strongly reducing conditions and greatest As solubility occur during periods of greatest rainfall and land submergence (Wichelns, 2016), which coincide with the panicle development and grain filling stages for Aus rice – and, to a lesser extent, Boro – when most As is taken up and translocated to the grain (Moulick et al., 2023). Farmers generally drain Boro fields 10–15 days before harvest to facilitate access. Reoxidation of the drained soil would tend to immobilise As and decrease uptake. For the Aman crop, most of the rain falls in the early growth stages (Fig. 1b), and the soil is less wet and presumably therefore less reducing during the grain filling period.

Second, the monsoon rains bring widespread flooding across lowland rice growing areas in Bangladesh with associated redistribution of water and sediment from areas upstream. Approximately 20 % of Bangladesh is annually flooded to at least 0.9 m depth (BARC, 2023). If the upstream water is uncontaminated, monsoon flooding may release As from contaminated soil by vertical mixing into floodwater standing on the soil surface, with subsequent removal in runoff to downstream areas (Dittmar et al., 2007, 2010; Roberts et al., 2010). However, if the upstream water and sediment are contaminated, this would bring As into ricefields. Both these scenarios are plausible depending on local conditions and distances to drainage systems and rivers.

Third, wet deposition of As during the monsoon might contribute to uptake (Savage et al., 2017), with a greater effect on Aus rice as the peak rainfall coincides with grain-filling. However, from Savage et al.'s (2017) estimated annual wet deposition of As in Bangladesh of 2.8 g ha^{-1} , assuming a paddy soil bulk density of 1 kg dm^{-3} and plough depth of 2 dm (Kirk, 2004), this is equivalent to just $1 \mu\text{g kg}^{-1}$ in the soil, which is negligible compared with the total soil As concentrations (Fig. 2b) or with plant-available As on the conservative assumption that this is of the order of a tenth of total As (Mandal et al., 2023). We therefore discount wet deposition as an important source of grain As.

3.3. Soil As

There was a wide range of total soil As concentrations in all three seasons but there were no significant differences between the seasons (Fig. 2b). Hence total soil As concentration could not account for the differences in grain As between the seasons. Consistent with this, reports

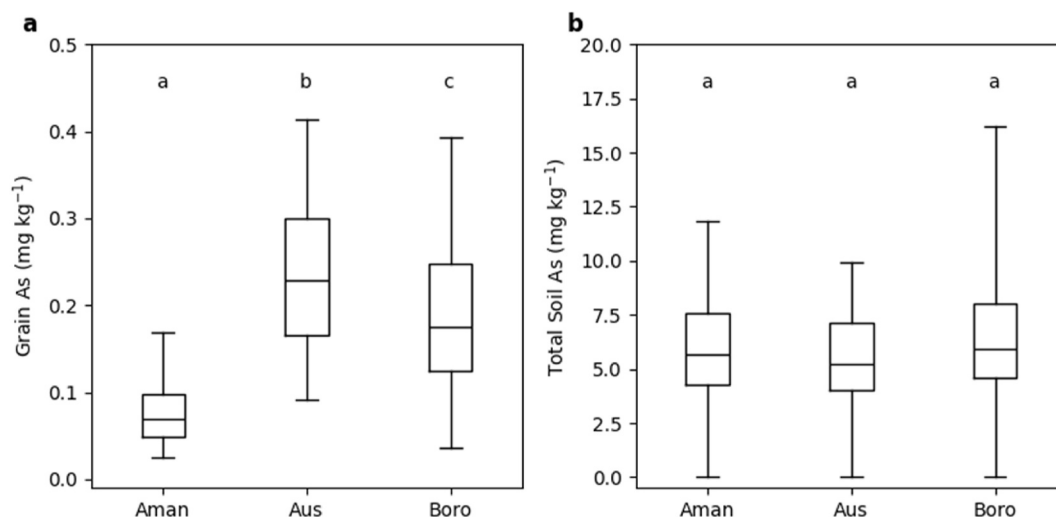


Fig. 2. Box plot showing distributions of (a) grain As concentrations for each growing season and (b) total soil As concentration. Data are means (solid line), lower and upper quartiles (box) and 5 and 95 percentiles (whiskers). Common letters indicate no significant differences between seasons. ANOVA results for variance in grain As between the seasons are $F = 272.3$, $p < 0.001$, indicating that there are strong differences between the seasons compared to within seasons. The results of a Tukey HSD post-hoc test for differences in grain As between specific seasons are Aman vs Aus: mean difference = 0.158 units with $p < 0.01$, indicating a significant difference between Aman and Aus seasons; Aman vs Boro: mean difference = 0.11, $p < 0.01$, also indicating a significant difference; Aus vs Boro: mean difference = -0.04 , $p < 0.01$, again indicating a significant difference. ANOVA results for variance in soil As between the seasons are $F = 0.64$, $p = 0.53$, indicating that there are no differences in total soil As between seasons.

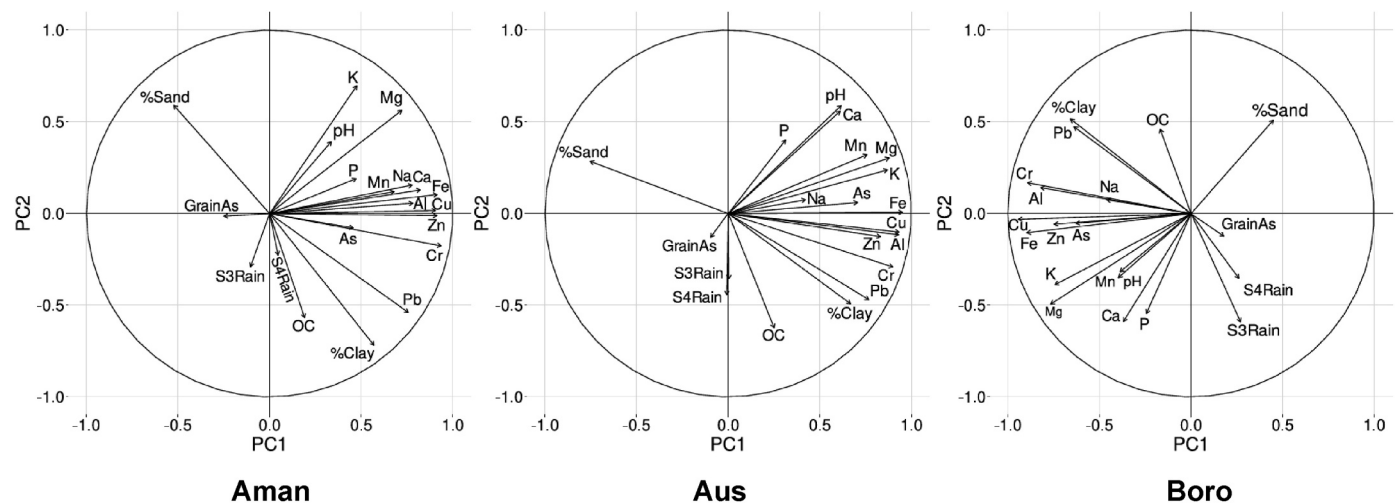


Fig. 3. Principal Component Analysis in each season for grain As concentration and rainfall during different rice growth stages (S3 panicle formation, S4 grain filling) and soil properties (clay content, sand content, organic C content, pH and contents of indicated elements).

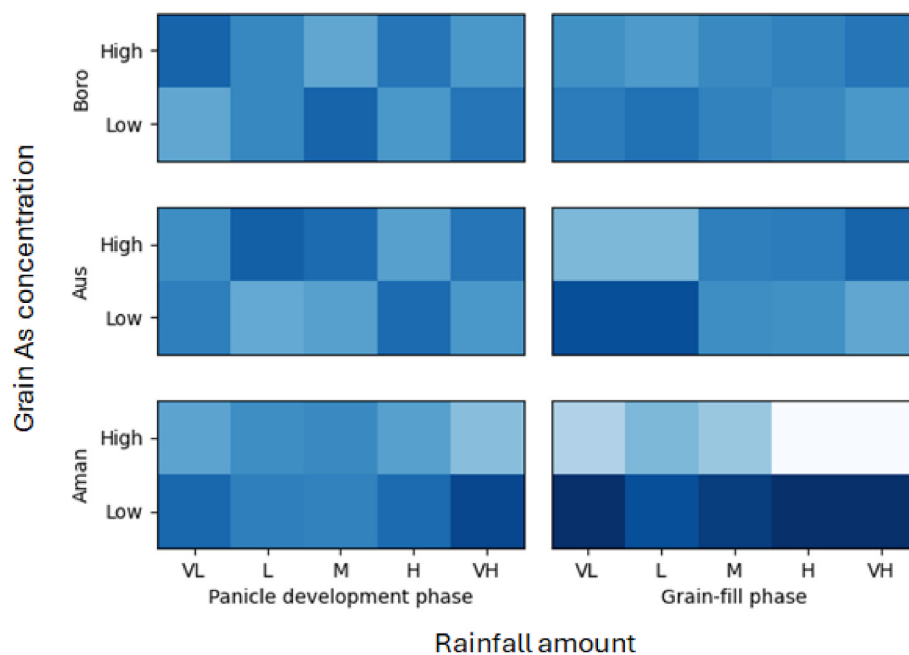


Fig. 4. Heatmaps showing conditional probabilities of high or low grain As linked to rainfall amounts during panicle development and grain-fill growth stages. Each colour square indicates the probability (the darker, the higher the probability) of high/low grain As in five categories of rainfall: VL-Very Low, L-Low, M-Medium, H-High, VH-Very High. For example, in the Aus season, very low rainfall during grain filling is associated with low grain As and very high rain is associated with high As. Upper and lower boxes of similar colour indicate similar conditional probabilities. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the literature show either no relation between grain As and total sol As (Zhao and Wang, 2020) or a hyperbolic relation with steeply increasing grain As at low concentrations ($<5 \text{ mg kg}^{-1}$) tending towards a maximum at higher concentrations (Williams et al., 2007; Lu et al., 2009; Suriyagoda et al., 2018). This indicates processes controlling As uptake and transfer to grain are efficient at low soil concentrations, but are impaired at high concentrations. Mean soil As concentrations in our dataset are well above the apparent thresholds for maximum grain accumulation. This would explain the absence of a strong relationship between grain and soil As.

The plant-availability of soil As depends on its distribution between the soil solid and soil solution, from which it is taken up by roots. The PCA results (Fig. 3) show grain As was associated with high rainfall in reproductive growth stages in Aus and Boro rice, consistent with greater

As solubility under wetter more-reducing conditions. The PCA results also indicate an association between grain As and soil organic carbon (OC) in Aus. This is consistent with more-reducing conditions driven by labile OC and associated greater As solubility. The results show no relation with soil pH in any of the seasons. This is expected because soil pH tends towards neutral following soil submergence, both in acidic soils due to H^+ consumption in redox reactions, and in alkaline soils due to CO_2 accumulation (Kirk, 2004). Soil clay content and mineralogy may also affect As solubility through adsorption on soil surfaces, but neither emerged as important in the PCA or BBN results.

Broadly, lowland rice soils in Bangladesh are divided between uplifted terrace areas of Pleistocene age, which occupy 8 % of the country, and floodplains of Holocene age which occupy 80 % of the country (Brammer, 1996). In our results, total soil As concentrations are

lower in soils from the Pleistocene terrace than the Holocene floodplain (means 4.41 ± 0.17 and 6.92 ± 0.24 mg kg⁻¹, respectively), and the range in concentration is greater in the Holocene soils (Fig. 5). This is consistent with previous work (Lu et al., 2009; Chowdhury et al., 2017). The likely explanation is that the Pleistocene sediments are more strongly weathered and leached of As, and the Holocene soils, which are younger and less weathered, are both less leached of their original As and better able to retain new As from irrigation water and other sources. Presumably, the proportion of soil As that is bioavailable will be greater in the more weathered and therefore less-strongly sorbing Pleistocene soils.

The As concentrations of non-irrigated soil reflect the As contents of the sediments, potentially augmented by redistribution of As from irrigated fields during monsoonal flooding. Many studies show an accumulation of As in the topsoil over one irrigation cycle (Meharg and Rahman, 2003; Panaullah et al., 2009; Dittmar et al., 2010; Javed et al., 2020). However, there is less evidence for year-on-year build-up. From the mean grain As content in Aus rice (0.23 mg kg⁻¹) and typical Aus grain yields (<3 t ha⁻¹, Al Mamun et al., 2021), the annual removal of As in grain would be <1 µg kg⁻¹ soil, so negligible in comparison with the total soil As concentrations. But As solubilised during soil submergence or added in irrigation water moves from the soil into the overlying floodwater by diffusion, convection and bioturbation, and is removed in runoff to rivers downstream when the floodwater recedes (Roberts et al., 2010). As well as such temporal variations in soil As, there are spatial gradients with distance from irrigation sources both within fields (Dittmar et al., 2007) and with distance along irrigation channels (Panaullah et al., 2009). These observations of spatial and temporal variations in soil As all point to a wide range in expected total soil As concentrations both locally and across regions, as apparent in our data.

Although we found no relation between grain As and soil As concentration, high soil concentrations can negatively affect rice yield (Panaullah et al., 2009; Huhmann et al., 2017). Panaullah et al. (2009) found yield declined from 7 to 9 to 2–3 t ha⁻¹ as soil As concentration increased from 10 to 70 mg kg⁻¹ across a field gradient, and Huhmann et al. (2017) estimated a yield loss of 7–26 % of the annual Boro harvest across Bangladesh due to high soil As. This is important for mitigation because yield is likely to affect farmer decisions more directly than rice grain As.

3.4. Water source

Grain As concentrations did not differ much within seasons between the different water sources (Fig. 6). The Aman and Aus fields were predominantly rainfed (77 and 52 % of all water sources over the cropping year, respectively); any irrigation water was predominantly applied to upland crops grown before or after the rice. By contrast, in Boro the main water sources were shallow (58 %) and deep tubewells (16 %) followed by rivers (13 %). Grain As concentrations did not differ between water sources in Boro rice, but there were some small

differences in Aus and Aman. Given that the Aus and Aman crops were predominantly rainfed, and that most supplemental irrigation was applied to upland crops before or after the rice, these differences may reflect other land management practices associated with the upland crops, such as the residual effects of fertilizers applied to cash crops.

In irrigated rice, traditionally the water is managed so that a shallow layer of standing water is maintained on the field for most of the season, a few cm deep. The water tends to be oxygenated by turbulent flow from pumps and along irrigation channels, and by photosynthetic aquatic organisms in the floodwater (Kirk, 2004). But increasingly, fields are managed without standing water to improve water use efficiency and decrease greenhouse gas emissions, and the soil is aerobic for much of the season which can greatly reduce As solubility and uptake by rice (Carrijo et al., 2022; Leavitt et al., 2025). This trend points to less As contamination of irrigated rice in future. By contrast, in rainfed rice the water is far less well managed and fields may suffer from both drought and excessive flooding (30–100 cm depth), often in the same season (Wade et al., 1999). Water standing on the field is less well oxygenated both because of its greater depth and because it may be cloudy with suspended sediment preventing growth of photosynthetic organisms (Colmer et al., 2014). The differences between irrigated and rainfed systems in depth and oxygenation of the floodwater will mean differences in redox profiles through the soil, potentially with more reducing conditions through the profile in rainfed rice during peak rainfall and hence greater As solubility.

While we did not find significant differences in grain As between sites with shallow versus deep tubewell water in Aus or Boro rice, in Aman grain As was higher at shallow tubewell sites. This difference would be consistent with the finding that deep (>approx. 40 m) tubewell water tends to be more contaminated being drawn from the contaminated aquifer (Mohana et al., 2020).

3.5. Rice genotype

There were no significant differences in grain As concentrations between genotypes in any of the seasons (Fig. 7), though some weak relationships did show up in the BBN analysis for Boro and Aman (Table S3). In Aman, the genotype Gota had an atypically large As concentration, but there were only small differences between the other genotypes. The greatest diversity of genotypes was in Aman (11 with ≥ 5 instances plus others), followed by Boro (9 plus others) and Aus (6 plus others). There was only one common genotype between Aman and Boro (Jamababu) and one between Aus and Boro (BRRI dhan 28), with none between Aman and Aus. Each of the three seasons has genotypes adapted to the prevailing conditions, and each has a set of widely grown varieties peculiar to the season (Al Mamun et al., 2021). Such adaptations explain the lack of common genotypes across the seasons. To a degree the lack of common genotypes confounds comparison of grain As across the seasons but is unavoidable.

Genotype differences in As uptake and grain loading have been

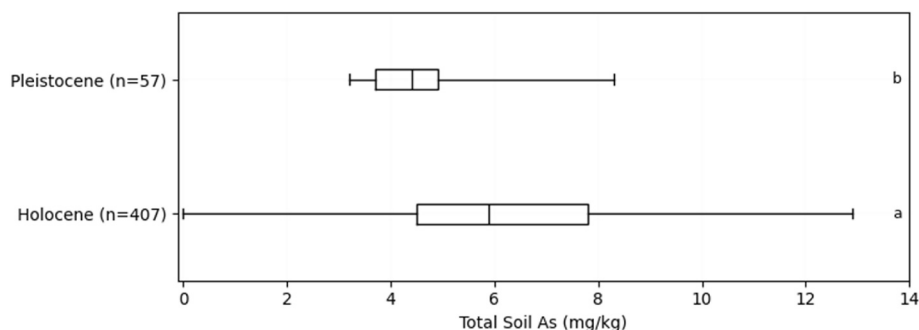


Fig. 5. Total As concentrations in soils from Pleistocene vs Holocene sediments for all seasons. Boxes and whiskers as in Fig. 2. Different letters indicate statistically significant differences. Welch's *t*-test: $t = -5.13$, $p < 0.001$, indicating significantly lower arsenic concentrations in Pleistocene sediments.

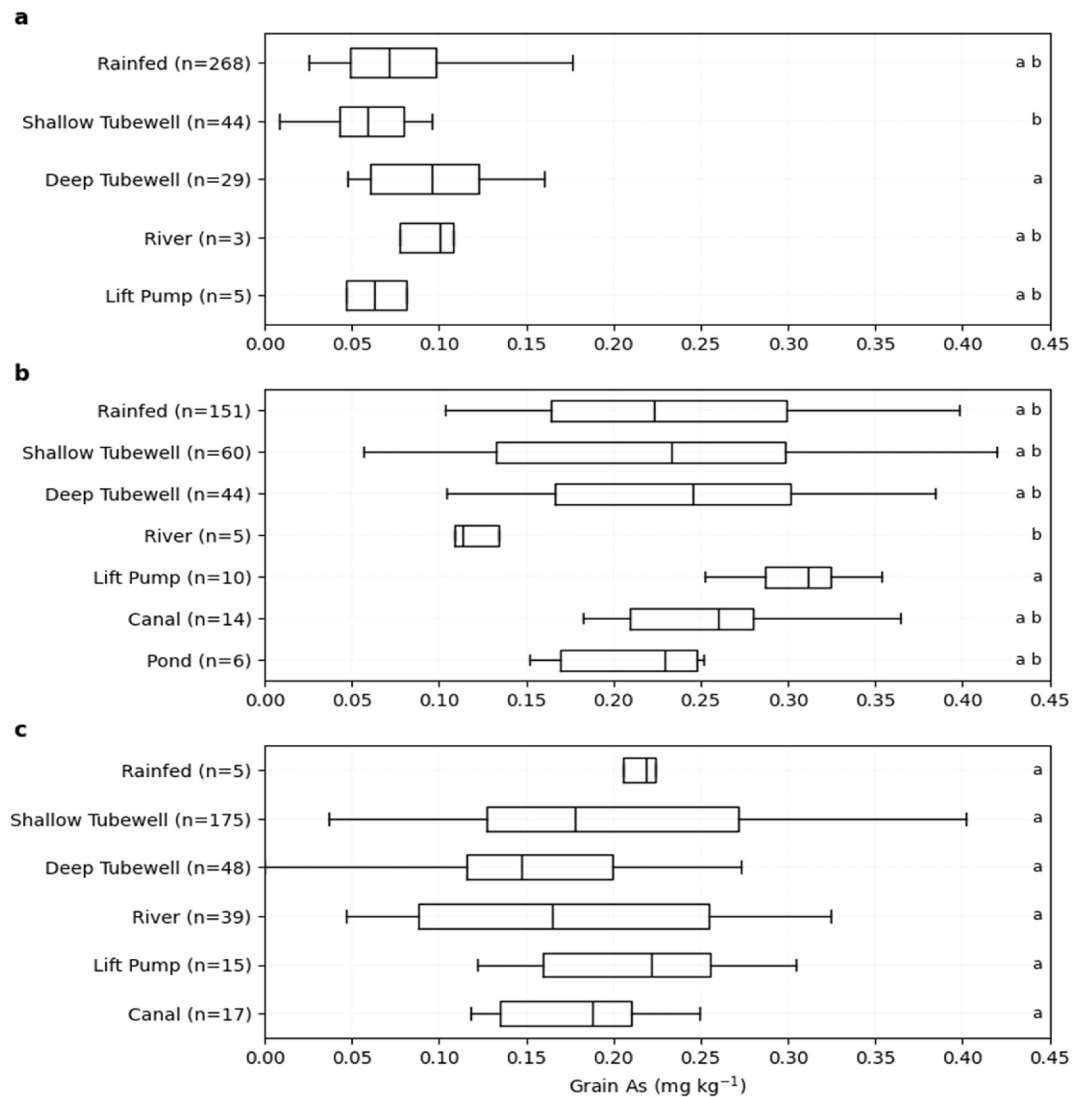


Fig. 6. Rice grain As concentrations in the three growing seasons as affected by the main sources of water in the rice fields: **a** Aman, **b** Aus, **c** Boro. Boxes and whiskers as in Fig. 2. The data are for all inputs of water during the sampling year, including that applied to upland crops grown before or after the rice. Different letters indicate groups are significantly different. ANOVA results for variance in grain As between irrigation methods are: Aman season: $F = 2.516$, $p = 0.0413$, indicating significant differences; Aus season: $F = 2.053$, $p = 0.0589$, suggesting no significant differences at the 5 % significance level; Boro season: $F = 1.735$, $p = 0.1263$, indicating no significant differences.

identified in previous work, linked to differences in retention in roots, root to shoot translocation and transfer to grain (Zhao and Wang, 2020; Leavitt et al., 2025). A further factor may be differences in release of organic substrates from roots and root debris fuelling soil reducing conditions (Dai et al., 2020), such as for traditional *aus* varieties versus modern high yielding *boro* varieties with small harvest indices. In a diverse panel of genotypes grown in multiple locations, Norton et al. (2012) found differences in grain As across four rice sub-populations (*aus*, *indica*, and tropical and temperate *japonicas*) but the relations differed between locations. The *aus* varieties had the greatest increase in grain As under flooded compared with non-flooded conditions.

3.6. Other variables

Inorganic phosphate fertilizers can be contaminated with As (Hartley et al., 2013) and fertilizer use is greater in Boro rice than the other seasons due to greater yield potentials. However, the BBN analysis did not pick up input use as an important variable in any of the rice seasons. The absence of relationships between grain As and proximity to industrial sources of contamination in any of the seasons is surprising. This

may be a reflection of the hyperbolic relation between grain As and soil As with a threshold near the background concentration in unirrigated soils (Section 3.3). Hence additional As inputs from industrial sources would not much alter grain As levels. Some of the variation in soil As concentrations (Fig. 2b) may have been related to industrial sources. The spatial distribution of soil As in part aligns with major rivers in the region, particularly to the south of the Dhaleswari river, which is polluted with industrial effluents (Islam et al., 2021; Majed and Islam, 2022) so that seasonal flooding downstream may release of As into rice fields that are not directly adjacent to industrial sources. However, the main source of variation in soil As appears to be geogenic.

The PCA and BBN results confirmed that grain As in Aus rice was linked to variables related to rainfall and land flooding. In the BBN analysis (Table S3), three variables were selected as informative for predicting grain As in all three seasons: flooding land type (obtained from soil maps – Methods), land topography (indicating inundation type as defined in the farmer questionnaire) and physiography (obtained from soil maps and indicating a spatial aspect to variation). Variables common to Boro and Aus, but not Aman, are total soil As concentration, main irrigation sources, groundwater As content, poor drainage and rain

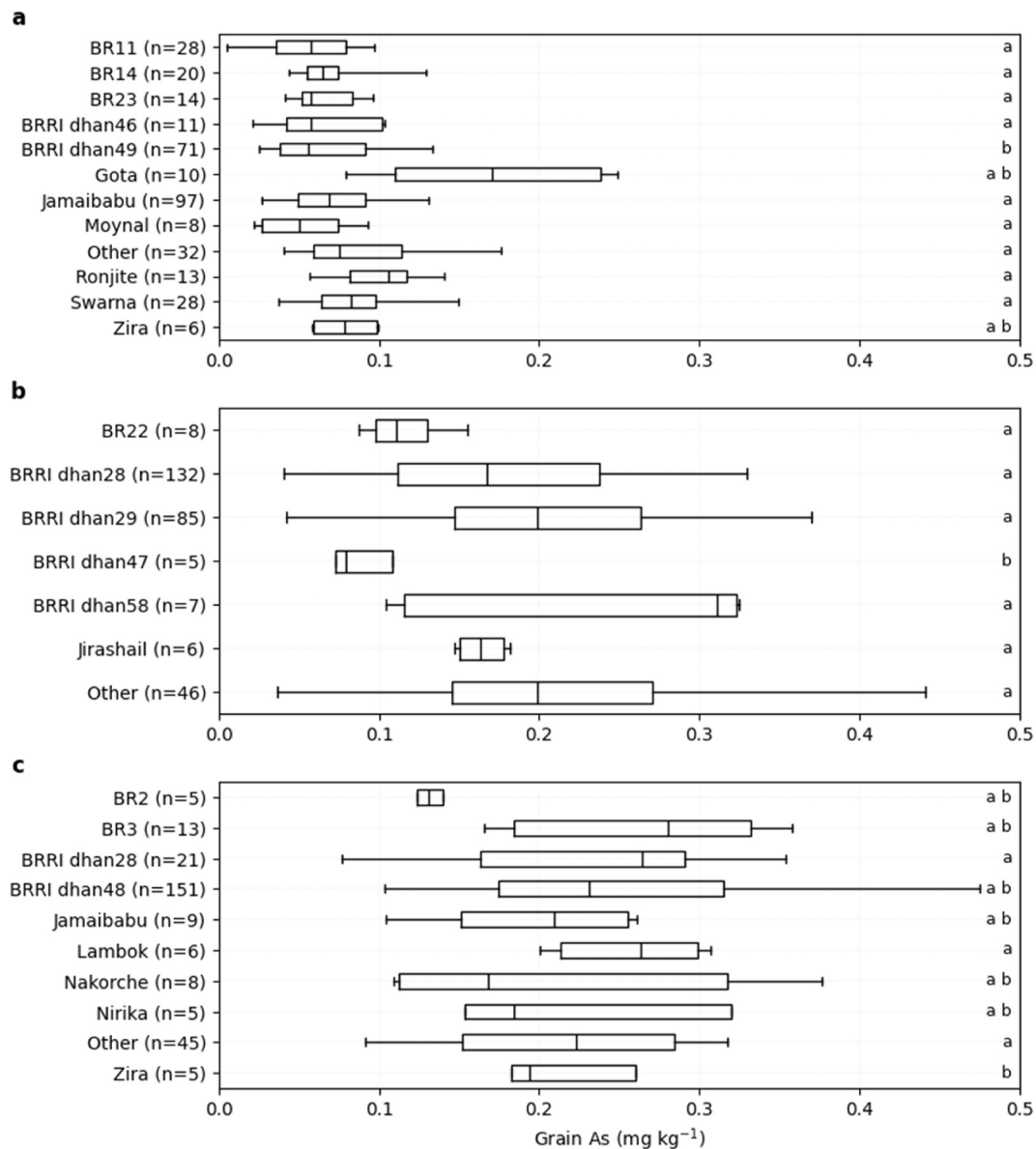


Fig. 7. Rice grain As concentrations in the three growing seasons summarised by genotype: **a** Aman, **b** Aus, **c** Boro. Boxes and whiskers as in Fig. 2. Different letters indicate groups are significantly different. ANOVA results for variance in grain As between genotypes are: Aman season: $F = 6.403$, $p = 1.26 \times 10^{-9}$, indicating highly significant differences; Aus season: $F = 1.582$, $p = 0.1206$, indicating no significant differences; Boro season: $F = 2.901$, $p = 0.0093$, indicating significant differences.

during grain filling. The selection of irrigation sources (which includes irrigation for pre-rice crops such as cash crops grown after Aus rice) and groundwater As for both Boro and the rainfed Aus season, suggests either a direct link between contaminated irrigation water and grain As, or an indirect link due to common drivers.

3.7. Future directions

Our results raise questions about the suitability of Aus rice as an alternative to irrigated Boro in Bangladesh, and by implication, the likelihood of As contamination of rainfed lowland rice in other parts of Asia with elevated soil As levels. Rice production in Bangladesh more than doubled between 1990 and 2020 with the adoption of modern Boro varieties and widespread use of shallow groundwater for irrigation (GRISP, 2013). This led to a shift away from Aus cropping to Boro. In 1970 the percentages of the area and production under Boro, Aus and Aman were (production in parenthesis): 9 (16), 33 (25) and 58 (59), respectively, whereas in 2020 they were 40 (52), 12 (9) and 48 (39) (Al

Mamun et al., 2021). The government is now promoting a shift back to Aus to reduce dependence on groundwater (Uddin and Dhar, 2018) which is increasingly depleted by Boro production and is subject to salinization from sea level rise (Dasgupta et al., 2015; Hassani et al., 2021). Such a shift may inadvertently increase exposure of the Bangladeshi population to As. Mitigation options are needed, tailored to rainfed lowland conditions. Though we did not find genotypic differences in grain As within the rice seasons in this survey, large differences are known from other studies (Zhao and Wang, 2020; Leavitt et al., 2025); in the absence of better water control, exploiting such differences in breeding programmes for rainfed lowlands may be the most promising approach for mitigation.

Other rice areas with As contaminated soils across S and SE Asia include the Indo-Gangetic Plain in northern and eastern India and the plains and deltas of the Irrawaddy River in Myanmar, the Mekong in Cambodia and the Red River in Vietnam (Fendorf et al., 2010; Podgorski and Berg, 2020). Rainfed lowland rice accounts for 40, 75, 75 and <10 % of the harvested rice area in these four countries, respectively (GRISP,

2013). Production from rainfed lowland systems must provide much of the projected increase in global rice demand over the coming decades (Yuan et al., 2021). Gaps between potential and actual yields of rainfed lowland rice are larger than in irrigated rice and there are opportunities to increase yields by fine tuning crop, soil and water management (Yuan et al., 2021, 2022). Irrigated rice is under increasing scrutiny for its water use efficiency and contribution to greenhouse gas emissions (Zhang et al., 2024; Abdo et al., 2025). The irrigated rice area is decreasing in some countries due to competition for water with industrial and residential uses (Yuan et al., 2022) and this trend is likely to continue with projected drier dry seasons though wetter wet seasons (Giorgi et al., 2019). These trends together suggest As contamination of irrigated rice may decrease in future with better water management but the problem in rainfed rice will remain unless it is given specific attention.

4. Conclusions

1. The greater grain As concentration in rainfed lowland Aus rice than irrigated Boro rice challenges the accepted wisdom that contaminated irrigation water is the main source of As contamination in rice.
2. High grain As in Aus rice was associated with high rainfall during the main growth and grain filling periods, when most As is taken up. We suggest this is due to stronger soil reducing conditions and hence greater As solubility during peak rainfall.
3. Based on available information on As concentrations in rainfall, wet deposition was not an important source of As.
4. Interactions between variables affecting As uptake into grain mean it is difficult to detect relationships with individual variables in even such a large dataset as ours. Given this complexity, it is important to take a holistic approach to assessing effects of changes in rice systems and management.
5. Given the importance of rainfed lowland rice for global rice supplies, now and in future, further research is needed (a) on the extent of contamination of rainfed rice in the areas at risk across Asia; (b) to better understand the mechanisms controlling As uptake into grain in different rice systems; and (c) to develop mitigation strategies for rainfed systems.

CRedit authorship contribution statement

Ben Ingram: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Muhammad Ashraful Habib:** Writing – review & editing, Investigation, Data curation. **Sarah E. Johnson-Beebout:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Cecilia Acuin:** Writing – review & editing, Project administration. **Ron Costanje:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Robert W. Simmons:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Guy J.D. Kirk:** Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. ASupplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2025.126856>.

Data availability

The data is available at <https://doi.org/10.57996/cran.ceres-2774>.

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