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Research article

Total arsenic and inorganic arsenic in Myanmar rice

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ABSTRACT

Myanmar is a major rice exporter. Rice is an important source of nourishment for its population. However, rice can be contaminated with toxic elements, including arsenic, long-term exposure to which has been linked to several illnesses, including cancer. There is a paucity of published data on arsenic in Myanmar rice. This study analysed rice (n = 50) from southern, middle and northern Myanmar for both total arsenic (T-As) (by ICP-MS) and inorganic arsenic (i-As) (by species–specific hydride generation ICP-MS or HPLC-ICP-MS). The mean concentration of T-As was 110 μg kg^{-1}(IQR 75–142 μg kg^{-1}), of which 86 μg kg^{-1} (IQR 58–113 μg kg^{-1}) was high toxicity i-As. The calculated mean i-As intake arising from typical consumption of this rice normalised to typical body weights in Myanmar was approximately 1 μg.kg-bw^{-1}.day^{-1}, close to the recently withdrawn WHO, PTWI of 2.1 μg.kg-bw^{-1}.$day^{-1}$and higher than the EFSA reported $BMDL_{05}$ for skin cancers of 0.06 μg.kg-bw^{-1}.day^{-1}.

1. Introduction

Arsenic contamination is a major environmental health hazard, potentially adversely affecting the lives of millions of people [1]. Such contamination is also a threat to rice production and quality in many Asian countries [2]. Rice may contain substantially more arsenic than other food crops [3]. This is because rice is the only major cereal crop grown under flood conditions and because arsenite As(III) follows silicic acid (H_4SiO_4) into root cells through aquaporins [3]. Arsenic is a class I carcinogen according to the International Agency for Research on Cancer [4] and is also a risk factor in cardiovascular and other common diseases [5–8]. Arsenate and arsenite are two inorganic arsenic (i-As) forms that are particularly toxic to humans.

According to World Health Organization (WHO) research, rice is one of the primary sources of inorganic arsenic exposure in humans [9,10]. Dimethylarsinic acid (DMA) and monomethylarsonic acid (MMA), the two most common forms of organic arsenic species found in terrestrial ecosystems, can potentially also be toxic albeit much less so than inorganic arsenicals. Further, MMA is typically only present in trace amounts in rice grains [9].

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Myanmar is primarily an agricultural country, with rice accounting for an estimated 13 % of the country's gross domestic product [11,12]. It is one of the world's top rice exporters and a producer of a diverse range of rice varieties, with the potential to capture the higher-value segments of the global fragrant rice market [13]. Paw San, popularly known as "Pearl rice," is a high-quality aromatic rice from Myanmar that was named the world's greatest rice in 2011 [13]. Rice is a major staple food in Myanmar, accounting for 25 % of the food consumed by wealthier households and 50 % of the food consumed by poorer households [12].

Because rice and other rice-derived foods are important components of Myanmar's daily diet, it is also essential to investigate potential sources of arsenic contamination in rice due to the associated health concerns [14,15]. A recent study by Ref. [16] estimated that the mean total concentration of As in 120 samples of Yangon rice (Ayeyawady) was 155 ± 52 μg kg^{-1}, which is slightly below the recommended limit for inorganic arsenic (200 μg kg^{-1}) set by the Food and Agriculture Organization of the United Nations and World Health Organization [17]. The estimated [16] mean daily intake of total arsenic of 1.34 ± 0.45 (μg.kg-bw^{-1}.day^{-1}) is somewhat below the provisional weekly tolerable intake of inorganic arsenic (equivalent to 2.1 μg.kg-bw^{-1}.day^{-1}) of the FAO [10] although this limit was recently withdrawn, we infer because it was insufficiently protective against the risks of cancers, such as of the bladder and lung and skin, and other detrimental health outcomes (*e.g.* cardiovascular disease) in humans [5–8,18]. Exposure to arsenic from rice consumption would be over and above that arising from exposure via drinking water [19,20] including from groundwater sources in Myanmar [21–23]. Therefore, exposure to arsenic, and, in particular, inorganic arsenic from rice consumption should be considered as a potential health concern.

Fig. 1. Myanmar rice sample locations. "L-x" refers to the location number and "n" to the total number of samples from each location. Please note that the locations are approximate. Base map from ArcGIS Pro 3.1.1 base map layers; country layers from DIVA-GIS.

Myanmar is one of the top rice consuming countries in the world, data on inorganic arsenic (i-As) in Myanmar rice is relatively sparse [14,24] and has been largely focussed on just one region, so this paucity of data is addressed in this study. The aim of this analytical study therefore was to: (i) determine the concentration of inorganic arsenic (i-As) as well as total (inorganic and organic) arsenic (T-As) in rice from a range of varieties and locations across Myanmar; (ii) estimate the mean daily arsenic intake for different population groups of Myanmar; and (iii) discuss implications for potential health risks arising from that intake.

2. Materials and methods

2.1. Data & data quality objectives (DQOs)

Analytical requirements for both total As and inorganic arsenic in rice samples arising from the study aims included accuracy and precision of better than ± 30 % at 3 × limit of detection (LOD) with a LOD of better than 1 μg kg^{-1}.

2.2. Sample collection

Rice samples (n = 50) were collected from fields and markets from a selected range of regions in southern, middle and northern Myanmar. The first set (samples 1–34) was collected from several locations (Lx), Yangon (L1, L3 and L5), Thanlyin (L2), Hlegu (L4), Eastern Yangon (L6), Sagaing (L7), Rakhine state (L8), South Yangon (L9), and Ayeyarwaddy (L10) in 2018 and the second set (samples 35–50) was collected from Kachin (L11 and L12), Sagaing (L13), Rakhine State (L14 and L15), Chin State (L16 and L17), and Ayeyarwady (L10) in 2016 as presented in Fig. 1 and Table S1.

2.3. Sample preparation and analysis

2.3.1. Chemicals and standards

Analytical reagent (AR) or higher-grade chemicals and standards were used. Nitric acid (69%–70 % wt.wt^{-1} HNO_3) (VWR, Avantor) was used for sample and standard preparation. Arsenic (As), arsenite (As(III)), arsenate (As(V)) (Sigma-Aldrich, 1000 μg mL^{-1}), dimethylarsinic acid (DMA) disodium salt tri hydrate (Merck Life Science), and monosodium acid methane arsonate sesquihydrate (MSMA) (CHEM Service) standards for Inductively Coupled Plasma (ICP) were used for calibration standard preparation. All acids were purified in the laboratory using sub-boiling acid distillation (DST-1000 acid purification system, Savillex). The purity of the acids and water was regularly checked and confirmed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and was found to be ≪1 μg.$L^{-1}$for arsenic. All solutions were prepared using deionised water (18.2 MΩ) type 1 ultrapure laboratory water (Avidity Science).

2.3.2. Standard solutions

Calibration standard solutions were prepared following the FDA-recommended serial dilution method (Element Analysis Manual (EAM) 4.11 and 4.7) [25,26]. Calibration standards, with arsenic concentrations between 0 and 5 μg.L^{-1}were used; with calibration standards re-run as unknowns every 20 samples. An internal standard of rhodium (Rh) (10 μg L^{-1}, Alfa Aesar) was used to improve analytical accuracy by enabling drift in analytical sensitivity during analytical runs to be corrected for. Any contamination arising from sample processing in the laboratory was estimated and corrected for using procedural blanks.

2.3.3. Standard reference materials (SRMs)

National Institute of Standards and Technology (NIST) rice flour Standard Reference Material (SRM) 1568b was used for quality control for both total As (certified value 285 ± 14 μg kg^{-1}) and inorganic arsenic (i-As) (certified value 92 ± 10 μg kg^{-1}) [27].

2.3.4. Pre-treatment of rice samples

After collection and transport to The University of Manchester, the rice grains were ground to a powder using a mortar and pestle, packed in plastic bags and stored at room temperature until digested. The grinding ensured more complete dissolution of all parts of the rice grains.

2.3.5. Sample preparation for total arsenic (T-As) analysis

The method specified in the FDA Element Analysis Manual (EAM): Section 4.7 [26] for total arsenic was used to prepare the rice samples. Ground (using a mortar and pestle) rice samples (including of the SRM) (0.5 g) were digested in 8.0 mL (for first set n = 1–34) or 5.0 mL (for second set n = 35–50) of double distilled concentrated nitric acid (69–70 % wt.wt^{-1}) and 1 mL of high purity 30 % wt. wt^{-1} hydrogen peroxide (H_2O_2) (Merck Life Science) using MARSXpress vessels digestion in a CEM Mars microwave system (see Table S2). All samples were diluted to approximately 50 mL with deionised water. For the first set of samples only, this was followed by 5 mL of 10 % vol.vol^{-1} hydrochloric acid (HCl) solution (Fisher Scientific), with deionised water added until a final volume of 100 mL was achieved. After that all samples were filtered using 0.45 μm polypropylene filters (Fisher Scientific),10 mL syringes (IVS10, HMC premedical S.P.A) and 5 mL of this filtered solution was diluted with 6 mL of deionised water to give a final HNO_3 concentration of approximately 2 % [26].

2.3.6. Sample preparation for arsenic speciation analysis (i-As)

For arsenic speciation analysis, ground rice samples (0.5 g) were extracted in 5 mL of 0.28 M HNO_3 and digested in the CEM Mars microwave system at 95 °C for 90 min then diluted with 3 mL of deionised water (see Table S2). Each sample was centrifuged at 3000 rpm for 10 min and filtered with 0.2 μm polypropylene filter then pH adjusted using 1 mL ammonium hydroxide 20 % vol.vol^{-1} solution (Sigma-Aldrich) (first set) or 2 M sodium hydroxide (NaOH) (Merck Life Science) (second set) to a pH of 9.95 ± 0.05 prior to analysis [25]. Hydrogen peroxide (H_2O_2) 30 % wt.wt^{-1} (0.1 mL) was added to oxidise arsenite (As(III)) to arsenate (As(V)) in order to minimise incomplete chromatographic separation of As(III) and DMA, noting that the oxidation state of i-As in rice was not an analytical objective of this study, because current regulations and guidance and health risk assessments [9,10,18] are agnostic as to the inorganic arsenic oxidation state.

2.3.7. Analytical instrumentation

Total arsenic was measured using inductively coupled plasma mass spectrometry (ICP-MS) (Agilent 7700) at the Manchester Analytical Geochemistry Unit (MAGU) at The University of Manchester under operating conditions summarized in Table S3. For inorganic arsenic, the first set of samples were analysed externally using species–specific hydride generation ICP-MS following low––temperature sample extraction for the separation of inorganic and organic arsenic species, with subsequent detection by ICP-MS, whilst the second set of samples were analysed at the Manchester Analytical Geochemistry Unit (MAGU) using High Performance Liquid Chromatography (Agilent 1260) coupled with an Inductive Coupled Plasma Mass Spectrometer (HPLC-ICP-MS) (Agilent 7700).

2.4. Inorganic arsenic exposure assessment and published input parameters

Estimated human daily intake of inorganic arsenic (i-As) was calculated using the following formula (1) [28].

$$\mathbf{EDI_i} = C_i \times \left(\frac{IR_r}{bw}\right) \tag{1}$$

where.

EDI_i = the estimated daily intake of i-As,

C_i = the i-As concentration in raw rice (dry weight),

IR_r = the daily intake rate of rice (on a raw rice, dry weight basis),

bw = an average typical body weight of the corresponding population group.

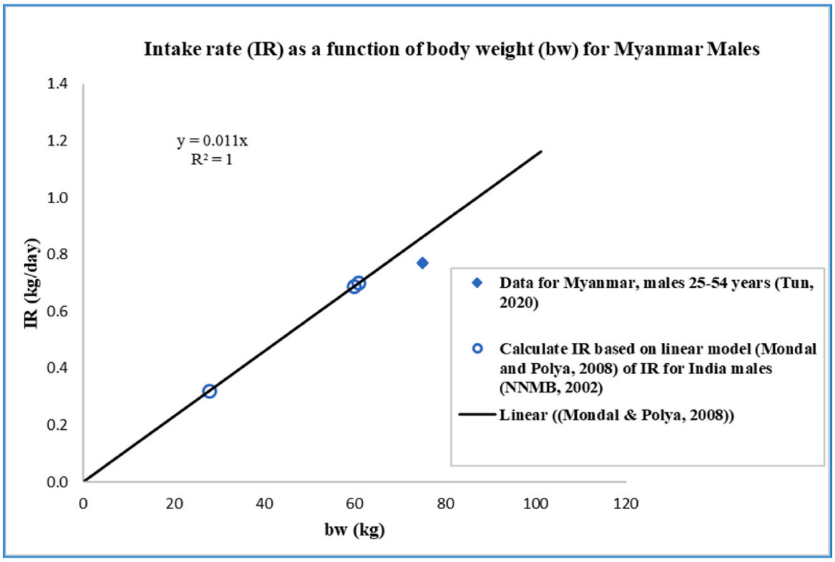
In doing so, we ignored the contribution of cooking water, on average, at a population scale, to change the inorganic arsenic content (on a dry weight basis) of rice – in the absence of individual cooking water arsenic concentrations and considering prior information on water arsenic concentrations in Myanmar [19,21,29] this seems to be a reasonable first order approximation in agreement with [30] who observed that cooking water contributed comparatively little to inorganic arsenic exposure compared to raw rice.

The published input parameters for body weight and rice intake used in the exposure model are summarized in Table 1. The age and gender dependent body weight of typical Myanmar children and adult that was used in the model was based on the [24,31] studies and [32] world data information. In addition, the proportion of population aged in various age classes was taken from the United Nations population fund World Population Dashboard in Myanmar [33]. The intake rates were taken from secondary sources where it was available but where it was not available it was calculated. For these categories a study by Ref. [24] on rice intake by the adult population of Myanmar specifically in Yangon reported a mean intake of 0.77 and 0.65 kg.day^{-1} for age 25–54 years males and females respectively. Similar results were also reported by Ref. [34] for the estimated mean daily intake of rice consumption in Myanmar (Burma), viz. 227 kg year^{-1} (0.62 kg.day^{-1}) for a 60 kg person, although a much higher high rice consumption rate (440 kg year^{-1}) has been reported recently by Ref. [35]. Using measured inorganic arsenic concentrations, inorganic arsenic intakes were then estimated for age 25–54 in Myanmar based on the ratio of their rice intake rate (IR) and body weight (bw) [24]. In the absence of detailed data of rice intake for age between 5 and 25 and also older than 60 years in Myanmar the rice intake rate values for those age groups were calculated based on the relationship between intake rate and body weight determined for nearby India [36] combined with available body weight data for the Myanmar population [31,32,37] (Table 1). The accuracy of and appropriateness of using that relationship is illustrated in Fig. 2, where it can been seen that the intake rate calculated by this method for age groups for which data is already

Table 1

Secondary data for input parameters used in the risk model (IR_r = rice intake (kg.day^{-1}), bw = body weight (kg)).

Input	Symbol	Parameter	Data reference
Rice intake rate (kg.day^{-1})	IR_r	Males - 0.77; Females - 0.65 (For Male bw 75 kg and Female 65 kg (25–54 years))	[24]
Age and Body weight (kg)	bw	5–12 years: Males 27.9; Females 27.9 18–25 years: Males 61 and Females 55 25–54 years: Males 75 and Females 65 >60 years: Males 60 and Females 54	[24,31,32,37]
Proportion of population aged:		0–14 years: 25 % 15–64 years: 69 % >65 years: 7 %	[33]



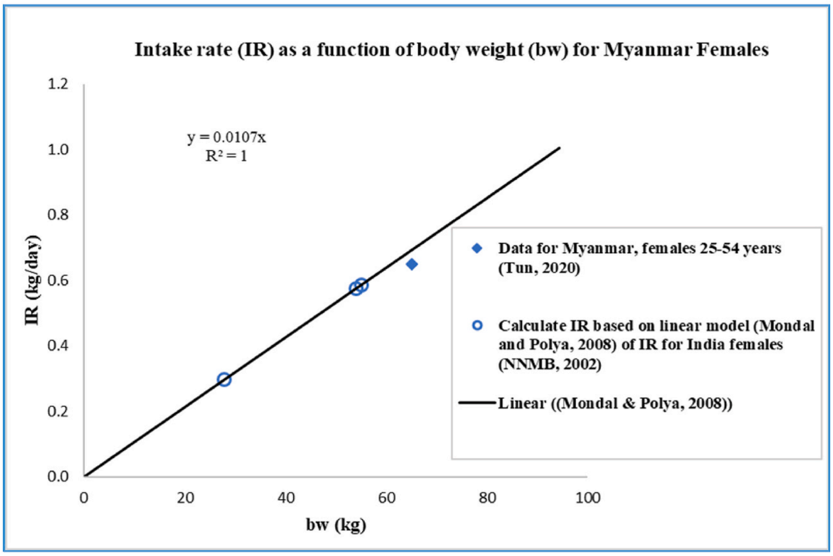


Fig. 2. Rice intake rates (IR) vs typical body weight (bw) for males and females in Myanmar. IR and bw data for males and females of Myanmar age 25–54 year (blue diamond) obtained from Ref. [24]. IR of other ages (blue circles) were calculated based on [36] (IR-bw relationship based on [38] diet survey for nearby India) and bw of Myanmar males and females [31,32,37].

available (*e.g.* ages 25 to 54) [24] are very close within 10 % of the reported value derived from using the intake-bodyweight relationship from Ref. [36].

3. Results and discussion

3.1. Analytical quality control data

Samples were analysed in two batches in both of which the precision of the analyses for T-As and i-As was assessed by replicate analyses. The mean precision for the first batch was 13 % for T-As and 20 % for i-As and up to 27 % for T-As and 6 % for i-As for the second batch of analyses. The accuracy was evaluated using (SRM) 1568b analysis and which indicated a recovery of 94 % of T-As and 109 % of i-As (1st batch) and 117 % of T-As and 131 % of i-As (2nd batch) all which were within or close to within the ±30 % control limit recommended by Ref. [39]. The possibility that the addition of hydrogen peroxide may have resulted in oxidation not only of As (III) but also of DMA, thereby changing i-As/T-As ratios in hydride generation – ICP-MS analyses as observed by Ref. [40] was considered – however we did not find a significant difference between the i-As/T-As ratios for the SRM between the two different techniques utilised in this study – perhaps in part because the hydrogen peroxide concentrations used in this study were much lower than the 1 %–3 % range in which such changes have previously been reported [40].

3.2. Total and inorganic arsenic concentration in rice

Measured T-As and i-As concentrations in Myanmar rice are summarized (Table 2). Myanmar rice T-As was found to range from 21 to 200 μg kg^{-1} with a mean of 110 μg kg^{-1} and an inter-quartile range from 75 to 142 μg kg^{-1}. This mean of T-As was slightly less than that of the two previous studies by Refs. [14,16] for Myanmar rice but are significantly lower than that those reported by Ref. [41] (580 ± 3 μg kg^{-1} (n = 12)) [42], (358 ± 35 μg kg^{-1} (n = 46)) [43], (340 ± 150 μg kg^{-1} (n = 18)) [44], (400 ± 100 μg kg^{-1} (n = 3)) [45], (210 ± 37 μg kg^{-1} (n = 6)), and [46] (510 ± 70 μg kg^{-1} (n = 2)) for different areas from nearby Bangladesh. However, it was not significantly different from arsenic in rice reported from other surrounding Asian countries including India (136 ± 80 μg kg^{-1} (n = 10)), China (117 ± 34 μg kg^{-1} (n = 36)), Thailand (110 ± 10 μg kg^{-1} (n = 3)), and Sri Lanka (140 ± 120 μg kg^{-1} (n = 11)) [2,14,41,46–49].

Most of the arsenic in the Myanmar rice samples was typically inorganic. The inorganic arsenic content of Myanmar rice was found to vary from 2 to 190 μg.$kg^{-1}$with a mean of 86 μg.$kg^{-1}$and an inter-quartile range from 58 to 113 μg kg^{-1}. This mean of i-As was not significantly different from in organic arsenic in rice reported from other surrounding Asian countries including Thailand [47] (80 ± 10 μg kg^{-1} (n = 2)), China [46] (70 ± 10 μg kg^{-1} (n = 3)) and Bangladesh (150 ± 40 μg kg^{-1} (n = 3)). However, it was significantly different from i-As in rice data reported by Ref. [47] from India (26 ± 10 μg kg^{-1} (n = 8)), Bangladesh [46] (170 ± 20 μg kg^{-1} (n = 3)) [50] (125 μg kg^{-1} (n = 65)), Cambodia [50] (129 μg kg^{-1} (n = 142)) and China [51] (112 ± 8 μg kg^{-1} (n = 17)).

The mean proportion of arsenic occurring as inorganic arsenic was 77 % with an inter-quartile range from 69 to 94 % (Fig. 3). The observed ranges exhibit no significant differences between the proportion of arsenic present as inorganic arsenic reported by Ref. [47], and both ranges are consistent with the prevalent high inorganic arsenic/total arsenic ratios observed in numerous different varieties of rice growing in Asian regions [47]. Furthermore, the mean of i-As in this study was not significantly different from studies of inorganic arsenic in rice reported for surrounding nations [2,42,46,47].

It clear that i-As concentration for some Myanmar rice samples was close to the limit of inorganic arsenic (200 μg kg^{-1}) set by the World Health Organization (FAO/WHO) [17] which raises concerns about its health effect on consumers.

Kachin state rice samples are an outlier compared to the other Myanmar rice samples with respect to the inorganic arsenic content, having an order of magnitude lower inorganic arsenic content, but they nevertheless have concentrations comparable to the other Myanmar rice samples for organic species. These samples come from the northern mountainous region of Myanmar (Fig. 1) and have been likely grown under relatively oxidizing conditions [52,53].

3.3. An exposure assessment of inorganic arsenic

The mean estimated inorganic arsenic intakes arising from consumption of Myanmar rice are shown (Table 3). These estimated exposures are of concern for human health in Myanmar. This is firstly because Myanmar is one of the largest rice consuming countries [12] and the mean i-As content found in this study of 1 μg.kg-bw^{-1}.day^{-1} is only somewhat lower than the recently withdrawn World Health Organization (WHO) provisional tolerable weekly intake (PTWI) for inorganic arsenic and which is equivalent to 2.1 μg.kg-bw^{-1}.day^{-1} [54]). This PTWI is under review as it is presumably considered to be insufficiently protective against the risks of cancers in humans [9]. Furthermore, these arsenic exposure estimates were higher than the benchmark dose lower confidence limit ($BMDL_{05}$) values of 0.06 μg.kg-bw^{-1}.day^{-1} for skin cancers reported by the European Food Safety Authority CONTAM panel on contaminants in the food chain [55].

Secondly, rice is not the only route of exposure to arsenic and several studies conducted in Myanmar have confirmed high levels of arsenic in groundwater [21–23]. Thirdly, studies conducted by Refs. [19,20] on drinking water found that 21 % of the tested samples exceeded the World Health Organization's recommended limit of 10 μg L^{-1} [56]. Furthermore, if rice is cooked using water that contains elevated levels of arsenic, studies have shown that the concentration of cooked rice might become further elevated [36,57–59]. Conversely parboiling in low arsenic water might result in a somewhat lowering of arsenic contents of consumed cooked rice [60].

3.4. An exposure assessment of organic arsenic

Inorganic arsenicals are generally considered to be more toxic than organic arsenicals, EFSA CONTAM [61] have recently calculated a reference point, $BMDL_{10}$ for urinary bladder tumours of 600 μg.kg-bw^{-1}.day^{-1} for DMA(V) - this value is much higher than plausible estimates of DMA(V) exposure from the consumption of Myanmar rice – confirming that exposure to i-As is a greater public health concern than exposure to DMA(V) in rice.

4. Conclusions

The concentrations of total arsenic and inorganic arsenic in local Myanmar rice collected from a wide range of locations across the country have been analysed by ICP-MS, HPLC-ICP-MS and hydride generation ICP-MS. Inorganic arsenic concentrations ranging from 2 to 190 μg.kg^{-1}were found with the maximum concentration being close to the limit for inorganic arsenic (200 μg kg^{-1}) recommended by the World Health Organization in polished white rice. The potential exposure to inorganic arsenic from rice consumption have been evaluated, albeit that it is recognised that future studies might improve these estimates through analysis of cooked rice and

Table 2
The concentrations ± Standard deviation (n = 3) ($\mu g.kg^{-1}$) of total arsenic (T-As) and inorganic arsenic (i-As) in Myanmar rice grains determined by ICP-MS, species–specific hydride generation ICP-MS and HPLC-ICP-MS and the proportion of T-As occurring as i-As (%). (Short <5 mm, Medium 5–6.5 mm and Long >6.5 mm).

No	Name of rice	Rice characteristic	Region	Inorganic As (i-As) ($\mu g.kg^{-1}$) ± Standard deviation	Total As (T-As) ($\mu g.kg^{-1}$) ± Standard deviation	(i-As/T-As) (%)
1	Bawh htun	White medium grain	Yangon	140 ± 28	195 ± 20	72 ± 16
2	Sintukha (Emahta)	White medium grain	Yangon	150 ± 30	140 ± 21	107 ± 27
3	Hotel taung payan	Brown medium grain	Yangon	150 ± 30	200 ± 21	75 ± 17
4	Bayjar	White short grain	Yangon	83 ± 17	83 ± 9	100 ± 23
5	Man-chit-tun	Brown medium grain	Yangon	190 ± 38	195 ± 21	97 ± 22
6	Paw san mhwe	White short grain	Yangon	95 ± 19	130 ± 21	73 ± 19
7	Nga Kyor taung pyan	White short grain	Yangon	80 ± 16	110 ± 21	73 ± 20
8	Khunni	White short grain	Yangon	110 ± 22	152 ± 21	72 ± 18
9	Day "90″	White medium grain	Yangon	150 ± 30	140 ± 21	107 ± 27
10	Shwe-man	White long grain	Thanlyin	120 ± 24	143 ± 21	84 ± 21
11	Zeeyar	White medium grain	Yangon	100 ± 20	130 ± 21	77 ± 20
12	Sinthwe	White medium grain	Yangon	100 ± 20	83 ± 9	120 ± 27
13	Manawtukha	White medium grain	Yangon	100 ± 20	121 ± 21	83 ± 22
14	Moe-tu-kha	White medium grain	Yangon	120 ± 24	129 ± 21	93 ± 24
15	Taung Pyan	White short grain	Hlegu	100 ± 20	103 ± 21	97 ± 28
16	Ngakyar	White short grain	Hlegu	140 ± 28	150 ± 21	93 ± 23
17	Patheinyin	White medium grain	Hlegu	78 ± 16	155 ± 21	50 ± 12
18	Thaimanaw	White medium grain	Hlegu	110 ± 22	167 ± 21	66 ± 16
19	Dagon(1)	White medium grain	Hlegu	130 ± 26	159 ± 21	82 ± 20
20	Bawh hlun	White medium grain	Hlegu	130 ± 26	170 ± 21	76 ± 18
21	Shwe-war	White short grain	Hlegu	89 ± 18	127 ± 21	70 ± 18
22	Pathein paw san	White short grain	Yangon	100 ± 20	100 ± 18	100 ± 27
23	Sin thwe	White long grain	Yangon	130 ± 26	120 ± 18	108 ± 27
24	Taung pyan	White short grain	Yangon	84 ± 17	179 ± 21	47 ± 11
25	Paw san	White short grain	Yangon	77 ± 15	90 ± 21	86 ± 26
26	Paw san yin	White short grain	Yangon	66 ± 13	93 ± 11	71 ± 16
27	Myungmya paw san	White short grain	Yangon	62 ± 12	74 ± 11	84 ± 20
28	Natalinn	White short grain	Eastern Yangon	64 ± 13	64 ± 21	99 ± 20
29	Yadanar-toe	White long grain	Eastern Yangon	41 ± 8	57 ± 11	71 ± 20
30	Myathidor paw san	White short grain	Sagaing	55 ± 11	65 ± 9	85 ± 21
31	Yepwe nga sein	White short grain	Rakhine State	65 ± 13	100 ± 18	65 ± 17
32	Ngasain	White short grain	South Yangon	110 ± 22	164 ± 15	67 ± 15
33	Emata(1)	White medium grain	Ayeyarwaddy	85 ± 17	110 ± 21	77 ± 21
34	Emata(2)	White medium grain	Ayeyarwaddy	71 ± 14	110 ± 21	65 ± 18
35	Hkauna Mam/Ja ra Mam	White medium grain	Kachin State	19 ± 1	41 ± 11	46 ± 13
36	Na Mam/Mayatan g Mam	White long grain	Kachin State	4 ± 0.2	41 ± 11	10 ± 3
37	Hka rang Mam/Kavin Mam	White long grain	Kachin State	6 ± 0.3	21 ± 6	29 ± 7
38	Hka rang Mam/Hka di Mam	White medium grain	Kachin State	2 ± 0.1	24 ± 5	8 ± 2
39	Mam Jahti	Yellow long grain	Kachin State	24 ± 2	30 ± 8	80 ± 22

(continued on next page)

Table 2 (*continued*)

No	Name of rice	Rice characteristic	Region	Inorganic As (i-As) ($\mu g.kg^{-1}$) ± Standard deviation	Total As (T-As) ($\mu g.kg^{-1}$) ± Standard deviation	(i-As/T-As) (%)
40	Paw San Mawe	White medium grain	Sagaing	47 ± 3	68 ± 18	69 ± 19
41	Paw San Mawe	White medium grain	Rakhine State	57 ± 3	79 ± 21	72 ± 19
42	Paw San Mawe	White medium grain	Rakhine State	52 ± 3	99 ± 25	53 ± 14
43	Paw San Mawe	White medium grain	Rakhine State	59 ± 3	117 ± 30	50 ± 13
44	Shwe Wa Min	White long grain	Chin State	56 ± 3	68 ± 9	82 ± 12
45	Aye Yar Min	White long grain	Chin State	54 ± 3	57 ± 15	95 ± 25
46	Sin Thu Ka	Yellow long grain	Chin State	148 ± 8	158 ± 26	94 ± 16
47	Paw San Mawe	Yellow long grain	Chin State	49 ± 3	48 ± 12	102 ± 26
48	Shwe Thaw	White long grain	Ayeyarwady	85 ± 5	88 ± 23	97 ± 26
49	San Yin	White medium grain	Ayeyarwady	73 ± 4	102 ± 5	72 ± 5
50	Thu Ka	White long grain	Ayeyarwady	114 ± 6	131 ± 34	87 ± 23

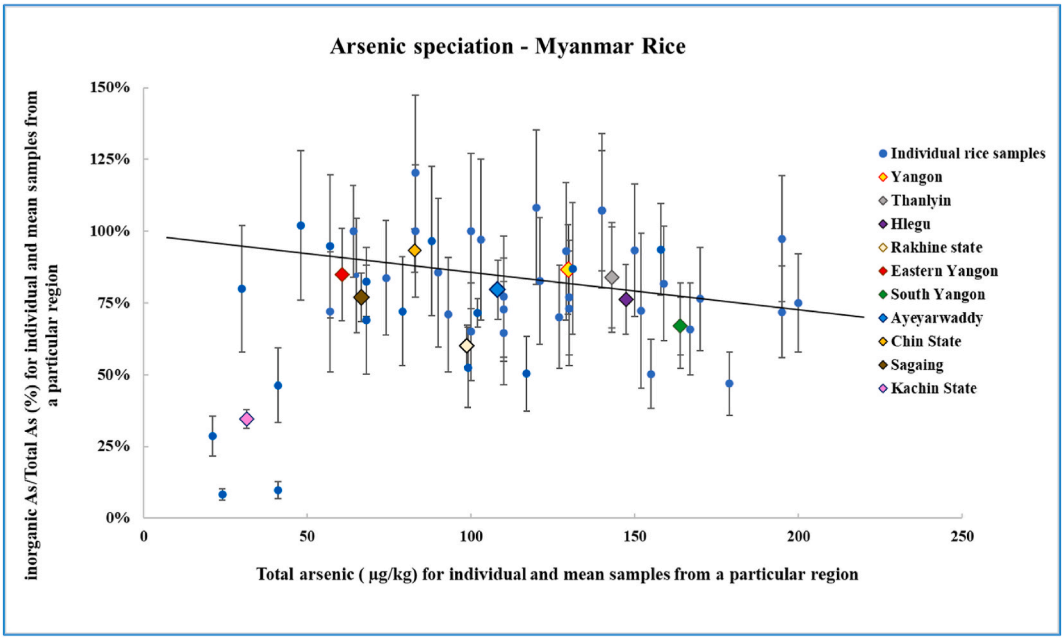


Fig. 3. Cross-plot of total-arsenic and inorganic-arsenic from individual Myanmar rice samples (blue circles) and regional means (diamonds). Analytical accuracy of i-As analyses is within or close to the 30 % control limit recommended by the FDA. Kachin state rice samples are an outlier with respect inorganic arsenic contents.

Table 3
Mean estimated inorganic arsenic intakes for males and females based on average body weight and rice consumption in Myanmar.

Gender	Age (years)	Body weight (bw) (kg)	Rice intake rate (IR) (kg. day^{-1})	Reference for IR/bw ratio	Mean inorganic arsenic intake ($\mu g.kg\text{-}bw^{-1}.day^{-1}$)
Males	5–12	27.9	0.32	(after [36])	1.0
	18–25	61	0.70		1.0
	25–54	75	0.77	[24]	0.9
	>60	60	0.69	(after [36])	1.0
Females	5–12	27.9	0.30	(after [36])	1.0
	18–25	55	0.59		0.9
	25–54	65	0.65	[24]	0.9
	>60	54	0.58	(after [36])	0.9

taking into account of reported preparation and consumption behaviour of representative participants. Our calculations suggest typical inorganic arsenic intake for adults is 1 μg.kg-bw^{-1}.day^{-1}close to the withdrawn World Health Organisation (WHO) provisional tolerable intake of 2.1 μg.kg-bw^{-1}.day^{-1}and higher than $BMDL_{05}$ values of 0.06 μg.kg-bw^{-1}.day^{-1}reported by the EFSA panel on contaminants in the food chain. The analytical data highlight potential risks for the Myanmar population associated with long exposure to inorganic arsenic found in Myanmar rice, especially since high levels of arsenic have been reported in groundwater utilised for cooking water and drinking water in various regions of Myanmar. The level of inorganic arsenic was very low in Kachin state rice, indicating its potential utility as a low inorganic arsenic rice. As these samples were likely grown under relatively oxidizing conditions, it is important in future work to analyse trace elements such as cadmium that tend to accumulate in rice grown under such relatively oxidizing conditions.

CRediT authorship contribution statement

May M. Alrashdi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Project administration. **Ilya Strashnov:** Writing – review & editing, Supervision, Methodology, Investigation. **Laura A. Richards:** Writing – review & editing, Investigation, Conceptualization, Funding acquisition. **Yin Min Tun:** Writing – review & editing, Investigation. **Ahmed Al Bualy:** Writing – review & editing, Methodology, Investigation, Data curation, Formal analysis, Funding acquisition. **David A. Polya:** Writing – review & editing, Supervision, Methodology, Conceptualization, Investigation.

Disclosure statement

The authors report there are no competing interests to declare.

Data availability

All data analysed during this study are provided within the manuscript and/or supplementary information files.

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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 A. Supplementary data

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