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A comparison of the effects of two cooking methods on arsenic species and nutrient elements in rice

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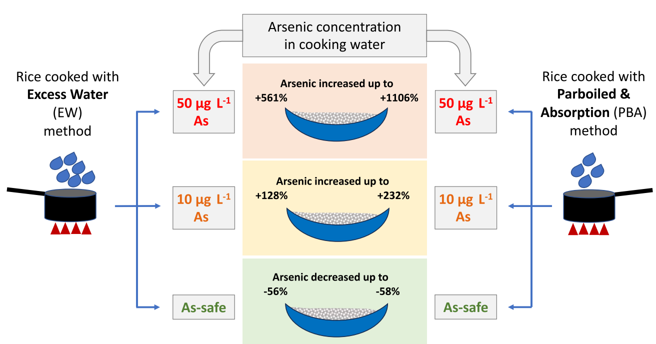
HIGHLIGHTS

- Rice was cooked with excess water (EW) and parboiled and absorbed (PBA) method.
- The effects of As-safe and As-spiked (10 and 50 μg L^{-1}) cooking water were compared.
- EW and PBA were equally effective in removing iAs when cooked with As-safe water.
- These methods significantly affected K, Fe, Cu and Mo when As-safe water was used.
- Arsenic exposure depended on the per capita rice consumption of the population.

GRAPHICAL ABSTRACT



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ABSTRACT

Rice is one of the major cereal crops in the world, contributing significantly towards the dietary energy and nutrition of more than half of the world's population. However, rice can also be a significant exposure route for inorganic arsenic (iAs). This risk is even greater if rice is cooked with iAs-contaminated water. Here, we quantified the effect of two cooking methods, excess water (EW) and parboiled and absorbed (PBA), on As species and essential nutrient elements (P, K, Mg, Fe, Zn, Mn, Cu, Se and Mo) in white, parboiled and brown rice cooked with As-safe (0.18 μg L^{-1}) and As-spiked (10 and 50 μg L^{-1}) tap water. Furthermore, we calculated the exposure risk using the margin of exposure (MOE) for both low (the UK) and high (Bangladesh) rice per capita consumption scenarios. The total micro and macronutrient content in cooked rice was measured using ICP-MS (Inductively Coupled Plasma Mass Spectrometry). An LC-ICP-MS (liquid chromatography-ICP-MS) method was used to quantify arsenic species. The results demonstrate that EW and PBA methods produced similar efficacy of iAs removal (54–58 %) for white and brown rice. However, the EW method was better at removing iAs from parboiled rice (~50 %) than PBA (~39 %). We found that cooked brown rice was superior to other rice types in many essential nutrient elements, and cooking methods significantly affected the loss of K, Fe, Cu and Mo. For both cooking methods, cooking with iAs-spiked water significantly increased iAs in all rice types: white > parboiled > brown. However, when using As-spiked water, the PBA method retained more iAs than EW. Our risk evaluations showed that cooking rice with 50 μg L^{-1} significantly raises the As-exposure of the Bangladesh

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population due to the high per capita rice consumption rate, reinforcing the importance of accessing As-safe water for cooking.

1. Introduction

Rice is one of the major food staples for more than half of the world's population, providing 30–70 % of the dietary energy requirements (Ranum et al., 2014). Although brown rice (wholegrain/unpolished) contains more nutrient elements than white rice (Menon et al., 2021b; Pinto et al., 2016; Saleh et al., 2019), 85 % of rice consumed is white (polished) (Se et al., 2015). In some regions, parboiled rice, produced by soaking, steaming, and drying the harvested paddy before milling, is preferred. This hydrothermal treatment enriches nutrient composition and texture of the cooked rice (Mridha et al., 2022).

The presence of inorganic arsenic (iAs) in rice is a significant health concern, as it is a Group 1 carcinogen (IARC, 2012), and it is one of the top 10 chemicals affecting public health (UNICEF-WHO, 2018). Arsenic in rice comprises As (III) and As (V) as iAs species; the former is more toxic than the latter (Hughes et al., 2011). Relatively small concentrations of organic As (oAs) forms such as dimethylarsenic acid (DMA) and monomethylarsonic acid (MMA) are also present in rice (Meharg et al., 2008), and these forms are 'possibly carcinogenic to humans' (Group 2B) (IARC, 2012). Due to this, the current regulations are based on iAs (Arcella et al., 2021). Previous studies have found that iAs concentrations in rice are significantly higher than oAs concentrations (Meharg et al., 2009; Menon et al., 2020; Saha et al., 2019). Also, brown and parboiled rice (He et al., 2012) are reported to have significantly higher concentrations of iAs than white rice.

According to EFSA (2014), dietary exposure to iAs in the EU population is mainly from processed grain-based products (non-rice), rice, milk and dairy products and drinking water. Furthermore, three portions of rice-based infant food (0.09 kg day^{-1}) were found to be an important exposure risk. Currently, in Europe, the levels of iAs in raw (uncooked) are set at a maximum of 0.20 mg kg^{-1} for white rice, 0.25 mg kg^{-1} for brown and parboiled rice, and 0.10 mg kg^{-1} for any products intended for infants and young children (European Commission, 2015). In contrast, in many Asian countries where rice is a major staple, per capita rice consumption is much higher than in the UK or European countries (OECD, 2015). For instance, the per capita rice consumption in Europe (and the UK) is ~5 kg year^{-1}, whereas, for Bangladesh, it is ~170 kg year^{-1} (OECD, 2015; Schenker, 2012). This difference in rice consumption could lead to a difference in iAs exposure risk through rice, which is particularly important for countries like Bangladesh, where iAs in rice is not currently regulated in contrast to many European countries.

Adopting different rice cooking practices has recently received attention as a promising strategy for reducing As exposure. Amongst these, cooking with excess water (EW) (with rice to water ratio of 1:6–12) or percolating cooking water is very effective at removing iAs to a significant extent in both white and brown rice (Atiaga et al., 2020; Carey et al., 2015; Chowdhury et al., 2020; Gray et al., 2015). These studies demonstrated 40–90 % As removal after cooking. However, this method can lead to the loss of some essential nutrient elements, such as K, Mg, Mn, Zn and Fe (Gray et al., 2015; Mwale et al., 2018). Mandal et al. (2019) found that cooking rice with low arsenic water (<5 μg L^{-1}) can reduce the As content of cooked rice by up to 64 %. However, when rice was cooked with As-contaminated water (range: 90–230 μg L^{-1}), the concentration of As increased significantly (0.219–0.664 mg kg^{-1}) in the cooked rice. On the contrary, the absorption method, in which rice is cooked until all the cooking water is absorbed, tends to be less effective at removing As from the raw rice (Atiaga et al., 2020; Gray et al., 2015; Naito et al., 2015) in comparison to the EW method. However, when the absorption method is combined with pre-cooking steps such as washing/rinsing, pre-soaking, parboiling, etc., it has been shown to remove more As (Atiaga et al., 2020; Menon et al., 2021a; Sharafi et al., 2019).

A recent study (Menon et al., 2021a) combined the excess water and absorption methods to capture the benefits of both approaches. In this method (referred to as the parboiled and absorbed, or PBA method), unwashed rice was added to pre-boiled de-ionised (DI) water (rice to water ratio 1:4) and simmered for 5 min, after which this water was discarded to remove the surface-bound As. The rice was then cooked using the absorption method with a suitable rice-to-water ratio (1:2). The cooking was carried out under low-to-moderate heat until the water was absorbed. The PBA method effectively removed 54 % and 73 % of iAs for brown and white rice while preserving essential nutrient elements such as Mn and Zn. However, this new method still needs to be studied in comparison with the EW method.

Nearly all previous studies (Mridha et al., 2022) used DI or double-distilled (DD) water in the experiments, creating a maximum concentration gradient of As between rice and water, resulting in maximum removal rates. However, DI or DD are mainly used in laboratory investigations, and they are not commonly used for domestic cooking. For instance, tap water is the main source of cooking water in households in the UK which is As-safe. The presence of As in cooking water can have the opposite effect of significantly increasing As in cooked rice and, therefore, needs to be considered in regions where access to As-safe water is limited (Chowdhury et al., 2020; Clemente et al., 2021; Roy Chowdhury et al., 2018; Signes-Pastor et al., 2012). According to Frisbie and Mitchell (2022), out of 176 countries, 136 countries (including the UK) follow the WHO limit for iAs in drinking water of 10 μg L^{-1}, whereas 40 countries use or allow more than this (e.g. 50 μg L^{-1} is used in some countries in Asia such as Bangladesh, Nepal, Myanmar, Pakistan etc.). There are 19 countries without regulations, suggesting that 32 % of the global population (particularly those of low- and middle-income countries) have yet to adopt the WHO limit. Therefore, it is important to assess the risk when using iAs concentrations of 10 μg L^{-1} or above in the cooking for various population groups.

Based on current evidence of the EW and absorption methods, we hypothesise that the EW method will likely remove more iAs and essential nutrient elements than the PBA method. The EW method involves continuous, uninterrupted rice cooking with a relatively large volume of water, followed by the disposal of the excess water (containing iAs removed from the rice) at the end of the cooking process. In contrast, water is not discarded in the second step of the PBA method; hence, more iAs and nutrient elements will likely be retained in the cooked rice. We also hypothesise that when there are elevated levels of iAs in the cooking water, PBA-cooked rice is likely to contain more iAs than EW-cooked rice for the same reasons stated earlier. Finally, it can also be hypothesised that the iAs exposure risk will increase with the per capita daily consumption of rice.

Thus, the objectives of the investigations were:

1. Compare EW and PBA for As species and essential nutrient elements in white, parboiled and brown rice when using iAs-safe cooking water.
2. Evaluate the effect of iAs-spiked (10 and 50 μg L^{-1}) cooking water on iAs in white, parboiled and brown rice cooked using the EW and PBA.
3. Compute margins of exposure (MOE) and compare the risks of rice types cooked with iAs-spiked water using various population groups from the UK and Bangladesh, representing low and high per capita rice consumption.

2. Methods

2.1. Sample collection and preparation

The overall experimental design was constructed to study the effects of different rice types, cooking methods, and iAs-spiked water on the retention of iAs species and nutrient elements in the cooked rice. We used white (polished), brown (unpolished) and parboiled types of Basmati rice (*Oryza sativa* L.), obtained from a major UK supermarket (origin not specified). These three rice types were cooked using 1) the EW method with a rice-to-water ratio of 1:6 by volume (Gray et al., 2015) and 2) the PBA method (Menon et al., 2021a), which consisted of two stages: first, short parboiling for 5 min, after which the unabsorbed cooking water was discarded, followed by a second cooking stage in which an appropriate amount of water was added and was absorbed by the rice. Note that the parboiling step in the PBA aims to enhance the removal of surface-bound arsenic from rice grains, regardless of the rice type.

Table 1
Two-way ANOVA results showing the effect of rice types, cooking methods and their interaction on As species, iAs and oAs.

2-Way ANOVA results					
Source of variation	SS	DF	MS	F (DFn, DFd)	p value
As(III)					
Interaction	2.92E−03	4	6.53E−04	F (4, 18) = 268.5	< 0.0001
Rice type	1.13E−02	2	3.87E−03	F (2, 18) = 1591	< 0.0001
Cooking method	1.30E−02	2	6.38E−03	F (2, 18) = 2621	< 0.0001
Residual	7.67E−05	18	2.43E−06		
As(V)					
Interaction	3.70E−05	4	9.25E−06	F (4, 18) = 11.45	< 0.0001
Rice type	5.12E−04	2	2.56E−04	F (2, 18) = 317.3	< 0.0001
Cooking method	4.29E−06	2	2.15E−06	F (2, 18) = 2.659	0.0974
Residual	1.45E−05	18	8.07E−07		
DMA					
Interaction	1.10E−06	4	2.74E−07	F (4, 18) = 0.09148	0.9839
Rice type	8.51E−05	2	4.26E−05	F (2, 18) = 14.20	0.0002
Cooking method	8.33E−05	2	4.17E−05	F (2, 18) = 13.89	0.0002
Residual	5.40E−05	18	3.00E−06		
MMA					
Interaction	7.40E−07	4	1.85E−07	F (4, 18) = 0.9700	0.4480
Rice type	8.00E−06	2	4.00E−06	F (2, 18) = 20.96	< 0.0001
Cooking method	5.03E−07	2	2.52E−07	F (2, 18) = 1.319	0.2921
Residual	3.43E−06	18	1.91E−07		
iAs					
Interaction	2.92E−03	4	7.30E−04	F (4, 18) = 171.3	< 0.0001
Rice type	1.13E−02	2	5.64E−03	F (2, 18) = 1323	< 0.0001
Cooking method	1.30E−02	2	6.52E−03	F (2, 18) = 1529	< 0.0001
Residual	7.67E−05	18	4.26E−06		
oAs					
Interaction	3.41E−07	4	8.51E−08	F (4, 18) = 0.02186	0.9990
Rice type	1.45E−04	2	7.26E−05	F (2, 18) = 18.65	< 0.0001
Cooking method	7.10E−05	2	3.55E−05	F (2, 18) = 9.115	0.0018
Residual	7.01E−05	18	3.89E−06		

Based on preliminary cooking trials, it was found that a rice-to-water ratio of 1:4 (by volume) throughout produced cooked rice with a good texture for all rice types for the PBA, ensuring experimental consistency and the cooking time of rice types varied between 12 and 20 min. The rice was cooked in glass beakers, loosely covered with watch glasses and heated on a laboratory-grade hotplate at medium power. Arsenic-safe tap water (0.18 ± 0.008 μg L^{-1}) was used for cooking. See Suppl. material 1 for the concentrations of other nutrient elements of interest in this study.

The above experiment (i.e. EW and PBA) was then repeated with concentrations of 10 and 50 μg L^{-1} As(V), prepared using As_2O_5 standard (1000 mg L^{-1} in 0.5 M nitric acid, supplied by VWR International) (based on Signes-Pastor et al., 2012) in tap water. Based on ICP-MS analysis, the concentrations of arsenic in the prepared solutions were 10.51 and 50.21 μg L^{-1}. A concentration of 10 μg L^{-1} is the recommended limit by WHO, whereas 50 μg L^{-1} represents national standards followed in several countries (Frisbie and Mitchell, 2022).

After cooking, the rice samples were placed for 5 min in a 500-μm sieve to cool (and, in the case of the EW rice, to drain any excess water), after which they were weighed and then oven-dried at 50 °C for a minimum of 48 h, or until no change in weight was observed. Three replicates of uncooked rice (of each type) were also dried at the same temperature. All oven-dried samples were powdered with a ceramic ball mill for chemical analysis performed in triplicate.

2.2. Sample digestion and chemical analysis

All rice powders were analysed for 32 elements, including P, K, Mg, Fe, Zn, Mn, Cu, Se, Mo and As, at The School of Bioscience, University of Nottingham, UK and previous publications describe the protocols in detail (Phiri et al., 2019; Menon et al., 2021b, 2021a, 2020). For total elemental analysis, approximately 0.2 g (dry weight) of the powdered rice sample was microwave-digested in 6 mL HNO_3 (Primar grade, Fisher Scientific, UK) in perfluoroalkoxy (PFA) vessels (Multiwave; Anton Paar GmbH, St. Albans, UK). The digested samples were diluted to 20 mL total volume in Milli-Q water (18.2 MΩ cm). This was then subsampled and further diluted 1-in-10 in Milli-Q water prior to elemental analysis using ICP-MS (Thermo-Fisher Scientific iCAP-Q; Thermo Fisher Scientific, Bremen, Germany). Subsequently, all samples were analysed for inorganic and organic arsenic species (As^{III}, As^{V}, DMA and MMA) using an LC-ICP-MS, using the extraction method described in a previous publication (Huang et al., 2010), which preserves individual As species. A detailed description is provided in Suppl. material 2.

2.3. Quality control and quality assurance

A NIST1568b standard rice powder (in triplicates) was also analysed for quality assurance and control. Recoveries (%) for total iAs (As^{III} and As^{V}), DMA and MMA were 90 ± 1, 105 ± 1 and 105 ± 3, respectively. For nutrient elements, the percentages (%) were P = 115 ± 5; K = 120 ± 4; Mg = 101 ± 3; Zn = 107 ± 2; Fe = 94 ± 2; Mn = 114 ± 4; Cu = 101 ± 5; Mo = 108 ± 2 and Se = 114 ± 1.

2.4. The margin of exposure (MOE)

We used MOE as an index (EFSA, 2014; Guillod-Magnin et al., 2018; Rintala et al., 2014) to compare health risks to the UK and Bangladesh population representing low and high per capita rice consumption, following our previous publication (Menon et al., 2021b). The MOE is

Table 2
Results from Tukey Post-hoc tests to compare different cooking methods on As species, iAs and oAs.

	Mean diff.	95.00 % CI of diff.		p value
		From	To	
As(III)				
Raw vs. EW	4.71E−02	4.53E−02	4.88E−02	<0.0001
Raw vs. PBA	4.51E−02	4.33E−02	4.69E−02	<0.0001
EW vs. PBA	−1.99E−03	−3.86E−03	−1.08E−04	0.0372
As(V)				
Raw vs. EW	1.36E−04	−9.45E−04	1.22E−03	0.9452
Raw vs. PBA	9.06E−04	−1.76E−04	1.99E−03	0.1102
EW vs. PBA	7.70E−04	−3.11E−04	1.85E−03	0.1922
DMA				
Raw vs. EW	3.99E−03	1.91E−03	6.07E−03	0.0003
Raw vs. PBA	3.39E−03	1.31E−03	5.47E−03	0.0016
EW vs. PBA	−5.99E−04	−2.68E−03	1.48E−03	0.747
MMA				
Raw vs. EW	−2.90E−04	−8.15E−04	2.36E−04	0.3587
Raw vs. PBA	−2.90E−04	−8.15E−04	2.36E−04	0.3585
EW vs. PBA	−7.22E−08	−5.26E−04	5.25E−04	>0.9999
iAs				
Raw vs. EW	4.72E−02	4.47E−02	4.97E−02	<0.0001
Raw vs. PBA	4.60E−02	4.35E−02	4.85E−02	<0.0001
EW vs. PBA	−1.22E−03	−3.70E−03	1.27E−03	0.4411
oAs				
Raw vs. EW	3.70E−03	1.33E−03	6.07E−03	0.0024
Raw vs. PBA	3.10E−03	7.27E−04	5.48E−03	0.0098
EW vs. PBA	−5.99E−04	−2.97E−03	1.78E−03	0.7981

calculated using simple steps as given below:

$$MOE = \frac{BMDL}{EDI} \quad (1)$$

where BMDL is the benchmark dose level (explained below), and EDI (Estimated Dietary Intake) in the above equation is calculated as:

$$EDI = \frac{AC \times ADC}{bw} \quad (2)$$

where:

AC is the average concentration of iAs in cooked rice (mg kg^{-1}, as shown in Fig. 3), and *bw* represents the average body weight of the local population (kg). Please note that *AC* in rice vary according to the rice product used. For the comparison of the two populations, we use the rice data obtained from this experiment for both the UK and Bangladesh scenarios, although we acknowledge that this may not be the case in all situations.
ADC is the average daily consumption rate of rice (kg day^{-1}). When calculating MOE for various target populations, we used example rice portions of 0.075, 0.05 and 0.025 kg day^{-1} for adults (male and female), 7-year-olds and 1-year-olds, respectively (The UK Government Service, 2015), although this may vary across the population and diet preferences. For Bangladesh, we used 0.474 kg day^{-1} for adult male and female, 0.313 and 0.075 kg day^{-1} for 7-year-olds and 1-year-olds, respectively (Kimmons et al., 2005; Menon et al., 2021b).

The body weights of the target population (UK) were obtained from the Office for National Statistics (2010) as 83, 70, 23 kg and 9 kg for adult males, females, 7-year-olds and 1-year-olds. Similarly, for Bangladesh, body weight data were obtained from the published

Table 3
Two-Way ANOVA results showing the effect of rice types, cooking methods and their interaction on different macro and micronutrient elements.

Source of variation	SS	DF	MS	F (DFn, DFd)	p value
P					
Interaction	8.04E+04	4	2.01E+04	F (4, 18) = 1.553	0.2294
Rice type	3.23E+07	2	1.61E+07	F (2, 18) = 1246	< 0.0001
Cooking method	5.96E+04	2	2.98E+04	F (2, 18) = 2.302	0.1288
Residual	2.33E+05	18	1.29E+04		
K					
Interaction	3.82E+05	4	9.55E+04	F (4, 18) = 16.64	< 0.0001
Rice type	1.57E+07	2	7.85E+06	F (2, 18) = 1368	< 0.0001
Cooking method	3.33E+06	2	1.66E+06	F (2, 18) = 289.9	< 0.0001
Residual	1.03E+05	18	5.74E+03		
Mg					
Interaction	1.59E+04	4	3.99E+03	F (4, 18) = 1.725	0.1884
Rice type	8.33E+06	2	4.17E+06	F (2, 18) = 1803	< 0.0001
Cooking method	4.30E+02	2	2.15E+02	F (2, 18) = 0.09294	0.9117
Residual	4.16E+04	18	2.31E+03		
Fe					
Interaction	2.53E+02	4	6.32E+01	F (4, 18) = 57.52	< 0.0001
Rice type	2.57E+03	2	1.28E+03	F (2, 18) = 1167	< 0.0001
Cooking method	2.03E+02	2	1.01E+02	F (2, 18) = 92.23	< 0.0001
Residual	1.98E+01	18	1.10E+00		
Zn					
Interaction	4.27E+00	4	1.07E+00	F (4, 18) = 1.187	0.3502
Rice type	7.50E+02	2	3.75E+02	F (2, 18) = 417.3	< 0.0001
Cooking method	1.17E+00	2	5.84E−01	F (2, 18) = 0.6493	0.5342
Residual	1.62E+01	18	8.99E−01		
Mn					
Interaction	1.58E+00	4	3.95E−01	F (4, 18) = 0.5392	0.7089
Rice type	1.69E+03	2	8.45E+02	F (2, 18) = 1153	< 0.0001
Cooking method	9.60E−01	2	4.80E−01	F (2, 18) = 0.6544	0.5317
Residual	1.32E+01	18	7.33E−01		
Cu					
Interaction	3.74E−01	4	9.36E−02	F (4, 18) = 5.355	0.0051
Rice type	5.24E+00	2	2.62E+00	F (2, 18) = 149.8	< 0.0001
Cooking method	4.20E−01	2	2.10E−01	F (2, 18) = 12.00	0.0005
Residual	3.15E−01	18	1.75E−02		
Se					
Interaction	2.29E−04	4	5.72E−05	F (4, 18) = 1.097	0.3880
Rice type	9.06E−06	2	4.53E−06	F (2, 18) = 0.08685	0.9172

(continued on next page)

Table 3 (*continued*)

Source of variation	SS	DF	MS	F (DFn, DFd)	p value
Cooking method	2.88E−04	2	1.44E−04	F (2, 18) = 2.765	0.0897
Residual	9.39E−04	18	5.21E−05		
Mo					
Interaction	3.73E−02	4	9.32E−03	F (4, 18) = 8.766	0.0004
Rice type	3.72E−01	2	1.86E−01	F (2, 18) = 175.0	< 0.0001
Cooking method	4.78E−01	2	2.39E−01	F (2, 18) = 224.6	< 0.0001
Residual	1.91E−02	18	1.06E−03		

literature (Khan et al., 2012; Menon et al., 2021b; Sultana et al., 2015) as 53, 47, 18, 8 kg for adult males, females, 7 and 1- year- olds.

In this paper, we used 0.003 mg kg^{-1} b.w. day^{-1} (body weight per day) in Eq. (1) as BMDL (95 % lower confidence limit of the benchmark dose) for iAs to calculate MOE. This represents the $BMDL_{0.5}$ (the subscript indicates the dose needed for a 0.5 % increase in the incidence of cancers), as used by the Committee of Toxicity (COT) in the UK (Food Standard Agency, 2016). The COT recommends a MOE > 10 to be safe.

2.5. Statistical analysis

An ordinary 2-way ANOVA was performed to analyse the effect of rice types (white, parboiled and brown) and cooking methods (EW and PBA) on As species and nutrient elements. The same approach was used to study the effect of cooking methods (EW and PBA) and concentration of As in cooking water (10 and 50 μg L^{-1}) on arsenic species (iAs and oAs) in each rice type (white, parboiled and brown). We used Tukey post-hoc pairwise comparison to compare different groups. All graphs and statistical analyses were made using Prism (Graphpad Software LLC, v. 10.0). Results from these statistical tests are provided in Tables 1–3.

3. Results and discussion

3.1. The effect of EW and PBA on As species

The concentration of inorganic (As (III), As (V) and combined) and organic (DMA and MMA and combined) species of different rice types before (raw) and after cooking with EW and PBA are shown in Fig. 1 (a–f). Compared to As (V), As (III) was significantly reduced in all rice types under both cooking methods. This could be due to greater solubility and mobility of As (III) in comparison to As(V), and this is consistent with previous findings (Atiaga et al., 2020). Similarly, DMA also decreased in comparison to MMA. Fig. 2a and b illustrates that EW and PBA reduced iAs concentration by >50 % for white and brown rice, and the difference between the EW and PBA was more pronounced for parboiled rice. The oAs removal was highest (~15 %) for the parboiled

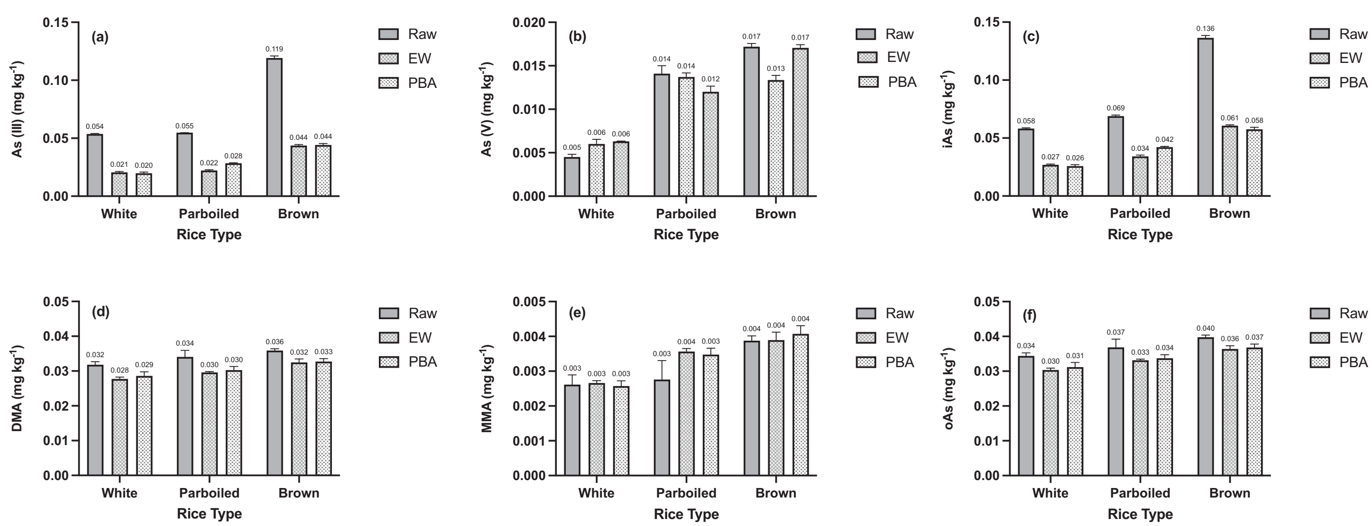

Fig. 1. (a–f). Changes in mean As (III) (a), As (V) (b), and iAs (c), DMA (d), MMA (e) and oAs (f) concentrations in cooked white, parboiled and brown rice using EW (excess water) and PBA (parboiled and absorbed) methods in comparison to raw (uncooked) rice. The error bars indicate the standard error of means (SEM).

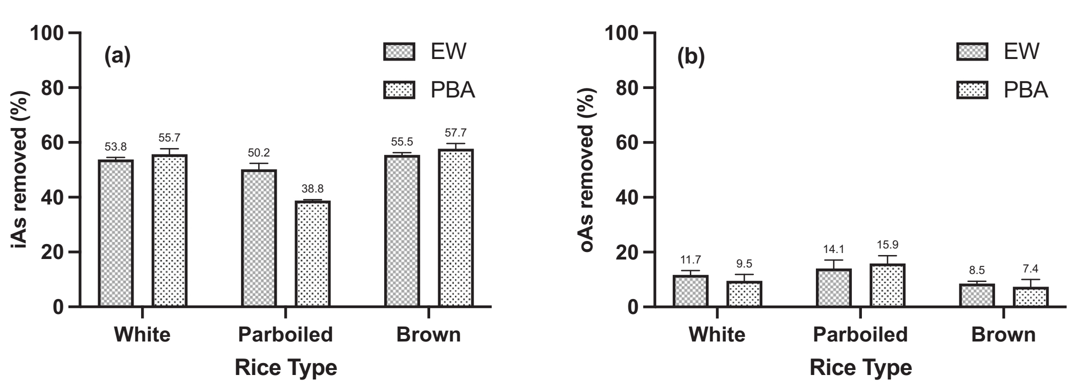

Fig. 2. (a–b). The amount of iAs and oAs removed in comparison to the Raw rice. The error bars indicate the standard error of means (SEM).

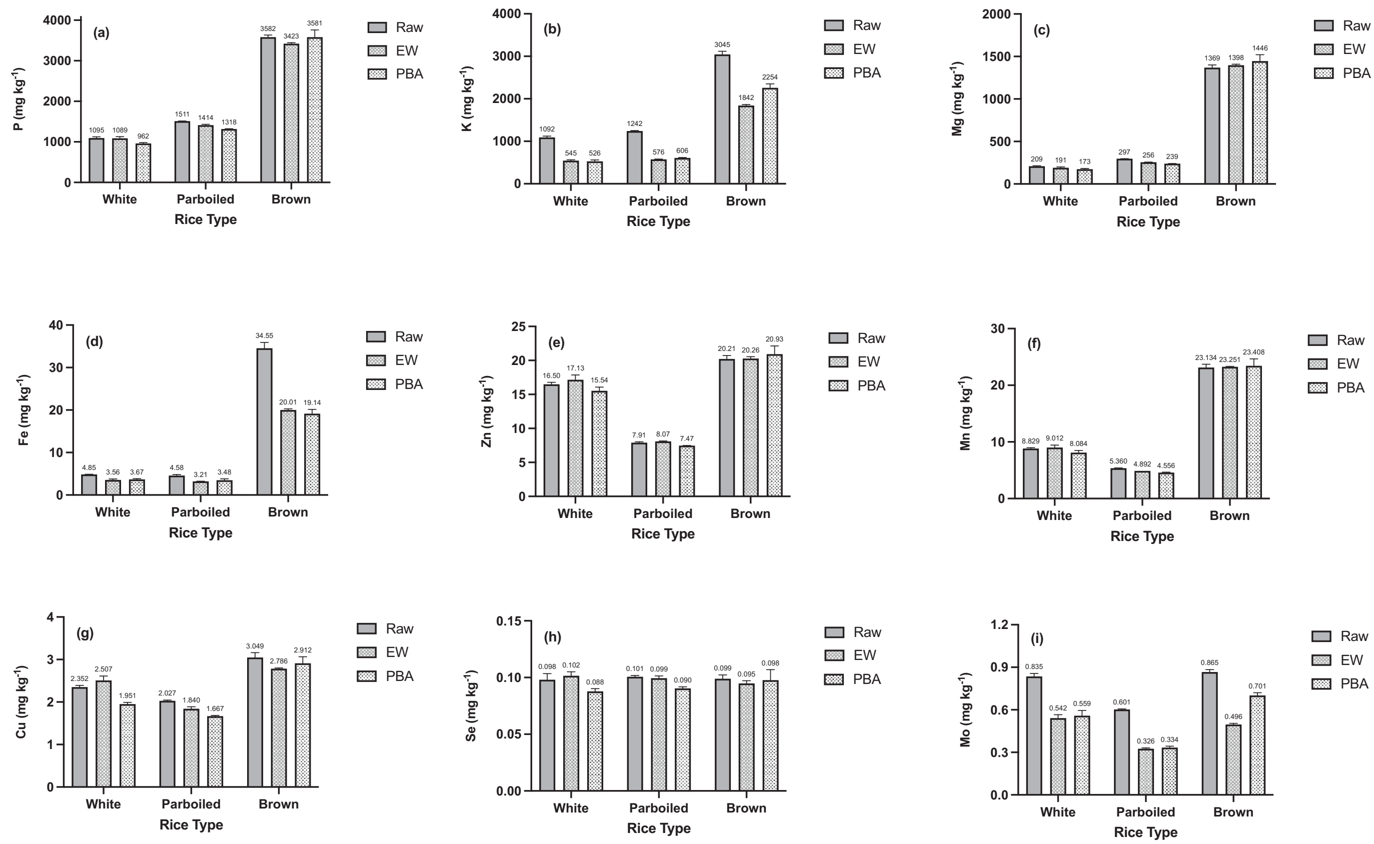

Fig. 3. (a–i). Changes in mean P (a), K (b), Mg (c), Fe (d), Zn (e), Mn (f), Cu (g), Se (h) and Mo (i) in cooked white, parboiled and brown rice using EW (excess water) and PBA (parboiled and absorbed) methods in comparison to raw (uncooked) rice. The error bars indicate the standard error of means (SEM).

rice, followed by the white (~10 %) rice type and brown rice (~8 %).

The statistical evaluation of the data is presented in Table 1 and showed that both cooking methods and rice types significantly influenced As (III), DMA, iAs and oAs. On the other hand, both As(V) and MMA concentrations were influenced by rice types only. Post-hoc tests (Table 2) showed a significant difference between raw vs. cooked (EW or PBA) for As(III), DMA, iAs and oAs. In addition, EW vs. PBA was significant for As(III).

In our previous investigation (Menon et al., 2021a), we used raw white and brown rice products (three types of each) with higher mean iAs concentrations (white = 0.129–0.234; brown = 0.195–0.326; mg kg^{-1}; no parboiled rice was used) than the ones we used here (white = 0.058, parboiled = 0.069 and brown = 0.136 mg kg^{-1}). The iAs losses were broadly within the observed losses reported by others from different rice types (Atiaga et al., 2020; Carey et al., 2015; Gray et al., 2015; Menon et al., 2021a; Raab et al., 2009), using the DI water. However, parboiled rice is included only in some studies; for example, a previous study that compared different rice types found a 50 % reduction in iAs from parboiled rice 25 % in medium and long-grain white rice and 40 % in brown rice when cooked with a 1:6 rice-to-water ratio, whereas the absorption method did not show any removal of iAs from rice (Gray et al., 2015). Similarly, (Chowdhury et al., 2020) reported a 58 % reduction in As (for As (III) and As (V), the removal was 54 and 62 %, respectively) when parboiled rice was cooked with As-safe water (1:3 rice to water ratio).

The difference in removal rates observed by different researchers is due to many factors. Our previous study noted considerable heterogeneity in rice products in iAs concentrations (Menon et al., 2021a). For example, the three raw brown rice samples used in our previous study had 0.195, 0.235 and 0.326 (iAs) mg kg^{-1}, whereas for white rice iAs concentrations were 0.129, 0.161 and 0.234 mg kg^{-1}. However, the much lower concentrations of iAs found in the white and brown rice samples used in this study would have resulted in a reduced concentration gradient between the iAs in the rice and the cooking water. Another crucial factor affecting the removal rate may be the quality of water used (i.e. tap water in the present study vs. DI or DD water in other studies), although further investigation is required to confirm this. Previous studies show that washing or rinsing the rice before cooking is effective in reducing iAs by 10–40 % (Atiaga et al., 2020; Gray et al., 2015; Menon et al., 2021a; Naito et al., 2015; Raab et al., 2009). Furthermore, our earlier study showed that when the absorption method was combined with practices such as washing for 5 min or pre-soaking for 30 min, iAs was reduced by 18 % in white and 44 % in brown rice (Menon et al., 2021a). Note that the PBA method does not require a washing step before cooking as the water after the first boiling step is discarded, sufficient to clean the rice and improve its colour.

Nevertheless, the present study concludes that PBA and EW are almost equally effective at As removal for white and brown rice, whereas the EW was found to be more efficient for parboiled rice than PBA. This is the first study comparing EW and PBA, and we found that the losses of iAs after cooking under EW and PBA were strikingly similar for the white and brown rice types, rejecting our hypothesis that EW would remove more iAs than the PBA method. If future studies were to repeat this comparison for several rice products, this would be a valuable addition to our understanding.

3.2. The effect of EW and PBA on nutrient elements

We compared several essential macro (P, K and Mg) and micronutrient (Fe, Zn, Mn, Cu, Se, Mo) elements to assess changes for different rice types when cooked with EW and PBA, as shown in Fig. 3 (2-way ANOVA and post-hoc tests results are provided in detail in Tables 3–4).

Table 4
Results from Tukey Post-hoc tests to compare different cooking methods on different macro and micronutrient elements.

	Mean diff.	95.00 % CI of diff.		p value
		From	To	
P				
Raw vs. EW	8.72E+01	−4.97E+01	2.24E+02	0.2609
Raw vs. PBA	1.09E+02	−2.82E+01	2.46E+02	0.1346
EW vs. PBA	2.15E+01	−1.15E+02	1.58E+02	0.9158
K				
Raw vs. EW	8.05E+02	7.14E+02	8.96E+02	<0.0001
Raw vs. PBA	6.65E+02	5.73E+02	7.56E+02	<0.0001
EW vs. PBA	−1.41E+02	−2.32E+02	−4.94E+01	0.0026
Mg				
Raw vs. EW	9.74E+00	−4.81E+01	6.76E+01	0.9038
Raw vs. PBA	5.57E+00	−5.23E+01	6.34E+01	0.9673
EW vs. PBA	−4.16E+00	−6.20E+01	5.37E+01	0.9816
Fe				
Raw vs. EW	5.73E+00	4.47E+00	6.99E+00	<0.0001
Raw vs. PBA	5.89E+00	4.63E+00	7.16E+00	<0.0001
EW vs. PBA	1.64E−01	−1.10E+00	1.43E+00	0.9413
Zn				
Raw vs. EW	−2.83E−01	−1.42E+00	8.58E−01	0.8046
Raw vs. PBA	2.26E−01	−9.15E−01	1.37E+00	0.8698
EW vs. PBA	5.08E−01	−6.33E−01	1.65E+00	0.5045
Mn				
Raw vs. EW	5.61E−02	−9.74E−01	1.09E+00	0.9894
Raw vs. PBA	4.25E−01	−6.05E−01	1.46E+00	0.5544
EW vs. PBA	3.69E−01	−6.61E−01	1.40E+00	0.6387
Cu				
Raw vs. EW	9.86E−02	−6.04E−02	2.58E−01	0.2784
Raw vs. PBA	3.00E−01	1.41E−01	4.59E−01	0.0004
EW vs. PBA	2.01E−01	4.19E−02	3.60E−01	0.0124
Mo				
Raw vs. EW	3.13E−01	2.73E−01	3.52E−01	<0.0001
Raw vs. PBA	2.36E−01	1.97E−01	2.75E−01	<0.0001
EW vs. PBA	−7.68E−02	−1.16E−01	−3.75E−02	0.0003
Se				
Raw vs. EW	6.12E−04	−8.08E−03	9.30E−03	0.9824
Raw vs. PBA	7.22E−03	−1.47E−03	1.59E−02	0.1137
EW vs. PBA	6.61E−03	−2.08E−03	1.53E−02	0.1561
Cd				
Raw vs. EW	−1.25E−03	−3.07E−03	5.72E−04	0.2141
Raw vs. PBA	2.13E−05	−1.80E−03	1.84E−03	0.9995
EW vs. PBA	1.27E−03	−5.50E−04	3.09E−03	0.204

Broadly, amongst the three rice types, brown rice was found to be superior in most nutrient elements except for Se and Mo (Fig. 3). The data presented in Fig. 3(a) showed that the P concentration in brown rice is 2–3 times higher than that of white or parboiled rice, and 2-way ANOVA tests revealed that the rice types significantly influenced the P concentration ($p < 0.0001$). In contrast, the cooking method had no significant effect ($p = 0.1288$). The interaction of these two factors was also found to be not significant ($p = 0.2294$). Like P, the K (Fig. 3(b)) concentrations in brown rice (before and after cooking) were much higher than in white and parboiled rice. There was ~50 % loss of K from both white and parboiled rice under both cooking methods. In contrast, K loss was less pronounced in brown rice: ~40 % loss under EW and ~25 % loss under PBA. In both parboiled and brown rice, PBA retained more K than EW. K content was significantly influenced ($p < 0.0001$) by the cooking method and rice type and their interaction. The concentration of Mg (Fig. 3(c)) in brown rice is 4–6 times higher than in white or parboiled rice, and it was significantly influenced by rice type ($p < 0.0001$). However, the cooking method ($p = 0.9117$) and interaction ($p = 0.1884$) were not statistically significant.

Our previous PBA study (Menon et al., 2021a) involving white and brown (3 each) rice types showed that average P, K and Mg losses were 22, 48 and 22 % from white rice, very similar to this study. However, we noted more K losses in this study under PBA than in our previous investigation for brown rice. A previous study using EW (1:6–10 rice to water) reported a 50–60 % loss of K and 22–24 % loss of Mg using brown or polished rice (Mwale et al., 2018); their results are largely comparable to our study.

Concentrations of Fe in the brown rice (raw or cooked) were nearly four times higher than the other two rice types (Fig. 3(d)). The loss of Fe after cooking (~25 % from white and parboiled rice) under both methods was slightly more in EW than PBA for these two rice types. In the case of brown rice, these cooking methods produced a similar loss (43–45 %). Statistical analysis showed that rice type ($p < 0.0001$) and cooking method ($p < 0.0001$), and also the interaction of these two factors ($p < 0.0001$), influenced Fe concentration in cooked rice. Post-hoc comparisons showed a significant difference between Fe in raw vs EW or PBA ($p < 0.0001$); however, there was no statistically significant difference between EW and PBA ($p = 0.9413$) (Table 4).

The concentration of Zn (Fig. 3(e)) was highest in brown rice, followed by white rice and parboiled rice, regardless of whether it was cooked or raw. The parboiled rice Zn concentrations were nearly a third of the brown rice and half of the white rice. Nevertheless, both cooking methods showed similar effects in retaining these elements after cooking. Statistically, rice type significantly affected Zn concentrations ($p < 0.0001$). In contrast, neither the cooking method ($p = 0.5342$) nor its interaction ($p = 0.3505$) with rice type significantly affected Zn.

Gray et al. (2015) compared Fe losses with EW and absorption methods and found that an EW (1: 6 rice to water ratio) led to 40–45 % loss in white rice and as high as 75 % from parboiled rice, but had no effect on brown rice. No significant loss in Fe was found for the absorption methods since no water was discarded during or after cooking. Mwale et al. (2018) reported a loss of up to 24.4 % from EW cooking methods, similar to the loss we found for white rice. They reported Zn loss as 7.7–14.2 %, whereas we found a maximum 6 % loss across the rice types and cooking methods. Somewhat similar results to ours were also reported by Sharafi et al. (2019) when they compared the regional cooking practices which are followed in Iran, such as 'Kateh' (an absorption method) and 'rinse cooking' (which is very similar to PBA). These methods produced a 10–30 % reduction in Fe and Zn, comparable results for the white and parboiled rice used in this study. A recent study (Azam et al., 2021) compared unfortified and Zn and Fe-fortified rice under different cooking methods and they found that the rice cooker method retained the highest Fe and Zn concentrations in comparison to the EW method. Though our results are in agreement with their findings for Fe, our current investigation did not show a difference between the two methods for Zn. However, our previous investigations on PBA with different rice types produced a similar outcome for Zn (Menon et al., 2021a).

Both raw and cooked brown rice contained approximately three times more Mn than white rice and approximately five times more than parboiled rice (Fig. 3(f)), and we found that the effect of rice types was statistically significant ($p < 0.0001$). However, Mn is not significantly influenced by the cooking method ($p = 0.5317$) and the interaction effect ($p = 0.5392$). The results were consistent with our previous study of the PBA method (Menon et al., 2021a). However, Gray et al. (2015) reported a 54–93 % loss of Mn in EW with a 1:6 ratio, where we observed a loss of 10–15 %, mainly from parboiled rice, similar to the findings from Mwale et al. (2018) who reported 16.5–20.8 % loss in Mn.

The concentration of Cu (Fig. 3(g)) was brown>white>parboiled. However, here we see that the loss of Cu is slightly higher in PBA

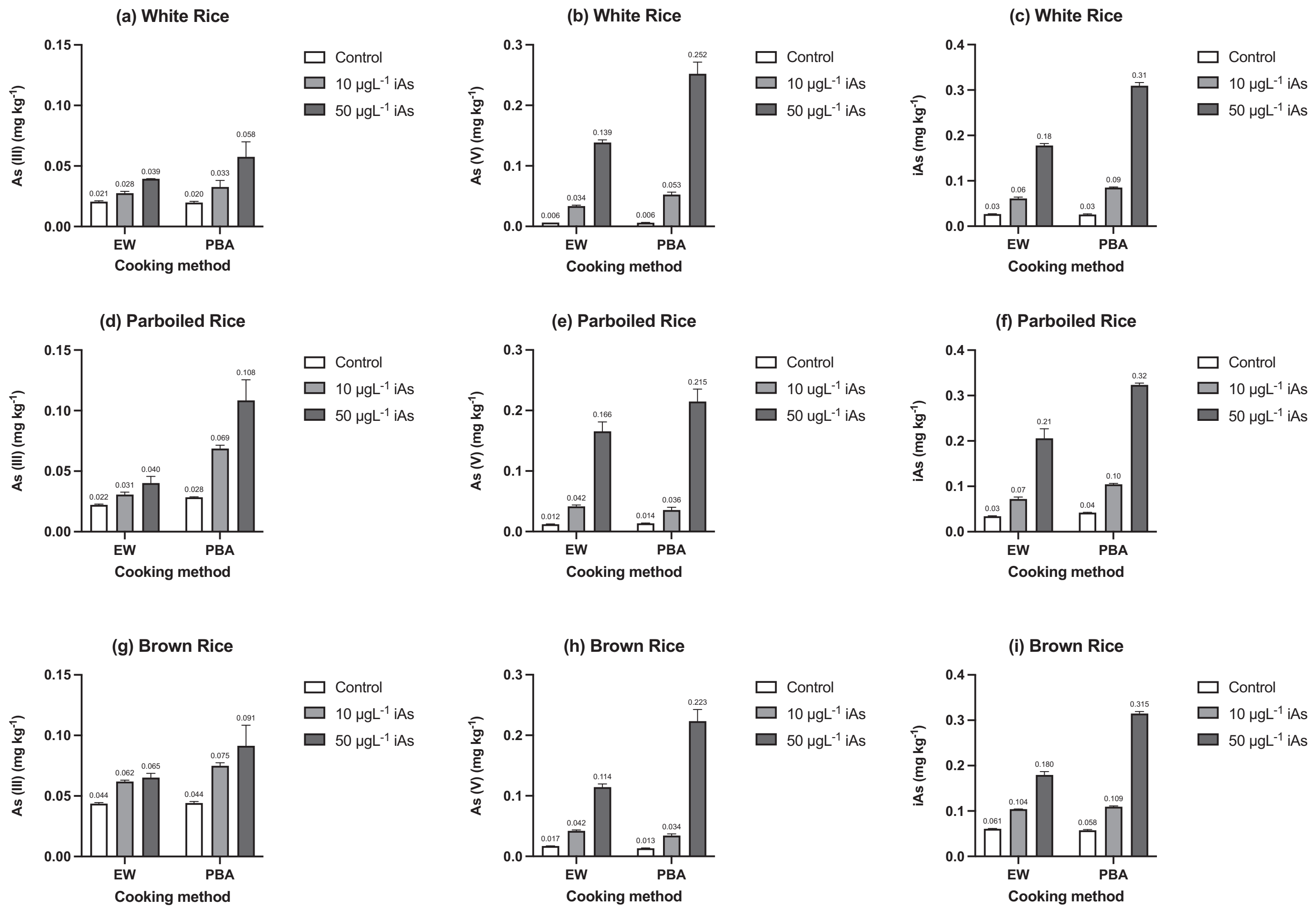

Fig. 4. (a–c). Changes in mean As (III), As (V) and iAs in white (a–c), parboiled (d–f) and brown (g–i) rice while using EW (excess water) and PBA (parboiled and absorbed) methods with 10 and 50 μg L^{-1} As (V) in the cooking water. The control was iAs-safe tap water. The error bars indicate the standard error of means (SEM).

compared to EW for white and parboiled rice types, though this was not the case for brown rice, in which EW produced greater losses than PBA. The PBA method produced losses of 5–18 % across the rice types, whereas the EW method achieved a maximum loss of 9 %.

Statistically, rice type ($p < 0.0001$), cooking method ($p = 0.0005$) and interaction ($p = 0.0051$) were found to influence Cu concentration in rice significantly. When raw, EW and PBA were compared to each other in a post-hoc comparison test, it was found that raw vs. PBA showed a significant difference ($p = 0.0004$), whereas raw vs. EW was statistically not significant ($p = 0.2784$). There was also a significant difference between EW and PBA ($p = 0.0124$). Cu loss reported by a previous study using EW (Mwale et al., 2018) was only 0.2 %, whereas 12–30 % was reported by (Sharafi et al., 2019).

The concentration of Se (Fig. 3(h)) was comparable in all rice types ($p = 0.9712$) and did not significantly alter after cooking ($p = 0.0897$). However, Mwale et al. (2018) reported a 12 % loss with the EW (1:6 ratio). For Mo, losses were ~ 35 % and 45 % for white and parboiled rice under both EW and PBA methods (Fig. 3(i)). However, the loss was 19 % in PBA compared to 43 % for EW for brown rice. Statistically, rice types ($p < 0.0001$), cooking methods ($p < 0.0001$) and their interaction ($p = 0.0004$) significantly influence Mo concentration in cooked rice. The findings were similar to a previous study (Mwale et al., 2018), which reported a 38.5 % loss under EW (1:6 ratio).

3.3. Effect of As-spiked cooking water on rice

Cooking rice with 10 or 50 μg L^{-1} As (V)-spiked cooking water increased both As species and the total iAs in all rice types (Fig. 4(a–i)). Since the spiked As comprised As (V), there were higher levels of As (V) than As (III) in the cooked rice, depending on the cooking method used. PBA tends to accumulate more As species than EW for all rice types. We also found there are some apparent differences between rice types.

For instance, for white rice, the increase in As (V) was ~6 and ~23 times when cooked with EW containing 10 and 50 μg L^{-1} As (V), and for PBA, the corresponding increase was ~23 and ~42 times. In contrast, for parboiled rice, both cooking methods showed a similar increase of As (V) by ~3 and ~15 times under 10 and 50 μg L^{-1} when As (V) was used. As (V) increased in brown rice by ~2.5 times under both methods of cooking using 10 μg L^{-1}. However, under 50 μg L^{-1}, As (V) increased 7 and 17-fold using EW and PBA, respectively. The iAs data (i.e. Fig. 4(c, f and i)) from each rice type was analysed separately using 2-way ANOVA (Table 5) and showed that the cooking method, As concentration of the cooking water and their interaction were significant ($p < 0.0001$).

In Fig. 5, we summarise the net increase in iAs for all rice types for both cooking methods while using 10 and 50 μg L^{-1} As (V) water compared to the control (i.e. cooked with As-safe tap water). The increase of iAs after cooking was white rice> parboiled rice>brown rice for all cooking methods and iAs (V) concentrations.

Under 10 μg L^{-1} EW cooking, iAs increased by 128, 111 and 72 % for white, parboiled and brown rice, respectively. There was a nearly five-fold increase in As in white (561 %) and parboiled rice (504 %) when cooked with 50 μg L^{-1}, whereas it was only 196 % for brown rice.

The PBA method using 10 μg L^{-1} As produced increases in iAs of 232, 148 and 90 % for white, parboiled and brown rice, respectively. At 50 μg L^{-1} PBA, there was a 1106 % increase in iAs obtained for white rice, 667 % for parboiled rice and 448 % for brown rice. The 2-way ANOVA test

Table 5
Two-way ANOVA results showing the effect of cooking methods, As concentrations in cooking water and their interaction on iAs.

Source of variation	SS	DF	MS	F (DFn, DFd)	p value
iAs					
White rice					
Interaction	1.49E−02	2	7.47E−03	F (2,12) = 183.2	< 0.0001
Cooking method	1.19E−02	1	1.19E−02	F (1,12) = 293.0	< 0.0001
As in cooking water	1.57E−01	2	7.85E−02	F (2, 12) = 1927	< 0.0001
Residual	4.89E−04	12	4.07E−05		
Parboiled rice					
Interaction	9.95E−03	2	4.97E−03	F (2, 12) = 20.73	0.0001
Cooking method	1.24E−02	1	1.24E−02	F (1, 12) = 51.67	< 0.0001
As in cooking water	1.70E−01	2	8.49E−02	F (2, 12) = 353.6	< 0.0001
Residual	2.88E−03	12	2.40E−04		
Brown rice					
Interaction	1.80E−02	2	9.01E−03	F (2, 12) = 233.6	< 0.0001
Cooking method	9.42E−03	1	9.42E−03	F (1, 12) = 244.1	< 0.0001
As in cooking water	1.15E−01	2	5.73E−02	F (2, 12) = 1486	< 0.0001
Residual	4.63E−04	12	3.86E−05		
oAs					
White rice					
Interaction	1.11E−05	2	5.56E−06	F (2, 12) = 1.388	0.2869
Cooking method	3.87E−06	1	3.87E−06	F (1, 12) = 0.9657	0.3452
As in cooking water	0.00012	2	5.92E−05	F (2, 12) = 14.80	0.0006
Residual	4.80E−05	12	4.00E−06		
Parboiled rice					
Interaction	5.19E−05	2	2.60E−05	F (2, 12) = 3.058	0.0845
Cooking method	2.65E−05	1	2.65E−05	F (1, 12) = 3.117	0.1029
As in cooking water	0.00011	2	5.70E−05	F (2, 12) = 6.717	0.0110
Residual	0.0001	12	8.49E−06		
Brown rice					
Interaction	4.64E−06	2	2.32E−06	F (2, 12) = 1.230	0.3265
Cooking method	1.60E−06	1	1.60E−06	F (1, 12) = 0.8468	0.3756
As in cooking water	0.00029	2	1.45E−04	F (2, 12) = 76.79	< 0.0001
Residual	2.26E−05	12	1.88E−06		

showed that rice type ($F(2, 24) = 104.2$; $p < 0.0001$), As concentration in cooking water ($F(3, 24) = 248.8$; $p < 0.0001$), as well as their interactions ($F(6, 24) = 23.61$; $p < 0.0001$), all significantly influenced iAs in the cooked rice. Post-hoc analysis of the groups (rice types) showed a significant difference between white vs. parboiled ($p < 0.0001$), white vs. brown ($p < 0.0001$) and parboiled vs. brown ($p < 0.0001$).

Broadly, there was a slight decline in oAs in all rice types when cooked with 10 or 50 μg L^{-1} As spiked water (Fig. 6(a–c)). The changes in oAs (mainly composed of DMA) in all rice types were significantly influenced by As concentration in cooking water ($p = 0.0006$ for white, $p = 0.0110$ for parboiled and $p \leq 0.0001$ for brown rice) but not by cooking methods ($p = 0.3452$ for white, $p = 0.01029$ for parboiled and $p = 0.3756$ for brown rice) or the interaction between the two factors ($p = 0.2869$ for white, $p = 0.0845$ for parboiled and $p = 0.3265$ for brown rice).

There are only two studies that are similar to our study. Signes-Pastor et al. (2012) used non-parboiled white and parboiled long-grain rice

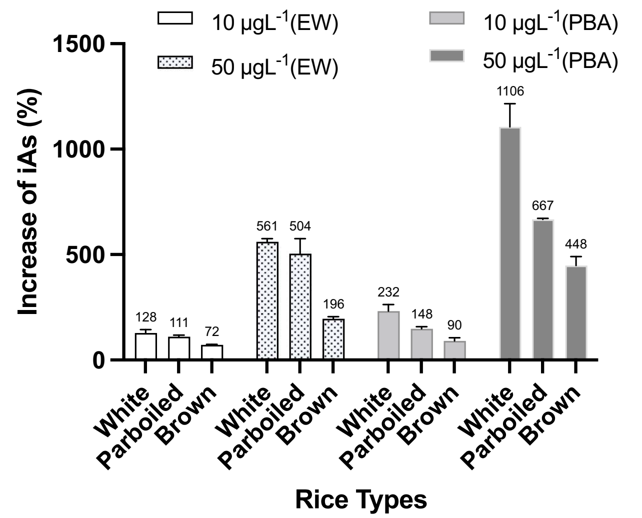

Fig. 5. Increase (%) in mean iA concentration in cooked white, parboiled and brown rice EW (excess water) and PBA (parboiled and absorbed) methods with 10 and 50 μg L^{-1} As (V) in the cooking water in comparison the control (iAs-safe tap water). The error bars indicate the standard error of means (SEM).

cooked (EW) with five different levels of As in the cooking water (0, 10, 47, 222 and 450 μg L^{-1}) - the first three levels of which are similar to ours. At 10 μg L^{-1}, the increase of As was 2 % for non-parboiled rice and 18.5 % for parboiled rice compared to rice cooked with As-safe water. However, at 47 μg L^{-1} for both rice types, the increase in As was 91 % for non-parboiled rice and 101 % for parboiled rice, which was nearly half of the value that we found in this study for white and parboiled (both long-grain) rice types cooked with 10 and 50 μg L^{-1}. Chowdhury et al. (2020) compared sunned and parboiled rice when cooked under different As concentrations in the cooking water (<3, 42 and 95 μg L^{-1}), which resulted in 256 and 531 % increase in As in cooked sunned rice in comparison to the ones cooked with As-safe water (<3 μg L^{-1}). Interestingly, parboiled rice did not show a similar increase (26 and 155 %).

In contrast, our study included brown rice, which showed the least accumulation of iAs when cooked with As (V)-spiked water compared to white and parboiled rice. This significant result suggests that brown rice could be a safer choice in regions with limited availability of iAs-safe water for cooking, reducing risk to vulnerable populations. We hypothesise that the bran layer in brown rice may act as a physical or chemical barrier, preventing the accumulation of iAs in the starchy interior part of the cooked rice, whereas in white or parboiled rice (both without the bran), the rice grain is likely to absorb and accumulate more iAs from the cooking water. Elements such as Fe or Mn are abundant in bran, and these elements may bind with iAs. The authors are currently investigating these hypotheses to provide a mechanistic understanding.

3.4. The margin of exposure (MOE)

The MOE is a straightforward risk calculator to evaluate the exposure risk, and generally, higher values (MOE > 10) are recommended and considered safe (FSA, 2016), although MOE > 1 was also used in some previous studies (Guillod-Magnin et al., 2018; Menon et al., 2021a, 2020; Rintala et al., 2014). For example, $BMDL_{0.1}$ (i.e. for a 0.1 % increase in the incidence of cancers) of 0.0003 mg kg^{-1} b.w. day^{-1} was used to assess the risks of rice and rice products.

Our MOE calculation (Table 6; detailed calculation of MOE is given in Suppl. material 3) for both the UK and Bangladesh showed a clear difference between the exposure between these populations for various rice types and the presence of iAs in the cooking water used. When As-safe water was used in the cooking, the MOE was highest for all rice types for all age groups in both countries regardless of the cooking

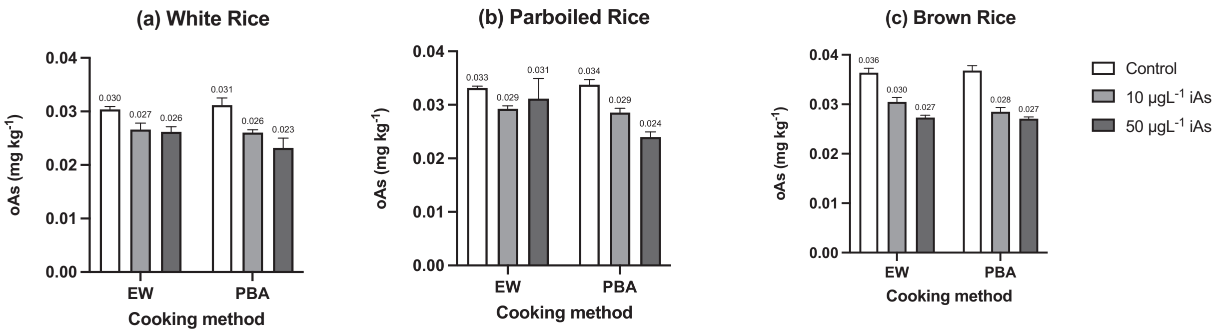

Fig. 6. (a–c). Changes in mean oAs concentration in cooked white, parboiled and brown rice using EW (excess water) and PBA (parboiled and absorbed) with 10 and 50 μg L^{-1} iAs in the cooking water. The control was iAs-safe tap water. The error bars indicate the standard error of means (SEM).

Table 6
The margin of exposure (MOE) for various target populations in the UK and Bangladesh for various rice types cooked with different iAs concentrations (10 and 50 μg L^{-1} and As-safe tap water). Detailed calculations are provided in Suppl Table 3 (Excel sheet).

	Target population	Body weight (BW) (kg)	Average daily consumption of rice (kg day^{-1})	MOE (White)		MOE (Parboiled)		MOE (Brown)	
				EW	PBA	EW	PBA	EW	PBA
UK									
Control (cooked with As-safe tap water)	Adult male	83	0.075	123.0	127.7	97.6	79.0	54.4	57.2
	Adult female	70	0.075	103.7	107.7	82.4	66.7	45.9	48.3
	7-year-old	23	0.05	51.1	53.1	40.6	32.9	22.6	23.8
	1-year-old	9	0.025	40.0	41.5	31.8	25.7	17.7	18.6
Cooked with 10 μg L^{-1} As (V)	Adult male	83	0.075	54.4	39.1	46.1	31.9	31.9	30.5
	Adult female	70	0.075	45.9	32.9	38.9	26.9	26.7	25.7
	7-year-old	23	0.05	22.6	16.2	19.2	13.3	13.3	12.7
	1-year-old	9	0.025	17.7	12.7	15.0	10.4	10.4	9.9
Cooked with 50 μg L^{-1} As (V)	Adult male	83	0.075	18.7	10.7	16.1	10.3	18.4	10.5
	Adult female	70	0.075	15.7	9.0	13.6	8.7	15.6	8.9
	7-year-old	23	0.05	7.8	4.5	6.7	4.3	7.7	4.4
	1-year-old	9	0.025	6.1	3.5	5.2	3.3	6.0	3.4
Bangladesh									
Control (cooked with As-safe tap water)	Adult male	53	0.474	12.4	12.9	9.9	8.0	5.5	5.8
	Adult female	47	0.474	11.0	11.4	8.7	7.1	4.9	5.1
	7-year-old	18	0.313	6.4	6.6	5.1	4.1	2.8	3.0
	1-year-old	8	0.075	11.9	12.3	9.4	7.6	5.2	5.5
Cooked with 10 μg L^{-1} As (V)	Adult male	53	0.474	5.5	3.9	4.7	3.2	3.2	3.1
	Adult female	47	0.474	4.9	3.5	4.1	2.9	2.9	2.7
	7-year-old	18	0.313	2.8	2.0	2.4	1.7	1.7	1.6
	1-year-old	8	0.075	5.2	3.8	4.4	3.1	3.1	2.9
Cooked with 50 μg L^{-1} As (V)	Adult male	53	0.474	1.9	1.1	1.6	1.0	1.9	1.1
	Adult female	47	0.474	1.7	1.0	1.4	0.9	1.7	0.9
	7-year-old	18	0.313	1.0	0.6	0.8	0.5	1.0	0.5
	1-year-old	8	0.075	1.8	1.0	1.6	1.0	1.8	1.0

method because we found a reduction in iAs in the cooked rice when As-safe water was used (Fig. 2). Also, EW and PBA have comparable MOEs when As-safe tap water (control) was used. For the As-safe water cooking scenario, the UK MOE values ranged from 18 to 128 across the rice types, whereas this was 3–13 for Bangladesh.

Cooking rice with 10 or 50 μg L^{-1} As-spiked water decreased the MOE (i.e. the exposure risk increases) for all rice types under both cooking methods, and the difference between the two methods was apparent (i.e. EW was found to be a safer method than PBA). This is expected with PBA because it allows the water to be fully absorbed into the rice instead of discarding it at the end of cooking, as in the case of EW. Therefore, the EW method is safer than PBA if no As-safe water is available.

However, the MOE values obtained for 10 μg L^{-1} As-spiked water were much lower (<10) for the Bangladesh population in comparison to the UK population (>10), putting all age groups at significant As-exposure risks. Bangladesh currently uses 50 μg L^{-1} as the regulatory limit for iAs in the water. Our data showed that cooking rice with 50 μg L^{-1} is unsafe as the MOE dropped to <2 for the adults and the young for Bangladesh, whereas for the UK population, MOE dropped <8, specifically for the young population. The main reason an average UK person is less exposed to iAs exposure is due to reduced average rice consumption (ADC) as well as the body weight difference of the target populations. Also, in particular, children <3 years are more exposed to iAs than adults as they consume more food relative to their body weight (Alexander et al., 2009). Therefore, preparing food using As-safe water is important to reduce the risks to infants and children. Also, cooking methods tested in this study are helpful to reduce risk further (EW or PBA) if As-safe water is used. As in the PBA, adding a parboiling step would benefit regions where rice cookers or pressure cookers are used. The use of other grains to replace rice in infant food products will reduce the As-exposure (Carey et al., 2018).

It may be noted that in this study, we calculated using rice products cooked in specific methods, and we acknowledge the fact that As-exposure could be through other sources. According to The Committee on Toxicity of Chemicals in Food, iAs contribute to approximately <12

% of total dietary arsenic in the UK population (COT, 2008). Other sources may include intake through drinking water through contaminated water and ambient air, although they are considered minor exposure routes. Apart from rice, fish could contribute to the dietary As; however, this is largely in the form of oAs (Public Health England, 2016). Based on a European dietary survey, intake of iAs was highest for infants (<12 m) and toddlers (12–36 m) through milk and dairy products, whereas for other age groups, this was grain-based products (EFSA, 2014). Furthermore, a survey by the Food Standards Agency concluded that substituting formula, cow or breast milk with rice milk could increase the exposure of iAs in infants and toddlers by up to four times (Food Standards Agency (FSA), 2009).

Consuming water and rice are still considered the main exposure pathways for the Bangladesh population. Arsenic-contaminated groundwater is present in 62 out of the 64 districts in Bangladesh (Rahaman et al., 2022) and groundwater drawn through tube wells is the primary source of drinking water for 97 % of the rural population (Flanagan et al., 2012) and the concentration of iAs ranges from 100 to 300 μg L^{-1} (Ahmad and Khan, 2015). It is estimated that 35–77 million people are exposed to >10 μg L^{-1}. Bangladesh has the highest per capita rice consumption in the world, and exposure through rice is significant, as demonstrated in this study.

On the other hand, the UK follows the WHO guideline (10 μg L^{-1}) on iAs in drinking water and the tap water we used for this experiment was 0.18 ± 0.008 μg L^{-1}. Furthermore, the UK follows the regulatory limits set for rice (European Commission, 2015) and therefore, the rice samples used in this study were within these limits. Since rice is not a staple food in the UK, the per capita daily consumption rate is very low in comparison to Bangladesh, significantly reducing the risk through rice consumption.

We acknowledge that this study used only three rice products out of several hundreds of rice products in the UK and used this data to assess the risk for two contrasting targeting populations differing in rice consumption and body weights.

However, an advantage of MOE is that it can be easily adapted to any scenario or region of interest. We also recognise that the use of 50 μg L^{-1} spiked iAs may not be a typical scenario in the UK, but it does match with current Bangladesh regulations. Further experiments are required to evaluate the risk through rice when cooked with a higher concentration of iAs in the cooking water to simulate rural areas of Bangladesh.

We urge policymakers in low-and middle-income countries that do not currently follow the WHO limit on iAs (32 % of the world population) to act on this information and call upon them to introduce the monitoring and regulations required to protect the population from further iAs exposure via food and water.

4. Conclusions

In this limited study, we compared two cooking methods (EW and PBA) and three rice types (white, parboiled and brown) under iAs-spiked water (10 or 50 μg L^{-1}). Our results showed that both EW and PBA effectively reduced the iAs concentrations in rice by >50 % for white and brown rice, whereas PBA was slightly less effective for parboiled rice than EW. Cooking methods significantly affected the retention of K, Fe, Cu and Mo; however, there was no significant difference for P, Mg, Zn, Mn and Se. As in previous investigations, this study also showed that brown rice has much higher concentrations of many essential nutrient elements than white and parboiled rice. We also found that it retained the least amount of iAs when cooked with iAs-spiked water compared to white or parboiled rice. Notably, the PBA method is also not recommended when using As-contaminated water. The evaluation of risk using the MOE suggested that cooking rice in water containing >10 μg L^{-1} iAs can raise the risk to the adults and children of the Bangladesh population due to the high per capita rice consumption. To achieve the United Nations' sustainable development goals on 'good health and well-being' (Goal 3) and 'clean water and sanitation' (Goal 6), it is crucial to implement a WHO limit of 10 μg L^{-1} iAs in countries where this limit is not currently in place.

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CRediT authorship contribution statement

Manoj Menon: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Andrea Nicholls:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Alan Smalley:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Edward Rhodes:** Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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