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Arsenic concentrations in brown rice and health risk assessment

Supalak Kongsri¹ and Chunyapuk Kukusamude^{1*}¹Nuclear Technology Research and Development Center (NTRDC), Thailand Institute of Nuclear Technology (Public Organization), 9/9 Moo 7, Saimoon, Ongkharak, Nakhon Nayok 26120, Thailand*Corresponding author: chunyapuk@tint.or.th

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Abstract

The concentration of arsenic (As) in fifty brown rice samples was analyzed using instrumental neutron activation analysis (INAA). The samples were irradiated for seven hours at the Thai Research Reactor (TRR-1/M1) in Bangkok, Thailand. After neutron irradiation, the gamma-ray intensity of the samples was measured using a high-purity germanium (HPGe) detector. The average As concentration found in the brown rice samples was 0.217 mg/kg. The As levels in the studied samples were below the Codex maximum permissible level of inorganic As (0.35 mg/kg). The estimated weekly intake (EWI) of As via brown rice consumption for males (3.176 µg/kg BW/week) and females (3.809 µg/kg BW/week) was below the previously established provisional tolerable weekly intake (PTWI) of 15 µg/kg BW. Thus, the findings suggest that the Thai population is not at significant risk of As exposure through brown rice consumption based on the EWI. However, the carcinogenic risk for both Thai males and females exceeded the acceptable risk threshold (10^{-4}), indicating a potential health concern over a lifetime of rice consumption.

Keywords: Arsenic, Carcinogenic risks, Estimated weekly intake, INAA, Thai population

1. Introduction

Rice is a staple food for more than half of the global population, with cultivation occurring in over 100 countries. Approximately 90% of global rice production originates from Asia [1]. Thailand is the second-largest rice-exporting country, following India [2]. Moreover, rice serves as the primary food source for the Thai population [3]. Rice provides a high energy content, comprising 70–80% carbohydrates, 7–8% protein, and a small proportion of fats and dietary fiber. Additionally, it contains essential vitamins and minerals, including phosphorus, magnesium, calcium, iron, niacin, and vitamins B1 and B2 [4,5]. However, despite its nutritional benefits, rice may also be contaminated with arsenic (As), which poses a potential health risk.

Arsenic contamination in rice is a matter of concern due to its toxicity. Arsenic is a naturally occurring toxic element found in soil, rocks, minerals, and water sources. Additionally, human activities such as mining, smelting, industrial processes, and agricultural practices contribute to its presence in the environment. Arsenic can accumulate in rice due to the use of pesticides, herbicides, and irrigation water containing As [6]. The element is absorbed through the roots and transported to stems, leaves, and grains. Depending on plant metabolism and methylation processes, different As forms accumulate in rice grains, altering their toxicity. Arsenic, which is chemically similar to phosphate, can replace phosphate in key enzymatic processes, thereby disrupting cellular respiration. Furthermore, As reacts with sulfhydryl groups such as glutathione and cysteine, inhibiting essential biochemical reactions and affecting organ function in living organisms [7].

Human exposure to As primarily occurs through contaminated food. Long-term exposure through inhalation, skin contact, or ingestion may lead to chronic health effects, including skin lesions, cancer, neurotoxicity,

cardiovascular diseases, and diabetes [8,9]. In particular, inorganic As is classified as a Group 1 human carcinogen by the Agency for Toxic Substances and Disease Registry [10]. Therefore, dietary exposure to As through rice consumption must be assessed to evaluate potential health risks.

Several studies have analyzed As concentrations in rice and conducted health risk assessments (HRA) using various analytical techniques, such as hydride generation atomic fluorescence spectrometry (HG-AFS) [11], atomic absorption spectrometry (AAS) [12], inductively coupled plasma optical emission spectrometry (ICP-OES) [13], inductively coupled plasma mass spectrometry (ICP-MS) [14,15], high-performance liquid chromatography coupled to ICP-MS (HPLC-ICP-MS) [16], and INAA [17]. INAA is a nuclear analytical technique that enables multi-element analysis with high sensitivity, accuracy, and non-destructive properties, without requiring concentrated acid digestion.

This study aims to:

- (i) Determine total As concentrations in brown rice samples.
- (ii) Assess the potential health risks of As exposure in the Thai population (male and female) across different age groups based on estimated daily intake (EDI), estimated weekly intake (EWI), and carcinogenic risk (CR).
- (iii) Conduct a probabilistic risk assessment using Monte Carlo simulations to evaluate cancer risk from long-term brown rice consumption.

2. Materials and methods

2.1 Sampling and sample preparation

Fifty mature brown rice samples were collected from paddy fields in southern Thailand. Due to the potential toxicity and carcinogenicity of As in rice, concentration and risk assessments were conducted. To ensure accurate analysis, the samples were carefully prepared. The rice samples were sun-dried for seven days, followed by pulverization and sieving through a 250 μm mesh. The powdered samples were then dried in an oven at 60°C until constant weight was achieved before INAA analysis.

2.2 Irradiation

Each powdered rice sample (100 mg) was weighed and sealed in polyethylene bags before being irradiated at a neutron flux of $1.8 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$ for seven hours at TRR-1/M1. The samples were left overnight (~15 hours) before gamma-ray measurement using an HPGe detector with 1.95 keV resolution at the ^{60}Co 1.33 keV gamma peak and 60% efficiency. A certified reference material (CRM), rice flour SRM 1568a (NIST, Gaithersburg, MD, USA), was irradiated alongside the samples for comparison.

2.3 Calculation of As concentration

The As concentration was determined using the following Equation (1) [18]:

$$C_{\text{sample}} = \frac{A_0 \text{ sample} \times W_{\text{standard}} \times C_{\text{standard}}}{A_0 \text{ standard} \times W_{\text{sample}}} \quad (1)$$

where C is a standard or sample concentration and W is the weight of the standard or sample. The peak area of gamma-ray activity at time = t was calculated using Equation (2):

$$A_0 = A_t e^{\lambda t} \quad (2)$$

where A_0 and A_t are the peak area of gamma-ray activity at time = 0 and time = t for the standard or sample, respectively, and λ is the decay constant.

2.4 Estimated daily intake and estimated weekly intake

HRA and As exposure via consumption of rice were estimated as in the previous method. The EDI and EWI were estimated by the following Equations (3) and (4), respectively [3,19].

$$EDI = \frac{C \times IR}{BW} \quad (3)$$

$$EWI = \frac{C \times IR \times 7}{BW} \quad (4)$$

Where C, BW, and IR represent As concentration (mg/kg), body weight (kg), and intake rate (g/day), respectively.

2.5 Carcinogenic risks

The CR is an incremental probability in developing cancer for each person's lifetime caused by an exposure to a potential carcinogen. The CR was estimated using the following Equation (5):

$$CR = EDI \times SF \quad (5)$$

Where the SF (mg/kg day) is the slope factor of the carcinogenic element (1.5 (mg/kg day) for inorganic As) [20]. Monte Carlo simulation of the obtained CR values from over the lifetime consumption of brown rice for Thai male and female population was conducted using SPSS Statistics 23 software.

3. Results and Discussion

In this study, method validation was performed using SRM 1568a to validate the analytical method. The measured value of As in the CRM was in good agreement with the certified value (0.29 mg/kg). The recovery was 96.6% and the precision (%RSD) was 4.5%, respectively. The value of LOD was 0.01 mg/kg.

3.1 Arsenic concentration in brown rice samples

The total As concentration in brown rice samples ranged from 0.067 to 0.40 mg/kg, with an average of 0.217 mg/kg. All measured inorganic As concentrations were below the Codex ML (0.35 mg/kg) [21]. Based on EFSA guidelines, inorganic As was estimated to constitute approximately 70% of total As [22]. Figure 1 shows total As and inorganic As concentration found in brown rice samples. It was found that concentrations of inorganic As found in all studied samples were less than the ML. The average, standard deviation (S.D.), minimum and maximum values are also summarized in Table 1.

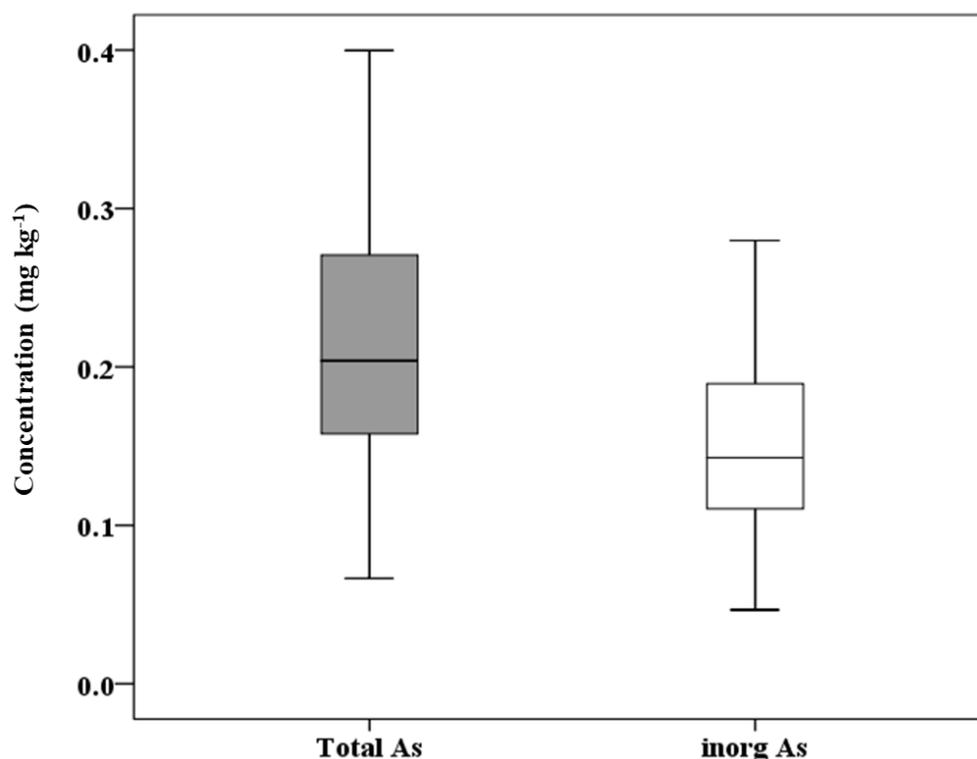


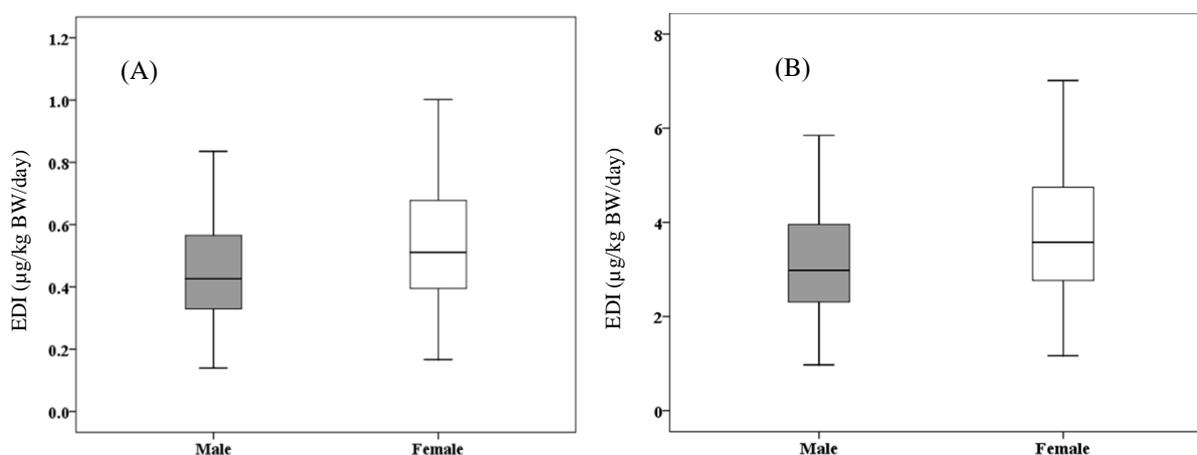
Figure 1 Box plots showing concentration (mg/kg) of total As and inorganic As (inorg As) obtained in brown rice samples.

Table 1 As concentration and estimated intake values for the Thai population.

	total As (mg/kg)	inorg As (mg/kg)	EDI ($\mu\text{g}/\text{kg BW}/\text{day}$)		EWI ($\mu\text{g}/\text{kg BW}/\text{day}$)	
			male	female	male	female
average	0.217	0.152	0.454	0.544	3.175	3.808
S.D.	0.078	0.055	0.163	0.195	1.141	1.368
min	0.067	0.047	0.139	0.167	0.974	1.168
max	0.400	0.280	0.835	1.002	5.848	7.013

3.2 Exposure from brown rice consumption

From the sufficient evidence of carcinogenicity in humans, As and inorganic As compounds classified as “carcinogenic to human” by the International Agency for Research on Cancer (IARC) [22]. In order to investigate risk assessment in exposure to As from consumption of brown rice, two categories, gender and ages were studied. The average intake rate for rice consumption per capita was 205.48 g/day [23]. The average body weight (BW) of Thai population (population size 13,442 people) in Thailand was 68.83 kg (male) and 57.40 kg (female), respectively. The average BW of each age group, 16-25, 26-35, 36-45, 46-59, and >60 years was 52.70, 56.26, 59.79, 60.05, and 58.58 kg, respectively [24]. EDI values of As for Thai male and female from consumption of brown rice were 0.45 and 0.54 $\mu\text{g}/\text{kg BW}/\text{day}$, respectively, as shown in Figure 2 (A). It was found that the EDI value of As for male population was lower than that of female population. This is because the average BW of Thai female population is lower than that of Thai male population [3]. This revealed that male population had lower risk of As exposure from consumption of brown rice. The values of EDI and EWI are also summarized in Table 1.

**Figure 2** Box plot illustrating the distribution of calculated (A) EDI and (B) EWI for Thai population.

The EWI values of As for Thai population were 3.176 $\mu\text{g}/\text{kg BW}/\text{week}$ (male) and 3.809 $\mu\text{g}/\text{kg BW}/\text{week}$ (female), respectively. Figure 2 (B) shows the distribution of calculated EWI for Thai population. The PTWI of 15 $\mu\text{g}/\text{kg BW}$, (2.1 $\mu\text{g}/\text{kg BW}/\text{day}$), was withdrawn by the Joint FAO/WHO Expert Committee on Food Additives (JECFA). As benchmark dose lower limit (BMDL) for 0.5% increased incidence of lung cancer (BMDL_{0.5}) was determined from epidemiological studies to be 3.0 $\mu\text{g}/\text{kg BW}/\text{day}$ [25]. Therefore, the previous PTWI was no longer appropriate. However, the calculated EWI values of As for Thai population were lower than the previous PTWI. In addition, the EDI of As for male and female population was > 5 and 6 times lower than the BMDL_{0.5}, respectively. This showed that Thai population was safe from exposure of As through brown rice consumption. The approximated EDI, EWI, CR, and PTWI for Thai population (male and female) and 5 different Age groups are summarized in Table 2. For different ages of Thai population, the ages and the values of EDI, EWI, and CR were dependent because the older ages have more time to expose As via rice consumption.

Table 2 Calculated EDI, EWI, PTWI, and CR of As exposure via brown rice consumption for Thai population.

Thai population	EDI±S.D. (µg/kg BW/day)	EWI±S.D. (µg/kg BW/day)	CR	PTWI (µg/kg BW)
Male	0.45±0.16	3.176±1.141	$6.80 \times 10^{-4} \pm 0.0002$	15 ^a
Female	0.54±0.20	3.809±1.368	$8.16 \times 10^{-4} \pm 0.0003$	
Age (years)				
16-25	0.14±0.05	0.99±0.35	$2.11 \times 10^{-4} \pm 0.00008$	
26-35	0.19±0.07	1.36±0.49	$2.91 \times 10^{-4} \pm 0.0001$	
36-45	0.25±0.09	1.74±0.63	$3.73 \times 10^{-4} \pm 0.0001$	
46-59	0.32±0.12	2.25±0.81	$4.82 \times 10^{-4} \pm 0.0002$	
>60	0.50±0.18	3.49±1.25	$7.47 \times 10^{-4} \pm 0.0003$	

^aThe PTWI (15 µg/kg BW) was withdrawn [3, 25].

3.3 Carcinogenic risks

Figure 3 shows the potential CR estimated for lifetime As exposure via brown rice consumption for Thai population. CR from consumption of brown rice in Thai male and female population are shown in Figure 3 (A) and 3 (B), respectively.

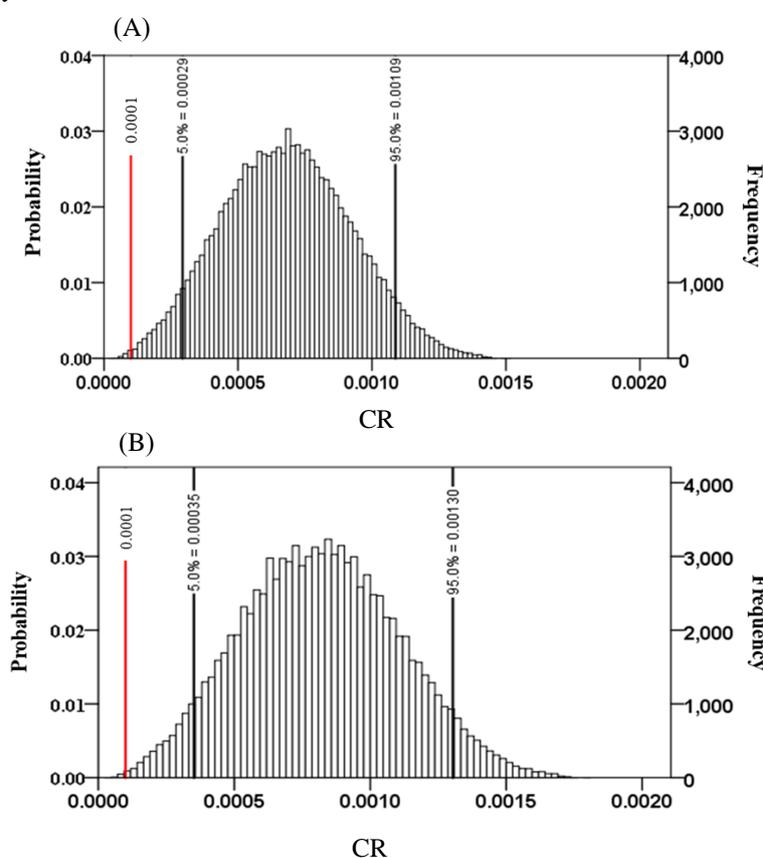


Figure 3 Simulation for CR of consumption of brown rice in Thai (A) male and (B) female population.

As depicted in Figure 3 (A and B), the CR of consumption of brown rice in Thai male and female population were 99.85% and 99.93%, respectively. Therefore, Thai population was at risk of cancer. Both Thai male and female had risks of carcinogenic effects over the lifetime consuming of brown rice as the obtained CR values were above the acceptable risk (10^{-4}). From the study, the maximum cancer probabilities resulting from brown rice consumption by Thai population were approximately 2 males and 2 females individuals in 1,000 individuals. In order to minimize the carcinogenic risks over the lifetime consuming of brown rice, it was suggested to reduce the amount of rice consumption per day [3]. In addition, farmers should avoid agricultural practices such as using agricultural contaminated water, agrochemical fertilizer, and metal-based pesticides that is possible to contaminate rice from As [3]. There is evidence that increased cancer in adults may occur as a result of exposure during childhood. For the developing of cancer, it was indicated that early expose of life is likely to be more important than exposure later in life [26]

4. Conclusions

This study demonstrated that INAA is a reliable technique for determining As concentration in rice, with a recovery of 96.6% and precision of 4.5%. The estimated EDI and EWI values were below the BMDL0.5 and previous PTWI thresholds. However, based on carcinogenic risk assessment, Thai males and females face an elevated lifetime cancer risk from brown rice consumption. To mitigate this risk, rice consumption patterns and agricultural practices should be carefully considered.

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