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CASE STUDY

Radiation hazards from natural radionuclides contained in rice from former tin mining land

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ABSTRACT

BACKGROUND AND OBJECTIVES: Rice (Oryza sativa L) cultivated at former tin mining land has the potential to absorb natural radionuclides from the soil where it grows. Radionuclides found in rice can po-tentially lead to exposure to ionizing radiation, thereby influencing the likelihood of developing. The aim of study is to assess the levels of natural radionuclides in rice, cal-culate the annual effective dose, and evaluate the additional lifetime cancer risk result-ing from radiation exposure via the consumption of rice.
METHODS: Rice sampling was carried out, then 1 kilogram was weighed and sealed in a standard Marinelli container. Placed for approximately 30 days before gamma spectrometer measurements to allow the decay products to reach secular equilibrium. Utilizing a high purity germanium detector, the radioactivity of the samples was quantified through a gamma spectrometer. Data obtained to calculate daily intake of radionu-clides, annual effective dose, and Lifetime Cancer Risk probability.
FINDINGS: Rice sourced from previous tin mining areas in Indonesia has been considered safe for consumption. While radium and uranium were not detected in the rice, elevated levels of Thorium and Potassium were observed, exceeds the reference value. The estimated annual effective dose that people receive by consuming rice is still lower than the an-nual limit for the general public recommendation and the world average. The estimat-ed risk of Indonesian people getting cancer due to rice consumption is 1.23 people per 10,000 population, lower than reference value (2.9 people per 10,000 population). The absence of cancer risk associated with this method indicates that the agricultural land in Bangka Belitung Province remains suitable for rice cultivation. This finding has holds significance within the realm of environmental risk assessment.
CONCLUSION: Rice samples obtained from former tin mining land actually did not contain the natu-ral radionuclides radium and uranium, but radionuclides thorium and potassium were found. The concentrations of radionuclides thorium and potassium exhibited varia-tions in activity levels, surpassing the reference value but remaining below the global average threshold. The annual effective dose is still lower than the average annual in-take dose in the world. The estimated risk of cancer from consuming rice was found to be 1.23 people per 10,000 population or a range of 0.55 to 2.67 people per 10,000 population who are potentially at risk of developing cancerThe lifetime risk of cancer-related death is reported to be lower than the public recommendation, with 2.9 indi-viduals per 10,000 population being affected. Rice consumers from former tin mining areas in Indonesia (Bangka) continue to be classified as safe.

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INTRODUCTION

Ingestion of natural radionuclides can result in exposure to ionizing radiation, posing a potential health risk due to the harmful effects on the human body. These radionuclides consist of charged particles and high-energy photons (Abu Bakar *et al*., 2019). These natural radionuclides are Uranium-238 (^{238}U), Thorium-232 (^{232}Th) and its derivatives Radium-226 (^{226}Ra), and Thorium-228 (^{228}Th), as well as Potassium-40 (^{40}K). Prolonged exposure to radiation emitted by naturally-occurring radionuclides carries substantial health hazards, such as the risk of developing long-term illnesses and sustaining harm to bodily organs (Moukadiri *et al.,* 2023). Uranium and its radioactive decay products have been identified as having carcinogenic properties, leading to the development of cancer in cases where human exposure surpasses established safety thresholds. Furthermore, these substances pose heightened risks associated with environmental radiation (Chen *et al.,* 2021). Prolonged exposure to uranium and its radioactive derivatives (radium) has been linked to kidney, human lungs, and respiratory system damage, ^{232}Th in lungs, liver, and skeletal tissue, while ^{40}K in muscles (Pinero-García *et al*., 2021). Previous research found transfer factor values for natural radionuclides ^{226}Ra, ^{238}U, ^{232}Th and ^{40}K in several foodstuffs (Nurtjahya *et al*., 2023). Fish, vegetables, fruit and tubers from tin mining areas contain natural radionuclides ^{226}Ra, ^{232}Th and ^{40}K (Syarbaini *et al*., 2014). Natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K were also found in foodstuffs from tin mining land in Nigeria (Muhammad *et al*, 2024). The data presented indicates the presence of natural radionuclide contamination in various food items sourced from tin mining areas. Rice serves as the primary grain in Indonesia's daily staple food diet. As a staple food for the Asian population, including Indonesia, the average consumption of rice in Indonesia is 0.222 kilogram (kg) per day per person (Central Statistics Agency, 2024). The natural radionuclides ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th, and ^{40}K are found in almost all food commodities including rice, but there will be concerns if rice plants are cultivated on former tin mining land. The government is actively expanding rice cultivation in different parts of Indonesia to address the essential requirements of the Indonesian populace and to serve as a significant revenue stream for indigenous farmers. The Bangka Belitung Province as the largest tin producer in Indonesia is one of the government's targets for rice self-sufficiency. Based on these reasons, research was conducted to determine the concentration of natural radionuclides ^{238}U, ^{232}Th and ^{40}K in rice products from former tin mining land. The assessment of radiological risks involves the calculation of daily intake of radionuclides and the annual effective dose experienced by individuals, along with the estimation of excess lifetime cancer risk (ELCR) in order to evaluate the potential long-term carcinogenic effects of consuming rice. Previous research conducted a health study on rice from the market, obtaining ^{226}Ra and ^{40}K (Muthmainah *et al*., 2020). Research on rice from former tin mining land has never been conducted in Indonesia. The primary objective of this study is to investigate the safety of rice consumption and assess the appropriateness of utilizing previously tin-mined areas for agricultural purposes. The hypothesis of this study is to determine the correlation between agricultural products from former tin mining land and cancer risk. The study seeks to assess the presence of natural radionuclides in rice, calculate the annual effective dose, and evaluate the additional lifetime risk of cancer resulting from radiation exposure through the consumption of rice. The aim of study is to assess the levels of natural radionuclides in rice, calculate the annual effective dose, and evaluate the additional lifetime cancer risk resulting from radiation exposure via the consumption of rice. The study area for this study is located between 02° 15' 0.0" south latitude to 106°00.0.00' east latitude, namely Bangka Belitung Province, Indonesia, which is known as the largest tin mining area in Indonesia. Rice was sampled in 2022-2023 from several areas, including Matras Village, Payung Village, Serdang Village, and Jelutung Village.

MATERIALS AND METHODS

Sample collection and preparation

The white rice samples (eight) and brown rice samples (three) were obtained from rice cultivation sites in Bangka Belitung Province, Indonesia, as illustrated in Fig. 1. Approximately 5 kg of each sample was placed in polyethylene plastic bags, labeled, and transferred to the laboratory (IAEA, 1989). The sample was subjected to drying at a temperature of 110 degrees Celsius (°C) in order to eliminate moisture content and achieve a consistent weight. Subsequently, it was finely ground using a grinder and sifted through 40 mesh sieves. Weighed ± 1 kg of dried sample and sealed in a standard Marinelli container

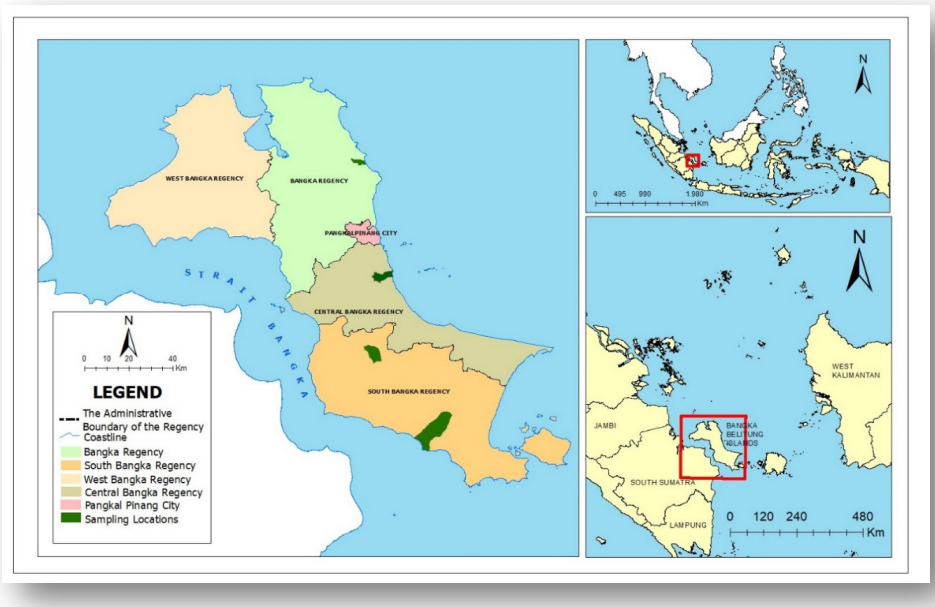


Fig. 1: Geographic location of the study area and sampling from Bangka Belitung Province, Indonesia

(volume 1 liter (L), stored for about 30 days before gamma spectrometer measurements to allow the decay products to reach secular equilibrium, following guidelines (IAEA, 1989; Olivares *et al.*, 2018).

Radionuclide measurement

The sample's radionuclides were quantified utilizing a gamma spectrometer equipped with a high-purity Germanium detector (HP Ge), coaxial p-type, and a relative efficiency of 60 percent (%). The energy calibration used 1.95 kiloelectron volt (keV) resolution (FWHM) for a peak of Cobalt-60 (^{60}Co) 1332 keV and Cesium-137 (^{137}Cs) for 24 hours. The radionuclide ^{238}U was measured as Protactinium-234 (^{234}Pa) at gamma energies of 1001 keV, ^{226}Ra was measured as Bismuth-214 (^{214}Bi) and Lead-214 (^{214}Pb) at gamma energies of 609.31 keV to 351.92 keV. Thorium-232 is measured as ^{228}Ac at 911.07 and 968.97 keV, while ^{228}Th is measured as ^{212}Pb and Talium-208 (^{208}Tl) at 238.63 keV and 583.2 keV, while ^{40}K is determined directly at energies of 1460.75 keV (Jibiri *et al.*, 2007). The assessment of uncertainty entailed the examination of variables including statistical counting, ambient noise, and systematic inaccuracies that may impact the outcome (Mellawati *et al.*, 2021). The uncertainty number displayed in the activity concentration table.

The activity concentration of radionuclide in the sample (concentration: C, Bacquerel per year (Bq/kg)

The activity concentration of radionuclides (Mellawati *et al.*, 2021) in rice samples was calculated using the efficiency formula using Eq. 1 (Jibiri *et al.*, 2007), and the uncertainty of the measurement (Mellawati *et al.*, 2021) and calculated using Eq. 2 (Jibiri *et al.*, 2007):

$$C = \frac{(Ns - Nb)}{(\varepsilon_\gamma \,.\, p\gamma \,.\, W)} \pm \sigma \quad (1)$$

$$\sigma = \sqrt{\frac{\sum(Xi - \bar{X})^2}{n}} \quad (2)$$

In this equation, C is the activity concentration of radionuclide in the sample (Bq/kg) N_S represents the gamma count rate (/s) of the sample, N_b is the background gamma count rate (/s), ε_γ is the efficiency of the HP Ge detector for a specific g-ray, p_γ the probability of gamma-ray emission, and W is the sample mass kilogram (kg), while is the uncertainty of the measurement.

Where, X_i represents the i data value, $\bar{x}$ is the average of data values, and n is the total number

of data points. For determining the minimum detectable concentration (MDC) with a 95 % confidence level, using Eq. 3 (Mellawati *et al*., 2021):

$$MDC = 4.66 \frac{\sqrt{\frac{N_b}{t^2_b}}}{\varepsilon_\gamma \cdot p_\gamma \cdot W \cdot C_f} \quad (3)$$

MDC is the minimum detectable concentration (Bq/kg), N_b is the background gamma count rate (/s), t_b is the background counting time (seconds), ε_γ is the efficiency of the HP Ge detector for a specific γ-ray, p_γ is the probability of gamma-ray emission, W is the sample mass kilogram (kg), and C_f is the self-absorption correction factor. The MDC measurement data for radionuclides ^{226}Ra, ^{238}U, ^{232}Th, ^{228}Th, and ^{40}K are 0.16; 0.26; 0.13; 0.25; and 1.35 Bq/kg.

Radiological health risk assessment (Daily radionuclide intake, estimation of effective dose due to ingestion, estimation of excess lifetime cancer risk)

The radionuclide's activity concentration is utilized in the computation of the daily intake that is deposited in the human body on a daily basis. The value is utilized in the computation of the annual effective dose in order to quantify the dose received for the purpose of implementing radiation protection protocols, as it signifies the risk associated with the effects of radiation exposure. Daily intake of radionuclides is considered to be the accumulation of ^{226}Ra, ^{238}U, ^{232}Th, ^{228}Th, and ^{40}K into the human body due to consumption of rice grown in former tin mining areas. Data on the average rice consumption level for Indonesians (per capita consumption per year) was 81.02 kg/year (Central Statistics Agency, 2024). The information provided allows for the estimation and calculation of the daily intake of radionuclides from consuming rice, as outlined in Eq. 4 (Jayasinghe *et al*. 2020; ICRP, 1996):

$$D_{in} = \frac{Ci \times Cing}{Yd} \quad (4)$$

Where, D_{in} is the individual's daily radionuclide intake (Bq/kg), C_i is the activity concentration of radionuclide (Bq/kg), C_{ing} is the per capita consumption per year, Y_d is the number of days consumed per year (365 days).

Radionuclide intake through ingestion is well described by the ICRP Human Gastrointestinal Tract Model (Jayasinghe *et al*. 2020; ICRP, 1996; Harb, 2015). The annual effective ingested dose can be calculated by multiplying the radioactivity of each radionuclide ingested per year by the dose conversion coefficient (Adedokun *et al*., 2019). The cumulative intake of radiation is calculated by adding together the individual doses of each radionuclide. Based on data on the activity concentrations of ^{232}Th, ^{228}Th and ^{40}K radionuclides detected in rice samples, as well as the amount of rice consumed per year, and the dose conversion factor for each specific radionuclide, an estimate of the annual effective dose received by the Indonesian people through rice consumption can be calculated. The annual effective dose estimation is derived from the methodology suggested by the United Nation Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (Saeed, 2011) using Eq. 5 (Adedokun *et al*., 2019):

$$AED = C \times R \times F_C \quad (5)$$

AED is the annual effective dose (Sv/y), C is the specific activity of radionuclides (Bq/kg), R is the annual rice consumption level (kg/y), for the average rice consumption of the Indonesian population is estimated at 81.02 kilogram per year(kg/y) (Central Statistics Agency, 2024) , F_C is the dose conversion factor for adult consumption (≥ 17 years) for the specific radionuclide ^{232}Th is 0.23×10^{-6} milisieverts per Becquerel (mSv/Bq), ^{228}Th is $0.7X10^{-7}$ mSv/Bq, and ^{40}K is 6.2×10^{-9} mSv/Bq. The calculation formula to obtain the estimated annual effective dose (ICRP, 1996), using Eq. 4 (Jayasinghe *et al*. 2020). The ELCR metric serves as a tool for assessing the possible carcinogenic impacts of extended ingestion of food items that contain radionuclides. As per the guidelines set by the ICRP, the risk coefficient for lethal cancer resulting from low levels of radiation exposure is 0.05 per Sievert (/Sv) (ICRP, 1996). The ELCR is calculated using an equation according to United nation UNSCEAR recommendations (UNSCEAR, 2000). The assessment of prolonged radiological risks in this investigation encompasses the mean lifespan or life expectancy (age) of the Indonesian population, with women having an average of 72.18 years and men having an average of men 70.17 years. The ELCR value data is intended to assess the potential for radiation exposure in the community and the possible biological impacts of such exposure due to rice consumption (UNSCEAR, 2000). ELCR is determined using Eq. 6 (UNSCEAR, 2000):

Table 1: The activity concentration (Bq.kg^{-1}) of ^{226}Ra, ^{238}U, ^{232}Th, ^{228}Th, and ^{40}K in Rice Samples

Sample Code	^{226}Ra	^{238}U	^{232}Th	^{228}Th	^{40}K
WR-1	< MDC	< MDC	0.26 ± 0.14	1.97 ± 0.20	42.80 ± 1.86
WR-2	< MDC	< MDC	0.39 ± 0.10	0.91 ± 0.11	40.21 ± 1.62
WR-3	< MDC	< MDC	< MDC	< MDC	25.69 ± 1.34
WR-4	< MDC	< MDC	0.19 ± 0.05	0.33 ± 0.13	54.82 ± 2.26
WR-5	< MDC	< MDC	0.58 ± 0.18	0.30 ± 0.06	66.64 ± 2.51
WR-6	< MDC	< MDC	0.37 ± 0.15	0.40 ± 0.08	30.43 ± 1.31
WR-7	< MDC	< MDC	0.57 ± 0.19	0.68 ± 0.28	30.20 ± 2.13
WR-8	< MDC	< MDC	1.91 ± 0.47	0.99 ± 1.41	61.64 ± 4.05
BR-1	< MDC	< MDC	0.23 ± 0.12	0.26 ± 0.03	40.61 ± 1.60
BR-2	< MDC	< MDC	0.16 ± 0.10	< MDC	48.46 ± 1.94
BR-3	< MDC	< MDC	< MDC	< MDC	44.45 ± 1.40
Min	< 0.16	< 0.26	< 0.13	< 0.25	25.69
Max	-	-	1.91	1.97	66.64
Average:	-	-	0.41	0.53	44.18
Range:	< MDC	< MDC	< 0.13–1.91	< 0.25–1.97	25.69–66.64
(UNSCEAR, 2000) (2000)	0.08	0.02	0.003	0.003	-

Note: WR is white rice, BR is brown rice

$$ELCR = AED \times DL \times RF \quad (6)$$

ELCR is Excess lifetime cancer risk, AED is the annual effective dose due to ingestion Sievert per year (Sv/y), DL is the average of life duration or the lifetime expectancy of Indonesian people is 74.18 for females, and 70.17 for males (Central Statistics Agency, 2024).

RESULTS AND DISCUSSION

Activity concentration of radionuclides

The activity concentrations of radionuclides in the white and brown rice samples are shown in Table 1.

The analysis results of eleven rice samples planted on former tin mining land in different villages showed that natural radionuclides ^{226}Ra and ^{238}U were not detected in either white or brown rice or their activity concentration was lower than the MDC as shown in Table 1. Radionuclides ^{232}Th and ^{228}Th were detected in almost all rice samples analyzed. Thorium and descendants have the potential to cause harm to the kidneys, liver, and lungs within the human body. After three days of exposure to thorium and thoron, physiological alterations in the lung, liver, and kidney are observed (Chaudhury *et al*., 2022). Statisticaly, concentrations of radionuclides varied, ^{40}K 25.69 to 66.64 Bq/kg, ^{232}Th <0.13 to 1.91 Bq/kg and ^{228}Th, <0.26 to 1.97 Bq/kg. Based on Internation Atomic Energy Agency (IAEA) guidelines (2016), the activity concentration has exceeded the reference value recommended by UNSCEAR (UNSCEAR, 2000). The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in rice samples in this study were compared with the same conditions (tin mines) in Nigeria, showing that the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in the rice samples were higher, 7.02; 8.18; and 123.98 Bq/kg (Muhammad *et al*, 2024). In a similar study, rice planted on land 20-50 km from tin mines in Nigeria also contained higher levels of ^{226}Ra, ^{232}Th, and ^{40}K, with each activity 28.01; 44.19; and 35.76 Bq/kg (Abdullahi *et al*, 2018). The fluctuation in radionuclide levels as indicated in Table 1 may be attributed to geological influences (Li *et al.*, 2024). The composition of the soil (Paiva *et al*., 2019) and underlying rocks formation can influence radionuclide concentrations (Kamunda *et al*., 2016). Certain mineral and geological formations may contain higher levels of radioctive elements like ^{232}Th, ^{228}Th ^{226}Ra and ^{238}U, which can affect soil (Li *et al.*, 2024) and subsequently crop uptake (Mellawati and Nurtjahya, 2023). Monitoring this concentration variation is crucial. Tracking changes over an extended period allows for the assessment of the effectiveness of actions taken on previously mined tin land. Epidemiological studies and biomonitoring offer valuable insights into the cumulative impacts of radiation exposure on human health, highlighting the significance of these implications in understanding the effects on the population (Syaiful Anwar and Yuniarti, 2022).

In general, ^{226}Ra, ^{232}Th, ^{40}K are found in rice and their values vary greatly. According to the literature, researchers from several countries in the world have reported that the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K each range between 1.08 to 109.26; 0.70 to 71.97; and 24.05 to 691.71 Bq/kg, even though the rice sample did not come from a former tin mining area (Table

Table 2: The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Bq/kg) in Rice samples investigated in the presence study compared with those reported in the literature

Origin	^{226}Ra	^{232}Th	^{40}K	Sources
Malaysia (Penang)	1.42	1.03	72.15	Alsaffar *et al*., 2015
Saudi Arabia	1,23	0.70	154.83	Al-Hassan *et al*., 2014
Italy	2.90	2.80	119.30	Desideri *et al*., 2014
India	3.07	34.30	120.80	Shanti *et al*. 2009
India	86.75	53.73	331.24	Najam *et al*., 2015
Ghana	4.72	4.33	104.36	Awudu *et al*. 2012
Saudi Arabia	1.08	1.19	83.08	Al-Zahrani, 2016
Iran	1.55	2.19	110.56	Pourimani and Anoosheh, 2015
Taiwan	0.62	-	24.05	Huang *et al*. 2023
Pakistan	1.50	1.00	195.80	Al-Hassan *et al*., 2014
Thailand	80.20	40.70	500.76	Najam *et al*., 2015
Iraq	51.15	71.97	691.71	Najam *et al*., 2015
Turkey	80.82	43.31	483.22	Najam *et al*., 2015
USA	109.26	13.67	231.87	Najam *et al*., 2015
Pakistan	73.45	32.56	502.71	Najam *et al*., 2015
Uruguay	107.21	17.85	305.91	Najam *et al*., 2015
Indonesia (Padang)	1.12	< 0.26	28.44	Muthmainah *et al*., 2020
Indonesia (Bangka)	< 0.16	0.41	44.18	Present study

2). The findings of this study indicate that the levels of natural radionuclides in the rice samples analyzed remain within acceptable limits. The study conducted by researchers hailing from India revealed that rice samples sourced from Thailand, Iraq, Turkey, the United States of America (USA), Pakistan, and Uruguay exhibited significantly elevated concentrations of ^{226}Ra (51.15 to 109.26 Bq/kg). Likewise, the radionuclide ^{232}Th ranges from 13.67 to 71.97 Bq/kg, and ^{40}K ranges from 231.87 to 691.71 Bq/kg (Najam *et al*., 2015). Rice samples from former tin mining land in Indonesia (Bangka) only contained relatively low radionuclides ^{232}Th, ^{228}Th, and ^{40}K, although they exceeded the reference levels recommended by UNSCEAR. Almost everyone who researched the radionuclide content in rice found that the activity concentration of ^{40}K radionuclides in rice tended to be higher than that of ^{226}Ra, ^{232}Th, and ^{228}Th, as shown in Table 2. The elevated concentration of ^{40}K in comparison to other radionuclides can be attributed to its prevalence in the soil and the widespread application of Nitrogen Phosphate Potassium (NPK) fertilizer during rice cultivation (Solehah and Samat, 2017). The hierarchy of radionuclide activity concentrations in rice generally follows the order: of ^{40}K > ^{232}Th > ^{238}U (Ugbede *et al*., 2021). These findings indicate that rice plants cultivated on former mining land have the potential to accumulate natural radionuclides, a similar phenomenon also observed in Indonesia (Bangka Belitung Province). Compared to rice from non-former mining land does not contain the radionuclide ^{232}Th, only ^{226}Ra. The absence of any previous mining activity suggests that the land in question does not pose any potential radiological health hazards. The activity concentration of ^{232}Th 1.12 Bq/kg and ^{40}K 28.44 Bq/kg (Muthmainnah *et al*., 2020), lower than research results. However, in all these cases, the concentrations recorded were within the safe limits set by the IAEA (UNSCEAR, 2000).

Daily radionuclide intake (Bq/day)

The accumulation of ^{232}Th, ^{228}Th, and ^{40}K in the human body through the daily intake of radionuclides from rice consumption is detailed in Table 3.

Data on the average level of rice consumption in Indonesia is 81.02 kilogram per year (kg/y) or 222 gram per day (g/d), and in this case, consumption of rice causes a daily intake averages ^{232}Th, ^{228}Th, and ^{40}K, on as much as 0.09; 0.12; and 9.81 Bq/day. The intake of radionuclides ^{232}Th and ^{228}Th was found to be at a maximum of 0.43 and 0.44 Bq/day, respectively. It is worth noting that ^{40}K contributed the highest daily intake among the radionuclides measured, at 5.70–14.79 Bq/day. Plants, including rice, have a significant requirement for potassium as an essential macronutrient, leading to the abundant presence of ^{40}K. (Islam *et al*., 2014). The use of NPK fertilizer during farming activities is also the cause of an increase in ^{40}K radionuclides in crop yields (rice), especially if farmers use high doses (Jibiri *et al*., 2007). This is due to the abun-

Table 3: The average daily intake (Bq/day), the annual effective dose (x10^{-6}), and ELCR value

Sample	Average daily intake (Bq/day)			Average annual effective dose (x10^{-6} mSv/y)				Excess lifetime Cancer Risk (x10^{-6})			
Code	^{232}Th	^{228}Th	^{40}K	^{232}Th	^{228}Th	^{40}K	Total	^{232}Th	^{228}Th	^{40}K	Total
WR-1	0.06	0.44	9.50	4.81	11.16	21.50	37.47	0.1735	0.4028	0.7759	135.23
WR-2	0.09	0.20	8.93	7.33	5,14	20.20	32.67	0.2647	0.1854	0.7289	117.91
WR-3	N	0.07	5.70	N	1.85	12.91	14.76	N	6.6912	0.4658	53.27
WR-4	0.04	0.10	12.17	3.54	2.47	27.54	33.54	0.1279	8.8991	0.9938	121.06
WR-5	0.13	0.07	6.76	1.0.89	1.70	15.28	27.87	0.3931	0.6122	0.5516	100.59
WR-6	0.08	0.09	14.79	6,85	2.25	33.47	42.58	0.2472	0.8129	0.0121	153.66
WR-7	0.42	0.22	13.69	35.65	5.61	30.96	72.23	0.0129	0.2026	0.0118	260.67
WR-8	0.13	0.15	6.70	10.69	3.86	15.17	29.72	0.3858	0.1392	0.5475	107.24
BR-1	0.04	N	10.76	2.97	N	24.34	27.31	0.1072	N	0.8785	98.57
BR-2	0.05	0.06	9.02	4.32	1.49	20.40	26.20	0.1557	5.3611	0.7361	94.55
BR-3	N	N	9.87	N	N	22.33	22.33	N	N	0.8058	80.58

Note: N=none

dance of ^{40}K radionuclides in nature, and the importance of this element in the growth of rice plants. The gamma dose levels (Table 3) resulting from the ingestion of radionuclides ^{232}Th, ^{228}Th, and ^{40}K in the rice samples analyzed varied between 0.0136 and 0.0722 microsievert per year (µSv/year), with an average of 0.03 µSv/year. It is important to note that these doses solely account for the impact of rice consumption and do not consider other variables like cooking methods or the inclusion of food additives like spices and salt. This value is lower than the world average (0.29 mSv/y) (UNSCEAR 2000) and the limit for the public (1 mSv/y) (ICRP 1996). In addition, the value is also smaller than that reported by Bangladesh: 64.23 µSv/y (Nahar *et al*., 2018), Iran: 20.50 to 68.40 µSv/y (Pourimani and Anoosheh, 2015), Nigeria: 38.60 µSv/y (Muhammad *et al*., 2024), and Saudi Arabia: 0.22 µSv/y (Al-Zahrani, 2016). Therefore, it is also important to calculate the risk of cancer (ELCR).

The excess lifetime cancer risk (ELCR)

The ELCR due to consumption of rice containing radionuclides is shown in Table 3. The estimated risk for the population in Indonesia in the range is 0.55 to 2.67 people or 1.23 people (mean) per ten thousand population lower than the UNSCEAR recommended value of 0.29 x 10^{-3} (Najam *et al.*, 2015; UNSCEAR, 2000). This value is smaller than that reported in Nigeria 1.34 (Abdullahi *et al*, 2018) and 4.5 people per ten thousand population (Muhammad *et al*., 2024). The evaluation of cancer risk associated with radiation hazards in the current study aligns with findings from nations with tin mining activities. Another illustration can be seen in the cultivation of vegetables in Peninsular Malaysia. Vegetables do not pose a significant radiological risk to individuals, even in the presence of elevated levels of radionuclides in the soil. The soil samples analyzed in this study exhibit external hazard indices below one, indicating their suitability for agricultural purposes (Solehah and Samat, 2017). The implications for public health in former tin mining areas are the nutritional conditions, which are caused by landscape changes and pollution (Efrizal, 2020). This information is not in line with research results which prove that former tin mining land is still suitable for agricultural use. Policy makers are faced with the challenge of enhancing the utilization of land in areas previously used for tin mining. It is imperative to enhance the nutritional status by carefully choosing agricultural products that are well-suited for cultivation on former mining sites (Efrizal, 2020). The local and central governments are paying more attention to reclamation, since it has been proven that former tin mining land can be used for rice farming. Policies aimed at public health and agricultural productivity may provide further research opportunities (Syaiful Anwar and Yuniarti, 2022). The study indicates a possibility of increasing agricultural operations in previous mining regions; however, it is essential to exercise caution regarding environmental and public health issues, particularly in locations with a background of mining activities. Mining of mineral ore is regarded one of the anthropogenic ways of increasing the activity-concentrations of natural radionuclide in the environment, which pose hazards if the accumulate in crops and are consumed by humans (Abdullahi *et al*, 2018).

CONCLUSION

The research results showed that rice samples obtained from former tin mining land did not contain the natural radionuclides ^{226}Ra and ^{238}U, but only contained the natural radionuclides ^{232}Th, ^{228}Th and ^{40}K. The activity concentrations of radionuclides ^{232}Th, ^{228}Th, and ^{40}K are quite variable with range between < 0.13 to 1.91 Bq/kg (average: 0.47 Bq/kg), < 0.25 to 1.97 Bq/kg (average: 0.57 Bq/kg), and 25.69 to 66.64 Bq/kg (average: 44.18 Bq/kg). This amount has exceeded the reference values set by UNSCEAR *viz,* ^{232}Th and ^{228}Th of 0.03 Bq/kg respectively. Although it is still lower than the average reported by several countries in the world, *viz*, ^{232}Th is 20.04 Bq/kg while ^{40}K is 237.22 Bq/kg. The collective mean daily consumption of radionuclides ^{232}Th, ^{228}Th, and ^{40}K from consuming rice varied between 5.78 to 14.96 Bq/d, with an average. The daily intake of radionuclides comes from ^{232}Th as much as 0.09 Bq/d, ^{228}Th 0.13 Bq/d, and ^{40}K 9.81 Bq/d. In facts that ^{40}K radionuclide is the largest contributor to daily intake of radionuclides. The average of total annual effective dose received by rice consumers shows a range between 0.15 to 0.72 x 10^{-3} µSv/y, or the average is 0.33x10^{-3} µSv. This effective dose comes from the daily intake of radionuclide ^{232}Th of 0.29 x 10^{-3} µSv, ^{228}Th 0.12 x 10^{-3} µSv, and ^{40}K 0.82 x 10^{-3} µSv. Nevertheless, this quantity remains below the global average annual effective dose of 0.29 mSv/y and the public limit set by ICRP recommendations of 1 mSv/y. Estimates of the lifetime risk of cancer in residents who consume rice from former tin mining areas show that as many as 1.23 people or ranging from 0.55 to 2.67 people per ten thousand population have a potential risk of developing cancer. The findings of this study indicate that the lifetime probability of cancer-related mortality is below the permissible threshold, specifically at 2.9 individuals per ten thousand members of the population. Based on the data presented, the conclusion drawn is that consuming rice grown on former tin mining land in Indonesia (Bangka Belitung Province) is considered safe. The study indicates that the land remains suitable for rice cultivation with no major safety issues. This discovery paves the way for the potential expansion of agricultural practices into regions once designated for mining purposes. The implication of these findings is that local and central governments could potentially reconsider regulations concerning the management of former mining land. The implementation of regulations and policy that prioritize public health, give a chance to facilitate ongoing research. The study focused on improving the caliber of agricultural goods cultivated on land that has been mined. Overall, the research points toward a positive outlook regarding the safety and usability of former tin mining land for agriculture, providing basis for policy review and potential expansion of agriculture activities in such areas.

AUTHOR CONTRIBUTIONS

J. Mellawati performed the conceptualization, methodology, supervision, project administration, writing, original draft preparation. N. Madyaningarum performed the writing, review, editing. E. A. Fajrianshah performed the visualization, formal analysis. E.B. Jumpeno helped in the methodology, review, editing. T.R.D. Larasati helped in sampling, formal analysis. N. Mulyana performed the formal analysis. E. Nurtjahya performed the project administration, investigation, resources. K. Khotimah helped in writing, review, editing, formal analysis.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
^{228}Ac	Actinium-228
AED	Annual effective dose
^{214}Bi	Bismuth-214
Bq/day	Becquerel per day
Bq/kg	Becquerel per kilogram
C	Activity concentration
^{o}C	Degree Celsius
C_f	The self-absorption correction factor
C_i	The activity concentration of radionuclide
C_{ing}	The per capita consumption per year
^{60}Co	Cobalt-60
D_{in}	The individual's daily radionuclide intake
DL	Duration of life
ELCR	Excess lifetime cancer risk
F_c	Dose conversion factor for adult consumption
g/y	Gram per year
g/d	Gram per day
IAEA	International Atomic Energy Agency
ICRP	The International Commission on Radiological Protection
^{40}K	Kalium-40
Kg	Kilogram
Kg/y	Kilogram per year
keV	Kiloelectron volt
L	Liter
MDC	Minimum detectable concentration
mSv/y	Millisieverts per year
NPK	Nitrogen phosphate potassium
N_s	Represents the gamma count rate
N_b	The background gamma count rate
^{234}Pa	Protactinium-234
^{214}Pb	Lead-214
^{212}Pb	Lead-218
p_γ	The probability of gamma-ray emission
R	Annual rice consumption level
^{226}Ra	Radium-226
RF	Risk Factor
/S	Per seconds
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USA	United State of America
/Sv	Per sieverts
Sv/y	Sievert per year
^{232}Th	Thorium-232
^{228}Th	Thorium-228
^{208}Tl	Talium-208
tb	Background counting time
^{238}U	Uranium-238

W	The sample mass
Y_d	Number of days consumed per year
$\mu Sv/y$	Microsieverts per year
ε_γ	The efficiency of the HP Ge detector

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