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Study of soil–to–plant transfer factors (TFs) of ^{226}Ra, ^{232}Th, and ^{40}K on plants cultivated on ex–tin mining land in Bangka Belitung, Indonesia

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ABSTRACT

Soil-to-plant transfer factors (TFs) are of fundamental importance in measuring the environmental impact due to the presence of radioactivity in soil and agricultural crops. The present study thus to measure soil-to-plant TFs of ^{226}Ra, ^{232}Th, and ^{40}K on horticultural plants cultivated on ex–tin mining land in Bangka Belitung islands. There were 21 samples of 15 species and 13 families from 17 locations comprising four vegetables species, five fruits species, three staple foods species, and three others. The TFs were measured in leaves, fruit, cereal, kernel, shoot, or rhizome. The results showed that ^{238}U and ^{137}Cs were almost not found in plants, whereas ^{226}Ra, ^{232}Th, and ^{40}K were measured. In soursop leaf, common pepper leaf, and cassava peel, on ^{226}Ra, the TFs for the non–edible parts, (0.42 ± 0.02; 1.05 ± 0.17; 0.32 ± 0.01 respectively) were significantly higher than soursop fruit, common pepper seed, and cassava root for the edible parts (0.01 ± 0.005; 0.29 ± 0.09; 0.04 ± 0.02 respectively).

1. Introduction

Tailings produced from tin-mining activities containing elevated levels of natural radionuclides (^{238}U, ^{232}Th, and ^{40}K) need to be disposed properly to prevent contamination (Adesiji, 2021).

The mining operations is found to have significantly affected the radionuclides concentration levels in the farmlands where tin spoil are in mix with the soil (Jibiri et al., 2011). Bangka Belitung islands of Indonesia has natural background radioactivity higher than undisturbed land because of tin mining operations (Syarbaini et al., 2014). The knowledge of natural radionuclides in contaminated farmlands is important because of possible accumulation and radiological implication in crops grown on tin spoils (Adesiji, 2021).

Radionuclide contamination of plants can occur after plants absorb water and mineral nutrients from soil contaminated with radionuclides. Of course, several chemical-physical factors will affect the transfer of radionuclides from soil to plants. The transfer factor (TF) of natural radionuclides is an important parameter for predicting migration and accumulation of radionuclides in the food chain (Adesiji, 2021). However, there is deficiency of information on the radionuclides in tin mining areas. According to the IAEA (2010), soil–to–plant transfer factors (TF) are the ratio of Bq.kg^{-1} dry weight of the plant to Bq.kg^{-1} of soil dry weight, and this can be used as an indicator of the ability of plants to absorb radionuclides (IAEA, 2009).

Several studies have been conducted in many countries to evaluate soil-to-plant TFs of natural radionuclides for staple food crops, vegetables, and timber species (Kolo et al., 2021; Aouidi et al., 2021; Van et al., 2021; Van et al., 2020; Ugbede et al., 2021; Solehah et al., 2016; Asaduzzaman et al., 2014).

Several radionuclides are known as naturally occurring radioactive materials (NORM), and these include ^{238}U, ^{232}Th, and their decay series, ^{226}Ra, ^{228}Th, and single decay radionuclides such as ^{40}K. These are ubiquitous but may be at elevated concentrations in mining areas including tin mines (Okeme et al., 2016; Irzon et al., 2018; Jibiri et al., 2011; Syarbaini et al., 2014; Adesiji, 2021).

Radium is similar to calcium, easily soluble, and forms compounds that can enter the human body. Internal contamination causes bone cancer, malignant tumors, leukemia, and anaplastic anemia, while

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thorium can cause biological effects on the lungs, liver, bones, and kidneys (Syaifudin et al., 2003). There are regulations for the natural radionuclides ^{226}Ra and ^{232}Th but there is none for ^{40}K in food. In relation to the radiation hazard, the Indonesian Minister of Health Regulation Number 70 of 2016 only regulates ^{40}K in drinking water for beta exposure (Regulation of the Minister of Health of the Republic of Indonesia Number 70, 2016).

Waste from inland tin mining has properties different from the unimpacted soil: the sand faction increases from about 70% to 97%, the macronutrient concentrations decline, C–organics are less than 2%, and the cation-exchange capacity (CEC) is very low (Nurtjahya and Agustina, 2015). To restore the land damaged by mining and to create an alternative economy for rural communities in the post-mining era in Bangka and Belitung, the Government encourages the private sector to cultivate former tin mining land as agricultural land. The agricultural businesses on tin spoils can be used as an indicator of the success of post-mining reclamation (Asmarhansyah and Hasan, 2018).

The problem is when contaminated land is used for food crop cultivation. The NORM radionuclides can enter the human food chain (Agus et al., 2017; Atipo et al., 2020).

The TF which varies with type of plant, soil characteristics, agricultural fertilizer management, manure application, climate, and the physical and chemical properties of the radionuclides (Okeme et al., 2016), is considered one of the important parameters used for environmental safety assessment, especially in nuclear-related environments. The purpose of the investigation is to identify the species of vegetables, fruits, or other food plants that are low accumulators of radioactive elements. This research has therefore become unavoidable to ensure that all agricultural products meet international safety standards from a radiation protection point of view. The findings will be used for recommendations to farmers who use tin spoils as agricultural land.

2. Material and methods

2.1. Study area

The land area of Bangka Belitung Province is approximately 16,42 km^2, at 104^0 50′ to 109^0 30′ east longitude and 0^0 50′ to 4^0 10′ south latitude. The Province of Bangka Belitung Islands is the largest tin producer in Indonesia and an area of 400 ha of former tin mining has been reclaimed into agricultural land by PT Timah Tbk., a publicly listed tin company (Fajrian, 2021). The soil and plant samples in this study were collected from farms using former tin mined land and from undisturbed sites in 3 regencies in Bangka and Belitung islands. The soil and plant samples were collected from 17 to 15 villages respectively. There were two villages had two plant locations each.

2.2. Sample preparation

2.2.1. Soil sample

One to two kg of composite soil samples were taken by 10 cm auger from every of 17 locations (Table 1) at a depth of 10–20 cm. The composite sample consisted of 5 sub-sites in each location, four diagonal points, and one in the center. The samples were put into plastic bags and transported to the laboratory. The soil was separated from impurities such as dry roots, stone, grasses, and other residual parts and dried in an oven at 110 °C to a constant weight. The dried soil sample was crushed, homogenized, sieved through a 2 mm sieve, and weighed into the Marinelli container. The Marinelli was sealed and stored for 30 days to allow radon and its short-lived progeny to reach secular radioactive equilibrium prior to measurements by gamma spectroscopy (USDOE, 1997).

2.2.2. Plant sample

There were 21 samples of 15 species and 13 families from 17 locations (Table 1), comprising four vegetables (spinach, chili pepper, cucumber, tomato), five fruits (papaya fruit and leaf, soursop fruit and leaf, guava, key lime, and dragon fruit), three staple foods (corn, cassava root and leaf, four varieties of brown rice, and two varieties of white rice), and three others (galangal rhizome, common pepper seed and leaf, and oil palm kernel). The number of individual samples of common pepper seed, common pepper leaf, oil palm kernel, soursop leaf and

Table 1
Soil and plant sample location.

Location/ sample code	Coordinates		Crops (vegetable, fruit, and others)	Soil Code	Plant Code
	Latitude (S)	Longitude (E)			
Gunung Pelawan, Bangka	1° 36′ 10.0″	105° 48′ 39.0″	tomato, cucumber, spinach, chili pepper, cassava root and leaf, papaya	S-1	Sp-1
Gunung Pelawan, Bangka	1° 35′ 02.0″	105° 50′ 09″	papaya, cassava root and peel		Sp-2
Jelitik, Bangka	1° 53′ 18.0″	106° 10′ 27.0″	tomato, cucumber, chili pepper, papaya fruit and leaf, cassava root and leaf, key lime	S-2	Sp-3
Balunijuk, Bangka	2° 3′ 39″	106° 4′ 30″	tomato, cucumber, chili pepper, spinach, key lime, common guava	S-3	Sp-12
Mayang, East Belitung	2° 41′ 53″	108° 6′ 31″	chili pepper	S-4	Sp-14
Jelitik, Bangka	1° 53′ 33″	106° 10′ 01″	papaya, cassava leaf		Sp-4
Lenggang, East Belitung	2° 57′ 36″	108° 9′ 13″	papaya fruit and leaf	S-5	Sp-9
Selingsing, East Belitung	2° 54′ 02″	108° 8′ 54″	chili, common pepper seed, dragon fruit		Sp-5
Riding Panjang, Bangka	1° 59′ 47″	106° 6′ 48″	cassava root, peel and leaf, galangal rhizome, key lime, common guava, oil palm kernel	S-6	Sp-10
Matras, Bangka	1° 47′ 22″	106° 5′ 39″	galangal rhizome, corn, white rice	S-7	Sp-6
Petaling, Bangka	2° 7′ 4.5″	106° 0′ 6.9″	galangal rhizome	S-8	Sp-13
Payung, South Bangka	2° 36′ 54.76″	106° 11′ 31.88″	white rice, corn	S-9	
Payung, South Bangka	2° 33.4′ 15.4″	106° 8′ 12.3″	corn, white rice, brown rice		Sp-16
Serdang, South Bangka	2° 55′ 31.1″	106° 20′ 14.3″	white rice (4 varieties), brown rice (2 varieties)	S-10	Sp-15
Rebo, Bangka	1° 54′ 52″	106° 8′ 19″	common pepper seed and leaf	S-11	Sp-8
Kimak, Bangka	1° 55′ 27″	106° 3′ 37″	soursop fruit and leaf	S-12	Sp-17
Permis, South Bangka	2° 30′ 32″	106° 0′ 54″	soursop fruit and leaf	S-13	Sp-11
Bangka Kota, South Bangka	2° 29′ 9,71″	106° 0′ 38,05″	soursop fruit and leaf	S-14	
Rambak, Bangka	1° 52′ 13.44″	106° 1′ 17.34″	oil palm kernel	S-15	
Air Duren, Bangka	2° 6′ 19.7″	106° 1′ 14.4″	oil palm kernel	S-16	Sp-7
Air Nyatoh, Gunung Muda, Bangka	1° 39′ 34.59″	105° 48′ 10.47″	papaya, cassava root, galangal rhizome	S-17	

cassava peel are 2 respectively, 6 individual samples of white rice, 4 individual samples each for tomato, papaya fruit, and cassava root, and 3 individual samples each for cucumber, spinach, chilli pepper, papaya leaf, cassava leaf, key lime, common guava, red dragon fruit, galangal rhizome, corn, and brown rice (Table 2). Samples were put into plastic bags and brought to the laboratory. There they were carefully washed. The fresh sample was weighed, then dried at 105 °C to a constant weight. The dry sample was crushed, and weighed 250 g into a Marinelli container, tightly closed, and allowed to stand for approximately 30 days to reach secular equilibrium before further gamma spectrometer measurements were taken (Mellawati et al., 2021).

2.2.3. Radioactivity analysis

Environmental radiation doses were measured (*in-situ*) at 4 former tin lands, 1 control at the surface, and a 1-m height in the study area with 5-point samplings as replicates of each parameter in each site. Portable radiation survey equipment used is survey meter Ludlum-19 from LUDLUM Measurement Incorporations, USA.

Table 2
The average of soil-to-plant transfer factors dry weight vegetable to dry weight soil.

Sample	Scientific name	Transfer factor (AM ± SE)		
Vegetables		^{226}Ra	^{232}Th	^{40}K
Tomato (n = 4)	*Solanum lycopersicum* L.	0.02 ± 0.01	0.05 ± 0.03	28.6 ± 6.9
Cucumber (n = 3)	*Cucumis sativus* L.	0.17 ± 0.10	0.09 ± 0.10	31.2 ± 9.4
Spinach (n = 3)	*Amaranthus viridis* L.	0.39 ± 0.01	0.20 ± 0.10	57.1 ± 9.1
Chili pepper (n = 3)	*Capsicum frutescens* L.	0.06 ± 0.30	0.12 ± 0.10	24.6 ± 7.0
Papaya leaf (n = 3)	*Carica papaya* L.	0.21 ± 0.10	0.18 ± 0.04	15.3 ± 1.9
Cassava leaf (n = 3)	*Manihot esculenta* Crantz	0.19 ± 0.10	0.49 ± 0.10	38.1 ± 12.8
Fruits				
Papaya (n = 4)	*Carica papaya* L.	0.12 ± 0.10	0.28 ± 0.10	28.1 ± 8.9
Key lime (n = 3)	*Citrus* × *aurantiifolia* (Christm.) Swingle	0.14 ± 0.04	0.43 ± 0.40	7.6 ± 3.8
Common guava (n = 3)	*Psidium guajava* L.	0.23 ± 0.04	0.07 ± 0.10	4.6 ± 3.4
Soursop (n = 3)	*Annona muricata* L.	0.07 ± 0.02	0.05 ± 0.03	17.1 ± 1.3
Dragon fruit (red) (n = 3)	*Selenicereus monacanthus* (Lem.) D.R.Hunt	0.33 ± 0.20	0.04 ± 0.01	10.6 ± 3.1
Rhizome, spices				
Galangal rhizome (n = 3)	*Alpinia galanga* (L.) Willd.	0.16 ± 0.10	0.48 ± 0.40	5.5 ± 3.1
Common pepper (n = 2)	*Piper nigrum* L.	0.29 ± 0.10	0.830 ± 0.003	0.42 ± 0.10
Staple foods				
Cassava root (n = 4)	*Manihot esculenta* Crantz	0.04 ± 0.02	0.20 ± 0.05	6.14 ± 0.90
Corn (n = 3)	*Zea mays* L.	BDL	0.06 ± 0.02	3.86 ± 0.20
White rice (n = 6)	*Oryza sativa* L.	BDL	0.01 ± 0.01	0.27 ± 0.10
Brown rice (n = 3)	*Oryza sativa* L.	BDL	BDL	0.3 ± 0.01
Others				
Oil palm kernel (n = 2)	*Elaeis guineensis* Jacq.	BDL	0.01 ± 0.01	1.1 ± 0.9
Common pepper leaf (n = 2)	*Piper nigrum* L.	1.05 ± 0.20	3.5 ± 1.6	5.8 ± 1.6
Soursop leaf (n = 2)	*Annona muricata* L.	0.40 ± 0.02	0.8 ± 0.2	3.6 ± 0.6
Cassava peel (n = 2)	*Manihot esculenta* Crantz	0.30 ± 0.01	1.4 ± 0.4	1.9 ± 0.2

The values in parenthesis indicate the number of individual samples analyzed. BDL denotes below detectable limit. AM denotes arithmetic mean, SE denotes standard deviation.

The radioactivity was measured by an Ortec P–type coaxial high-purity germanium (HPGe) detector with a relative efficiency of 60% and a resolution of 1.95 keV (FWHM) for the peak of 1.33 keV ^{60}Co for 24 h. The detector was coupled to a computer-based multi-channel analyser, and the gamma-ray spectrum was recorded by a personal computer-based 4096-channel analyzer and processed by Maestro software gamma for spectrum analysis. Radionuclide of ^{226}Ra was evaluated from 609.31 keV peak of ^{214}Bi or 351.92 keV peak of ^{214} Pb keV, ^{232}Th radionuclide was evaluated from ^{228}Ac (911.07 and 968.97 keV), while ^{40}K radionuclide was evaluated directly at gamma energies (1460.75 keV) (Chen et al., 2005). The minimum detectable concentration (MDCs) measurements of ^{226}Ra, ^{232}Th, and ^{40}K with 5 replicates each obtained 0.00279; 0.3727; and 10.42 Bq.kg^{-1} respectively.

Equation-1 was used to calculate radioactivity concentrations from these measurements:

$$A\ (Bq.kg-1) = \frac{Ns - Nb}{\varepsilon\,\gamma\ \ p\gamma\ W}\ \pm\ \sigma \quad (1)$$

where A is radionuclide concentration in the sample (soil or crops) in Bqkg^{-1}, N_s is sample gamma counting rate/counts per second (cps), Nb is background gamma counting rate (counts per seconds/cps), εγ is the detector efficiency of specific γ-ray (%), pγ is the transition probability of gamma decay (yield), *W* is sample weight (kg) is uncertainty of concentration measurement. The minimum detectable activity (MDA) calculation with a 95% confidence level uses the following equation-2: (Chen et al., 2005)

$$\mathrm{MDA} = 4.66\,\frac{\sqrt{\frac{N_{BG}}{t_{BG}}}}{\varepsilon\,\gamma.\ p\gamma.\ W.Cf} \quad (2)$$

where MDA is the minimum detectable activity (Bq.kg^{-1}), N_{BG} is the background gamma counting rate (counts per seconds/cps), t_{BG} is counting time of background (seconds), εγ is the detector efficiency of specific γ–ray (%), pγ is the transition probability of gamma decay (yield), W is the sample weight (kg), Cf is the self-absorption correction factor.

2.2.4. Statistical inference

Statistical analysis for the significant difference test between 2 variables (edible and non-edible parts) was carried out by means of paired *t*-test. Significant differences were considered at the 95% confidence level (α = 5%) for soursop fruit versus soursop leaf, common pepper seed versus common pepper leaf, and consumable root portion of cassava versus its peel.

3. Results and discussion

Surface radiation dose measured at the surface and 1-m above the surface are 0.094 and 0.096 respectively at undisturbed soil (Balunijuk – S3), and at the surface and 1-m height in range between 0.100-0.124 and 0.394–0.412 μSv/hr respectively for the four former tin mining (Gunung Pelawan – S1; Riding Panjang – S-6; Rebo – S-11; and Kimak – S-12). The surface radiation dose at non-mined soil is lower than the mined soil. The surface radiation dose for the study area are in the global range for surface radiation dose 0.079–0.9 μSv/hr.

Only 70% of the total soil samples contained ^{238}U with a range of <MDC to 67.7 Bq.kg^{-1} with a mean of 18.8 Bq.kg^{-1}, and 28% contained ^{137}Cs with a range of <MDC to 0.64 Bq.kg^{-1} with a mean 0.08 Bq.kg^{-1}. Van et al. (2020) also found that in the activity concentration of ^{137}Cs, <0.3 to <1.4 Bq.kg^{-1} in leafy vegetables, and <0.2 to 0.72 ± 0.2 Bq.kg^{-1} in tubers, was the lowest among the four radionuclides ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs studied in all vegetable crops in Vietnam. The researchers concluded that no satisfactory conclusion can be drawn for ^{137}Cs because its activity concentration was the limit of detection. Likewise, neither of these radionuclides in this study was found in the analyzed crops. The detailed discussion is, therefore, focused on ^{226}Ra, and ^{232}Th.

3.1. Radioactivity content in soil

The mean of the activity concentrations (Bq.kg^{-1}) of ^{226}Ra, ^{232}Th, and ^{40}K ranged from 8.52 to 97.3, 7.17 to 323.1, and 14.73 to 231.9 in the soil samples. At tin tailings in Nigeria, Adesiji (2021) reported the geometric mean of the activity concentrations (Bq.kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th ranged from 179.65(2.88) to 3421.52(3.64), 90.35(3.37) to 1992.61(1.85) and 273.06(5.37) to 25232.30 (1.33) in the soil samples. At the former tin mining farmland in Malaysia (Solehah et al., 2016), the range activity concentration in soil is between 51.8 and 71.8 (Bq.kg^{-1}), 64.2 and 78.0 (Bq.kg^{-1}), and 210.5 and 244.3 (Bq.kg^{-1}) for ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

A positive correlation between ^{226}Ra and ^{232}Th concentrations in soil was statistically significant ($P < 0.001$). In the study of the transfer factors, and radiological hazards of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were studied for selected vegetables and soils in Vietnam, Van et al. (2020) reported that the TF of ^{232}Th was three times higher than that of ^{226}Ra. Therefore, the TFs of radionuclides also depend on the characteristics of each element.

3.2. Soil–to–plant transfer factors

The TF values of various types of food crops are shown inTable 2.

The TF values for ^{226}Ra ranged from 0.02 to 0.39 (vegetables), 0.07–0.33 (fruits), and 0.0–1.1 (cereal, staple foods, rhizomes, others). The highest TF values for ^{226}Ra in vegetables were in spinach (0.39), for fruits in dragon fruit (0.33), and common pepper seed (0.29).

The TF values of ^{232}Th ranged from 0.05 to 0.49 (vegetables), 0.04–0.43 (fruits), and 0.0–3.5 (cereal, staple foods, rhizomes, others). The highest TF value for ^{232}Th was found in common pepper leaf at 3.5. Most of the TF value of ^{40}K from soil to plants for almost all species was greater than 1 as K (potassium) is a macro-mineral that is needed for plant growth.

Rice (white and brown) and cassava are staple foods in some areas in Indonesia and in India. The TF values for ^{226}Ra, ^{232}Th and ^{40}K in rice from Bangka were 0; 0.01; 0.3, while from India 0.08; 0.14; 0.06 (Shanthi et al., 2012), and from Ibaji rice producing area in Nigeria were 0.81; 0.87; 0.09 (Okeme et al., 2016). The TF values for ^{226}Ra, ^{232}Th, and ^{40}K in cassava root from Bangka were 0.04; 0.2; 6.1, while from Malaysia 0.06; 0.001; 1.58 and India were 0.06; 0.11; 0.09 respectively (Solehah et al., 2016; Shanthi et al., 2012).

The TF values for ^{226}Ra, ^{232}Th, and ^{40}K in cassava leaf from Bangka were higher than those in cassava root, i.e. 0.19; 0.49; 38.1 respectively in leaf, and 0.04; 0.2; 6.14 respectively in root. However, the values in peel were the highest on ^{226}Ra and ^{232}Th. From another study, the highest cassava TF value for ^{232}Th of naturally occurring radionuclides from communities in Ghana's oil and gas rich basin was 0.10 (Doyi et al., 2018). Adesiji and Ademola (2019) reported that soil to cassava plant TF of ^{232}Th on a tin mining impacted soil in Nigeria was between 0.006 and 0.49 for root samples, 0.03 and 0.65 in stem samples and 0.03 and 1.54 in the leaf samples. Their study showed that the leaf compartment had the highest TF values than other samples. The TFs values vary as it depends on the plant species which different species need different levels of nutrients from the soil, the soil properties, and also different degrees of mining extraction in each site due to tin ore availability and the history of re-mining, and the agricultural practice on each site. Inorganic or organic fertilizers, especially the phosphates, are known to contain significant concentration of naturally occurring radioactive materials (^{238}U, ^{232}Th, ^{40}K) and their daughters (Kolo et al., 2021; Ugbede et al., 2021).

3.3. Activity concentration difference of radionuclide in edible and non–edible crop parts

The difference in activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides in the edible and non–edible parts of the plant is shown in Table 3. In the table, it can be seen that some plants have TF ^{226}Ra and ^{232}Th from soil–to–leaves (non–edible parts of the soursop leaf, common pepper leaf, and cassava peel) higher, and significantly higher on ^{226}Ra compared to the edible parts (soursop fruit, common pepper seed and cassava root consumable portion). The concentrations of ^{226}Ra and ^{232}Th of non–edible parts of the plant were as much as 20 to 42 times (soursop), 3 to 4 times (common pepper), and 8 to 9 times (cassava) more than those of the edible parts. According to Shanthi et al. (2012), most food crops will show that the non–edible part will accumulate more radionuclides than the edible part. There are several factors that influence the translocation of radionuclides in plants, age of the plant, different species, physiological properties of different species (Brown and Sherwood, 2012), height of the plant (Wilkins et al., 1996 in Brown and Sherwood, 2012), depends on soil characteristics (Pulhani et al., 2000), and depends upon mode of interaction with the materials (Gupta et al., 2016). Herbaceous plant which grows closer to the ground it is therefore likely to receive more contamination level. Study of transfer of thorium and uranium from soil to different parts of medicinal plants, root were higher than those for leaf, stem, fruit and seed (Oufni et al., 2011). In cassava root, it is likely that root surface i.e. bark and peel, where phloem is (Alves 2002), has more contact with the contaminated soil than the inner part of it. Mature lemon fruit, chili pepper fruit, orange fruit, pomegranate fruit, and cassava root had lower ^{137}Cs activity concentration than their leaves (Velasco and Anjos, 2021). In a field trial of Thorium and Uranium uptake and bioaccumulation by wheat-grass (*Triticum repens* L.) and plantain (*Plantago major* L.), mean concentrations of U and Th were higher on leaves of wheat-grass compared to its root than on leaves of plaintain compared to its root (Shtangeeva et al., 2006).

Adesiji and Ademola (2019) reported that the TF value of leaf cassava grown on tin-mining-impacted soil in Nigeria had the highest reading. As boiled young and mature cassava leaves are consumed in some parts of Indonesia, this habit would be interesting to monitor in future study.

4. Conclusions

The surface radiation dose at the surface and 1-m above on crops cultivated at former tin mining land in Bangka Belitung, 0.100–0.124 and 0.394–0.412 μSv/hr respectively, is higher than those at the non-mined soil, 0.094 and 0.096 μSv/hr respectively. The surface radiation dose for the study area are in the global range for surface radiation dose. The mean of the activity concentrations (Bq.kg^{-1}) of ^{226}Ra, ^{232}Th, and ^{40}K ranged from 8.52 to 97.3, 7.17 to 323.1, and 14.73 to 231.9 in the soil samples, which are lower than the readings in Nigeria (Adesiji, 2021), and not much different to those in Malaysia (Solehah et al., 2016). No proper conclusion can be drawn for ^{238}U and ^{137}Cs as their activity concentrations in soil low and were not found in analyzed crops.

The TF values for ^{226}Ra ranged from 0.02 to 0.39 (vegetables), 0.07–0.33 (fruits), and 0.0–1.1 (cereal, staple foods, rhizomes, others). The TF values of ^{232}Th ranged from 0.05 to 0.49 (vegetables), 0.04–0.43 (fruits), and 0.0–3.5 (cereal, staple foods, rhizomes, others). Most of the TF value of ^{40}K from soil to plants for almost all species was greater than 1, as K (potassium) is a macro-mineral that is needed for plant growth. The TFs values vary as it depends on the plant species, the soil properties, the history of mining or re-mining, and the agricultural practice on each site.

In soursop leaf, common pepper leaf, and cassava peel, on ^{226}Ra, the TFs for the non–edible parts, (0.42 ± 0.02; 1.05 ± 0.17; 0.32 ± 0.01 respectively) were significantly higher than soursop fruit, common pepper seed, and cassava root for the edible parts (0.01 ± 0.005; 0.29 ±

Table 3
Mean Transfer Factors of edible and non-edible of soursop, common pepper, and cassava.

	^{226}Ra		^{232}Th		^{40}K	
	edible	non-edible	edible	non-edible	edible	non-edible
Soursop	fruit	leaf	fruit	leaf	fruit	leaf
	0.010 ± 0.005	0.42 ± 0.02**	0.040 ± 0.005	0.83 ± 0.15	3.93 ± 0.19	3.60 ± 0.61
Common pepper	seed	leaf	seed	leaf	seed	leaf
	0.29 ± 0.09	1.05 ± 0.17**	0.830 ± 0.003	3.46 ± 1.64	0.42 ± 0.11	5.84 ± 1.75
Cassava	consumable portion	peel	consumable portion	peel	consumable portion	peel
	0.04 ± 0.02	0.32 ± 0.01**	0.14 ± 0.07	1.36 ± 0.43	1.34 ± 0.19	1.88 ± 0.15

Stars (**) denotes significant differences between edible and non-edible of the same plant species in the same radionuclide; paired *t*-test with at the 95% confidence level (α = 5%).

0.09; 0.04 ± 0.02 respectively).

Soil to plant transfer factor for the studied radionuclides computed for the crops cultivated on former tin mining appears to be generally moderate. However, continuous radiological monitoring of the crops is encouraged to check accumulation effects due to long-term consumption.

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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