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Study of soil to plant transfer factors of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in Vietnamese crops

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The study of staple food products is crucial to assure public safety and provides input for predictive dose assessment models. To further this goal, the activity concentrations, transfer factors, and radiological hazards of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were studied for ten pairs of selected vegetables and soils in Tien Le near Hanoi in Vietnam. This is the first study in this area for Vietnamese vegetable samples. The ten most popular vegetables in Vietnamese diet were selected, namely choy sum, crown daisy, lettuce, cabbage, Malabar spinach, beans, sweet potato, potato, kohlrabi and carrot. The research results showed that the activity concentrations observed in vegetable crops did not present the previously reported strong correlation to those in soil. The ranges of TFs of ^{226}Ra, ^{232}Th, and ^{40}K were $4 \times 10^{-2} – 6.9 \times 10^{-1}$, $8 \times 10^{-2} – 9.7 \times 10^{-1}$; and 1.0×10^{0}–1.6×10^{1}, respectively. Values for leafy vegetables and tubers exceed previous world range figures for Th and K. The soil has been evaluated for radiological hazard indices, which predict almost no risk to human health in the study area.

1. Introduction

Natural radionuclides are omnipresent, e.g. in soil, water, air, food and even our bodies contain natural radioactive materials. Radionuclides in soil and air can be absorbed by plants (IAEA, 2010). The consumption of plants that contain high levels of radioactive nuclides can be dangerous for the health of humans and animals (Chakraborty et al., 2013; Chibowski and Gladysz, 1999). Therefore, estimating the amount of radioactivity which is transferred from soil to plants is very important to assure safety and for predictive models. To date, many investigations have been conducted to determine the soil-to-plant transfer factors (TF) of natural and artificial radionuclides for the most important crops in different countries.

In general, the soil-to-plant TFs of natural radionuclides in different plants have been extensively investigated, however in most cases the number of samples are fairly small, and often the data is not connected to soil or climate parameters, just geographical location (IAEA, 2010; IAEA, 2009; Vandenhove et al., 2009). These reviews have shown that the TFs can vary greatly; and are strongly dependent on the radionuclide, the species of plant as well as climatic, soil and geographical conditions ((IAEA, 2010; IAEA, 2009; Vandenhove et al., 2009). This makes it important to evaluate transfer factors locally, since there might be up to order of magnitude differences between real conditions and international data compilations.

Vietnam is an agricultural country (above 80% of the population is working in agriculture), where vegetable crops are very popular. However, to date no research has been conducted on the estimation of soil-to-plant transfer factors of radionuclides in general and to vegetable crops in particular. This is the first study in Vietnam with regard to calculating soil-to-plant TFs of radionuclides. Agricultural land in Vietnam is mainly alluvial. The study area is located in the Red River Delta region, with monsoon-influenced tropical climate (Cwa according to the Köppen climate classification system), and four separate seasons a year including spring, summer, autumn and winter. The principal use of agricultural land in the region is growing various vegetable crops. Vietnam is currently investing in modernizing and industrializing its agriculture, which goes together with increasing fertilizer use. Currently a lot of physical labor and small machinery is being used, and usual growing patterns include growing four different vegetables on the same field each year, one per season, with using fertilizers two times for each season. Vegetables pose an important part of the Vietnamese diet, especially leafy vegetables and various tubers and roots, however the

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Table 1
Examples for soil to plant transfer factors from previous studies in other countries.

Crop group	Country	N		Soil to plant transfer factors ^{226}Ra	^{232}Th	^{40}K	^{137}Cs	References
Non-leafy vegetable	Iraq	7	Indiv	1.1×10^{-2} –5.3×10^{-2}	1.4×10^{-2} –3.5×10^{-2}	1.1×10^{0}–3.7×10^{0}	N.a.	Azeez et al. (2019)
	Jordan	10	Indiv	1×10^{-2} – 9×10^{-2}	7×10^{-2} – 4.2×10^{-1}	5×10^{0}–8×10^{0}	N.a.	Ababneh et al. (2009)
	Malaysia	10	Indiv	6×10^{-3} – 3.1×10^{-2}	2×10^{-3} – 1.3×10^{-2}	–	N.a.	Aswood et al. (2013)
	Ghana	13	Indiv	1.2×10^{-1} – 1.2×10^{0}	3×10^{-2} – 1.7×10^{-1}	8.1×10^{0}–2.1×10^{1}	N.a.	Adjirackor et al. (2017)
	Syria	48	GM	Nm	Nm	1×10^{0}–5×10^{0}	N.a	Al-Masri et al., 2008
Legumes			GM	1.39×10^{-02}	5.26×10^{-04}	N.a	N.a	Vandenhove et al. (2009)
	Pakistan	1	Indiv	1.2×10^{-1}	2.1×10^{-1}	1.9×10^{-1}	3.9×10^{-1}	Khan et al. (2010)
Tubers	Iraq	1	Indiv	3.0×10^{-2}	2.2×10^{-2}	1.7×10^{0}	N.a	Azeez et al. (2019)
	Poland	N.a.	Indiv	6×10^{-3} – 9×10^{-3}	4×10^{-3} – 7×10^{-2}	1.7×10^{0}–4.3×10^{0}	N.a	Komosa et al. (2005)
	Pakistan	1	Indiv	1.2×10^{-1}	2.1×10^{-1}	1.9×10^{-1}	N.a	Khan et al. (2010)

N.a.: not available, AM: arithmetic mean, GM: Geometric mean, Indiv: individual.

Table 2
Some physical properties of soil in Tien Le vegetable field, Ha Noi.

Vegetable crop	pH	Organic matter (%)	N (%)	P_2O_5 (%)	K_2O (%)	Grain contents (%) Clay (<0.002 mm)	Silt (0.02–0.002 mm)	Sand (2–0.02 mm)
Choy sum	6.8 ± 0.5	3.65 ± 0.33	0.08 ± 0.01	0.22 ± 0.02	1.31 ± 0.11	8.1 ± 0.6	45.8 ± 3.5	46.1 ± 3.2
Crown daisy	6.5 ± 0.4	3.12 ± 0.29	0.11 ± 0.01	0.24 ± 0.02	1.00 ± 0.1	8.9 ± 0.7	49.2 ± 3.8	41.9 ± 3.2
Lettuce	6.3 ± 0.4	2.85 ± 0.28	0.09 ± 0.01	0.21 ± 0.02	1.33 ± 0.12	9.1 ± 0.7	55.2 ± 4.1	35.7 ± 3.8
Cabbage	6.2 ± 0.4	3.19 ± 0.29	0.09 ± 0.01	0.22 ± 0.02	1.38 ± 0.13	9.5 ± 0.7	50.7 ± 4.0	39.8 ± 3.6
Malabar spinach	6.4 ± 0.4	3.52 ± 0.33	0.09 ± 0.01	0.22 ± 0.02	1.23 ± 0.12	10.8 ± 0.8	51.5 ± 4.1	37.7 ± 3.9
Beans	6.9 ± 0.6	3.24 ± 0.31	0.11 ± 0.01	0.24 ± 0.02	1.41 ± 0.12	8.1 ± 0.6	48.7 ± 4.0	43.2 ± 4.1
Sweet potato	6.7 ± 0.5	2.58 ± 0.27	0.10 ± 0.01	0.27 ± 0.02	1.14 ± 0.11	9.1 ± 0.7	51.5 ± 4.5	39.4 ± 3.3
Potato	6.4 ± 0.4	2.57 ± 0.24	0.08 ± 0.01	0.30 ± 0.03	1.35 ± 0.12	8.5 ± 0.6	48.7 ± 4.4	42.8 ± 3.9
Carrot	6.8 ± 0.5	2.52 ± 0.28	0.12 ± 0.01	0.24 ± 0.02	0.98 ± 0.1	7.9 ± 0.6	49.2 ± 4.5	42.9 ± 3.2
Kohlrabi	6.9 ± 0.6	2.59 ± 0.25	0.08 ± 0.01	0.13 ± 0.02	1.21 ± 0.11	8.5 ± 0.6	49.8 ± 4.3	46.1 ± 3.6
Min	6.2	2.52	0.08	0.13	0.98	7.9	45.8	35.7
Max	6.9	3.65	0.12	0.30	1.41	10.8	55.2	46.1
Average	6.6	2.98	0.09	0.23	1.23	8.9	50.0	41.6

available data sources use different methodologies and categorization, making the comparison and utilization of these consumption values difficult (Figuié, 2003).

2. Materials and methods

2.1. Study area

The study area is in the Tien Le vegetable village which is located at a latitude of 21,⁰01′11″ north and a longitude of 105,⁰40′51″ east in the Tien Yen commune of the Hoai Duc District in the western corner of Hanoi, the capital of Vietnam. This is one of the largest vegetable supply areas for Hanoi. Each day, this village supplies around 15 tons of vegetables for customers, mostly in Hanoi. The soil in the study area is alluvium from the Red River Delta region and physical properties of the soil are presented in Table 2.

2.2. Sampling and sample processing

Ten types of vegetable crops in Tien Le village were collected for this study, namely choy sum, crown daisy, lettuce, cabbage, Malabar spinach, beans, sweet potato, potato, kohlrabi and carrot. These are ten of the most popular vegetables in Vietnam. In this study, 5-kg samples of each fresh crop were collected. All vegetable samples were washed to remove any traces of soil, dust and surface contamination. The edible parts of the plants were separated (tubers were peeled, the husks of beans were removed, etc.) Then the samples were chopped into small pieces and dried in an electric oven at 65 °C for about 72 h to a constant weight. The dried samples were then milled into a powdered and sieved through a 2 mm mesh sieve. The powder was weighed and hermetically sealed in plastic containers for 30 days until a secular equilibrium between the radium and its daughter radionuclides was reached for both kind of samples.

Corresponding to the ten vegetable samples, ten 1-kg soil samples of each were also collected at the same time and from the same locations. The soil sampling points were chosen at the corners of a square centered on the vegetable sampling points. The sides of the square were at less 1 m long. The samples were taken by a sampling tool built for this purpose. The cylindrical tube tool was built with diameter and height (5 × 50cm), this tool has a handle and is marked at the sampling depth. The area and depth of sampling was matched to the depth of the specific plant being sampled (from surface to above of 20–30 cm based on the root system). All study samples were collected during spring. The vegetables were being harvested at maturity. After collecting, foreign objects, such as stones or roots, were removed, the sample was put into plastic boxes, then mixed until a homogeneous status was achieved. Then the soil samples were dried at 110 °C to a constant weight. The dried samples were then milled into a powder and sieved through a 2 mm mesh sieve. The powder was weighed and hermetically sealed in cylindrical plastic containers for 30 days to reach a secular equilibrium between the radium and its daughter radionuclides.

3. Measurement method

After the secular equilibrium between the radium and its daughter radionuclides was reached, activity concentration measurements were performed using a High Purity Germanium (HPGe) detector. The analysis was performed using GammaVision software. The energy resolution of the detector was 1.9 keV at the 1.33 MeV ^{60}Co gamma-ray peak. To reduce natural background at the laboratory, the detector was shielded by a 10-cm-thick old-lead cylinder with a 1 mm-thick cadmium and 1 mm-thick copper inner lining. The soil and vegetable samples were

Table 3
Activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in vegetable crops and soil in Tien Le vegetable field (geometric mean (GM), geometric standard deviation (GSD), arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max).

Crop group	Vegetable crops	Activity concentration in soil (Bq/kg in dry)				Activity concentration in vegetable crops (Bq/kg in dry)			
		^{226}Ra	^{232}Th	^{40}K	^{137}Cs	^{226}Ra	^{232}Th	^{40}K	^{137}Cs
Leafy vegetables	Choy sum	20.9 ± 0.8	26.5 ± 1.5	271 ± 2	0.47 ± 0.09	1.56 ± 0.16	4.94 ± 0.49	1523 ± 18	<0.5
	Crown daisy	23.8 ± 1.0	23.8 ± 2.4	299 ± 3	0.55 ± 0.10	16.4 ± 1.6	23.0 ± 2.6	4751 ± 28	<1.0
	Lettuce	22.1 ± 1.4	29.6 ± 1.2	317 ± 6	0.19 ± 0.02	5.05 ± 1.04	11.3 ± 1.4	2688 ± 22	<1.4
	Cabbage	24.5 ± 1.0	34.0 ± 0.6	340 ± 3	1.24 ± 0.14	1.74 ± 0.17	4.10 ± 0.61	971 ± 9	<0.4
	Malabar spinach	24.5 ± 0.9	17.9 ± 0.4	331 ± 3	0.65 ± 0.09	1.65 ± 0.40	4.30 ± 0.52	690 ± 6	<0.3
	AM	23.2	26.4	312	0.62	5.28	9.5	2125	
	SD	1.6	6.1	27	0.39	6.39	8.1	1656	
	GM	23.1	25.8	311	0.52	3.26	7.4	1671	
	GSD	1.1	1.3	1.1	2.0	2.8	2.1	2.2	
Max	24.5 ± 0.9	34.0 ± 0.6	340 ± 3	1.24 ± 0.14	16.4 ± 1.6	23.0 ± 2.6	4751 ± 28	<1.4	
Min		20.9 ± 0.8	17.9 ± 0.4	271 ± 2	0.19 ± 0.02	1.56 ± 0.16	4.10 ± 0.61	690 ± 6	<0.3
Legumes	Beans	24.8 ± 0.9	36.1 ± 0.7	379 ± 4	0.61 ± 0.10	2.59 ± 0.69	6.47 ± 0.97	710 ± 9	<0.5
Tubers	Sweet potato	26.2 ± 0.1	31.4 ± 0.1	255 ± 3	0.75 ± 0.05	1.03 ± 0.22	2.51 ± 0.31	262 ± 3	<0.4
	Potato	28.7 ± 1.4	38.4 ± 1.0	269 ± 4	0.14 ± 0.07	7.01 ± 0.59	4.46 ± 1.45	1244 ± 10	0.72 ± 0.2
	Carrot	26.5 ± 0.9	31.2 ± 0.7	235 ± 3	0.80 ± 0.09	2.27 ± 0.25	3.31 ± 0.49	792 ± 5	<0.3
	Kohlrabi	14.8 ± 0.8	22.0 ± 0.6	271 ± 3	0.89 ± 0.12	1.34 ± 0.20	3.26 ± 0.49	1010 ± 20	<0.2
	AM	24.1	30.8	258	0.65	2.91	3.39	827	
	SD	5.4	5.8	14	0.30	2.41	0.70	363	
	GM	23.3	30.2	257.1	0.52	2.16	3.32	715	
	GSD	1.4	1.3	1.1	2.4	2.3	1.3	2.0	
Max	28.7 ± 1.4	38.4 ± 1.0	271 ± 3	0.89 ± 0.09	7.01 ± 0.59	4.46 ± 1.45	1244 ± 10	0.72 ± 0.2	
Min	14.8 ± 0.8	22.0 ± 0.6	235 ± 3	0.14 ± 0.07	1.03 ± 0.22	2.51 ± 0.31	262 ± 3	<0.2	
Overall									
AM	23.7	28.9	297	0.63	4.1	6.77	1464		
SD	3.8	6.5	44	0.30	4.7	6.2	1328		
GM	23.3	28.3	293.7	0.53	2.70	5.31	1092		
GSD	1.2	1.3	1.2	2.0	2.4	1.9	2.2		
Max	28.7 ± 1.4	38.4 ± 1.0	379 ± 4	1.24 ± 0.14	16.4 ± 1.6	23.0 ± 2.6	4751 ± 28	<1.4	
Min	14.8 ± 0.8	17.9 ± 0.4	235 ± 3	0.14 ± 0.07	1.03 ± 0.22	2.51 ± 0.31	262 ± 3	<0.2	

N.a.: not available.

counted for 259,200 s and 518,400 s, respectively, to minimize the statistical counting error, moreover, the activity calculation were carried out based on two standard reference materials, IAEA-375 and IAEA-446. The detector is regularly calibrated and the aforementioned two reference materials are measured to validate the results and check detector stability.

The activity concentrations of radionuclides in the samples were determined based on their respective gamma lines. The gamma lines of ^{214}Bi (609.3 keV, 1120.3 keV and 1764.5 keV) were used to determine the activity concentration of ^{226}Ra, while the lines of ^{228}Ac (911.2 keV, 969.0 keV) and ^{208}Tl (583.0 keV) were used for ^{232}Th, assuming secular equilibrium, 1460.0 keV was used for ^{40}K and 661.6 keV for ^{137}Cs.

The minimum detectable activities are 0.27 Bq/kg for ^{214}Bi, 0.64 Bq/kg for ^{228}Ac, 2.2 Bq/kg for ^{40}K and 0.15 Bq/kg for ^{137}Cs, respectively for 350 g sample and 259,200 s counting time.

3.1. Determination of soil-to-vegetable crop transfer factors

Transfer factors (TF) are commonly used to evaluate the transfer of radionuclides from soil to vegetable crops (Azeez et al., 2019; Cengiz, 2018; Ibikunle, 2019) The TF can be calculated by the following equation:

$$TF = \frac{Activity\ concentration\ of\ nuclide\ of\ interest\ per\ kg\ dry\ plant\ mass\ [Bq\ kg_{dry}^{-1}]}{Activity\ concentration\ of\ that\ nuclide\ in\ dry\ soil\ within\ the\ rooting\ area\ [Bq\ kg_{dry}^{-1}]} \quad (2)$$

The upper 20–30 cm layer of the soil was used for the TF calculation depending on the vegetable.

In order to show a clearer picture on the data the following values were calculated: geometric mean (GM); geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (min) and maximum (max) values. GM and GSD are preferable to AM and SD due to the general log-normal distribution of the TF values. Normality of the data was assessed with the Shapiro Wilk's and Kolgomorov-Smirnov tests. Only the log-transformed data showed normal distribution.

3.2. Radium equivalent activity concentration

The radioactivity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soils are non-uniform. The radium equivalent activity concentration (Ra_{eq}) is often used to determine the total radioactivity concentration of a sample. Ra_{eq} is calculated based on the estimation that 10 Bq/kg of ^{226}Ra, 7 Bq/kg of ^{232}Th and 130 Bq/kg of ^{40}K exhibit the same gamma dose rate. Therefore, the Ra_{eq} is calculated by the following equation (Beretka and Matthew, 1985):

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (3)$$

Table 4
Soil to vegetable crop transfer factors for ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs.

Crop group	Vegetable crops	^{226}Ra	^{232}Th	^{40}K	^{137}Cs	
Leafy vegetables	Choy sum	7×10^{-2}	1.9×10^{-1}	5.6×10^{0}	Less than 9×10^{-1}	
	Crown daisy	6.9×10^{-1}	9.7×10^{-1}	1.6×10^{1}	Less than 1.8×10^{0}	
	Lettuce	2.3×10^{-1}	3.8×10^{-1}	8.5×10^{0}	Less than 7.5×10^{0}	
	Cabbage	7×10^{-2}	1.2×10^{-1}	2.9×10^{0}	Less than 3×10^{-1}	
	Malabar spinach	7×10^{-2}	2.4×10^{-1}	2.1×10^{0}	Less than 4×10^{-1}	
	AM	2.3×10^{-1}	3.8×10^{-1}	7.0×10^{0}		
	SD	2.7×10^{-1}	3.4×10^{-1}	5.6×10^{0}		
	GM	1.4×10^{-1}	2.9×10^{-1}	5.4×10^{0}		
	GSD	1.56	1.41	1.43		
	Min	7×10^{-2}	1.2×10^{-1}	2.1×10^{0}		
	Max	6.9×10^{-1}	9.7×10^{-1}	1.6×10^{1}		
	Temperate	GM	9.1×10^{-2}	1.2×10^{-3}	1.3×10^{0}	6.0×10^{-2}
		Min	1.8×10^{-3}	9.4×10^{-5}	1.2×10^{0}	3.0×10^{-4}
		Max	1.3×10^{2}	2.1×10^{-1}	1.3×10^{0}	9.8×10^{-1}
	Sub-tropical	GM	N.a.	N.a.	N.a.	3.8×10^{-2}
		Min	N.a.	N.a.	N.a.	1.1×10^{-3}
		Max	N.a.	N.a.	N.a.	1.4×10^{0}
	Tropical	GM	2.7×10^{-2}	3.4×10^{-5}	N.a.	9.8×10^{-1}
		Min	3.0×10^{-3}	1.8×10^{-5}	N.a.	1.1×10^{-1}
		Max	4.3×10^{-1}	7.6×10^{-5}	N.a.	2.9×10^{0}
Legumes	Bean	1.0×10^{-1}	1.8×10^{-1}	1.9×10^{0}	Less than 8×10^{-1}	
	Temperate	GM	1.4×10^{-2}	5.3×10^{-4}	N.a.	4.0×10^{-2}
		Min	3.2×10^{-4}	2.5×10^{-5}	N.a.	1.0×10^{-3}
		Max	6.2×10^{0}	4.8×10^{-1}	N.a.	7.1×10^{-1}
	Sub-tropical	GM	N.a.	N.a.	N.a.	$1.6*10^{-2}$
		Min	N.a.	N.a.	N.a.	$2.0*10^{-3}$
		Max	N.a.	N.a.	N.a.	$3.1*10^{-1}$
	Tropical	GM	2.1×10^{-2}	6.3×10^{-5}	N.a.	N.a.
		Min	7.6×10^{-4}	2.6×10^{-5}	N.a.	N.a.
		Max	2.7×10^{-1}	2.1×10^{-4}	N.a.	N.a.
Tuber	Sweet potato	4×10^{-2}	8×10^{-2}	1.0×10^{0}	Less than 6×10^{-1}	
	Potato	2.4×10^{-1}	1.2×10^{-1}	4.6×10^{0}	5.1×10^{0}	
	Carrot	9×10^{-2}	1.1×10^{-1}	3.4×10^{0}	Less than 4×10^{-1}	
	Kohlrabi	9×10^{-2}	1.5×10^{-1}	3.7×10^{0}	Less than 3×10^{-1}	
	AM	1.2×10^{-1}	1.1×10^{-1}	3.2×10^{0}		
	SD	9×10^{-2}	3×10^{-2}	1.5×10^{0}		
	GM	9×10^{-2}	1.1×10^{-1}	2.8×10^{0}		
	GSD	1.38	1.12	1.34		
	Min	4×10^{-2}	8×10^{-2}	1.0×10^{0}		
	Max	2.4×10^{-1}	1.5×10^{-1}	4.6×10^{0}		
	Temperate	GM	1.1×10^{-2}	2×10^{-4}	N.a.	5.6×10^{-2}
		Min	2.4×10^{-4}	1.3×10^{-5}	N.a.	4.0×10^{-3}
		Max	3.9×10^{0}	1.8×10^{-2}	N.a.	6.0×10^{-1}
	Sub-tropical	GM	N.a.	N.a.	2.4×10^{-1}	6.5×10^{-2}
		Min	N.a.	N.a.	1.0×10^{-1}	9.0×10^{-3}
		Max	N.a.	N.a.	4.1×10^{-1}	4.1×10^{-1}
	Tropical	GM	1.9×10^{-3}	8.9×10^{-6}	2.7×10^{0}	4.3×10^{-1}
		Min	5.2×10^{-4}	2.9×10^{-6}	N.a.	6.0×10^{-2}
		Max	1.4×10^{-2}	3.5×10^{-5}	N.a.	10×10^{-1}

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively.

4. Results and discussion

4.1. Activity concentration

The activity concentrations of the samples of vegetable crops and soil are presented in Table 3.

In general, the activity concentrations of radionuclides in soil samples in this study are similar to the world average values of 35, 30 and 400 Bq/kg for ^{226}Ra, ^{232}Th and ^{40}K, respectively (UNSCEAR, 2010). A previous large scale survey in Vietnam indicated an average of 42.8 ± 18.2 Bq/kg for ^{226}Ra, 59.8 ± 19.8 Bq/kg for ^{232}Th and 412 ± 231 Bq/kg for ^{40}K in the country (Huy et al., 2012). Our results in the Tien Le village show concentrations somewhat on the lower end. The activity concentrations of ^{137}Cs were lower than those of other radionuclides in this study. In addition, little variation is observed between the activity concentrations of radionuclides in the soil around different vegetable crops. These variations may be due to differences in local conditions as well as the amounts of fertilizer applied to different vegetable crops.

The highest activity concentrations of these radionuclides were found in leafy vegetables (^{40}K in choy sum; ^{226}Ra and ^{232}Th in crown daisy). By contrast, the lowest activity concentration of the four radionuclides was found in tuber vegetables. Sweet potato contained the lowest activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K. The variations in activity concentrations of radionuclides in vegetables may be due to the metabolic characteristics and availability of radionuclides in each vegetable. The activity concentrations of ^{40}K in all of the vegetables were considerably greater than those of ^{226}Ra and ^{232}Th. This is probably because potassium is a primary nutrient required for the growth of vegetables (Prajapati and Modi, 2012). Potassium is used in plant metabolism so it is essential. Furthermore, the activity concentrations of ^{40}K in the soil samples were greater than those of ^{226}Ra and ^{232}Th. Moreover, ^{40}K is the most soluble in natural water of the radionuclides studied. This leads to a greater degree of mobility of ^{40}K in comparison with ^{226}Ra and ^{232}Th (Hafsi et al., 2014; Kumar et al., 2008). Unlike ^{40}K, the activity concentration of ^{137}Cs was by far the lowest among the four

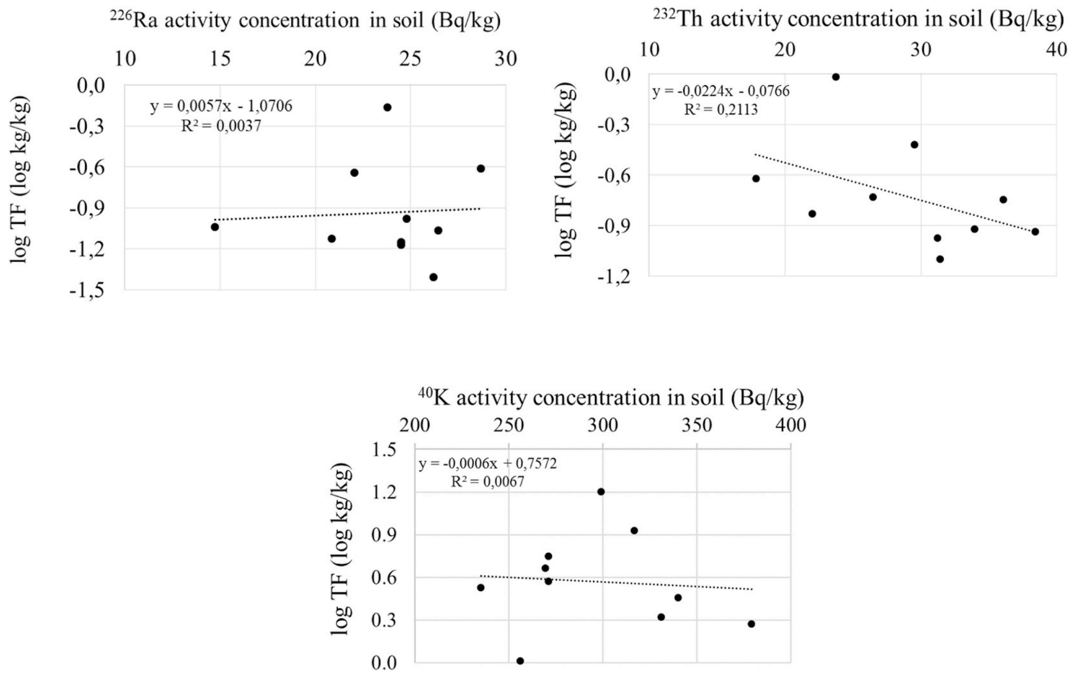

Fig. 1. Correlation between activity concentrations of radionuclides in soils and the log TF.

radionuclides studied in all vegetable crops.

4.2. Transfer factor

Based on the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in the soil and vegetable crops, the soil-to-vegetable crop transfer factors (TFs) were calculated and presented in Table 4. The data in this table show that the ranges of TFs of ^{226}Ra, ^{232}Th, ^{40}K were $4 \times 10^{-2} – 6.9 \times 10^{-1}$, $8 \times 10^{-2} – 9.7 \times 10^{-1}$ a 1.0×10^{0}–1.6×10^{1}, respectively. In general, the values of soil-to-plant TFs vary greatly. This may be attributed to the different types of vegetable crops.

The soil-to-vegetable crop transfer factors of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in different types of vegetables are shown in Table 4. Overall, the soil-to-vegetable crop TFs of ^{40}K were considerably greater than those of ^{226}Ra and ^{232}Th. The main reason probably is that vegetables have a high demand for potassium which is one of the principal nutrient elements for vegetable crops (Prajapati and Modi, 2012). Besides, K is highly mobile and highly soluble in water (Kumar et al., 2008; FAO, 2016; IAEA, 2014), so it is easily transported from the soil to vegetables. The research results in this study also show that the transfer factors of ^{40}K in all vegetable crops are greater than 1 while those of ^{226}Ra and ^{232}Th are less than 1. This indicates that the activity concentrations of ^{40}K in vegetable crops are higher than those in the soil. The research results also show that the TFs of ^{40}K in leafy vegetables, e.g. choy sum, crown daisy and lettuce, are higher than those in tuber and legumes. This can be attributed to the higher biochemical potassium demand and its availability to edible leafy vegetables rather than to other crops. As is shown in Table 4, the TFs of ^{226}Ra and ^{232}Th in some leafy vegetables, e.g. crown daisy and lettuce, are slightly higher than those in other crops. This can be attributed to the variation in the metabolic characteristics of different vegetables. Table 4 also reveals that the TF of ^{232}Th is slightly greater than that of ^{226}Ra in almost all crops except for potato. This finding is the opposite to that of Azeez et al. (2019) and ^{232}Th is reportedly less mobile than ^{226}Ra in natural waters (IAEA, 2014).

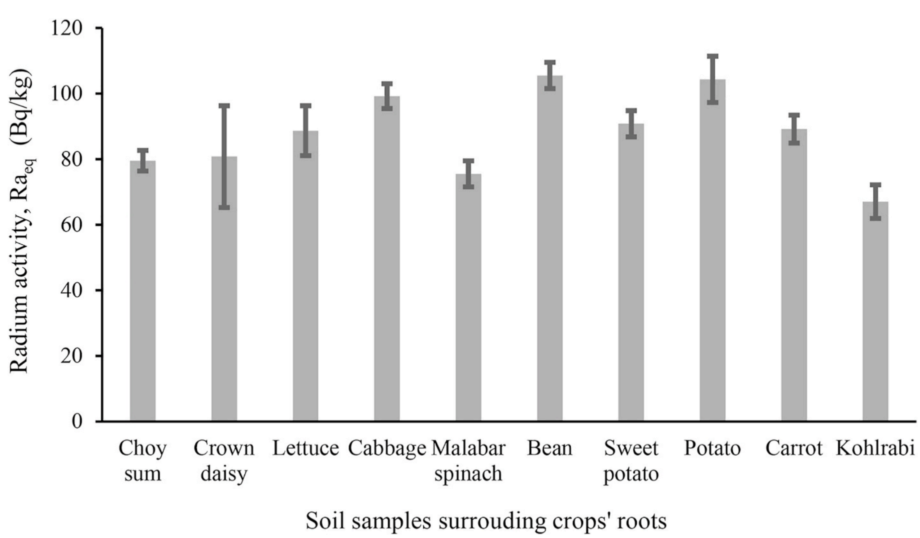

Fig. 2. Radium equivalent activity Raeq in Tien Le vegetable field, Hanoi, Vietnam.

However, the results of the present study are similar to those of Cengiz (2018), who reported that the TF of ^{232}Th was three times higher than that of ^{226}Ra in samples of pasture grass from Turkey. Therefore, the TFs of radionuclides depend not only on the characteristics of each element but also on their availability to the plant and the metabolic nature of each plant.

The relationship between the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K in soil and the log-transformed TF is shown in Fig. 1. It can be seen that in case of ^{226}Ra and ^{40}K the linear correlations between the activity concentrations of the isotopes in the surrounding soil and the log TF were very weak ($R^2 \leq 0.05$), and not significant according to the Pearson Correlation coefficient (p 0.64 and 0.88 for ^{226}Ra and ^{40}K). In case of ^{232}Th the value of R^2 is higher, still the correlation is weak, and not significant to the Pearson Correlation coefficient (p 0.54). This indicate that deriving activity concentrations of radionuclides in crops by using the ones in soils should be considered with care. The research results of Azeez et al. (2019) also indicate that the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil do not solely affect their activity concentrations in plant crops.

For the activity concentration of natural radioactive elements, namely ^{226}Ra, ^{232}Th and ^{40}K, in vegetable crops the physiochemical indices of the soil such as potassium (K), cation-exchange capacity, calcium, organic content, their availability to the plant and the metabolic features of the category of vegetable is more important than the mere activity concentrations in soil (Aswood et al., 2013; Guillen et al., 2017). There is some contradiction on whether during the analysis of the soil-to-plant TF for the long-lived natural radionuclides U, Ra and Th the dependency of the TF on the soil concentration should be considered or not. Sheppard and Sheppard (1985) and Sheppard and Evenden (1988) reported a log-normal dependency for the TF of uranium on soil concentration, however there are reports for the contrary, Blanco et al. (2002) did not find the same relation in their experiment. The review by Vandenhove et al. (2009) covered a wide range of soil concentrations (7–250,000 Bq/kg for U, 4–60 000 Bq/kg for Ra and 4–89 000 Bq/kg for Th), including different soil groups and crop groups and experimental conditions, but reported no relation found between TF or log TF and the soil concentration ($R^2 < 0.01$). An admitted limitation is that non-linearity can contribute to the uncertainty in the TF.

It should be noted that the current study has a limited number of samples, it should be followed up with a more extensive study, including soil parameters to put the values in context.

The soil-to-plant TFs of ^{226}Ra, ^{232}Th and ^{40}K obtained in the present study are presented in Table 4 and are compared with results from previous studies in other countries around the world and are presented in Table 1. These comparisons show the merit and possible necessity of domestic transfer factor measurements to provide accurate base information for better predictive dose assessment models.

4.3. Radium equivalent activity concentration

The maximum value of Ra_{eq} in soil should be less than 370 Bq/kg to ensure its external dose does not exceed 1.5 mGy/h (UNSCEAR, 1988). Fig. 2 presents Ra_{eq} calculated in soil samples from the study area. It can be shown that the Ra_{eq} ranges from 67.1 to 105.5 Bq/kg. The small variation in Ra_{eq} in this study is due to variations in activity concentrations of natural radionuclides within the studied crop field. In general, it is significantly lower than the maximum value of 370 Bq/kg. Consequently, the other derivable hazard indices will be also significantly lower than recommended limits.

5. Conclusions

An experimental study on transfer of radionuclides for different types of vegetable crops in Vietnam is presented for the first time. These data give the opportunity to fill a lack of information and gives the opportunity for more accurate and location specific dose assessment and environmental transport models. The study covers vegetables of great importance in the local diet. The observed ranges of TFs of ^{226}Ra, ^{232}Th and ^{40}K were $4 \times 10^{-2} – 6.9 \times 10^{-1}$, $8 \times 10^{-2} – 9.7 \times 10^{-1}$; and $1.0 \times 10^{0}–1.6 \times 10^{1}$, respectively. No proper conclusion can be drawn for ^{137}Cs as its activity concentrations in crops were at the limit of detection. For leafy vegetables crown daisy, lettuce and Malabar spinach exceed the ranges reported in IAEA, 2010 for Th, and choy sum, crown daisy, lettuce, cabbage and Malabar spinach exceed the ranges reported in IAEA, 2010 for K, while for tubers the values of sweet potato, potato, carrot and kohlrabi exceed the ranges reported in IAEA, 2010 for Th and K (IAEA, 2010) (See Table 4). It has to be acknowledged that the data presented is limited in scope, only one, albeit locally important area has been sampled, and one value has been derived for each of the selected 10 plants.

Regarding radiological hazards, our results indicate that the derivable radiological hazard indices, e.g. absorbed gamma dose rate, annual effective dose equivalent, external and internal radiation indices predict an insignificant impact on human health. The study area exhibits a low lifetime risk of cancer due to exposure to natural radionuclides.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ababneh, A.M., Masa'deh, M.S., Ababneh, Z.Q., Awawdeh, M.A., Alyassin, A.M., 2009. Radioactivity concentrations in soil and vegetables from the northern Jordan Rift Valley and the corresponding dose estimates. Radiat. Prot. Dosimetry 134, 30–37.
Adjirackor, T., Darko, E.O., Sam, F., 2017. Naturally occurring radionuclide transfer from soil to vegetables in some farmlands in Ghana and statistical analysis. Radiat. Environ. 40, 34–43.
Al-Masri, M.S., Al-Akel, B., Nashawani, A., Amin, Y., Khalifa, K.H., Al-Ain, F., 2008. Transfer of ^{40}K, ^{238}U, ^{210}Pb, and ^{210}Po from soil to plant in various locations in south of Syria. J. Environ. Radioact. 99, 322–331.
Aswood, M.S., Jaafar, M.S., Bauk, S., 2013. Assessment of radionuclide transfer from soil to vegetables in farms from Cameron Highlands and Penang,(Malaysia) using neutron activation analysis. Appl. Phys. Res. 5, 85.
Azeez, H.H., Mansour, H.H., Ahmad, S.T., 2019. Transfer of natural radioactive nuclides from soil to plant crops. Appl. Radiat. Isot. 147, 152–158.
Beretka, J., Mathew, P.J., 1985. Natural radioactivity of Australian building materials, industrial wastes and by-products. Health Phys. 48, 87–95.
Blanco, R.P., Vero Tomé, F., Lozano, J.C., 2002. About the assumption of linearity in soil-to-plant transfer factors for uranium and thorium isotopes and ^{226}Ra. Sci.Tot. Environ. 284, 167–175.
Cengiz, G.B., 2018. Transfer factors of ^{226}Ra, ^{232}Th and ^{40}K from soil to pasture-grass in the northeastern of Turkey. J. Radioanal. Nucl. Chem. 319, 83–89.
Chakraborty, S.R., Azim, R., Rahman, A.R., Sarker, R., 2013. Radioactivity concentrations in soil and transfer factors of radionuclides from soil to grass and plants in the Chittagong city of Bangladesh. J. Phys. Sci. 24, 95–113.
Chibowski, S., Gladysz, A., 1999. Examination of radioactive contamination in the soil-plant system and their transfer to selected animal tissues. Polish J. Environ. Stud. 8, 19–23.
FAO, 2016. Medium-term Prospects for Raw Materials, Horticulture and Tropical Products. Food and Agriculture Organization of the United Nations (FAO), Rome.
Figuié, Muriel, 2003. VEGETABLE CONSUMPTION BEHAVIOUR IN VIETNAM. Sustainable Development of Peri-Urban Agriculture in South-East Asia (Susper). French Agricultural Research Centre for International Development, CIRAD, Hanoi.

Guillen, J., Baeza, A., Salas, A., Munoz-Munoz, J.G., Munoz-Serrano, A., 2017. Factors influencing the soil to plant transfer of radiocaesium. In: Impact of Cesium on Plants and the Environment. Springer International Publishing, Switzerland, pp. 19–33.
Hafsi, C., Debez, A., Abdelly, C., 2014. Potassium deficiency in plants: effects and signaling cascades. Acta Physiol. Plant. 36, 1055–1070.
Huy, N.Q., Hien, P.D., Luyen, T.V., Hoang, D.V., Hiep, H.T., Quang, N.H., Long, N.Q., Nhan, D.D., Binh, N.T., Hai, P.S., Ngo, N.T., 2012. Natural radioactivity and external dose assessment of surface soils in Vietnam Radiat. Prot. Dosim. 151, 522–531.
IAEA, 2009. Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments. International Atomic Energy Agency, Vienna. IAEA-TECDOC-1616.
IAEA, 2010. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater, Technical Reports Series 472. International Atomic Energy Agency, Vienna.
IAEA, 2014. The Environment Behavior of Radium: Revised Edition. International Atomic Energy Agency, Vienna (Technical Reports series no. 476).
Ibikunle, S.B., Arogunjo, A.M., Ajayi, O.S., 2019. Characterization of radiation dose and soil-to-plant transfer factor of natural radionuclides in some cities from south-western Nigeria and its effect on man. Sci. Afr. 3, 1–10.
Khan, H.M., Chaudhry, Z.S., Ismail, M., Khan, K., 2010. Assessment of radionuclides, trace metals and radionuclide transfer from soil to food of Jhangar Valley (Pakistan) using gamma-ray spectrometry. Water. Air. Soil Pollut. 213, 353–362.
Komosa, A., Chibowski, S., Reszka, M., IAEA, 2005. Natural radioisotope level differentiation in arable and noncultivated soils at leczna-wlodawa lake District. In: IAEATECDOC-1472: Naturally Occurring Radioactive Materials (NORM IV). IAEA, Vienna, pp. 117–126.
Kumar, A., Singhal, R.K., Preetha, J., Rupali, K., Narayanan, U., Suresh, S., Mishra, M.K., Ranade, A.K., 2008. Impact of tropical ecosystem on the migrational behavior of K-40, Cs-137, Th-232, U-238 in Perennial plants. Water. Air. Soil Pollut 192, 293–302.
Prajapati, K., Modi, H.A., 2012. The importance of potassium in plant growth-A review. Indian J. Plant Sci. 1, 1177–1186.
Sheppard, S.C., Evenden, W.G., 1988a. The assumption of linearity in soil and plant concentration ratios: an experimental evaluation. J. Environ. Radioact. 7, 221–247.
Sheppard, M.I., Sheppard, S.C., 1985. The plant concentration ratio concept as applied to natural uranium. Health Phys. 48, 494–500.
UNSCEAR, 1988. Sources, Effects of Ionizing Radiation, Annex B: Exposure of the Public and Workers from Various Sources of Radiation. United Nations, New York. Technical Report.
UNSCEAR, 2010. Sources and Effects of Ionizing Radiation. UNSCEAR 2008 Report to the General Assembly with Scientific Annexes. United Nations Scientific Committee on the Effects of Atomic Radiation, New York.
Vandenhove, H., Olyslaegers, G., Sanzharova, N., Shubina, O., Reed, E., Shang, Z., Velasco, H., 2009. Proposal for new best estimates of the soil-to-plant transfer factor of U, Th, Ra, Pb and Po. J. Environ. Radioact. 100, 721–732.