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The plant transfer factor of natural radionuclides and the soil radiation hazard of some crops

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Abstract In the present study, the transfer factors of the natural radionuclides ^{238}U, ^{232}Th, and ^{40}K were estimated for several crops cultivated in farms in the suburbs of Baghdad and one farm in Al-Najaf. The transfer factor (T_F) is the ratio of activity transfers from soil to plant. The specific activities of the natural radionuclides were measured with a gamma-ray spectrometer with a HPGe detector. The crops include cereals (rice and wheat), fruits (lemons and oranges), podded vegetables (vigna and okra), fruity vegetables (chili peppers and *Solanum melongena*), and leafy vegetables (*Apium graveolens*, *Raphanus sativus*, and *Ocimum basilicum*). The results showed that the highest transfer factors for ^{238}U, ^{232}Th, and ^{40}K are 0.32, 0.70, and 3.44, respectively, in wheat. The average transfer factors for ^{238}U and ^{232}Th were founded 0.23 and 0.2 which are lower than the default unitiy value but the 1.85 were reported for ^{40}K higher than unity.

Keywords Transfer factor (T_F) · Crop · Soil · HPGe detector · Specific activity

Introduction

Natural and artificial radionuclides are transferred to plants through uptake from the soil via roots and absorption directly through leaves (James et al., 2011; Vandenhove et al., 2009). While some radionuclides are taken up as homologues of primary elements, others are taken up regardless of their biological emergency. For the growth and reproduction of vegetation, there are sixteen essential elements: hydrogen, carbon, nitrogen, oxygen, sulfur, phosphorus, calcium, potassium, iron, magnesium, zinc, manganese, molybdenum, copper, chlorine, and boron (Karunakara et al., 2013; Linsalata, 1994). However, a number of natural radioactive elements like ^{238}U, ^{232}Th, and ^{40}K, cosmogenic radionuclides such as ^{7}Be and artificial radionuclides such as ^{137}Cs and ^{90}Sr are present in plants in assorted concentrations (Karunakara et al., 2013). According to UNSCEAR, individual plants experience an 83% annual effective dose from natural radionuclides, 16% is contributed by primordial ^{40}K, and the remaining 1% is due to artificial radionuclides (UNSCEAR, 2008).

The soil-to-plant transfer factor (T_F), or the ratio of the concentration of radioactivity in the crop-to-soil radioactivity per unit mass (Bq kg^{-1} dry mass), is used to study the impact of radionuclides on the

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environment. T_{Fs} are convenient indices for establishing the degree of uptake of radionuclides from soil to plants. T_{Fs} are the most important parameters for modeling and simulating impact assessments of contamination in the surrounding environment.

Since T_{FS} strongly depend on the soil and vary from site to site, site-specific data is recommended (James et al., 2011). In most countries in Europe and the USA, the T_{Fs} for most important agricultural products are known. In the rest of the world, especially developing countries, T_{Fs} are not so easily available. Therefore, the estimation of T_{Fs} in a country like Iraq is vital (IAEA, 2006).

Radionuclides present in the soil and not used in plant metabolism are absorbed regardless of their radioactive characteristics (Asaduzzaman et al., 2015). Soil flow by natural and fallout radionuclides has a nonstop radiological effect, since these radionuclides are transferred to the human body through the food chain and drinking water. Plant uptake is the major cause for the relocation of radionuclides from the soil into human foodstuffs (Shanthi et al., 2012; Shanthi et al., 2012). Radionuclides in the edible portions of plants may be a source of exposure (Shanthi et al., 2012). Nevertheless, radionuclide distribution and uptake in plants depend on various factors such as the kind and amount of clays, soil pH, exchangeable calcium and potassium, the physicochemical properties of the radionuclide, the kind of crop (species, variety, and cultivation practices), fertilizer application, irrigation, plowing, liming, climate conditions, organic matter content, etc. (Pulhani et al., 2005). Diet is the main cause of internal human exposure to radioactive elements (Saeed et al., 2012). After absorption by the root, radionuclides are transported into the plant along with other nutrients or minerals needed for their growth and reproduction (James et al., 2011). These radionuclides translocate toward various portions of the plant through the vascular system, including the xylem and phloem. They accumulate in various edible portions and lead to a continuous radiation dose once consumed (Pulhani et al., 2005).

The soil-to-plant transfer factor is one of the significant parameters widely used in the evaluation of internal radiation dose from food consumption (Tsukada et al., 2002). The transfer factor depends on soil properties, vegetation type, the type of radionuclides, and the climatic conditions (Asaduzzaman et al., 2015). Various studies on the transfer of natural radionuclides from soil to plant have been carried out in several regions around the world and have observed a notable difference in values (Alharbi & El-Taher, 2013; Currie, 1968; Mheemeed et al., 2014; Ononugbo et al., 2019; Pulhani et al., 2005; Shanthi et al., 2012; Shayeb et al., 2017; Velasco et al., 2012; Wang et al., 2015).

However, there seems to be little data on the transfer of natural radionuclides from soil to plant in the environment. Therefore, the current study aims to determine the natural radionuclide T_F in some agricultural crops under natural field conditions. It will consider the concentration of the radioactive isotopes ^{40}K, ^{226}Ra, and ^{232}Th in soil and plants. Finally, it will calculate the absorbed dose rate (Dr) due to gamma radiation in outdoor air 1 m above the soil surface, the radium equivalent activity (Ra_{eq}), the gamma index (I_γ), the external hazard index (H_{ex}), and the internal hazard index (H_{in}).

Materials and methods

Sample collection and processing

The transfer factors of ^{238}U, ^{232}Th, and ^{40}K from the soil into cultivated plants were examined for ten crop samples in agricultural areas in the outskirts of Baghdad and one crop sample from the Al-Mishkab district in Al-Najaf. The region is known for cultivating the finest type of rice in the world (amber) (Fig. 1 and Table 1). The crops include cereals (rice and wheat), fruits (lemon and orange), podded vegetables (vigna and okra), fruity vegetables (chili pepper, *Solanum melongena*), and leafy vegetables (*Apium graveolens*, *Raphanus sativus*, and *Ocimum basilicum*). The crop samples were collected with cultivated soil. The samples were prepared by separating them from nonedible parts and drying, crushing, and sifting them with a sieve (630 µm mesh size). They were fully mobilized in sealed Marinelli beakers and stored for 30 days so that a secular equilibrium between ^{238}U and ^{232}Th with their decay products was reached.

Soil samples were collected at a depth of 20 cm below the soil surface. These samples were prepared by removing unwanted materials such as roots, gravel, stone, and leaves. About 1 kg of soil was dried in an oven at 100 °C for 1 h to achieve a constant dry weight. The samples were crushed into a fine powder, homogenized and placed inside a Marinelli beaker to be examined 30 days later via gamma-ray spectrometry.

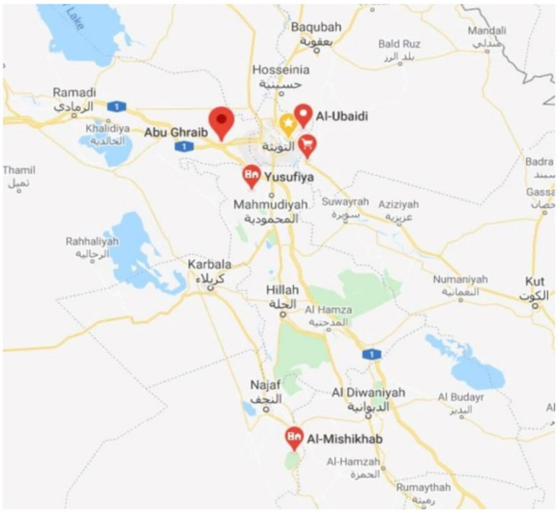

Fig. 1 Locations of the plants under study

Gamma-ray spectrometry with a HPGe detector

The specific activity of ^{238}U, ^{232}Th, and ^{40}K in the samples under study were measured via shielded γ-ray spectrometry with a HPGe detector (a cylindrical single crystal with a dimension of 3×3 inches) connected to a multi-channel analyzer (model: DSPEC-LF, ORTEC, USA). The HPGe detector was calibrated with a ^{152}Eu source (activity = 1 µCi) with the following energy lines: 121.8, 244.7, 344.3, 411.1, 778.9, 964.0, 1085.8, 1112.0, 1299, and 1408.0 keV.

For the present work, calibration efficiency was achieved with a standard mixture source. The source contains ten mixed radionuclides: ^{241}Am-^{109}Cd-^{139}Ce-^{57}Co-^{60}Co-^{137}Cs-^{113}Sn-^{88}Sr-^{88}Y-^{203}Hg. This source is specialized for gamma spectroscopy calibration systems. The measuring time for the background and the samples was 24 h (Ammer et al., 2017). Figure 2 shows the radionuclides in the spectrum of the standard mixed source. Table 2 shows the information of isotopes in the mixed source. The uncertainty of the measured specific activity concentration of samples (U_A) is estimated by Eq. 1 (Kadhim et al, 2021):

$$\frac{U_A}{A} = \sqrt{\left(\frac{U_N}{N}\right)^2 + \left(\frac{U_B}{B}\right)^2 + \left(\frac{U_\varepsilon}{\varepsilon}\right)^2 + \left(\frac{U_M}{M}\right)^2 + \left(\frac{U_{P_\gamma}}{P_\gamma}\right)^2} \tag{1}$$

where U_N is the uncertainty of the sample count rate; U_B is the uncertainty of background count rate; U_ε is the efficiency uncertainty at choose energy; U_M is the uncertainty of spices mass measurements; and U_{P_γ} is the uncertainty gamma line. The average uncertainty 6% is founded in the present measurements.

Specific activity

The specific activities, Bq kg^{-1}, for i radionuclide (A_i) at energy peak E_γ are calculated as follows (Kadhim & Ridha, 2019):

$$A_i(E_\gamma) = \frac{N}{t \times I_\gamma(E_\gamma) \times \varepsilon(E_\gamma) \times m} \tag{2}$$

where N is the net peak area, I_γ is the abundance of energy E_γ, t is the time of measurement, ε is the detection efficiency at photo peak energy, and m is the weight of the sample.

The lower limits of detection (LLD [Bq kg^{-1}]) used to estimate the lowest activity of a specific

Table 1 Crop and soil information

No.	Crop	Location	Crop code	Mass (kg)	Soil code	Mass (g)
1.	Rice	Mishikhab	C1	693.11	S1	1200
2.	Lemon	Tarmiya	C2	391.13	S2	962.86
3.	Vigna	Yusufiya	C3	359.62	S3	1048.27
4.	Wheat	Abu Ghraib	C4	903.4	S4	1155.41
5.	Orange		C5	419.92	S5	955.37
6.	Chili pepper		C6	445.33	S6	926.86
7.	*Solanum melongena*	Tuwaitha	C7	240.21	S7	1081
8.	Okra		C8	428.19	S8	921.68
9.	*Apium graveolens*		C9	582.11	S9	992.93
10.	*Raphanus sativus*	Al-Obeidi	C10	338	S10	1125
11.	*Ocimum basilicum*		C11	468.8	S11	1172

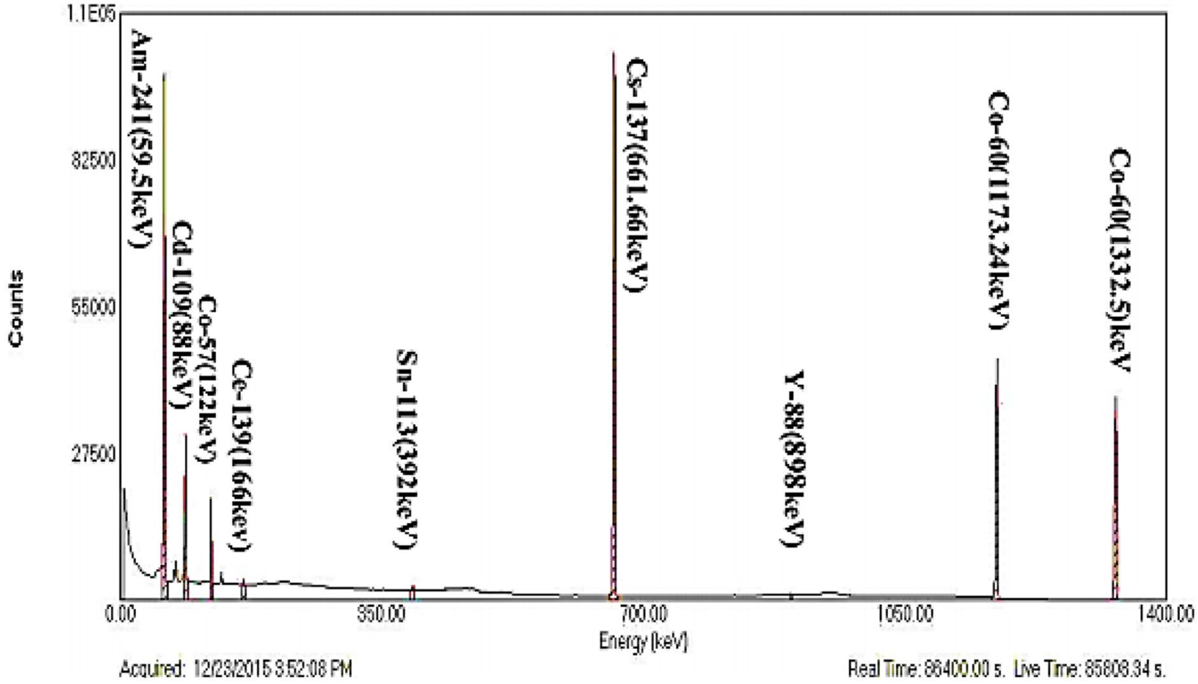

Fig. 2 The detected radionuclides in the spectrum of the standard mixed source

radionuclide at the time of measurement are listed in Table 3 for ^{238}U, ^{232}Th, and ^{40}K (Currie, 1968). Table 3 shows the radionuclides detected in the samples and some other important information. Figures 3 and 4 show the spectrum of the soil and crop samples (S7 and C7) of *Solanum melongena*.

Soil-to-crop T_F

The T_F from soil to crop is calculated from the specific activity of the natural isotope in both crop and soil samples by Eq. 2 (Alharbi & El-Taher, 2013; Karunakara et al., 2013; Mheemeed et al., 2014):

$$\mathrm{TF} = \frac{\text{The specific activity of an isotope in a crop}\left(\text{in Bq kg}^{-1}\text{ dryweight}\right)}{\text{The specific activity of an isotope in soil}\left(\text{in Bq kg}^{-1}\text{ dryweight}\right)} \tag{3}$$

Table 2 Radionuclides with energy peak E (keV), half-life $t_{1/2}$, decay constant λ, original activity A_o, activity at time of measurement A_t, intensity I (%), and efficiency ε (%) for each isotope in the mixed source

No.	Radionuclides	E (keV)	$t_{1/2}$ (day)	λ (day^{-1})	A_o (kBq)	A_t (kBq)	I (%)	ε (%)
1	^{241}Am	59.5	157,800	4.39×10^{-6}	4.433	4.414	35.9	0.005
2	^{109}Cd	88	462.60	0.0015	16.17	3.816	3.7	0.018
3	^{139}Ce	166	137.50	0.005	0.74	0.006	79.9	0.022
4	^{57}Co	122	271.26	0.0026	0.855	0.073	85.6	0.025
5	^{60}Co	1173.24	1925.4	0.0004	2.659	1.88	99.88	0.005
6	^{60}Co	1332.5	1925.4	0.0004	2.659	1.88	99.98	0.005
7	^{137}Cs	661.66	11,019	0.0001	2.439	2.296	85.1	0.009
8	^{113}Sn	392	115.1	0.006	3.087	0.009	64.97	0.014
9	^{88}Y	898	106.6	0.0065	3.995	0.008	93.7	0.005

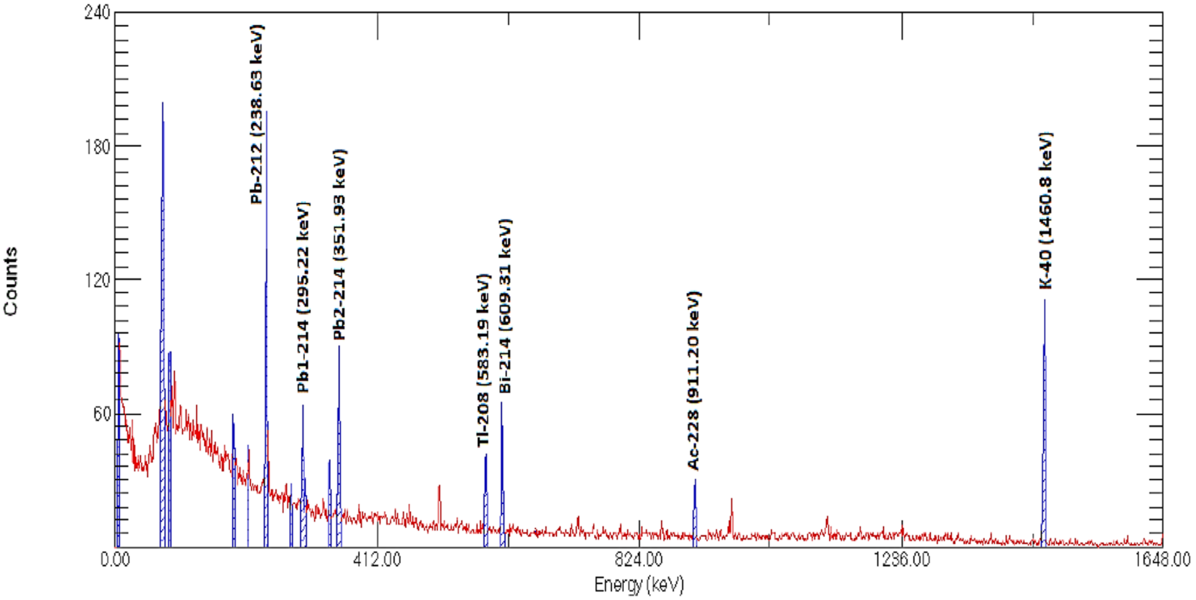

Fig. 3 Spectrum of (S7) sample, *Solanum melongena*

Radiation hazard parameters

The radiation hazard parameters for the soil and crop samples were calculated. The absorbed dose rate (D_γ) due to gamma radiation in outdoor air 1 m above the soil surface, the radium equivalent activity (Ra_{eq}), the gamma index (I_γ), the internal hazard index (H_{in}), the annual effective dose rate (E_{ff}), and the annual gonadal dose equivalent (AGDE) were calculated via the following equations 3, 4, 5, 6, 7, 8 and 9 (UNSCEAR, 2000, 2008, 2010):

$$D\gamma(\mathrm{nGy\ h}-1) = 0.462\mathrm{A_{Ra}} + 0.621\mathrm{A_{Th}} + 0.0417\mathrm{A_K} \quad (4)$$

$$\mathrm{Ra(eq)} = \mathrm{A_{Ra}} + 1.43\mathrm{A_{Th}} + 0.077\mathrm{A_K} \quad (5)$$

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \leq 1 \quad (6)$$

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \quad (7)$$

$$\mathrm{Eff\ \ dose(mSv\ y-1)} = \mathrm{D\gamma(nGy\ h-1)} \times 8760 \times 0.7 \times (\mathrm{103mSv.10-9)nGy} - 1 \times 0.2 \quad (8)$$

$$\mathrm{AGDE(mSv\ y-1)} = \left(3.09\mathrm{A_{Ra}} + 4.18\mathrm{A_{Th}} + 0.314\mathrm{A_K}\right) \times 10-3 \quad (9)$$

Table 3 The lower detection limits for each radionuclide, their related series, half-lives, gamma energies and intensities (Currie, 1968)

No.	Series	Isotope	$t_{1/2}$	E_γ (keV)	I_γ (%)	LLD (Bq kg^{-1})
1		^{214}Pb	27.06 m	295.22	18.42	0.6234
2	^{238}U	^{214}Pb	27.06 m	351.93	35.6	0.3951
3		^{214}Bi	19.9 m	609.31	45.49	0.46
4		^{226}Ra	1600 y	186.21	3.64	0.8219
5		^{235}U	7.04×10^8 y	185.71	57	0.0554
6	^{232}Th	^{212}Pb	10.64 h	238.63	43.6	0.2646
7		^{208}Ti	3.053 m	583.19	85	0.1470
8		^{228}Ac	6.15 h	911.20	25.8	0.7704
9	^{40}K	^{40}K	1.24×10^9 y	1460.8	10.66	11.514

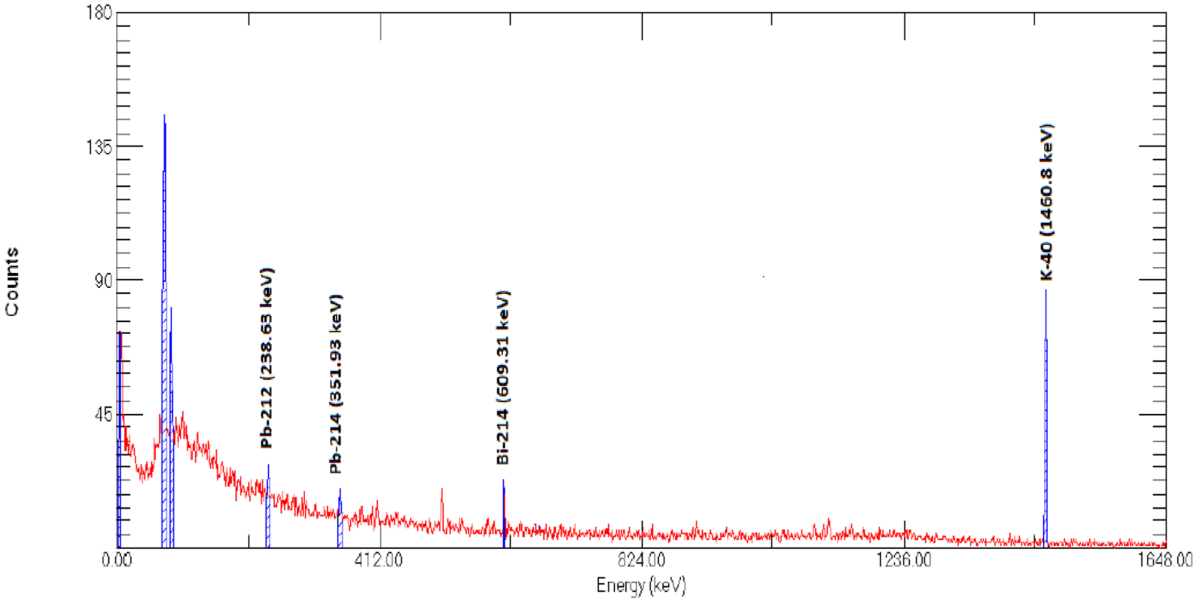

Fig. 4 Spectrum of (C7) sample, *Solanum melongena*

where A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K, respectively (Kadhim & Ridha, 2019; UNSCEAR, 2008).

Results and discussion

Specific activity

^{238}U, ^{232}Th, and ^{40}K activity are detected in the soil and crop samples with ^{214}Pb and ^{214}Bi from the uranium-238 series, ^{212}Pb, ^{208}Tl, and ^{228}Ac from the thorium-232 series and the single radionuclide ^{40}K. Cesium-137 was not detected in any of the samples, which indicates that these areas are not contaminated. The ^{238}U, ^{232}Th, and ^{40}K specfic activity concentrations, Bq kg^{-1}, are presented in Figs. 5, 6, and 7 as cumulative bars for soil and crop samples.

The ^{238}U specific activities of the soil varied from 16.66 ± 4.08 to 11.87 ± 3.53 Bq kg^{-1}. The ^{232}Th soil specific activities had a low value of 12.19 ± 3.49 Bq kg^{-1}and a high value of 37.46 ± 6.12. The ^{40}K specific activities of the soil samples ranged from 242.38 ± 15.57 Bq kg^{-1} to 308.67 ± 17.57 Bq kg^{-1}.

The specific activities of all crop samples for ^{238}U were below LLD except for C4 (wheat), which had an activity of 4.13 ± 2.07 Bq kg^{-1}. The specific activities of ^{232}Th range from LLD for C6 (chili pepper) to 8.61 ± 2.34 Bq kg^{-1} for C4 (wheat). However, the ^{40}K specific activity ranges from 39.94 ± 6.31 for C1 (rice) to 972.19 ± 31.17 Bq kg^{-1} for C7 (*Solanum melongena*).

Table 4 presents the soil and crop mean specific activities of ^{238}U and ^{232}Th, which are below the worldwide average for most samples under consideration. For the *Solanum* and *Raphanus sativus* soils, the specific activities of ^{232}Th are higher than

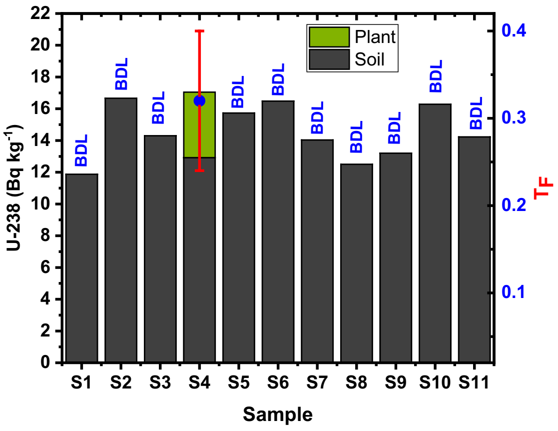

Fig. 5 Specific activities (^{238}U) of soil and plant samples with the transfer factor (T_F) for each

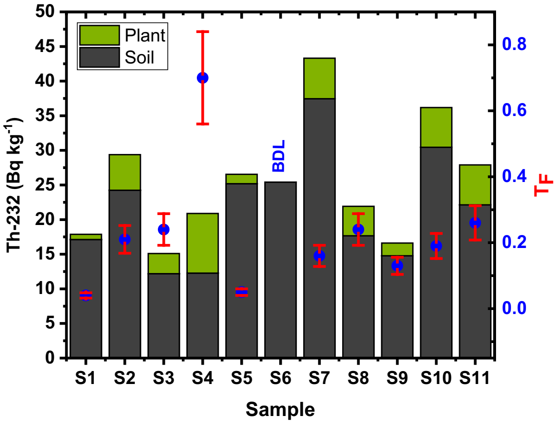

Fig. 6 Specific activities (^{232}Th) of soil and plant samples with the transfer factor (T_F) for each

the worldwide average. This is due to the erosion of ^{232}Th, which was adsorbed in the soil. However, ^{238}U is removed simply with irrigation water. Also, this variation in radioactivity could result from the type of soil deposit and the geotechnical characteristic of the area. This may cause a higher accumulation of ^{232}Th than ^{238}U (Asaduzzaman et al., 2015; Jilbert et al., 2016; Zubair & Shafiqullah, 2020).

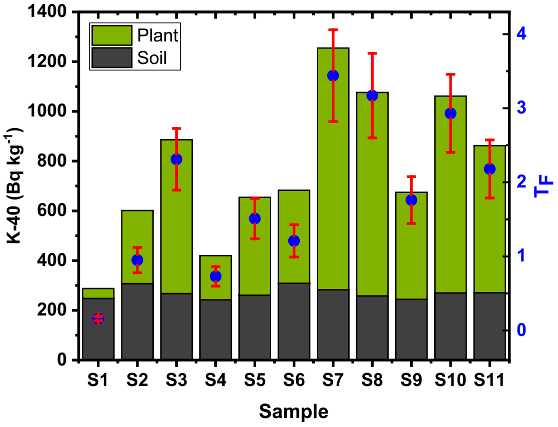

Fig. 7 Specific activities (^{40}K) of soil and plant samples with the transfer factor (T_F) for each

The specific activities of ^{40}K for soil samples fall within the worldwide range (400 Bq kg^{-1}), but the crop samples of vigna, okra, *Apium graveolens*, *Raphanus sativus*, and *Ocimum basilicum* have higher specific activities of ^{40}K than the world average. This is due to the cation exchange capacity (CEC) in the soil, the pH of the soil and the type of soil (Asaduzzaman et al., 2015).

Transfer factor

The soil-to-crop T_F is calculated from Eq. 2 and listed in Table 4. The maximum T_F value of ^{238}U is 0.32 for wheat. The maximum value of T_F for ^{232}Th is 0.7 in wheat; for ^{40}K, it is 3.44 in *Solanum melongena*.

The variations in T_F for different soils may be due to soil features such as granulometric production, mineralogical/organic matter content, pH, and hydrological conditions within the soil (Asaduzzaman et al., 2015; Jilbert et al., 2016; Zubair & Shafiqullah, 2020). The biological variability inherent in plants and differences between types and species are likely sources of the variations in transfer factors. Soil control, crop-farming technologies, the growing period, and the properties of root distribution also have an effect. The above parameters may change soil properties or cause the redistribution of radionuclides in the root zone; consequently, they influence radionuclide uptake in crops.

The kinds of soil and farming data are significant factors because the behaviors of radionuclides depend on the sampling conditions and soil properties. The soil-to-plant transfer of natural radionuclides is heavily influenced by the soil's physiochemical properties, such as potassium (K) content, cation exchange capacity (CEC), organic matter content, calcium (Ca) content, etc. (Asaduzzaman et al., 2015).

Hazard parameters

Tables 5 and 6 show the radiation hazard parameters of the crop and soil samples. The results show that all these parameters are below the global limits and world averages.

For crops, the highest radiation parameters were reported for C7 (*Solanum melongena*), while the lowest were reported for C1 (rice). For soil, the highest values were reported for S7, the soil collected from Al-Tuwaitha used to cultivate *Solanum melongena*. The lowest values were reported for S4, the soil collected from Abu Ghraib in which wheat was cultivated.

Table 4 The specific activities and transfer factor of the radionuclides in soil samples

No.	Crop	Sample type	Mean specific activity (Bq kg^{-1})		
			^{238}U	^{232}Th	^{40}K
1	Rice	S1	11.87	17.13	247.72
		C1	B.D.L*	0.75	39.94
		Transfer factor	B.D.L	0.04	0.16
2	Lemon	S2	16.66	24.24	307.76
		C2	B.D.L	5.15	293.78
		Transfer factor	B.D.L	0.21	0.95
3	Vigna	S3	14.30	12.19	267.82
		C3	B.D.L	2.91	618.33
		Transfer factor	B.D.L	0.24	2.31
4	Wheat	S4	12.92	12.27	242.38
		C4	4.13	8.61	177.66
		Transfer factor	0.32	0.70	0.73
5	Orange	S5	15.73	25.19	260.75
		C5	B.D.L	1.35	393.83
		Transfer factor	B.D.L	0.05	1.51
6	Chilli pepper	S6	16.48	25.41	308.67
		C6	B.D.L	B.D.L	374.50
		Transfer factor	B.D.L	B.D.L	1.21
7	*Solanum melongena*	S7	14.03	37.46	282.52
		C7	B.D.L	5.85	972.19
		Transfer factor	B.D.L	0.16	3.44
8	Okra	S8	12.50	17.66	258.17
		C8	B.D.L	4.26	818.08
		Transfer factor	B.D.L	0.24	3.17
9	*Apium graveolens*	S9	13.20	14.77	244.33
		C9	B.D.L	1.85	430.35
		Transfer factor	B.D.L	0.13	1.76
10	*Raphanus sativus*	S10	16.28	30.44	270.02
		C10	B.D.L	5.75	791.39
		Transfer factor	B.D.L	0.19	2.93
11	*Ocimum basilicum*	S11	14.22	22.13	270.90
		C11	B.D.L	5.77	591.42
		Transfer factor	B.D.L	0.26	2.18
Max		Soil	16.66	37.46	308.67
		Crop	4.13	8.61	972.19
		Transfer factor	0.32	0.70	3.44
Min		Soil	11.87	12.19	242.38
		Crop	B.D.L	0.75	39.94
		Transfer factor	B.D.L	B.D.L	0.16
Mean ± SE		Soil	14.38 ± 0.51	21.72 ± 2.38	269.19 ± 6.89
		Crop	4.13 ± 0.38	4.22 ± 0.81	500.13 ± 86.4
		Transfer factor	0.32	0.20	1.85

*B.D.L the value lower than LLD

Table 5 Radium equivalent (Ra_{eq}), H_{in}, I_γ, D_γ, E_{ff} dose, and AGDE for soil

Code	Ra_{eq} (Bq kg^{-1})	H_{in}	I_γ	D_γ (nGy h^{-1})	E_{ff} dose (mSv y^{-1})	AGDE (mSv y^{-1})
S1	55.44	0.182	0.208	26.1	0.032	0.193
S2	75.02	0.248	0.279	35.1	0.043	0.258
S3	52.35	0.180	0.198	25.1	0.031	0.186
S4	49.13	0.168	0.185	23.5	0.029	0.174
S5	71.83	0.236	0.265	33.3	0.041	0.243
S6	76.59	0.251	0.285	35.8	0.044	0.262
S7	89.35	0.279	0.328	40.8	0.050	0.296
S8	57.64	0.189	0.216	27.2	0.033	0.200
S9	53.14	0.179	0.199	25.2	0.031	0.186
S10	80.61	0.262	0.296	37.1	0.046	0.270
S11	66.72	0.219	0.248	31.2	0.038	0.229
Max	89.35	0.279	0.328	40.8	0.050	0.296
Min	49.13	0.168	0.185	23.5	0.029	0.174
Global limit	370	≤1	≤1	55	1	0.3

Table 6 Radium equivalent (Ra_{eq}), H_{in}, I_α, I_γ, D_γ, E_{ff} dose, and AGDE for crops

Code	Ra_{eq} (Bq kg^{-1})	H_{in}	I_γ	D_γ (nGy h^{-1})	E_{ff} dose (mSv y^{-1})	AGDE (mSv y^{-1})
C1	4.15	0.011	0.017	2.13	0.003	0.017
C2	29.98	0.081	0.124	15.45	0.019	0.122
C3	51.77	0.140	0.221	27.59	0.034	0.223
C4	30.12	0.092	0.116	14.66	0.018	0.109
C5	32.25	0.087	0.138	17.26	0.021	0.140
C6	28.84	0.078	0.125	15.62	0.019	0.128
C7	83.23	0.225	0.353	44.18	0.054	0.356
C8	69.09	0.187	0.294	36.76	0.045	0.297
C9	35.78	0.097	0.153	19.09	0.023	0.154
C10	69.15	0.187	0.293	36.57	0.045	0.294
C11	53.79	0.145	0.226	28.25	0.035	0.226
Max	83.23	0.225	0.353	44.18	0.054	0.356
Min	4.15	0.011	0.017	2.13	0.003	0.017
Global limit	370	≤1	≤1	55	1	0.3

Conclusions

Natural radionuclides were detected in crop and soil samples. The specific activities of all crop samples for ^{238}U were below LLD except for C4 (wheat). The absence of cesium in all samples indicates that these areas are not contaminated. The average specific activities of radionuclides in uranium-238 and thorium-232 chains were below the worldwide average in crop samples. The specific activities of potassium-40 were above the worldwide average in most of the crop samples, although the activities in the soil samples were below the recommended value set by UNSCEAR (2000). The soil-to-crop transfer factor (T_F) values were higher than the default values set by IAEA. The radiation hazard parameters are lower than the global limits. The highest radiation hazard parameters for soil were detected in the sample from Al-Tuwaitha in which *Solanum melongena* was cultivated; this is because the soil sample from this region has the highest value of ^{232}Th, 37.46 Bq kg^{-1}. This may be related to the proximity of this farm to the Iraqi Atomic Energy Commission. The highest radiation hazard parameters for crops were detected in *Solanum melongena* because it has the highest value of ^{40}K, 972.19 Bq kg^{-1}. This may be related to the nature of this crop, which has a high potassium content.

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References

Alharbi, A., & El-Taher, A. (2013). A study on transfer factors of radionuclides from soil to plant. *Life Science Journal, 10*(2), 532–539.

Ammer, H. A., Kadhim, N. F., Karim, M. S., & Ridha, A. A. (2017). Hazard Indices and Age Group Parameters of Powder Milk Consumed in Iraq. *Higher Education Research*, *2*(5), 117–122. https://doi.org/10.11648/j.her.20170205.11

Asaduzzaman, K., Khandaker, M. U., Amin, Y. M., & Mahat, R. (2015). Uptake and distribution of natural radioactivity in rice from soil in north and west part of peninsular Malaysia for the estimation of ingestion dose to man. *Annuls of Nuclear Energy, 76*, 85–93. https://doi.org/10.1016/j.anucene.2014.09.036

Currie, L. A. (1968). Limits for qualitative detection and quantitative determination: application to radiochemistry. *Analytical Chemistry, 40*(3), 586–593. https://doi.org/10.1021/ac60259a007

IAEA, I. A. E. A. (2006). Classification of soil systems on the basis of transfer factors of radionuclides from soil to reference plants. *IAEA-TECDOC-1497*. https://doi.org/10.1051/radiopro/2002097

James, J. P., Dileep, B. N., Ravi, P. M., Joshi, R. M., Ajith, T. L., Hegde, A. G., & Sarkar, P. K. (2011). Soil to leaf transfer factor for the radionuclides 226Ra, 40K, 137Cs and 90Sr at Kaiga region India. *Journal of Environmental Radioactivity, 102*(12), 1070–1077. https://doi.org/10.1016/j.jenvrad.2011.07.011.

Jilbert, E., Nguelem, M., Ndontchueng, M. M., & Motapon, O. (2016). Determination of 226 Ra, 232 Th, 40 K, 235 U and 238 U activity concentration and public dose assessment in soil samples from bauxite core deposits in Western Cameroon. *Springerplus, 5*(1253), 1–12. https://doi.org/10.1186/s40064-016-2895-9

Kadhim, N. F., Khalaf, H. N. B., Hassan, H. A., & Mostafa, M. Y. A. (2021). Determining the natural radioactivity of spices widely used in Iraq. *International Journal of Environmental Analytical Chemistry,* 1–12. https://doi.org/10.1080/03067319.2021.1901897

Kadhim, N. F., & Ridha, A. A. (2019). Radiation hazards of the moassel consumed in Baghdad/Iraq using NaI(Tl) gamma spectroscopy. *International Journal of Environmental Science and Technology, 16*(12), 8209–8216. https://doi.org/10.1007/s13762-019-02373-9

Karunakara, N., Rao, C., Ujwal, P., Yashodhara, I., Kumara, S., & Ravi, P. M. (2013). Soil to rice transfer factors for 226Ra, 228Ra, 210Pb, 40K and 137Cs: A study on rice grown in India. *Journal of Environmental Radioactivity, 118*, 80–92. https://doi.org/10.1016/j.jenvrad.2012.11.002

Linsalata, P. (1994). Uranium and Thorium Decay Series Radionuclides in Human and Animal Foodchains-A Review, 633–642.

Mheemeed, A. K., Najam, L. A., & Hussein, A. K. (2014). Transfer factors of 40K, 226Ra, 232Th from soil to different types of local vegetables, radiation hazard indices and their annual doses. *Journal of Radioanalytical and Nuclear Chemistry, 302*(1), 87–96. https://doi.org/10.1007/s10967-014-3259-y

Ononugbo, C. P., Azikiwe, O., & Avwiri, G. O. (2019). Uptake and Distribution of Natural Radionuclides in Cassava Crops from Nigerian Government Farms. *Journal of Scientific Research and Reports*, (January 2020), 1–15. https://doi.org/10.9734/jsrr/2019/v23i530130

Pulhani, V. A., Dafauti, S., Hegde, A. G., Sharma, R. M., & Mishra, U. C. (2005). Uptake and distribution of natural radioactivity in wheat plants from soil. *Journal of Environmental Radioactivity, 79*(3), 331–346. https://doi.org/10.1016/j.jenvrad.2004.08.007

Saeed, M. A., Yusof, S. S., Hossain, I., Ahmed, R., Abdullah, H. Y., Shahid, M., & Ramli, A. T. (2012). Soil to rice transfer factor of the natural radionuclides in Malaysia. *Romanian Reports of Physics, 57*(9–10), 1417–1424.

Shanthi, G., Kumaran, J. T. T., Raj, G., G. A., & Maniyan, G. C. (2012). Transfer factor of the radionuclides in food crops from high-background radiation area of south west India. *Radiation Protection Dosimetry, 149*(3), 327–332.

Shanthi, G., Thanka, T., kumaran, J., Allen Gnana raj, G., & Maniyan, C. G. (2012). Transfer factor of the radionuclides in food crops from high-background radiation area of south west India. *Radiation Protection Dosimetry, 149*(3), 327–332. https://doi.org/10.1093/rpd/ncr235

Shayeb, M. A., Alharbi, T., Baloch, M. A., & Rahman Alsamhan, O. A. (2017). Transfer factors for natural radioactivity into date palm pits. *Journal of Environmental Radioactivity, 167*, 75–79. https://doi.org/10.1016/j.jenvrad.2016.11.014

Tsukada, H., Hasegawa, H., Hisamatsu, S., & Yamasaki, S. (2002). Transfer of 137Cs and stable Cs from paddy soil to polished rice in Aomori. *Japan. Journal of Environmental Radioactivity, 59*(3), 351–363. https://doi.org/10.1016/S0265-931X(01)00083-2

UNSCEAR. (2000). Exposures from natural radiation sources (Annex B) Sources and Effects of Ionizing Radiation 84–141. https://doi.org/10.1097/00004032-199907000-00007

UNSCEAR. (2008). *Sources and Effects of Ionizing Radiation United Nations Scientific Committee on the Effects of Atomic Radiation* (Vol. I).

UNSCEAR. (2010). *Sources And Effects Of Ionizing Radiation - Exposures of The Public And Workers From Various Sources*

Of Radiation - UNSCEAR 2008 Report. United Nations Publication (Vol. I).

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. *Journal of Environmental Radioactivity, 100*(9), 721–732. https://doi.org/10.1016/j.jenvrad.2008.10.014

Velasco, H., Cid, A. S., Anjos, R. M., Zamboni, C. B., Rizzotto, M., Valladares, D. L., & Juri Ayub, J. (2012). Variability of 137Cs and 40K soil-to-fruit transfer factor in tropical lemon trees during the fruit development period. *Journal of Environmental Radioactivity, 104*(1), 64–70. https://doi.org/10.1016/j.jenvrad.2011.09.016

Wang, Z. T., Zheng, J., Tagami, K., & Uchida, S. (2015). Newly derived transfer factors for Th, Am, Pu, and Cl since publication of IAEA TRS No. 472: a review. *Journal of Radioanalytical and Nuclear Chemistry*, *306*(1), 11–20. https://doi.org/10.1007/s10967-015-4260-9

Zubair, M., & Shafiqullah. (2020). Measurement of natural radioactivity in several sandy-loamy soil samples from Sijua, Dhanbad, India. *Heliyon, 6*(February), 0–7. https://doi.org/10.1016/j.heliyon.2020.e03430