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Soil-to-crop transfer of natural radionuclides in farm soil of South Africa

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Abstract The activity concentration of natural radionuclides in farm soil and most common indigenous food crops (maize, potato, cowpea) in oil-producing (Philippi, Uitenhage, and Hertenbos farms) and non-oil-producing (Ukulinga farm) areas of South Africa was measured using a Hyper Pure Germanium detector. Consequently, the transfer of these radionuclides from soil-to-crops was estimated. The mean activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K for farm soil samples are 30.71 ± 11.77, 31.97 ± 8.90, 345.97 ± 98.62 Bq.kg^{-1} for Philippi; 18.67 ± 6.70, 31.55 ± 11.48, 191.93 ± 33.39 Bq.kg^{-1} for Uitenhage; 38.03 ± 17.44, 41.18 ± 31.54, 381.89 ± 163.40 Bq.kg^{-1} for Hartenbos; and 8.47 ± 2.87, 8.65 ± 3.52, 94.22 ± 25.97 ± 25.97 Bq.kg^{-1} for Ukulinga. The mean activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K for crop samples are 4.54 ± 1.47, 4.87 ± 1.69, 140.18 ± 35.38 Bq.kg^{-1} for Philippi; 9.17 ± 4.79, 3.85 ± 1.87, 136.75 ± 22.04 Bq.kg^{-1} for Uitenhage; 7.97 ± 2.91, 4.62 ± 2.40, 105.97 ± 48.65 Bq.kg^{-1} for Hartenbos; and 4.23 ± 1.63, 2.72 ± 1.19, 48.36 ± 15.55 Bq.kg^{-1} for Ukulinga. The activity concentration and soil-to-crop transfer factors for ^{40}K were found to be much higher, possibly because this element is critical in crop growth. The results showed that the crop samples' transfer factor is in the order cowpea>potato>maize. This study showed that activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in crops and the corresponding transfer factors depend on activity concentrations of the same radionuclides in soil.

Keywords Activity concentration · Crops · Farm soil · HPGe detector · NORMs · transfer factor

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Introduction

The environment contains different degrees of natural radioactive materials (NORMs), which vary by geographical location and are enhanced by human activities through industrialization (Karahan and Bayulken 2000; IAEA 2007). Natural radionuclides include the primordial radionuclides ^{235}U, ^{238}U, ^{232}Th and their decay chains, ^{14}C, and ^{3}H cosmogenic radionuclides, and ^{40}K (Morcos et al. 1992; UNSCEAR 2000; Larivière and Guérin 2010; Ajanaku et al. 2018; Ilori and Alausa 2019). Naturally occurring radionuclides are available in various samples of the environment, including air, water, plant, and soil (Barišić 1996; Poschi and Nollet 2007). Oil exploration, extensive uses of fertilizers on farmlands, and mining activities have also been established as primary sources of radiation to the environment and a source of radiological risk to humans (IAEA 1994; NRC 1999; Carvalho 2017). South Africa's oil and gas sector has been the leading importers and consumers of radioactive materials from 1913 principally for its oil exploration (SAES 2018). The oil and gas reserves at Bredasdorp and deep marine basins have been primarily explored, leading to massive oil produce in South Africa since 1987 (van Wyk 1989).

These industrial activities may lead to an increase in the background radiation of an environment such as the rivers, soils, and a transfer to humans (ICRP 1991; IAEA 2007; Sunday et al. 2019; Ali et al. 2019).

Natural radionuclides present in the soil contributes to its uptake and translocation into edible parts of plants, driven by several factors, such as soil characteristics, plant types, atmosphere, environmental contamination, and agricultural practices (Thabayneh and Jazzar 2013; Sunday et al. 2019). Radionuclide transfers from soil-to-crops are known as the main route by which radionuclides are transferred to humans through crops' ingestion. This transfer is defined as a transfer factor and is known to be the most significant human contribution to the dose of radiation (IAEA 1994; El-Gamal et al. 2019).

Assessment of radionuclides in food crops grown in areas suspected of high radiation is critical in evaluating radionuclides' transfer from soil-to-crops and their risk levels to public health (Khan et al. 1992; Khan et al. 2010; Gilbert et al. 2018). Governments are required to concentrate not only on appropriate food supplies for their people but also on food sources that are chemically and radiological safe (UNSCEAR 2000). This is part of the UN's primary objective of sustainable food security, which is to help the member states ensure that their citizens have access to sufficient, nutritionally suitable, and considerably safe foods for human consumption (Jibiri et al. 2007; Pérez-Escamilla 2017; Yadav et al. 2018; El-Bilali et al. 2019).

South Africa has one of the most diverse and comprehensive crop farming systems growing mainly in vegetables, fruit, nuts, and grain (Abalu and Hassan 1998; Dredge 2015). South African climate varies from subtropical to the Mediterranean, allowing for a multitude of opportunities for agriculture (Singh and Singh 2017). Thus, the most common indigenous food crops (maize, potato, and cowpea) grown and consumed in South Africa were collected for this present study.

Therefore, this study aims to estimate the activity concentrations of natural radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in farm soils and crops grown in oil-producing (Philippi, Uitenhage, and Hartenbios farms) and non-oil-producing (Ukulinga farm) areas of South Africa. Also, the transfer of these radionuclides from soil-to-crops is evaluated.

Materials and methods

Collection of samples

This study's samples were selected from farms at oil-producing areas and a farm from the non-oil-producing area in South Africa. Soil samples were collected at random within clear boundary areas of the farmland. The soil samples were taken at a depth of 5–10 cm using a well-cleaned field trowel, where the crop roots are located (Jibiri et al. 2007; Senthilkumar et al. 2010; Usikalu et al. 2014). The farm soil samples for each sampling point were each packaged in labeled polythene packets. The samples of crops (cowpea, maize, and potato) were picked randomly from each selected farm. The samples collected for this study are ready to be harvested and consumed (Jibiri et al. 2007; Tchokossa et al. 2013; Adedokun et al. 2019). The crops were washed thoroughly, packed into labeled polythene packets. The sealed polythene packets containing the soil and crop samples were transferred to the physics discipline laboratory at the University of KwaZulu-Natal, Pietermaritzburg, South Africa. The coordinates were measured and recorded at each sampling location using a Geological Position System (GPS) device. The sample codes, sampling locations, and GPS coordinates are shown in Tables 1 and 2. Figure 1 illustrates the areas of the farmlands selected for the study in South Africa.

Preparation of samples

The soil samples collected from the farms were air-dried for five days at a laboratory temperature of approximately 27 °C and relative humidity of about 70% (IAEA 1989). Extraneous materials such as plant roots, stones, and decaying plant materials were removed from each of the samples and then dried in an electronic oven at a temperature of 105 °C until moisture was extracted from all soil samples, and a constant weight was obtained (Tufail et al. 2006; Abu-Khadra and Eissa 2008; Noli et al. 2017). The crop samples were further cleaned while the edible parts were cut into pieces that were air-dried in the laboratory for over seven days (Gilbert et al. 2018; Adedokun et al. 2019). The crop samples were then dried in an oven at 70 °C until a constant dried weight was obtained for each sample (IAEA 1989; Jwanbot et al. 2013). The dried samples were blended into fine powders using an electric blender and sieved

Table 1 The sampled crops from farmlands within oil-producing regions

Sample codes	Common names	Species	Family	Locations	GPS coordinates
C1, C2	Cowpea (sorghum)	*Vigna unguiculata*	Euphorbiaceae	Philippi farms	34° 01′ 10.9″ S
C3, C4	Potato (root vegetable)	*Solanum tuberosum*	Solanacaea		18° 33′ 46.5″ E
C5, C6	Maize (grain)	*Zea mays*	Poaceae		
C7, C8	Cowpea (sorghum)	*Vigna unguiculata*	Euphorbiaceae	Uitenhage farms	33° 54′ 55.5″ S
C9, C10	Potato (root vegetable)	*Solanum tuberosum*	Solanacaea		25° 18′ 44.6″ E
C11, C12	Maize (grain)	*Zea mays*	Poaceae		
C13, C14	Cowpea (sorghum)	*Vigna unguiculata*	Euphorbiaceae	Hartenbos Farms	34° 06′ 13.2″ S
C15, C16	Potato (root vegetable)	*Solanum tuberosum*	Solanacaea		22° 03′ 43.9″ E
C17, C18	Maize (grain)	*Zea mays*	Poaceae		

through a 2-mm pore size mesh to homogeneity (Darko et al. 2015). The sieved parts were weighed into previously weighed Polyvials clear 100 ml plastic pill bottles (IAEA 1989) to obtain each soil and crop samples' actual weight. The pill bottles were sealed and stored for at least 28 days to allow natural radionuclides and their short-lived progeny to achieve secular radioactive equilibrium (Haque and Ferdous 2017; IAEA 2007; Gilbert et al. 2018). The samples were counted for 3600 s using the Hyper Pure Germanium (HPGe) detector to estimate the radionuclide activity concentration in the dry samples (Doyi et al. 2017).

Instrumentation

The HPGe detector was used in this analysis for counting and detecting the radionuclide content in the samples. The detector was cooled to liquid nitrogen temperature, yielding spectroscopic data. and pulses proportional to the photon energy captured (Wallbrink et al. 2002; Simon et al. 2012; Guembou et al. 2017). The detector used is 62.5 mm in diameter, 59.5 mm in length with 45% relative efficiency, and 2.2 KeV resolutions on the 1332-KeV ^{60}Co line. A fully fitted multichannel analyzer (MCA) was connected to the detector, including a pre-amplification stage, amplifier stage, and display terminal. For the gamma-ray detection experiment, each sample was placed directly on the detector for 36,000 s of exposure (Adedokun et al. 2019). In addition to the uncertainty associated with each particular nuclide, the gamma-ray value transition defined from the data spectra was used to determine the specific activity concentration for each radionuclide of interest (Turhan and Gürbüz 2008; Joel et al. 2016). An estimate of the specific activity concentration was obtained using the weighted average of each nuclide of interest. Data were gathered and analyzed using PalmtopMCA software, which was installed on the computer. The measurements were performed at the Environmental Radiation Laboratory (ERL) of iThemba LABS in Cape Town, South Africa.

Energy and efficiency calibration

For the calibration, a volume source with the same geometry as the sample was used to determine the activity concentration of radionuclide present in the samples. The energy calibration was performed by comparing the specific gamma-ray energies in the standard reference material spectrum with the spectrometer channel number. The detector undergoes a full energy peak and efficiency calibration using generic ^{226}Ra, ^{232}Th, and ^{40}K reference sources with an activity concentration of 3252 Bq, 4938.8 Bq, and 13910.8 Bq, respectively. This expression gives the equation relating to the energy and channel number (Joel et al. 2016):

Table 2 The sampled crops from farmlands at non-oil-producing region (control)

Sample codes	Common names	Species	Family	Locations	GPS coordinates
C19, C20	Cowpea (sorghum)	*Vigna unguiculata*	Euphorbiaceae	Ukulinga farms	29° 39′ 45.3″ S
C21, C22	Potato (root vegetable)	*Solanum tuberosum*	Solanacaea		30° 24′ 17.7″ E
C23, C4	Maize (grain)	*Zea mays*	Poaceae		

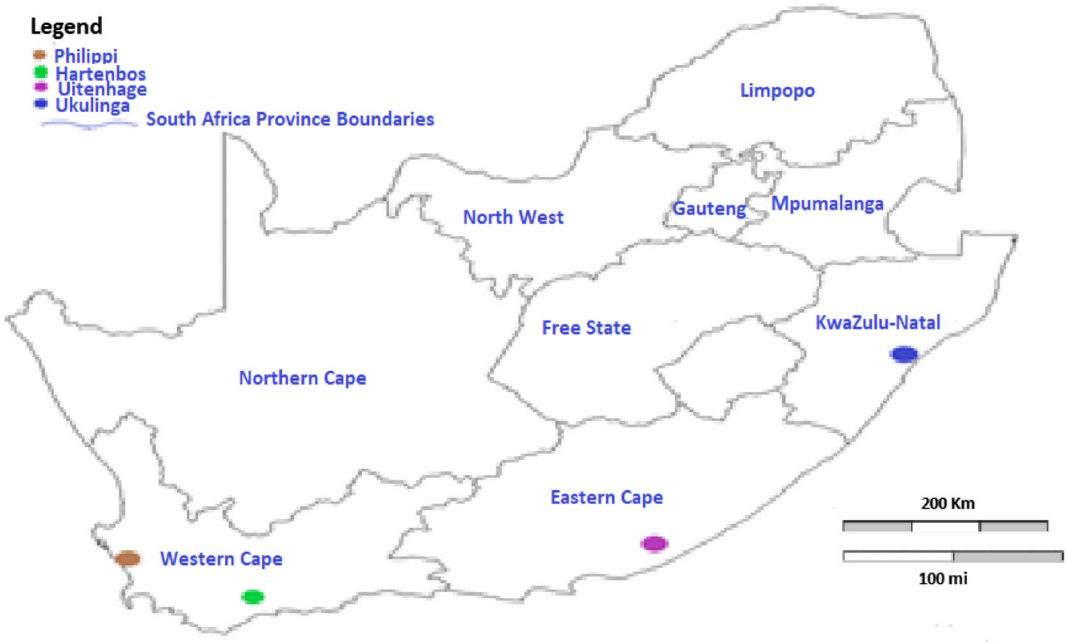

Fig. 1 South Africa map showing the sampling locations for this study

$$E_\gamma = C_1 + C_2 C_N \tag{1}$$

where E_γ is the energy in KeV, C_N is the channel number for a given radionuclide, while C_1 and C_2 are the calibration constants for a given geometry.

The efficiency calibration was performed by acquiring a calibration standard spectrum until the total absorption peak count rate can be determined with a statistical uncertainty of less than 1% at a 95% confidence point. For the calculation of photo peaks, the net count rate was established to evaluate the output for all the energies used at the measurement time. The output was linked by the count rate correlation and the standard source (Adukpo et al. 2010; Darko et al. 2015):

$$\left(E_\gamma\right)_\varepsilon = \frac{N_e}{(A_c{*}P_b{*}t_c)} \tag{2}$$

where N_e is the full energy peak net count corresponding to the energy probability of gamma photons E_γ and gamma emission P_b, A_c is the standard source activity, and the counting time is t_c.

Therefore, the energy efficiency was plotted as a function of the peak energy and extrapolated for the measurement geometry used to calculate the efficiencies at other peak energies (Chowdhury et al. 1999; Adukpo et al. 2010). The standard reference source was measured for 3600 s (Jibiri and Fasae 2012; Darko et al. 2015; Mekongtso et al. 2016), and the spectrum obtained was used to generate the efficiency curve, and power fitting was performed to get the best R^2 value (Fig. 2).

Calculation of activity concentration

The activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in Bq.kg^{-1} (dry weight) was calculated based on measured efficiency, net count rate, mass, and sample count time of the detector. It is presented in the expression (Jibiri and Fasae 2012):

$$A_c = \frac{C_\gamma}{P_\gamma \cdot m_s \cdot E_f \cdot t_c} \tag{3}$$

where A_c is the activity concentration for each sample, C_γ is the net peak energy, P_γ is the probability of gamma-ray decay, m_s is the mass of the sample in kg, E_f is the efficiency of the detector, and t_c is the total counting time in seconds.

For the gamma analysis, each sample was placed directly on the detector for a 36,000-s exposure duration. The gamma-ray significance transition defined from the data spectra and the uncertainty associated with

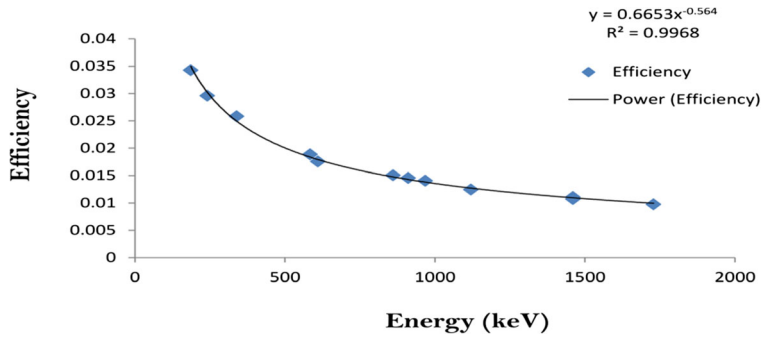

Fig. 2 Efficiency calibration curve showing the detection efficiency as a function of the gamma-ray energy used for the HPGe detector

each particular nuclide was to assess the radionuclides' activity concentration (Solak et al. 2014). A better approximation of activity concentration was obtained by utilizing each nuclide's weighted average of interest's specific activity.

Transfer factor

The transfer of natural radionuclides from farm soils to crops is determined from the measured concentration of activity in farm soils and corresponding crops. Hence, the soil samples' radionuclides interact with the soil composition and are passed to the soil solutions and soil particles. The proportion of these radionuclides that are passed to the soil solution may be incorporated into crops through plants' roots (Abdulaziz and El-Taher 2013; Gilbert et al. 2018). The transfer factor values were calculated using Eq. 4 from the measured radionuclide in the crops with the farm soils:

$$TF = \frac{A_c}{A_s} \tag{4}$$

where A_c is the activity of radionuclides in crops and A_s is the activity of radionuclides in farm soils, in Bq.kg^{-1} dry weight, respectively. The radionuclide transfer factor from soil-to-crop can be used as an index for evaluating trace elements' retention or the transfer of elements from soil to crop (Sabine and Gerald 2002; Yadav et al. 2018).

Results and discussion

Table 3 displays the results of the naturally occurring radionuclide activity in farm soils in different areas of South Africa. Figure 3 shows the distribution of ^{226}Ra, ^{232}Th, and ^{40}K in farm soil samples from the areas studied.

The activity concentration values for farm soil samples at Philippi farm ranged from 14.26 ± 1.19 to 48.89 ± 8.17 Bq.kg^{-1} with a mean value of 30.71 ± 11.77 Bq.kg^{-1} for ^{226}Ra, 22.30 ± 1.41 to 45.11 ± 3.22 Bq.kg^{-1} with a mean value of 31.97 ± 8.90 Bq.kg^{-1} for ^{232}Th, and 237.68 ± 10.89 to 486.51 ± 40.05 Bq.kg^{-1} with a mean value of 345.97 ± 98.62 Bq.kg^{-1} for ^{40}K.

The activity concentration values for farm soil samples at Uitenhage farm ranged from 10.52 ± 1.12 to 25.82 ± 3.02 Bq.kg^{-1} with a mean value of 18.67 ± 6.70 Bq.kg^{-1} for ^{226}Ra, 13.06 ± 1.93 to 44.33 ± 5.21 Bq.kg^{-1} with a mean value of 31.55 ± 11.48 Bq.kg^{-1} for ^{232}Th, and 140.19 ± 10.92 to 229.79 ± 12.08 Bq.kg^{-1} with a mean value of 191.93 ± 33.39 Bq.kg^{-1} for ^{40}K.

The activity concentration values for farm soil samples at Hartenbos farm ranged from 16.47 ± 1.28 to 64.86 ± 3.01 Bq.kg^{-1} with a mean value of 38.03 ± 17.44 Bq.kg^{-1} for ^{226}Ra, 16.83 ± 1.52 to 88.60 ± 1.17 Bq.kg^{-1} with a mean value of 41.18 ± 31.54 Bq.kg^{-1} for ^{232}Th, and 135.20 ± 17.49 to 604.80 ± 13.42 Bq.kg^{-1} with a mean value of 381.89 ± 163.40 Bq.kg^{-1} for ^{40}K.

The activity concentration values for farm soil samples at Ukulinga farm ranged from 5.59 ± 2.21 to 12.96 ± 2.91 Bq.kg^{-1} with a mean value of 8.47 ± 2.87 Bq.kg^{-1} for ^{226}Ra, 4.52 ± 2.05 to 14.11 ± 2.73 Bq.kg^{-1} with a mean value of 8.65 ± 3.52 Bq.kg^{-1} for ^{232}Th, and 62.70 ± 22.58 to 126.51 ± 21.21 Bq.kg^{-1} with a mean value of 94.22 ± 25.97 Bq.kg^{-1} for ^{40}K.

The activity concentrations of radionuclide in soil have significant variations that can be due to soil types, soil composition, and extensive fertilizer applications in the farmlands, geological features, and presence of natural resources such as oil (Ghazwa et al. 2016; Adjirackor et al. 2017). Potassium is abundant in all soil samples compared to uranium and thorium, which may be due to its presence in the soil as solutions. ^{40}K also occurs as exchangeable K^+ ion adsorbed or released from soil particle surfaces and organic matter (Ashley

Table 3 Activity concentration of natural radionuclides in soil samples from the studied farm areas.

Sample codes	Sampling areas	^{226}Ra Bq.kg^{-1}	^{232}Th	^{40}K
S1	Philippi farms	27.62 ± 3.42	29.07 ± 1.02	237.68 ± 10.89
S2		14.26 ± 1.19	31.29 ± 1.47	288.06 ± 9.48
S3		29.33 ± 4.41	45.11 ± 3.22	486.51 ± 40.05
S4		38.25 ± 2.84	39.78 ± 1.18	287.17 ± 10.24
S5		48.89 ± 8.17	22.30 ± 1.41	330.00 ± 15.68
S6		25.94 ± 6.22	24.25 ± 2.01	446.38 ± 37.81
Range		14.26–48.89	22.30–45.11	237.68–486.51
Mean		30.71 ± 11.77	31.97 ± 8.90	345.97 ± 98.62
S7	Uitenhage Farms	23.52 ± 2.91	44.33 ± 5.21	166.85 ± 12.46
S8		24.61 ± 1.13	13.06 ± 1.93	214.42 ± 11.14
S9		14.14 ± 1.52	30.09 ± 3.38	140.19 ± 10.92
S10		25.82 ± 3.02	27.00 ± 2.49	210.05 ± 10.47
S11		10.52 ± 1.12	43.00 ± 2.53	190.31 ± 15.22
S12		13.41 ± 1.67	31.83 ± 7.02	229.79 ± 12.08
Range		10.52–25.82	13.06–44.33	140.19–229.79
Mean		18.67 ± 6.70	31.55 ± 11.48	191.93 ± 33.39
S13	Hartenbos Farms	16.47 ± 1.28	17.46 ± 2.39	455.05 ± 31.32
S14		22.58 ± 1.44	16.83 ± 1.52	135.20 ± 17.49
S15		64.86 ± 3.01	88.60 ± 1.17	604.80 ± 13.42
S16		42.85 ± 1.81	73.75 ± 1.21	382.54 ± 29.24
S17		35.26 ± 1.27	25.41 ± 1.09	447.27 ± 42.51
S18		46.16 ± 2.31	25.00 ± 1.36	266.47 ± 15.07
Range		16.47–64.86	16.83–88.60	135.20–604.80
Mean		38.03 ± 17.44	41.18 ± 31.54	381.89 ± 163.40
S19	Ukulinga Farms	7.90 ± 1.66	7.94 ± 3.21	62.70 ± 22.58
S20		6.16 ± 1.40	14.11 ± 2.73	93.25 ± 22.18
S21		5.59 ± 2.21	4.52 ± 2.05	105.95 ± 20.41
S22		7.34 ± 1.26	8.68 ± 5.29	64.68 ± 15.27
S23		12.96 ± 2.91	11.00 ± 3.22	112.24 ± 11.38
S24		10.86 ± 1.51	5.63 ± 2.41	126.51 ± 21.21
Range		5.59–12.96	4.52–14.11	62.70–126.51
Mean		8.47 ± 2.87	8.65 ± 3.52	94.22 ± 25.97

et al. 2006). All values reported for the farm soils at the non-oil-producing area (Ukulinga farm) were below the world average values. In contrast, some values reported for the farm soils at the oil-producing areas (Philippi, Uitenhage, and Hartenbos farms) are above the world average values of 33, 45, and 450 Bq.kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

Table 4 shows the measurement of activity concentrations of natural radionuclides in crop samples of different areas of South Africa. Figure 4 shows the distribution of ^{226}Ra, ^{232}Th, and ^{40}K in crop samples from the areas studied.

The activity concentration values for crop samples at Philippi farm ranged from 3.08 ± 2.60 to 7.18 ± 4.08 Bq.kg^{-1} with a mean value of 4.54 ± 1.47 Bq.kg^{-1} for ^{226}Ra, 3.58 ± 1.19 to 8.25 ± 2.17 Bq.kg^{-1} with a mean value of 4.87 ± 1.69 Bq.kg^{-1} for ^{232}Th, and 53.12 ± 30.93 to 209.20 ± 23.26 Bq.kg^{-1} with a mean value of 140.18 ± 35.38 Bq.kg^{-1} for ^{40}K.

The activity concentration values for crop samples at Uitenhage farm ranged from 4.99 ± 2.38 to 18.33 ± 2.09 Bq.kg^{-1} with a mean value of 9.17 ± 4.79 Bq.kg^{-1} for ^{226}Ra, 2.25 ± 1.68 to 7.32 ± 2.36 Bq.kg^{-1} with a mean value of 3.85 ± 1.87 Bq.kg^{-1} for ^{232}Th, and 105.94 ±

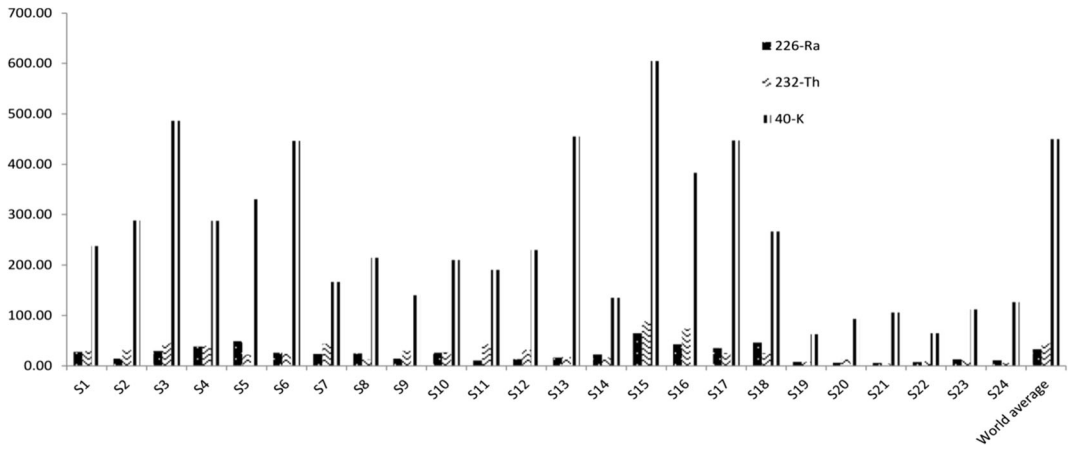

Fig. 3 Distribution of ^{226}Ra, ^{232}Th, and ^{40}K in farm soil samples from the areas studied

Table 4 Activity concentration of natural radionuclides in crop samples from the studied areas.

Sample codes	Sampling areas	^{226}Ra Bq.kg^{-1}	^{232}Th	^{40}K
C1	Philippi farms	7.18 ± 4.08	4.36 ± 2.66	183.01 ± 17.85
C2		4.42 ± 4.11	4.40 ± 1.25	195.88 ± 34.58
C3		3.08 ± 2.60	4.06 ± 1.93	209.20 ± 23.26
C4		3.26 ± 2.74	3.58 ± 1.19	120.61 ± 22.67
C5		4.58 ± 2.98	8.25 ± 2.17	53.12 ± 30.93
C6		4.70 ± 1.43	4.54 ± 1.68	79.26 ± 29.92
Range		3.08–7.18	3.58–8.25	53.12–209.20
Mean		4.54 ± 1.47	4.87 ± 1.69	140.18 ± 35.38
C7	Uitenhage farms	9.33 ± 3.57	2.25 ± 1.68	133.48 ± 20.58
C8		7.17 ± 2.22	4.57 ± 2.74	169.39 ± 18.95
C9		6.08 ± 2.11	2.98 ± 1.31	131.78 ± 14.79
C10		18.33 ± 2.09	3.30 ± 2.26	153.34 ± 15.53
C11		4.99 ± 2.38	2.70 ± 1.41	126.58 ± 28.74
C12		9.12 ± 5.97	7.32 ± 2.36	105.94 ± 28.27
Range		4.99–18.33	2.25–7.32	105.94–169.39
Mean		9.17 ± 4.79	3.85 ± 1.87	136.75 ± 22.04
C13	Hartenbos farms	5.27 ± 2.28	2.86 ± 1.45	182.02 ± 20.21
C14		5.42 ± 3.20	3.03 ± 1.22	75.71 ± 17.93
C15		9.08 ± 4.88	8.86 ± 4.24	120.96 ± 31.81
C16		5.57 ± 3.98	5.90 ± 2.58	91.81 ± 31.73
C17		11.54 ± 2.58	4.32 ± 2.50	40.10 ± 16.38
C18		10.93 ± 2.62	2.75 ± 1.91	125.24 ± 36.86
Range		5.27–11.54	2.75–8.86	40.10–182.02
Mean		7.97 ± 2.91	4.62 ± 2.40	105.97 ± 48.65
C19	Ukulinga farms	4.40 ± 1.26	2.58 ± 1.94	54.20 ± 32.85
C20		3.06 ± 1.77	1.27 ± 1.04	58.03 ± 18.95
C21		4.40 ± 1.66	3.31 ± 1.09	32.17 ± 21.63
C22		4.15 ± 2.63	1.35 ± 1.01	49.20 ± 27.14
C23		4.94 ± 2.06	3.88 ± 1.70	28.06 ± 8.87
C24		4.43 ± 2.01	3.90 ± 1.56	68.51 ± 11.84
Range		3.06–4.94	1.27–3.90	28.06–68.51
Mean		4.23 ± 1.63	2.72 ± 1.19	48.36 ± 15.55

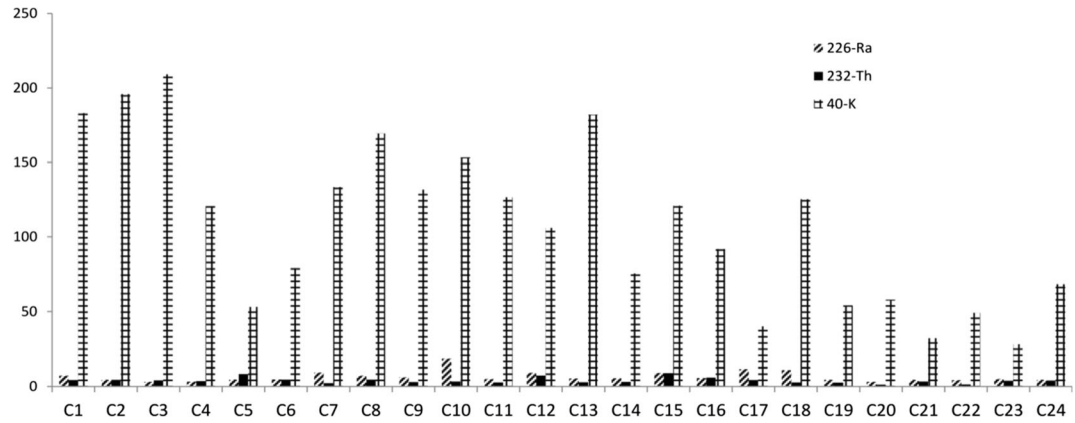

Fig. 4 Distribution of ^{226}Ra, ^{232}Th, and ^{40}K in crop samples from the areas studied

28.27 to 169.39 ± 18.95 Bq.kg^{-1} with a mean value of 136.75 ± 22.04 Bq.kg^{-1} for ^{40}K.

The activity concentration values for crop samples at Hartenbos farm ranged from 5.27 ± 2.28 to 11.54 ± 2.58 Bq.kg^{-1} with a mean value of 7.97 ± 2.91 Bq.kg^{-1} for ^{226}Ra, 2.75 ± 1.91 to 8.86 ± 4.24 Bq.kg^{-1} with a mean value of 4.62 ± 2.40 Bq.kg^{-1} for ^{232}Th, and 40.10 ± 16.38 to 182.02 ± 20.21 Bq.kg^{-1} with a mean value of 105.97 ± 48.65 Bq.kg^{-1} for ^{40}K.

The activity concentration values for crop samples at Ukulinga farm ranged from 3.06 ± 1.77 to 4.94 ± 2.06 Bq.kg^{-1} with a mean value of 4.23 ± 1.63 Bq.kg^{-1} for ^{226}Ra, 1.27 ± 1.04 to 3.90 ± 1.56 Bq.kg^{-1} with a mean value of 2.72 ± 1.19 Bq.kg^{-1} for ^{232}Th, and 28.06 ± 8.87 to 68.51 ± 11.84 Bq.kg^{-1} with a mean value of 48.36 ± 15.55 Bq.kg^{-1} for ^{40}K.

The results showed that the crops predominantly absorb the natural radionuclides of ^{226}Ra, ^{232}Th, and ^{40}K. Potassium (^{40}K) appears highest in all crop samples because it is an essential resource for plant growth and crops take up significant quantities of potassium during their life cycle (Jibiri et al. 2007; White and Brown 2010; Parikh and James 2012). ^{40}K was highest in potato (*Solanum tuberosum*) of C3 with a value of 209.20 ± 23.26 Bq.kg^{-1} at Philippi farm, ^{232}Th was highest in potato (*Solanum tuberosum*) of C15 with a value of 8.86 ± 4.24 Bq.kg^{-1} at Hartenbos farm, and ^{226}Ra was highest in potato (*Solanum tuberosum*) of C10 with a value of 18.33 ± 2.09 Bq.kg^{-1} at Uitenhage farm. Hence in the present study, natural radionuclides are the highest activity in potato samples. ^{40}K has the highest concentration, followed by ^{226}Ra and ^{232}Th, respectively. The geological location, soil formation properties, chemical characteristics, soil pH in which the crops are grown, and other natural resources such as oil and gas may also influence the variations in radionuclide concentration in crop samples from different farmlands of the study areas (Abalu and Hassan 1998; Ajanaku et al. 2018).

Table 5 shows naturally occurring radionuclide transfer factor values from soil-to-crop samples in the areas under this study. Potassium has the highest transfer factor value, then radium and followed by thorium (^{40}K > ^{226}Ra > ^{232}Th). In the oil-producing areas, the highest transfer factor values of 0.71, 0.37, and 0.94 were recorded for ^{226}Ra, ^{232}Th, and ^{40}K, respectively. In contrast, in the non-oil-producing area (control), the highest transfer factor values of 0.79, 0.73, and 0.86 were recorded for ^{226}Ra, ^{232}Th, and ^{40}K, respectively. The amount of fertilizers administered to farmlands can also account for higher potassium values in all soil and crop samples (Ashley et al. 2006; Bramki et al. 2018; Hasanuzzaman et al. 2018). The activity concentrations of natural radionuclides in the soil of the study area and its soil-to-crop transfer values do not pose any radiological threats to human health as the values reported were below the recommended limits (UNSCEAR 2000; 2008). Table 6 shows the values for the activity concentration of natural radionuclides in farm soil samples from the studied areas compared with those from other parts of the world.

Table 5 Soil-to-crops transfer factors in the samples from the studied areas

Sample codes		^{226}Ra	^{232}Th	^{40}K
S1–C1	Philippi farms	0.26	0.15	0.77
S2–C2		0.31	0.14	0.68
S3–C3		0.11	0.09	0.43
S4–C4		0.09	0.09	0.42
S5–C5		0.09	0.37	0.16
S6–C6		0.18	0.19	0.18
Range		0.09–0.31	0.09–0.37	0.16–0.77
Mean		0.17	0.17	0.44
S7–C7	Uitenhage farms	0.40	0.05	0.80
S8–C8		0.29	0.35	0.79
S9–C9		0.43	0.10	0.94
S10–C10		0.71	0.12	0.73
S11–C11		0.47	0.06	0.67
S12–C12		0.68	0.23	0.46
Range		0.29–0.71	0.05–0.35	0.46–0.94
Mean		0.50	0.15	0.73
S13–C13	Hartenbos farms	0.32	0.16	0.40
S14–C14		0.24	0.18	0.56
S15–C15		0.14	0.10	0.20
S16–C16		0.13	0.08	0.24
S17–C17		0.31	0.17	0.09
S18–C18		0.25	0.11	0.47
Range		0.13–0.32	0.08–0.18	0.09–0.56
Mean		0.23	0.13	0.33
S19– C19	Ukulinga farms	0.56	0.32	0.86
S20–C20		0.50	0.09	0.62
S21–C21		0.79	0.73	0.30
S22–C22		0.57	0.16	0.76
S23–C23		0.38	0.35	0.25
S24–C24		0.41	0.69	0.54
Range		0.38–0.79	0.09–0.73	0.25–0.86
Mean		0.53	0.39	0.56

Conclusion

In this study, the HPGe detector was used to measure the activity concentration of natural radionuclides in farm soils and crops grown in oil-producing (Philippi, Uitenhage, and Hertenbos farms) and non-oil-producing (Ukulinga farm) areas of South Africa, and consequently, the transfer of these radionuclides from soil-to-crops was estimated. The values reported showed a higher activity concentration in farm soils collected at the oil-producing areas compared to the non-oil-producing area. Most values reported for the farm soils at the non-oil-producing area are below the recommended world average values. In contrast, some values reported for the farm soils at the oil-producing areas are above the recommended world average values of 33, 45, and 450 Bq.kg^{-1} (UNSCEAR 2008) for ^{226}Ra, ^{232}Th, and ^{40}K, respectively. Potassium appears

Table 6 Activity of natural radionuclides in farm soil samples from the studied areas compared with those from other parts of the world

Country (location)	^{226}Ra	^{232}Th	^{40}K	References
Malaysia	45.11–111.4	51.83–127.35	99.2–172.85	Ghazwa et al. (2016)
Turkey	7.4–79.8	9.5–170.8	35.7–913.8	Ayşe and Meryem (2017)
India	18.22–90.30	34.80–124.68	80.42–181.41	Singh et al. (2005)
Pakistan	30.3–38.7	50.6–64.0	560–635.6	Akhtar et al. (2005)
Algeria	23.72–65.47	26.45–27.10	220.80–260.70	Bramki et al. (2018)
Philippi	14.26–48.89	22.30–45.11	237.68–486.51	Present study (South Africa)
Uitenhage	10.52–25.82	13.06–44.33	140.19–229.79	
Hartenbos	16.47–64.86	16.83–88.60	135.20–604.80	
Ukulinga	5.59–12.96	4.52–14.11	62.70–126.51	
World average	33	45	450	UNSCEAR (2008)

highest in all soil and crop samples for the estimated transfer factors. ^{40}K is an essential resource for plant growth (White and Brown 2010), and crops take up large quantities of this potassium during their life cycle (Ashley et al. 2006; Jibiri and Fasae 2012). ^{40}K has the highest value in C3, ^{232}Th has the highest value in C15, and ^{226}Ra has the highest value in C10 at Philippi, Hartenbos, and Uitenhage farm soils, respectively, all within the oil-producing areas. The results showed that the crop samples' transfer factor is in the order cowpea>potato>maize. This study showed that activity concentration ^{226}Ra, ^{232}Th, and ^{40}K in crops depend on activity concentrations of the same radionuclides in soil. This study's results can be used as baseline and reference evidence for future investigations in other areas of the study.

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