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Soil-to-maize Transfer Factor of Natural Radionuclides in a Tropical Ecosystem of Nigeria

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Abstract: Soil-to-plant transfer factor (TF) is a parameter utilized in predicting the accumulation of radionuclides in the plant system. Virgin soil from an uncultivated area and tailings from an abandoned tin mining site were used to formulate three soil groups. Group A (virgin soil only), group B (tailings only) and group C (equal mixture by mass of the virgin soil and tailings). Pot experiments were performed using the soil groups to determine the transfer factors of ^{40}K, ^{238}U and ^{232}Th in maize (*Zea mays* L.) plants for the tropical ecosystem of Nigeria. The activity concentrations of ^{40}K, ^{238U} and ^{232}Th in the soil groups and the maize plant compartments (seed, stem, leaf and root) were determined using NaI(Tl) gamma-detector. The geometric mean (GM) of the TF values for ^{40}K, ^{238}U and ^{232}Th respectively ranged from 0.02 to 0.27, below detectable limit (BDL) to 0.008 and 0.01 to 0.09 in the in the seeds; 0.04 to 1.74, BDL to BDL and 0.01 to 0.29 in the stems; 0.03 to 0.93, BDL to 0.33 and 0.02 to 0.08 in the leaves and 0.03 to 1.29, 0.05 to 0.38 and 0.08 to 0.41 in the roots.. Potassium-40 had the highest TF values and exhibited the plant accumulation strategy for all the plant compartments. The stem samples had the highest TF for ^{40}K and BDL values for ^{238}U for all the soil groups. Significance differences were observed only in the accumulation of ^{40}K and ^{232}Th across the soil group.

Keywords: Radioactivity, potassium, mining, Gamma-ray detectors, calibration

1. INTRODUCTION

Exposure of humans to ionizing radiation of natural and anthropogenic origin is inevitable. The two main contributors to radiation of natural origin are the high energy cosmic ray particles striking the air molecules in the atmosphere and primordial radioactive nuclides in naturally occurring radioactive substances existing in the earth crust [1,2]. Through weathering of the earth crust, primordial radionuclides enter the soil [3]. The radionuclides in the soil are taken up by plants via their root, and can be transferred to human when crops harvested from such plants are consumed, leading to internal exposure to ionizing radiations. Radionuclides ingested through food consumption are major radiation pathways for long term health considerations and contribute significantly to the average radiation doses to various organs and tissues in the human body [4].

The uptake of radionuclides from the soil by plants, normally expressed as soil-to-plant transfer factor (TF), transfer coefficient (TC) or concentration ratio (CR), is defined as the ratio of the activity concentration in a plant part (in Bq kg^{-1} dry weight) to the activity concentration in the soil (in Bq kg^{-1} dry weight) [5,6]. The TF is essential for estimating and predicting the radionuclide concentration in agricultural crops so as to calculate radiological dose impact to human beings when the plants are ingested [7,8]. So many factors have been identified to affect the accumulation of radionuclides in plants. These factors include concentration of radionuclides in soil, soil pH, climate, speciation of radionuclides in soil solution, organic content of the soil, soil type etc. [9]. The uptake of the radionuclides are also regulated by processes that change the mobility of the physicochemical forms of the radionuclides [10]. The transfer of radionuclide from soil to plant is also element specific, as a result, root uptake of all the isotopes of a given element is identical [11,12]. These various factors introduce great variability in the values of the TF, spanning from one to two orders of magnitude for each element in farm crops [13]. The biological variability in plants of different varieties and species has the likelihood of introducing variability in TF [13]. These variability is however reduced when plant group or species are taken into consideration [14]. Thus, there is need to categorise the TF parameter according to plant type.

Technical Report Series No 472 (TRS-472) of IAEA [13] compiled data on radionuclide transfer factors for temperate and tropical ecosystem, sufficient data were not obtained for most radionuclides for some plants, especially for the tropical region. For instance, no TF value of ^{40}K was reported for any compartment of maize plant, whereas TFs for ^{238}U and ^{232}Th were reported only for maize grains. The TFs on different soil types were also not adequately reported, due to unavailability of data [13]. There is also a dearth of data on the TF of radionuclides of common crops (cassava, cowpea, maize, rice)in Nigeria. This gap was observed in the IAEA [13], as no data was obtained from any African country for the reported TF values for the tropical ecosystem. Hence, the aim of this work, which is to determine the TF of maize plant for the tropical ecosystem of Nigeria for different soil groups. Maize (*Zea may* L.)

also known as corn is a major staple food in Nigeria because of its starch content, having a frequency of consumption of 20.1 % in Nigeria [15].

2. MATERIALS AND METHODS

2.1 Sample collection, experiment and preparation

Samples of tailings were collected from an abandoned tin mining site in Jos because of the high activity concentration of ^{40}K, ^{238}U and ^{232}Th that has been reported in literature [4,16-22]. The geology of the study area was extensively discussed [21]. Samples of virgin soil from uncultivated area were also collected. Studies of this nature add a given quantity of the radionuclide of interest to soil, because of the non-availability of radionuclides in the laboratory, samples of tailings collected were added to some portion of the virgin soil to create different activity concentrations of ^{40}K, ^{238}U and ^{232}Th. Three groups of soil for planting were prepared from the tailings and the virgin soil. Group A was made up of soil sample from the virgin land only, group B was made up of the tailings only and group C was made of equal ratio by dry mass of the tailings and virgin soil. The mixture of soil samples from the virgin area and the tailings is to create a different activity concentration. The radioactivity concentrations of ^{40}K, ^{238}U and ^{232}Th were measured for ten samples from each of the soil groups before planting. Ten planting pots, each of 29 cm height and 23 cm diameter, were prepared from each of the soil group. Maize seeds (code: TZPB), collected from Institute of Agricultural Research and Training (IAR&T) Ibadan, Nigeria were planted in each pot. The pots were placed in an open space where they were exposure to adequate sunlight and were watered daily until maturity at about four months.

Fertilizer was not applied to the plant, this is to remove the complexity that the application of fertilizer might introduce, since it has been established that most fertilizer contains radionuclides in appreciable quantity [23]. At maturity, the crops and entire plant system of the survived plants were harvested, thoroughly washed with clean water, labeled and dried separately at room temperature. The plant system was then separated into the plant compartments (seed, stem, leaves, and roots). Each sample of the plant compartment was then oven dried until it attains a constant mass. The samples were separately grinded, weighted, packed in a cylindrical container of height 8.0 cm and diameter 7.0 cm and sealed to make it air-tight. The sealed samples were labeled and stored for more than four weeks in order to allow for the attainment of secular equilibrium of ^{238}U and ^{232}Th with their respective progeny [23].

2.2 Activity measurement and transfer factor

The counting system used was a 7.6 cm × 7.6 cm NaI(Tl) scintillation detector by Bicron (Model No. 1002 series), sealed with a photo multiplier tube and connected through a preamplifier base to a Canberra series 10-plus multi-channel analyser (MCA). Single calibrated gamma sources (^{22}Na, ^{137}Cs, and ^{60}Co) from the Nucleus Inc., Oak Ridge, TN, USA and reference sources (RGK-1, RGU-1, RGTh-1) from the International Atomic Energy Agency (IAEA) were used for the energy calibration of the spectrometer. Calibration was done for gamma energy range of 0.511

MeV to 2.615 MeV. In order to quantify the radionuclides present in the samples, efficiency calibration was carried out using reference sources; ENV 950050 prepared from Rocketdyne laboratories, Canoga Park, California, USA and IAEA 152 for the soil and food matrices, respectively.

The samples were placed symmetrically on top of the detector and measured for a counting time of 10 hours. The net area under the corresponding peaks in the energy spectrum was computed by subtracting counts due to Compton scattering of higher peaks and other background sources from the total area of the peaks [20]. From the net area, the activity concentrations C in the samples were obtained using equation 1 [24-26];

$$C = \frac{A}{tE_pYm} \quad (1)$$

where A is the net area under the photopeak, t is the counting time 36,000 s (10 hrs), E_p is the detection efficiency, Y is the gamma yield and m is the mass of the samples in kg. The 1.460 MeV photopeak was used for the measurement of ^{40}K while the1.760 MeV photopeak from ^{214}Bi and the 2.614 MeV photopeak from ^{208}Tl were used for the measurement of ^{238}U and ^{232}Th, respectively. The lower limit of Detection (LLD) of the detector at 95 % level of confidence for each of the radionuclide was calculated from the background count. A total of thirty (30) soil samples and ninety-two (92) maize compartment samples were analysed. Samples that have activity concentrations equal of less than the LLD are termed below detectable limit (BDL).

Table 1: Soil properties of the soil groups [29]

S/N	Soil ID	pH	Organic Matter (g/kg)	Clay (g/kg)	Silt (g/kg)	Fine Sand (g/kg)	Soil classification
1	Group A	6.63	22.42	134	114	752	Sandy loam
2	Group B	6.83	6.84	34	14	925	Sand
3	Group C	6.86	12.92	74	74	852	Loamy sand

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Table 2: The activity concentrations (Mean ± STD) of ^{40}K, ^{238}U and ^{232}Th in $Bq.kg^{-1}$ for the soil samples

Sample	Number of Samples	^{40}K	^{238}U	^{232}Th
Group A	10	374.01 ± 590.51	242.13 ± 429.10	1776.08 ± 4164.89
Group B	10	5008.18 ± 2427.16	2354.98 ± 1260.39	26211.90 ± 7178.22
Group C	10	1573.93 ± 3123.65	2763.90 ± 2345.77	15294.77 ± 6924.46

Table 3: The activity concentrations in Bq kg^{-1} (Mean ± STD) and transfer factors (GM ± GSD) of ^{40}K, ^{238}U and ^{232}Th in the compartments of maize plant

Soil group	Plant parts	Number of samples	Activity concentration (Bq kg^{-1})			Transfer factor		
			^{40}K	^{238}U	^{232}Th	^{40}K	^{238}U	^{232}Th
Group A	Seed	7	105.43 ± 37.21	BDL	318.46 ± 499.96	0.27 ± 1.36	BDL	0.09 ± 2.78
	Stem	7	685.08 ± 245.70	BDL	828.87 ± 783.01	1.74 ± 1.39	BDL	0.29 ± 3.01
	Leaf	7	371.13 ± 137.34	80.06 ± 5.60	304.31 ± 221.50	0.93 ± 1.14	0.33 ± 1.05	0.08 ± 3.70
	Root	7	561.34 ± 372.74	245.47 ± 322.23	1065.80 ± 1035.16	1.29 ± 1.71	0.38 ± 5.18	0.41 ± 2.43
Group B	Seed	8	127.04 ± 115.46	25.58 ± 23.08	1098.08 ± 854.13	0.02 ± 2.14	0.008 ± 2.00	0.03 ± 2.04
	Stem	8	299.90 ± 198.23	BDL	485.51 ± 276.73	0.04 ± 2.22	BDL	0.02 ± 1.97
	Leaf	8	190.83 ± 165.21	BDL	826.37 ± 1182.03	0.03 ± 2.04	BDL	0.02 ± 2.35
	Root	8	243.77 ± 252.77	367.19 ± 442.38	3831.23 ± 2282.00	0.03 ± 2.41	0.17 ± 2.45	0.13 ± 1,72
Group C	Seed	8	283.50 ± 325.77	BDL	433.72 ± 671.35	0.12 ± 2.49	BDL	0.01 ± 4.00
	Stem	8	328.59 ± 185.61	BDL	184.49 ± 81.32	0.15 ± 2.88	BDL	0.01 ± 1.40
	Leaf	8	349.48 ± 477.59	18.08 ± 9.53	238.05 ± 64.64	0.13 ± 2.61	0.006± 1.48	0.02 ± 1.27
	Root	8	298.94 ± 504.20	185.36 ± 120.82	1648.80 ± 913.12	0.08 ± 3.31	0.05 ± 2.37	0.08 ± 2.59

The TF of ^{40}K, ^{238}U and ^{232}Th for all the maize compartment samples were calculated using equation 2 [12, 27];

$$TF = \frac{Activity \text{ concentration of plant (Bq kg}^{-1}\text{, dry weigth)}}{Activity \text{ concentration of soil (Bq kg}^{-1}\text{, dry weigth)}} \quad (2)$$

The geometric mean (GM) and geometric standard deviation (GSD) were used to summarise the data of the TF.

3. RESULTS AND DISCUSSION

The soil properties of the soil groups are presented in Table 1. The three soil groups are slightly acidic with pH ranging from 6.63(group A) to 6.86 (group C). The organic matter content ranged from 6.84 (group B) to 22.42 (group A) g/kg. The clay and silt contents ranged from 34 to 134 g/kg and from 14 to 114 g/kg, respectively while the fine sand content ranged from 752 to 925 g/kg. Table 2 gives the mean activity concentrations of ^{40}K, ^{238}U and ^{232}Th of the soil groups. Thorium-232 had the highest activity concentration for all the soil groups. The highest and least activity concentration of ^{40}K and ^{232}Th were observed in group B and group A, respectively. While for ^{238}U, the highest and least activity concentrations were observed in group C and group A, respectively.

The mean activity concentration of ^{40}K in $Bq.kg^{-1}$ for the maize compartments (table 3) ranged from 105.43 in maize seeds harvested from soil group A to 685.08 in stem sample harvested from soil group A, ^{238}U ranged from BDL (seed and stem samples from groups A and C; stem and leaf sample for group B) to 367.19 $Bq.kg^{-1}$ in root sample harvested from soil group B while ^{232}Th ranged from 184.49 in the stem samples harvested from soil group C to 1648.80 $Bq.kg^{-1}$ in the root sample harvested from soil

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group C. The geometric mean (GM) of the TF values for ^{40}K (table 3) in the plant compartments from group A varied from 0.27 (seed) to 1.74 (stem); for group B it varied from 0.02 (seed) to 0.04 (stem) and for group C, it varied from 0.08 (root) to 0.15 (stem). A two-way ANOVA performed on the data showed significant difference in the geometric means of the TF values of ^{40}K in soil groups B and C ($p < 0.05$) as well as between the stem and seed samples ($p = 0.01$). Potassium-40 had the highest TF values across the samples of the maize compartments except for the seed and root samples harvested from soil group B. It has been established that the uptake of radionuclides from soil is element specific and is also facilitated by the radionuclide similarity to plant essential nutrient [9,12], therefore the high values observed for the ^{40}K could be as a result of its similarity to the stable potassium which is one the essential elements for proper plant growth. According to [28], potassium activates the enzymes that maintain the turgidity of the cells, this could be the reason for the highest values of ^{40}K observed in the stem samples for each of the group, since the cell around the stem need to be turgid enough to carry the weight of the maize cobs.

The GM of the TF of ^{238}U (table 3) in the plant compartments ranged from BDL (seed and stem) to 0.38 (root) for group A; BDL (stem and leaf) to 0.17 (root) for group B and from BDL (seed and stem) to 0.05 (root) for group C. No significant difference was observed for ^{238}U for the soil groups ($p = 0.40$) and for the plant compartments ($p = 0.46$). Uranium-238 had the least TF in most of the samples. The TF of ^{238}U for all the stem samples harvested from the three soil groups were BDL.

For ^{232}Th the GM of the TF (table 3) in the plant compartments ranged from 0.08 (leaf) to 0.41 (root) for group A; 0.02 (stem and leaf) to 0.13 (root) for group B and from 0.01 (seed and stem) to 0.08 (root). There was significant difference in the geometric mean of the TF values of ^{232}Th between group A and B ($p < 0.05$), and for soil group A and C ($p < 0.05$) but the difference between group B and C was not significant ($p = 0.83$).

Sheppard and Evenden *et al*., 1988 observed that the TF of radionuclides decreased as the concentration of the radionuclides in the soil increased was termed the plant accumulation strategy. Potassium-40 maintained the plant accumulation strategy for each plant compartment across the soil group, but this was not observed for ^{238}U and ^{232}Th. Comparing the TF of ^{238}U for maize seed to the TF values of IAEA, 2010 (table 4), a difference of one order of magnitude was observed for ^{238}U while that of ^{232}Th had two orders of magnitude difference.

5. Conclusion

The TF values of ^{40}K, ^{238}U and ^{232}Th in maize plant compartments were evaluated in this work using activity concentrations of each radionuclide in the plant compartment and soil samples. The plant accumulation strategy was observed only for ^{40}K. Potassium-40 had the highest TF when compared with the TF of ^{238}U and ^{232}Th. For all the soil groups, the stem compartment had the highest TF for ^{40}K and BDL values for ^{238}U. Uranium-238 had most of the least TF values.

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Table 4: Comparison of the TF values obtained in the present work and the TF values from IAEA 2010 of the cereals (maize) for the tropical region

Plant part	Soil type	Nos. of data (N)	^{40}K	^{238}U	^{232}Th	Reference
Maize grain	All	2	-	8.7×10^{-2}	-	IAEA, 2010
	Loam	6	-	-	1.9	IAEA, 2010
	Sand	1	-	1.5×10^{-3}	-	IAEA, 2010
Maize seeds	Sandy loam	7	2.7×10^{-1}	BDL	9.0×10^{-2}	Present study
	Sand	8	2.0×10^{-2}	8.0×10^{-3}	3.0×10^{-2}	Present study
	Loamy sand	8	1.2×10^{-1}	BDL	1.0×10^{-2}	Present study

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