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Impact of soil physicochemical properties on the transfer of natural radionuclides from soil to Cassava in Parts of Akwa Ibom State, Nigeria

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Abstract

The transfer of natural radionuclides from soil to cassava is essential in studying the influence of soil properties on the movement of elements. This study investigated the impact of soil physicochemical properties on the soil-to-plant transfer of ^{238}U, ^{232}Th, and ^{40}K from agricultural soils to cassava tubers across three Local Government Areas (LGAs): Uyo, Ibiono Ibom, and Itu, in Akwa Ibom State, Nigeria. A total of 12 paired soil and cassava samples were collected and prepared according to standard protocols. Activity concentrations of the radionuclides were measured using a NaI(Tl) gamma-ray spectrometer at the Centre for Energy Research and Development, Obafemi Awolowo University, Ile-Ife, Nigeria. Soil physicochemical parameters were determined using established laboratory methods. Mean transfer factor (TF) values for ^{238}U, ^{232}Th, and ^{40}K ranged from 0.73–1.04, 0.57–1.11, and 1.33–1.51 respectively across the three LGAs, revealing pronounced radionuclide-specific and spatial variability in transfer efficiency. Pearson correlation analysis revealed statistically significant relationships between soil physicochemical parameters and transfer factors. Clay content showed a strong positive correlation with ^{238}U ($r = 0.995$, $p < 0.05$), while soil organic matter was strongly negatively correlated with $TF_{th}(^{232}Th)$ ($r = -1.000$, $p < 0.05$). The $TF_k(^{40}K)$ exhibited a significant positive correlation with exchangeable Ca ($r = 0.998$, $p < 0.05$) and Na ($r = 0.999$, $p < 0.05$). The predominantly sandy, acidic soils of the study area facilitated moderate to high radionuclide mobility. These findings contribute essential baseline radiological and pedological data for cassava-growing communities in Akwa Ibom State.

Keywords: Transfer Factor; Physicochemical Properties; Cassava; Radionuclides; Correlation

1. Introduction

Naturally occurring radioactive materials (NORMs) are found everywhere on the earth's crust, comprising the primordial radionuclides uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K), along with their radioactive progeny [1,2,3]. These radionuclides are distributed across geological formations and are regularly encountered in soils, sediments, rocks and water bodies. Although background levels are generally considered non-hazardous, geochemical variability, anthropogenic disturbance, and elevated geological deposits can significantly increase concentrations beyond globally established reference levels, posing measurable radiological risks to exposed populations [4,5].

Soil represents the primary reservoir of naturally occurring radionuclides in terrestrial ecosystems, and radionuclide transfer from soil to food crops through root uptake constitutes one of the most important exposure pathways for the general public [6,7]. The soil-to-plant transfer factor (TF), defined as the ratio of radionuclide activity concentration in a plant tissue to that in the corresponding soil (both expressed on a dry weight basis), is the essential parameter used in radioecological modelling to quantify this transfer process [8,9,10,11]. However, transfer factor (TF) values are known to exhibit considerable variability, influenced by soil physicochemical properties such as pH, organic matter

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content, texture, cation exchange capacity, and exchangeable base composition as well as plant species, radionuclide speciation, and climatic conditions [6,9].

Cassava (Manihot esculenta Crantz) is the predominant root-tuber crop across the coastal and inland communities of Akwa Ibom State in southern Nigeria [12,13], constituting a major source of dietary carbohydrate and, consequently, a critical food chain pathway for potential radionuclide ingestion [14,15,16]. Akwa Ibom State, situated within Nigeria's Niger Delta region, is characterised by acidic, sandy loam soils, high rainfall, significant petroleum industry activity, and dense agricultural communities that depend on subsistence farming [17]. The physicochemical properties of soils in this environment are expected to significantly regulate the bioavailability and transfer of radionuclides to crops; however, systematic investigations linking measured soil parameters to radionuclide transfer coefficients for cassava in this specific agroecological zone remain sparse.

Several studies conducted in Nigeria and across the West African sub-region have assessed radionuclide activity concentrations in soils and cassava, but comparatively few have rigorously characterised the mechanistic influence of soil physicochemical parameters on transfer factor variability [14,18,4,7,13]. Globally, the International Atomic Energy Agency's Technical Reports Series No. 472 [6] has acknowledged that tropical ecosystem transfer data remain underrepresented relative to temperate region data, and has called for expanded regional studies from Africa and other tropical zones to improve the robustness of radiological assessment models [6,19]. The IAEA Modelling and Data for Radiological Impact Assessment (MODARIA II) programme (2016–2019) made significant strides in revising tropical transfer parameter databases, yet data from southern Nigeria remain scarce [19,5].

The coastal and sub-coastal communities of Akwa Ibom State rely heavily on cassava as a dietary staple. Despite the well-established presence of NORMs in the region's soils linked to geogenic sources and potentially to hydrocarbon exploration activities, there is insufficient comprehensive data linking soil physicochemical characteristics to the transfer of ^{238}U, ^{232}Th, and ^{40}K into cassava tubers specifically across inland Local Government Areas (LGAs) such as Uyo, Ibiono Ibom, and Itu. Without this data, it is impossible to assess the dietary radiation exposure for communities in these areas, and to identify the specific soil properties that most significantly drive radionuclide bioavailability. This knowledge gap hinders the development of targeted remediation strategies and undermines the accuracy of radiological risk assessments for the local population.

The main aim of this study is to determine the impact of soil physicochemical properties on the transfer of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) from agricultural soils to cassava tubers in selected Local Government Areas of Akwa Ibom State, Nigeria.

2. Materials and Methods

2.1. Study Area and Sampling

The study was carried out in Akwa Ibom State, located in the south-south geopolitical zone of Nigeria, within the Niger Delta region (approximately latitude 4°30′N to 5°30′N and longitude 7°30′E to 8°30′E) [20]. The state is characterised by a tropical wet climate, high annual rainfall (1,800–3,000 mm), high humidity, and predominantly acidic, sandy loam soils derived from coastal plain sands and alluvial deposits [17]. Cassava cultivation is practised extensively across the state, with virtually all households engaged in subsistence farming. The crop is highly adaptable to diverse ecological zones, possesses ability to withstand drought, and capable of producing substantial yields even under low-input conditions [21,22,23].

Samples were collected from three LGAs: Uyo (the state capital), Ibiono Ibom, and Itu. Figure1 shows the map of the study area indicating the sampling sites. These LGAs were selected to represent the range of agroecological conditions and human settlement patterns in the central and inland portions of the state. In each LGA, four replicate sampling points were identified at active cassava farmlands. At each sampling point, one composite soil sample (0–20 cm depth) and one cassava tuber sample were collected in close spatial proximity (within 1.5 m of each other), ensuring that each soil-plant pair was representative of the same microenvironment [13]. A total of 12 soil samples and 12 cassava tuber samples were obtained.

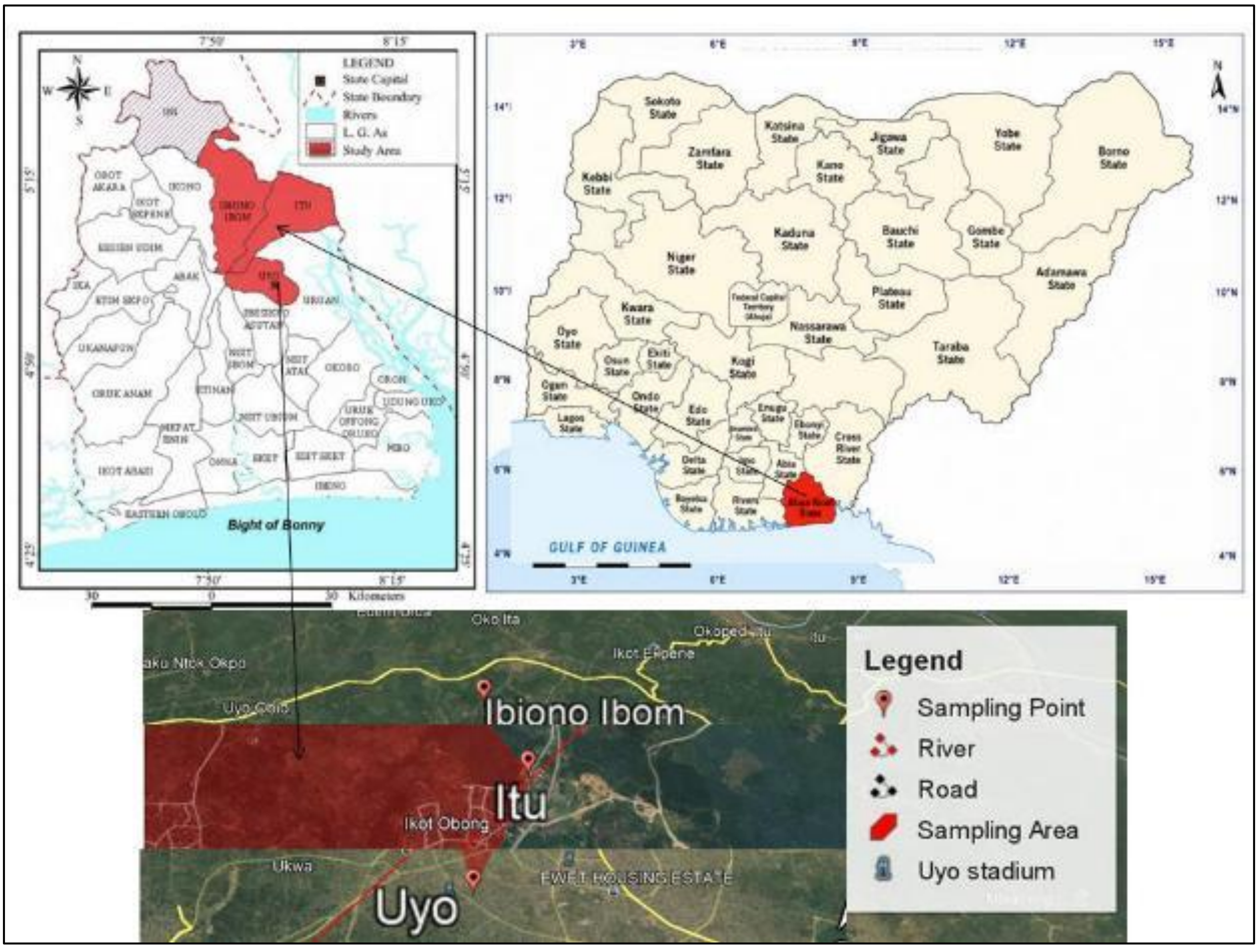

Figure 1 Map of the study area showing the sampling sites

2.2. Sample Preparation

2.2.1. Cassava Preparation

Freshly harvested cassava tubers were thoroughly washed with clean tap water to remove all adhering soil particles. The tubers were then peeled and rinsed in deionised water to eliminate any surface contamination. The rinsed tubers were grated into fine particles and sun-dried for approximately five days to achieve removal of moisture [16]. After complete drying, the samples were ground into a fine powder using a porcelain mortar and pestle and sieved through a 2 mm stainless steel mesh sieve. Sample weights were determined to be within a range of 200–300 g, after which each sample was placed in a sealed container in preparation for gamma spectrometric analysis.

2.2.2. Soil Preparation

Collected soil samples were first air-dried in a clean, dust-free environment to remove surface moisture. The samples were subsequently oven-dried at 105°C until a constant weight was achieved. The dried soils were ground using a porcelain pestle and mortar and sieved through a 2 mm mesh sieve to remove coarse particulate matter. The resultant fine material, weighing between 500–600 g per sample, was packaged in airtight, labelled polyethylene bags and dispatched to the Centre for Energy Research and Development (CERD), Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria, for gamma spectrometric analysis.

2.3. Gamma Spectrometric Analysis

The activity concentrations of 238U, 232Th, and 40K in both soil and cassava samples were determined using a sodium iodide, thallium activated [NaI(Tl)] gamma-ray spectrometer at CERD, Obafemi Awolowo University. Sealed samples were allowed to stand for a minimum of four weeks prior to counting to ensure secular equilibrium between parent radionuclides and their short-lived progeny [13,14]. Counting times were sufficiently long (typically ≥ 10,000 s) to achieve acceptable counting statistics. Activity concentrations were reported in Bq/kg on a dry weight basis.

2.4. Soil Physicochemical Analysis

The following physicochemical parameters were determined for each soil sample

Particle Size Distribution: The hydrometer method [24,25] was used. Fifty grams (50 g) of air-dried soil was dispersed in sodium hexametaphosphate ($NaPO_3$) solution, stirred for 10 minutes in a mechanical stirrer, transferred to a 1,000 mL measuring cylinder filled with deionised water, and vigorously shaken. Hydrometer readings were recorded at 2-hour intervals. The percentages of sand, silt, and clay were calculated, and the textural class was determined using the USDA soil textural triangle.

Soil pH: Measured in a 1:1 (w/v) soil-to-distilled water suspension using a glass electrode pH metre. Twenty grams of air-dried soil were suspended in 20 mL of deionised water, allowed to equilibrate for 30 minutes with occasional stirring, and the pH recorded [25].

Soil Organic Carbon (SOC): It was determined by the Walkley–Black wet oxidation method [26]. Briefly, 2 g of soil was treated with 10 mL of 1 N potassium dichromate ($K_2Cr_2O_7$) and concentrated H_2SO_4 [27]. The mixture was back-titrated with 0.5 N ferrous sulphate solution. SOC (%) was calculated using Equation 1 [13]:

$$SOC(\%) = (B - T) * 0.003 * 100 * 1.33 \qquad (1)$$

where B is the blank titre value and T is the sample titre value.

Soil Organic Matter (SOM): Calculated from SOC using Van Bemmelen's factor:

$$SOM(\%) = SOC * 1.724 \qquad (2)$$

Exchangeable Bases (Ca, Mg, Na, K): It was extracted using 1 M ammonium acetate (NH_4OAc) at pH 7.0 and determined by flame photometry [26]. The effective cation exchange capacity (ECEC) was calculated as:

$$ECEC\left(\frac{cmol}{kg}\right) = Ca + Mg + Na + K \qquad (3)$$

2.5. Calculation of Transfer Factor

The soil-to-plant transfer factor (TF) was calculated for each radionuclide according to the method of Essien et al. [14], Chakraborty et al. [28] and Nyong et al. [13] using equation (4) and consistent with IAEA [6] guidelines:

$$TF = \frac{A_p}{A_s} \qquad (4)$$

where A_p (Bq/kg dry weight) is the activity concentration of the radionuclide in the cassava tuber and A_s (Bq/kg dry weight) is the corresponding activity concentration in the soil. Calculations for mean values of radiological and physicochemical parameters were done for each LGA.

2.6. Statistical Analysis

IBM SPSS Statistics (version 26.0) was used to carry out Pearson correlation analysis in order to distinctly show the statistical relationship among physicochemical properties, transfer factors and radionuclide activity concentrations. Statistical significance was estimated at 0.05 and 0.01 levels (two-tailed).

3. Results

3.1. Activity Concentrations and Soil Physicochemical Parameters

Table 1 presents the mean activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in both soil and cassava samples, alongside the key soil physicochemical parameters across the three study LGAs. Activity concentrations of ^{238}U in soil ranged from 13.61 Bq/kg (Ibiono Ibom) to 15.61 Bq/kg (Itu), while ^{232}Th ranged from 21.66 Bq/kg (Itu) to 36.24 Bq/kg (Uyo). Potassium-40 (^{40}K) activity concentrations in soil ranged from 461.48 Bq/kg (Ibiono Ibom) to 652.43 Bq/kg (Itu). Soil pH across all LGAs was acidic, ranging from 4.48 (Ibiono Ibom) to 5.10 (Itu). Soil organic carbon (% SOC) was relatively uniform (4.84–4.97%), while SOM varied more widely (6.11–8.47%).

Table 1 Mean values of activity concentrations of radionuclides and soil physicochemical parameters across selected LGAs in Akwa Ibom State

LGA	238U (Bq/kg)	232Th (Bq/kg)	40K (Bq/kg)	pH	SOC (%)	SOM (%)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	Na (cmol/kg)
Uyo	14.92	36.24	604.10	4.60	4.97	6.11	0.02	4.63	2.64	0.06
Ibiono Ibom	13.61	26.43	461.48	4.48	4.97	8.40	0.02	5.90	2.54	0.08
Itu	15.61	21.66	652.43	5.10	4.84	8.47	0.03	4.64	4.64	0.06

SOC = soil organic carbon; SOM = soil organic matter; K = potassium; Ca = calcium; Mg = magnesium; Na = sodium. Activity concentrations are reported in Bq/kg (dry weight).

3.2. Soil Particle Size Distribution and Radionuclides Transfer Factors

Table 2 presents the particle size distribution (% sand, % silt, % clay) and the corresponding transfer factors (TFs) for ^{238}U, ^{232}Th, and ^{40}K across the three LGAs. Sand was the dominant fraction in all LGAs, confirming the predominantly sandy textural class of soils in the study area. The soils were predominantly sandy in texture, with sand fractions ranging from 76.17% (Itu) to 79.78% (Uyo), clay from 12.47% (Ibiono Ibom) to 15.55% (Itu), and silt from 6.01% (Uyo) to 9.56% (Ibiono Ibom).TF values for ^{238}U ranged from 0.73 (Ibiono Ibom) to 1.04 (Uyo), TF values for ^{232}Th from 0.57 (Itu) to 1.11 (Uyo), and TF values for ^{40}K from 1.33 (Itu) to 1.51 (Ibiono Ibom). Across all three LGAs, potassium-40 consistently showed the highest transfer efficiency, followed by uranium-238 and then thorium-232, though the ranking between TF^{u}(^{238}U) and TF_{th}(^{232}Th) varied across sites.

Table 2 Soil particle size distribution and mean radionuclide transfer factors for cassava across selected LGAs in Akwa Ibom State

LGA	% Sand	% Silt	% Clay	TF_u (^{238U})	TF_{th} (^{232}Th)	TF_k (^{40}K)
Uyo	79.78	6.01	14.21	1.04	1.11	1.34
Ibiono Ibom	77.64	9.56	12.47	0.73	0.60	1.51
Itu	76.17	7.61	15.55	0.93	0.57	1.33

TF_u (^{238}U) = transfer factor for ^{238}U; TF_{th} (^{232}Th) = transfer factor for ^{232}Th; TF_k (^{40}K) = transfer factor for ^{40}K.

3.3. Pearson Correlation Analysis

Table 3 presents the full Pearson correlation matrix for all measured radiological and physicochemical variables. The following deductions were made:

- ^{238}U activity concentration was strongly positively correlated with pH (r = 0.869), clay content (r = 0.995), and exchangeable Mg (r = 0.791), and negatively correlated with Ca (r = −0.938) and Na (r = −0.941);
- ^{232}Th activity concentration was strongly positively correlated with % sand (r = 0.996) and negatively correlated with % clay (r = −0.249) and exchangeable Mg (r = −0.723);
- ^{40}K was strongly positively correlated with pH (r = 0.815) and clay (r = 0.979) and negatively correlated with Ca (r = −0.968) and Na (r = −0.970);
- TF_u(^{238}U) was strongly positively correlated with % clay (r = 0.692) and % silt (r = −0.994, negative), suggesting clay as a key predictor of uranium transfer;
- TF_{th}(^{232}Th) was near-perfectly negatively correlated with SOM (r = −1.000, $p < 0.05$), indicating that elevated organic matter content strongly suppresses thorium transfer to cassava;
- TF_k(^{40}K) was significantly positively correlated with Ca (r = 0.998, $p < 0.05$) and Na (r = 0.999, $p < 0.05$), and negatively correlated with clay content (r = −0.921).

Table 3 Pearson correlation matrix for radionuclide activity concentrations, soil physicochemical parameters, and transfer factors

	^{238}U	^{232}Th	^{40}K	pH	%SOC	%SOM	K	Ca	Mg	Na	% Sand	% Silt	% Clay	TF_u	TF_{th}	TF_k
^{238}U	1															
^{232}Th	−0.149	1														
40K	0.049	−0.049	1													
pH	0.869	−0.618	0.815	1												
%SOC	−0.764	0.751	−0.696	−0.983	1											
%SOM	−0.150	−0.955	−0.249	0.358	−0.522	1										
K	0.764	−0.751	0.696	0.983	−1.000**	0.522	1									
Ca	−0.938	−0.202	−0.968	−0.644	0.494	0.483	−0.494	1								
Mg	0.791	−0.723	0.725	0.990	−0.999*	0.486	0.999*	−0.530	1							
Na	−0.941	−0.196	−0.970	−0.650	0.500	0.477	−0.500	1.000**	−.0536	1						
% Sand	−0.237	0.996	−0.139	−0.687	0.808	−0.925	−0.808	−0.113	−0.782	−0.107	1					
% Silt	−0.687	−0.616	−0.757	−0.238	0.057	0.822	−0.057	0.896	−0.099	0.893	−0.543	1				
% Clay	0.995	−0.249	0.979	0.915	−0.826	−0.049	0.826	−0.898	0.849	−0.901	−0.335	−.0609	1			
TF_u	0.762	0.527	0.823	0.342	−0.165	−0.755	0.165	−0.939	0.207	−0.937	0.448	−0.994	0.692	1		
TF_{th}	0.127	0.962	0.226	−0.380	0.542	−1.000*	−0.542	−0.463	−0.506	−0.457	0.933	−0.808	0.025	0.739	1	
TF_k	−0.956	−0.147	−0.981	−0.686	0.542	0.433	−0.542	0.998*	−0.577	0.999*	−0.057	0.870	−0.921	−0.918	−0.412	1

* Correlation significant at the 0.05 level (2-tailed); ** Correlation significant at the 0.01 level (2-tailed). TF_u = TF (^{238}U); TF_{th} = TF (^{232}Th); TF_k = TF (^{40}K); SOC = soil organic carbon; SOM = soil organic matter.

4. Discussion

The measured mean activity concentrations of ^{238}U in soil (13.61–15.61 Bq/kg), ^{232}Th (21.66–36.24 Bq/kg), and ^{40}K (461.48–652.43 Bq/kg) across the three LGAs in this study are broadly comparable with values previously reported for soils in Akwa Ibom State and the broader Niger Delta region. Akpan et al. [17] reported ^{238}U, ^{232}Th, and ^{40}K concentrations in soils and beach sediments from the Akwa Ibom coastline ranging from 9–44, 3–72, and 35–250 Bq/kg, respectively. The ^{232}Th concentrations observed in the present study are within the upper range of the global average of 30 Bq/kg recommended by UNSCEAR [1], particularly in Uyo (36.24 Bq/kg), which warrants continued monitoring. The relatively elevated ^{232}Th in Uyo may reflect localised geochemical enrichment in coastal plain sands, which are known in the Niger Delta to carry elevated thorium signatures from upstream fluvial transport of mineral-rich deposits.

In comparison, Orosun et al. [4] reported activity concentrations of ^{238}U and ^{232}Th in soils from gold and beryllium mining sites in Kwara State, Nigeria, that were substantially higher than those found in this study, reflecting the amplifying effect of mining on NORM concentrations. Similarly, Tyovenda et al. [18], working in Taraba State, reported mean ^{232}Th values of 87.23–141.14 Bq/kg and ^{238}U values of 25.37–71.20 Bq/kg in farmland soils, markedly higher than the values in this study and attributed to the region's mineralogically diverse basement complex geology. The present results, derived from coastal plain sandy soils of Akwa Ibom, thus represent a distinctly different and comparatively lower-activity; geological endmember, underscoring the critical importance of geomorphological context in interpreting Nigerian radioactivity data.

The TF values calculated in this study reveal important information about radionuclide mobility in the soil-cassava system. $TF_u(^{238}U)$ values of 0.73–1.04 indicate moderate to high uranium transfer efficiency. $TF_{th}(^{232}Th)$ values of 0.57–1.11 show the greatest spatial variability, with markedly higher transfer in Uyo relative to Itu and Ibiono Ibom. $TF_k(^{40}K)$ values of 1.33–1.51, all exceeding unity. This confirms that cassava accumulates potassium from soil at concentrations exceeding those in the source soil, which is consistent with the essential biological role of potassium in plant nutrition and its active uptake via specialised ion channels. In the work carried out by Nyong et al. [13], potassium transfer factors ranged between 1.20 to 1.35 across all the LGAs (Abak, Ikot Ekpene, Ukanafun and Etim Ekpo). This was in consistence with the present study. The high values of TF_k affirm the well-established role of ^{40}K as an important macronutrient accumulated by cassava [13].

Parvin et al. [5], in a study of radionuclide transfer in agricultural soils from the Barapukuria coal mining area, Bangladesh, using HPGe gamma spectrometry, reported ^{238}U, ^{232}Th, and ^{40}K TF values that showed strong dependence on soil pH, organic carbon, and clay content, conclusions that are structurally identical to the present study. TF values for root crops in Bangladesh (^{40}K: 1.1–1.8; ^{238}U: 0.5–0.9) are of the same order of magnitude as those found in Akwa Ibom State, despite the markedly different mining context, suggesting that soil physico chemistry rather than contamination source exerts overriding control over transfer efficiency in tropical soils.

Nurtjahya et al. [9], investigating TFs of ^{226}Ra, ^{232}Th, and ^{40}K for staple crops (including cassava) cultivated on ex-tin mining land in Bangka Belitung, Indonesia, a tropical lateritic soil context; reported ^{232}Th TF values for root crops ranging from 0.04 to 0.56, broadly lower than the $TF_{th}(^{232}Th)$ of 0.57–1.11 observed in the present study. The higher $TF_{th}(^{232}Th)$ values in Akwa Ibom State may reflect the comparatively lower organic matter and clay CEC of coastal plain sands compared with Indonesian lateritic soils, resulting in less thorium fixation and greater bioavailability. These comparisons collectively highlight that even within tropical ecosystems, significant variability in TF exists that is fundamentally driven by soil type, mineralogy, and geochemistry.

According to the review carried out by Olabimtan et al. [7] within the Niger Delta region, $TF_k(^{40}K)$ values for cassava were consistently above 1.0 across all the sampled sites. The Olabimtan et al. [7] review noted that ^{40}K typically exhibits the highest TF among natural radionuclides in Nigerian cassava, attributed to its role as an essential plant nutrient actively concentrated by root tissues.

The IAEA handbook [6] provides reference TF values for root crops in tropical environments. The potassium TF values observed here (1.33–1.51) are consistent with, though somewhat lower than the higher-end TF values for 40K reported globally for root crops, reflecting the moderate available potassium concentrations of the study soils. The TF_u values in the present study are higher than those reported by Tyovenda et al. [18] for cassava in Taraba State ($TF_u \approx 0.27–0.74$), likely because the acidic, sandy soils of Akwa Ibom State reduce uranium sorption to soil particles, enhancing its bioavailability. This finding is consistent with the well-established geochemical principle that uranium mobility and plant uptake increase markedly under acidic conditions [5,29].

Essien et al. [14], studying cassava transfer factors in Ikot Ekpene LGA of Akwa Ibom State using the same NaI(Tl) spectrometry approach, reported ^{238}U and ^{232}Th transfer factors broadly comparable with those in the present study, providing internal consistency across Akwa Ibom datasets. Similarly, Olabimtan et al. [7], in their comprehensive review of Nigerian soil-to-plant transfer factors, noted that uranium TF values in cassava across the Niger Delta region consistently exceeded those for thorium, attributed to the comparatively higher chemical mobility of hexavalent uranium (UO_2^{2+}) under oxidising acidic conditions relative to thorium, which is strongly sorbed to organic matter and clay surfaces.

The high $TF_{th}(^{232}Th)$ observed in Uyo (1.11), relative to Ibiono Ibom and Itu (0.57–0.60), is noteworthy. Uyo had the highest ^{232}Th soil activity concentration (36.24 Bq/kg) but also higher clay content (14.21%) and the lowest SOM (6.11%) among the three LGAs. The lower SOM in Uyo soils would reduce the organic complexation of thorium, making it comparatively more bioavailable, while the elevated clay content could paradoxically serve as a surface for thorium mobilisation under highly acidic conditions through cation displacement [9].

Soil pH is one of the most critical determinants of radionuclide bioavailability in soil-plant systems [29]. In the present study, soil pH across all LGAs was strongly acidic (4.48–5.10), and significant positive correlations were found between pH and the activity concentrations of ^{238}U ($r = 0.869$) and ^{40}K ($r = 0.815$). The strong positive relationship between pH and ^{238}U concentration in soil, and its corresponding influence on TF, reflects the dual role of pH: under more acidic conditions, uranium dissolution from mineral phases is enhanced, but competing sorption processes can also be altered. The consistent acidity of soils in this study is characteristic of coastal plain sands in southern Nigeria, where intense leaching under high rainfall conditions removes base cations and reduces buffering capacity [17].

Globally, acidic soil conditions (pH < 5.5) are well-established drivers of elevated uranium and thorium bioavailability in tropical agricultural settings. Parvin et al. [5], studying radionuclide transfer in agricultural soils around the Barapukuria coal mining site in Bangladesh, a similarly tropical context, confirmed that soil pH exerted one of the strongest influences on spatial variability in TF values for ^{238}U, with lower pH soils consistently yielding higher TF values. The results of the present study are fully consistent with these global observations.

Soil organic matter (SOM) is a critical regulator of radionuclide speciation and mobility. Organic matter provides abundant functional groups (carboxyl, hydroxyl, phenolic) that form stable organo-metal complexes with actinides, thereby reducing their availability for root uptake. In the present study, near-perfect negative correlation between SOM and $TF_{th}(^{232}Th)$ ($r = -1.000$, $p < 0.05$) was obtained whereas in the work of Nyong et al. [13], a little-above-fair negative correlation between SOM and $TF_{th}(^{232}Th)$ ($r = -0.621$) was found. This confirms that thorium (a highly reactive lithophilic element) is effectively appropriated by organic matter in these soils, and that even modest reductions in SOM (as seen in Uyo relative to Ibiono Ibom and Itu from Table 1) result in substantially elevated thorium transfer to cassava.

This finding aligns with the conclusions of Nurtjahya et al. [9], who studied soil-to-plant transfer of ^{226}Ra, ^{232}Th, and ^{40}K on ex-tin mining land in Bangka Belitung, Indonesia, and found that organic-matter-rich soils consistently yielded lower TF values for thorium. Similarly, the systematic review by Olabimtan et al. [7] noted that across Nigerian soils, elevated organic carbon content was associated with reduced uranium and thorium TF values in root crops. The finding in this study shows that SOC is strongly negatively correlated with both ^{238}U activity in soil ($r = -0.764$) and positively with $TF_{th}(^{232}Th)$ via its interaction with SOM further reinforces the role of organic carbon as a mobilisation moderator.

Soil texture significantly influences radionuclide retention and mobility. Clay particles, with their high specific surface area and permanent negative charge, provide abundant adsorption sites for cationic radionuclide species, potentially reducing their solution-phase concentration and plant availability. However, the strong positive correlation found in this study between clay content and $TF_u(^{238}U)$ ($r = 0.692$) suggests a more complex relationship, possibly reflecting the predominance of 1:1 clay minerals (kaolinite) in tropical soils of southern Nigeria, which have lower cation exchange capacity than 2:1 clays typical of temperate soils and thus retain uranium less effectively [6]. The near-total sand dominance (76–80%) in all study LGAs reflects the coastal plain sand geology of Akwa Ibom State, which inherently limits the anion-exchange buffering capacity of these soils and contributes to the relatively high TF values observed for all three radionuclides.

Sand content showed a strong positive correlation with ^{232}Th in soil ($r = 0.996$), consistent with the association of thorium with heavy mineral fractions (zircon, monazite, ilmenite) that are concentrated in the coarse sand fraction of fluvially derived coastal plain sands [19]. The strong negative correlation between % silt and $TF_u(^{238}U)$ ($r = -0.994$) implies that LGAs with higher silt content exhibit lower uranium transfer, potentially due to the relatively higher CEC of silt particles compared with sand.

Exchangeable cations (particularly Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) influence radionuclide availability through ionic competition at root uptake sites and through their effects on soil pH and CEC. The very strong positive correlation between $TF_K(^{40}K)$ and both exchangeable Ca ($r = 0.998$, $p < 0.05$) and Na ($r = 0.999$, $p < 0.05$) in this study is an important mechanistic finding. Although K^{+} and Ca^{2+}/Na^{+} do not share the same uptake pathway, elevated base cation concentrations alter the ionic environment of the rhizosphere, potentially enhancing the mobilisation of potassium from non-exchangeable soil pools through cation exchange competition, thereby indirectly facilitating greater ^{40}K uptake by cassava roots. This is consistent with observations by Thien et al. [29], who demonstrated that multi-element ionic competition at root surfaces is a key determinant of observed TF variability.

The strongly negative correlation between Ca and ^{238}U activity ($r = -0.938$) and ^{40}K activity ($r = -0.968$) in soil suggests that liming or the natural occurrence of calcium-rich conditions would suppress radionuclide concentration in the soil solution. This has direct implications for soil management: agricultural practices that increase soil calcium through liming could simultaneously improve soil pH, reduce uranium and potassium bioavailability, and lower TF values in cassava.

5. Conclusion

This study has demonstrated that soil physicochemical properties exert significant and statistically quantifiable influence on the transfer of naturally occurring radionuclides (238U, 232Th, and 40K) from agricultural soils to cassava tubers in Uyo, Ibiono Ibom, and Itu LGAs of Akwa Ibom State, Nigeria. The predominantly acidic, sandy soils of the study area, a characteristic feature of Nigeria's coastal plain sand geomorphology, facilitate moderate to high radionuclide mobility, yielding transfer factor values that in several cases exceed unity, particularly for 40K.

Soil organic matter emerged as the dominant suppressor of thorium transfer (TFth(232Th)) vs. SOM: $r = -1.000$, $p < 0.05$), while clay content positively drove uranium transfer efficiency. Exchangeable base cations, particularly Ca and Na, were strongly correlated with TFk(40k), highlighting the ionic competition dynamics at the root-soil interface. Soil pH, universally acidic across the study area, amplified radionuclide solubility and availability, consistent with global findings for tropical soils.

The transfer factor values recorded in this study are of the same order of magnitude as those recently reported from comparable tropical ecosystems in Indonesia, Bangladesh, and other Nigerian sites, lending confidence to the methodological rigour of the dataset. These findings contribute essential, locally characterised data to the international database of tropical soil-to-plant transfer parameters, directly addressing a data gap repeatedly identified by the IAEA as critical for the accuracy of radiological risk models in African tropical ecosystems.

From a public health and food safety perspective, the elevated TFk(40K) values and moderate TFu(238U) values in cassava cultivated on these acidic, low-organic-matter soils indicate that dietary exposure to 238U and 40K through cassava consumption warrants quantitative assessment as part of a comprehensive radiological health risk evaluation for communities in Akwa Ibom State. Furthermore, soil management interventions, including the application of organic amendments to increase SOM and liming to raise soil pH, represent evidence-based strategies that could meaningfully reduce radionuclide transfer to cassava in this agroecological setting.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there was no conflict of interest in the course of carrying out this research.

References

[1] UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). Sources and Effects of Ionizing Radiation. UNSCEAR 2008 Report to the General Assembly with Scientific Annexes. United Nations, New York, 2008.

[2] Aniebone VO, Chukwu-Okeah GO and Adegbie AT. Radionuclide actions, processes and presence in water and sediments, a review. International Journal of Ground Sediment and Water, 10: 559–571, 2020. https://doi.org/10.5281/zenodo.4029785.

[3] Popoola OJ, Olubi OE, Adewalure OS and Raphael AE. Elevated natural radionuclides in soils and stream sediments: pollution, spatial distribution, radiological hazards, and cancer risks in peri urban Emure Ekiti, southwest Nigeria. Discover Soil, 2(70), 2025. https://doi.org/10.1007/s44378-025-00074-z

[4] Orosun MM, Usikalu MR, Oyewumi KJ, Omeje M, Awolola GV, Ajibola O,and Tibbett M. Soil-to-plant transfer of 40K, 238U and 232Th and radiological risk assessment of selected mining sites in Nigeria. Heliyon, 8(11): 1-9, 2022. https://doi.org/10.1016/j.heliyon.2022.e11534

[5] Parvin T, Islam S, Ferdous J, Shuvo, SD and Bakshi PK. Spatial distribution and soil-to-plant transfer factors of radionuclides in agricultural soil around the Barapukuria coal mining site, Bangladesh. Environmental Science: Processes and Impacts, 7, 2025. https://doi.org/10.1039/d4em00653d

[6] IAEA (International Atomic Energy Agency). Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. Technical Reports Series No. 472. IAEA, Vienna, 2010.

[7] Olabimtan SO, Chifu EN, Hafeez YH and Nasir, M. Measurement of transfer factors from soil-to-plant/food crop of naturally occurring radionuclide materials (NORMs) in Nigeria: A review. Dutse Journal of Pure and Applied Sciences, 9(3b), 173–193, 2023.

[8] Velasco H and Anjos RM. A review of 137Cs and 40K soil-to-plant transfer factors in tropical plants. Journal of Environmental Radioactivity, 235-236: 1-7, 2021. https://doi.org/10.1016/j.jenvrad.2021.106650

[9] Nurtjahya E, Mellawati J, Pratama D and Syahrir S. Study of soil–to–plant transfer factors (TFs) of 226Ra, 232Th, and 40K on plants cultivated on ex–tin mining land in Bangka Belitung, Indonesia. Journal of Environmental Radioactivity, 261(2): 107144, 2023. https://doi.org/10.1016/j.jenvrad.2023.107144

[10] Akpan SA, Nyong AB, Akpan D, Essien IE and Akpan EN. Assessment of activity concentration of radionuclides and their transfer factors from the soil to maize plants in Essien Udim Local Government Area of Akwa Ibom State, Nigeria. World Journal of Applied Science and Technology, 15(2): 169-174, 2023. https://dx.doi.org/10.4314/wojast.v15i2.3

[11] Kanmi AS, Ibrahim U, Goki NG, Rilwan U, Sayyed MI, Wais TY, Namq BF and Najam LA. Estimation of soil-to-plant transfer factor across six local government areas of Kwara state, Nigeria. Journal of Environmental Radioactivity, 280: 107548, 2024. https://doi.org/10.1016/j.jenvrad.2024.107548

[12] Nyong AB, Umoren EB, Akpan DN, Ekott EE, Ebong GA and Essien IE. Transfer factors of 40k, 232th and 238u from soil to cassava system from farmlands in selected parts of Akwa Ibom State, Nigeria. World Journal of Applied Science and Technology, 15(2): 186-191, 2023. https://dx.doi.org/10.4314/wojast.v15i2.5

[13] Nyong AB, Akpan DN, Atat JG, Essien IE and Ekott EE. The effect of physicochemical properties of soil on the rate of natural radionuclides uptake by cassava in parts of Akwa Ibom State, Nigeria. Journal of Applied Chemical Science International, 17(1): 217-218, 2026. https://doi.org/10.56557/jacsi/2026/v17i110583

[14] Essien I, Akankpo A, Nyong A and Inyang E. Determination of activity concentrations and soil to cassava transfer factors of natural radionuclides in Ikot Ekpene Local Government Area, Akwa Ibom State, Nigeria. Journal of Geography, Environment and Earth Science International, 25(7): 28-35, 2021. https://doi.org/10.9734/jgeesi/2021/v25i730296

[15] Amakom CM, Orji CE, Eke BC, Iroegbu C and Ojakominor BA. Gross alpha and beta activity concentrations in soil and some selected Nigerian food crops. International Journal of Physical Sciences, 13(11):183-186, 2018. https://doi.org/10.5897/IJPS2018.471

[16] Amakom CM, Orji CE, Okeoma KB and Echendu OK. Radiological analysis of cassava samples from a coal mining area in Enugu State, Nigeria. Environmental Health Insights, 17: 1-8, 2023. https://doi.org/10.1177/11786302231199836

[17] Akpan AE, Ebong ED, Ekwok SE and Eyo JO. Assessment of radionuclide distribution and associated radiological hazards for soils and beach sediments of Akwa Ibom Coastline, southern Nigeria. Arabian Journal of Geosciences, 13(753): 1-12, 2020. https://doi.org/10.1007/s12517-020-05727-7

[18] Tyovenda AA, Ocheje JA, Terver S and Uttah EU. Investigation of the radiological risk of farmlands and the transfer factor from soil to crops in Jalingo and Wukari LGA of Taraba State, Nigeria. Journal of Environmental Protection, 13, 1–14, 2022. https://doi.org/10.4236/jep.2022.131001

[19] Doering C, Twining J, Rout S, Iurian A and Howard B. A revised IAEA data compilation for estimating the soil to plant transfer of radionuclides in tropical environments. Journal of Environmental Radioactivity, 232(10657): 1-10, 2021. https://doi.org/10.1016/j.jenvrad.2021.106570

[20] Ema E, Etim E, Tom A, Ansa I, Ituen U, Ekpenyong R, Inyanam M and Akpan U. Remote sensing based-assessment of land use and land cover dynamics in mangrove vegetation, Akwa Ibom State, Nigeria (1986-2024). Gobal Journal of Environmental Science and Sustainability, 2(2): 92-103, 2025. https://doi.org/https://doi.org/10.69798/93599792

[21] Food and Agriculture Organization of the United Nations (FAO). The state of food and agriculture 2019: moving forward on food loss and waste reduction (FAO Report). FAO, Rome, Italy, 2019.

[22] Kehinde AD, Ogundeji AA. Distributive impacts of non-farm income on output and farm income of cassava farmers in Southwestern Nigeria. Scientific African, e01535, 2023.

[23] Ayanwale A, Kehinde A and Ogundeji A. Assessing the determinants of cassava yield and its impact on household food security in Nigeria. SN Social Sciences (A Springer Nature Journal), 6(90): 1-34, 2026. https://doi.org/10.1007/s43545-026-01337-4

[24] Bouyoucos GJ. A recalibration of the hydrometer method for making mechanical analyses of soils. Agronomy Journal, 43(9), 434–438, 1951.

[25] Amakom CM, Orji CE, Eke BC, Okoli UA and Ndudi CS. The influence of selected soil physicochemical properties of radionuclide transfer in cassava crops. International Journal of Plant and Soil Science, 14(1): 1-7, 2017. https://doi.org/10.9734/IJPSS/2017/30913

[26] Black CA, Evans DD, White JL, Ensminger LE and Clark FE. Methods of Soil Analysis (Part 1). Physical and Mineralogical Properties Including Statistics of Measurements and Sampling. American Society of Agronomy Inc., Madison, 1965. https://doi.org/10.2134/agronmonogr9.1

[27] Bahadori M. and Tofighi H. A modified walkley-black method based on spectrophotometric procedure. Communications in Soil Science and Plant Analysis, 47(2): 213-220, 2016. https://doi.org/10.1080/00103624.2015.1118118

[28] Chakraborty SR, Azim R, Rahman AKMR and Sarker R. Radioactivity concentrations in soil and transfer factors of radionuclides from soil to grass and plants in the Chittagon city of Bangladesh. Journal of Physical Science, 21(1): 95 -113, 2013.

[29] Thien BN, Ba VN, Vy NTT and Loan TTH. Estimation of the soil to plant transfer factor and the annual organ equivalent dose due to ingestion of food crops in Ho Chi Minh city, Vietnam. Chemosphere, 259(127432): 1-7, 2020. https://doi.org/10.1016/j.chemosphere.2020.127432