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# Natural radionuclides in flood-affected rice agroecosystems: distribution patterns, transfer dynamics, and radiological implications

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## Abstract

This study assessed the redistribution of natural radionuclides and associated radiological risks in flood-affected rice agroecosystems of Hadejia, Jigawa State, Nigeria. Radiation surveys and sample collection were conducted shortly after floodwater recession. A total of 50 soil and rice samples were analyzed using gamma spectrometry. The mean activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K were 11.58 ± 0.41, 16.32 ± 1.28, and 470.24 ± 25.13 Bq/kg in soil, and 2.01 ± 0.15, 2.24 ± 0.17, and 130.22 ± 2.19 Bq/kg in rice, respectively. The corresponding radiological indices due to soil exposure were below world averages and recommended safety limits. Soil-to-rice transfer factors followed the order $^{40}$K (0.30) > $^{226}$Ra (0.18) > $^{232}$Th (0.17), consistent with the existing literature. The annual effective dose from rice consumption (0.06 ± 0.01 mSv/y) was below the public dose constraint of 0.3 mSv/y. Regression analysis showed strong dependence of $^{226}$Ra uptake on soil concentration ($R^2$ = 0.815), weak correlation for $^{232}$Th ($R^2$ = 0.304), and no significant relationship for $^{40}$K ($R^2$ = 0.006). Spatial and normalized analyses revealed localized hotspots linked to flood-induced sediment deposition. The radiological risk was low, although continued monitoring is recommended.

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## 1. Introduction

The effects of climate change have continuously manifested in sub-Saharan Africa through extreme weather conditions, resulting in increased precipitation and flooding, which have now become perennial phenomena [1, 2]. The major consequences include disruption of agricultural ecosystems through the submersion of floodplains, lowlands, and adjoining upland areas that are susceptible to conventional floodwater meandering [3]. This delicate interaction between flooding and the agricultural landscape has profound implications for food security and public health. On the one hand, soils in areas susceptible to inundation often exhibit elevated fertility due to changes in nutrient and organic-matter content caused by the deposition of sediments transported by floodwaters. On

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the other hand, flooding creates anaerobic conditions that affect microbial metabolism, alter biogeochemical nutrient cycling, and change the concentrations of toxic elements and naturally occurring radionuclides [3]. Despite these challenges, farmers continue to cultivate a variety of crops in flood-prone farmlands because of the perceived soil-fertility benefits.

There is a dual concern associated with elevated concentrations of natural radionuclides in soil and other environmental media: chemical toxicity and radiological toxicity. Chemical toxicity arises from the intrinsic chemical properties of an element and its interactions with biological systems, whereas radiological toxicity results from exposure to ionizing radiation emitted during radioactive decay. For natural radionuclides, radiological effects generally constitute the primary concern at environmental concentrations, while chemical toxicity may become relevant only at substantially elevated levels [4]. Naturally occurring radioactive materials (NORM) are integral components of the Earth's crust. Their concentrations in the biosphere are often enhanced by anthropogenic activities such as mining, excavation, and mineral processing [5]. Elevated levels of NORM can pose long-term risks to public health [6, 7]. Radioactive materials can be mobilized through various processes, including wind dispersal, rainfall, flooding, animal activity, and human actions. Among these processes, wind and flooding are the most effective mechanisms for large-scale redistribution, both of which are intensified by climate variability [2, 3, 8]. The most significant natural radionuclides of radiological concern include series radionuclides such as $^{238}$U and $^{232}$Th and non-series radionuclides such as $^{40}$K. These radionuclides, owing to their long half-lives, are major contributors to background radiation in the environment [5].

Human contact with these radionuclides occurs through ingestion, inhalation, dermal absorption, and external irradiation. Prolonged exposure may result in adverse health effects, including cancer [9]. Apart from external exposure to NORM in the environment, radionuclides can be transferred to the human body through the food chain [10]. Agricultural produce cultivated from soil containing elevated NORM concentrations can potentially pose a significant threat of radiological exposure when consumed. For example, several studies have reported appreciable amounts of natural radionuclides in food crops such as rice, millet, sorghum, okra, potatoes, and other agricultural produce [9–13]. These findings emphasize the importance of continuous monitoring of food crops to safeguard public health.

In northern Nigeria, artisanal mining of solid minerals such as gold, tin, tantalum, lithium, and other rare-earth metals is widespread [14]. The consequences of these unregulated mining activities are far-reaching for the environment because mining activities have been linked to elevated NORM concentrations [6, 14, 15]. Because most mining pits are not backfilled, the overburden is often left as heaps around mining sites. With excess rainfall occasioned by climate change, mine tailings, overburden rocks, and contaminated water from mines are rapidly transported by floodwater. As a result of the violent mass movement and meandering of floodwaters, substances transported by floods are crushed into fine sediments that may be rich in NORM. These sediments are deposited together with nutrients in floodplains and submerged catchment areas and may potentially be absorbed with nutrients by food crops grown in the landscape.

Jigawa State is among the flood-prone states in Nigeria, with several reported flood disasters and losses of lives, livelihoods, and hectares of arable farmland over many years [1, 16]. Despite the perennial flood challenges, Jigawa State is among the major rice-producing states in Nigeria, with Hadejia as a major rice-producing area in the state [2, 17]. Rice is widely consumed in Nigeria and constitutes an important component of the national diet. Hadejia, Jigawa State, is one of the major rice-producing areas in northern Nigeria and is frequently affected by seasonal flooding. Flood events can alter the distribution of naturally occurring radionuclides through sediment transport and deposition, potentially influencing their concentrations in agricultural soils and subsequent uptake by food crops.

Despite the agricultural importance of the area, information on the radiological characteristics of flood-affected rice agroecosystems remains limited. Therefore, this study was undertaken to evaluate the activity concentrations of naturally occurring radionuclides in soils and rice grains collected from flood-affected and non-flooded farmlands in Hadejia Local Government Area, Jigawa State, Nigeria. The study further assessed soil-to-rice transfer factors and associated radiological risks arising from rice consumption. The significance of investigating radionuclide uptake in rice has been recognized in several regions because rice constitutes a major dietary component and may serve as a pathway for human exposure to natural radionuclides. Studies conducted in Bangladesh [10], Vietnam [7], Indonesia [9] and Ebonyi State, Nigeria [12], have evaluated the occurrence, transfer, and accumulation of natural radionuclides in rice and associated agricultural soils. These studies demonstrated that radionuclides can be transferred from soil to rice grains, thereby contributing to internal radiation exposure through dietary intake. Consequently, continued assessment of radionuclide concentrations in rice-producing regions remains important for food safety and radiological risk evaluation.

## 2. Materials and methods

### *2.1. Study area*

Hadejia town in Hadejia Local Government Area of Jigawa State is located between latitudes 12.270° N and 12.4506° N and longitudes 10.0404° E and 10.226° E. Hadejia is bounded by Kirikasamma, Mallam Madori, and Auyo Local Government Areas to the east, north, and west, respectively (Figure 1). The entire Hadejia town and its suburbs are known for extensive production of rice, millet, guinea corn, and groundnuts [1, 2]. The major floodplain is along the Hadejia River, a major Nigerian river that drains

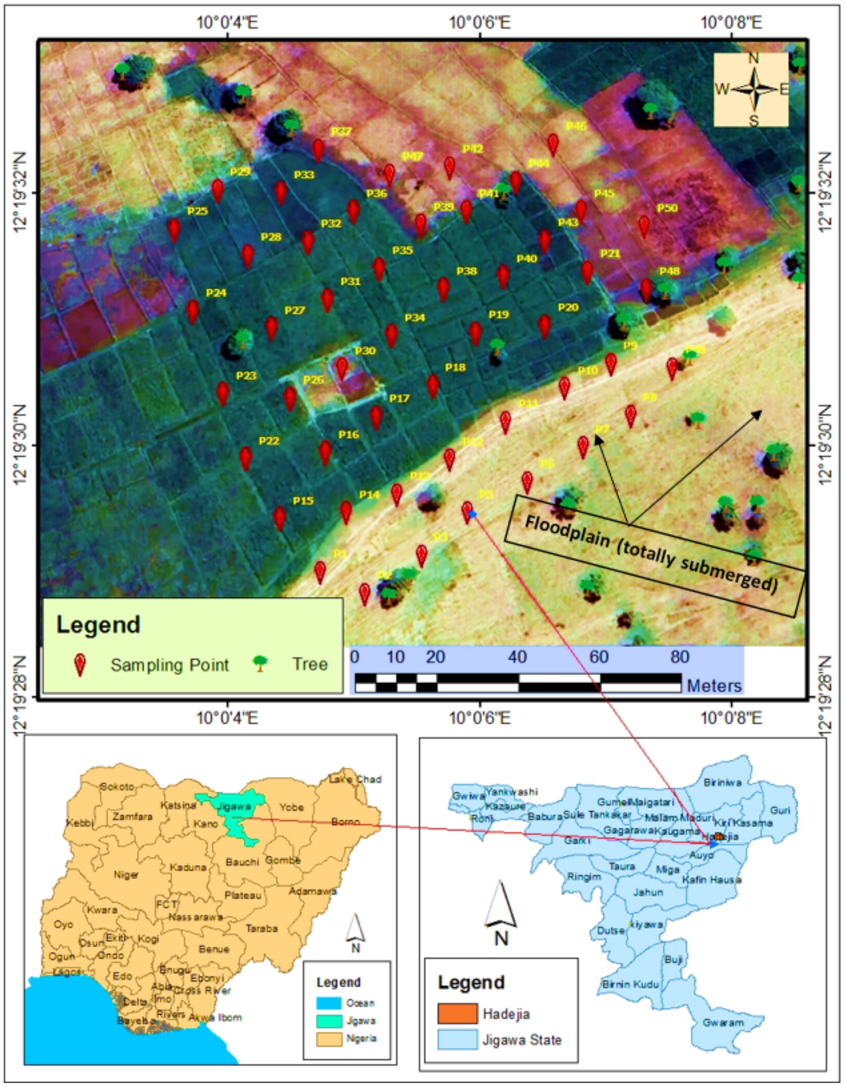


Figure 1: Map of Nigeria (bottom left), map of Jigawa State (bottom right), and Google map of Hadejia showing the sampling locations.

into Lake Chad. The floodplain and its catchment areas are used for extensive rice farming in both the rainy and dry seasons (Figure 2). The Hadejia River is extremely useful for sustaining dry-season irrigation farming and fishing [18]. The climatic conditions, vegetation, and seasonal variation in Hadejia have been described in detail elsewhere [2, 17].

### 2.2. Materials

The research used the following materials at different stages of the study. For the reconnaissance survey and selection of sampling locations, a portable radiation survey meter (QG GMC-series Geiger counter; serial number QGDMC-800), calibrated on 8 February 2025 at the Nigerian Secondary Standard Dosimetry Laboratory with certificate number NIRPR/YVI/25/043 and calibration factor of 0.97±0.09, was used together with a Global Positioning System (GPS)-enabled camera, a pen, and a notebook. For sample collection, the materials included a plastic hand shovel, polythene bags, hand gloves, boots, zipped plastic bags, indelible ink, masking tape, a GPS device, a pen, and a notebook. For sample preparation, an oven, sieve, mortar and pestle, 100 ml plastic bottles, masking tape, indelible ink, and a laboratory bench were used. Spectrometric analysis involved a sodium iodide detector, desktop computer, and spectrum-analysis software. Data analysis was performed using a personal computer, Microsoft Excel 2021, and Python data-analysis tools.

### 2.3. Background radiation survey

Before sample collection, an in situ background radiation survey was conducted as part of the reconnaissance exercise. The survey results were used to identify flood-affected farmlands with relatively elevated ambient radiation levels and to delineate the

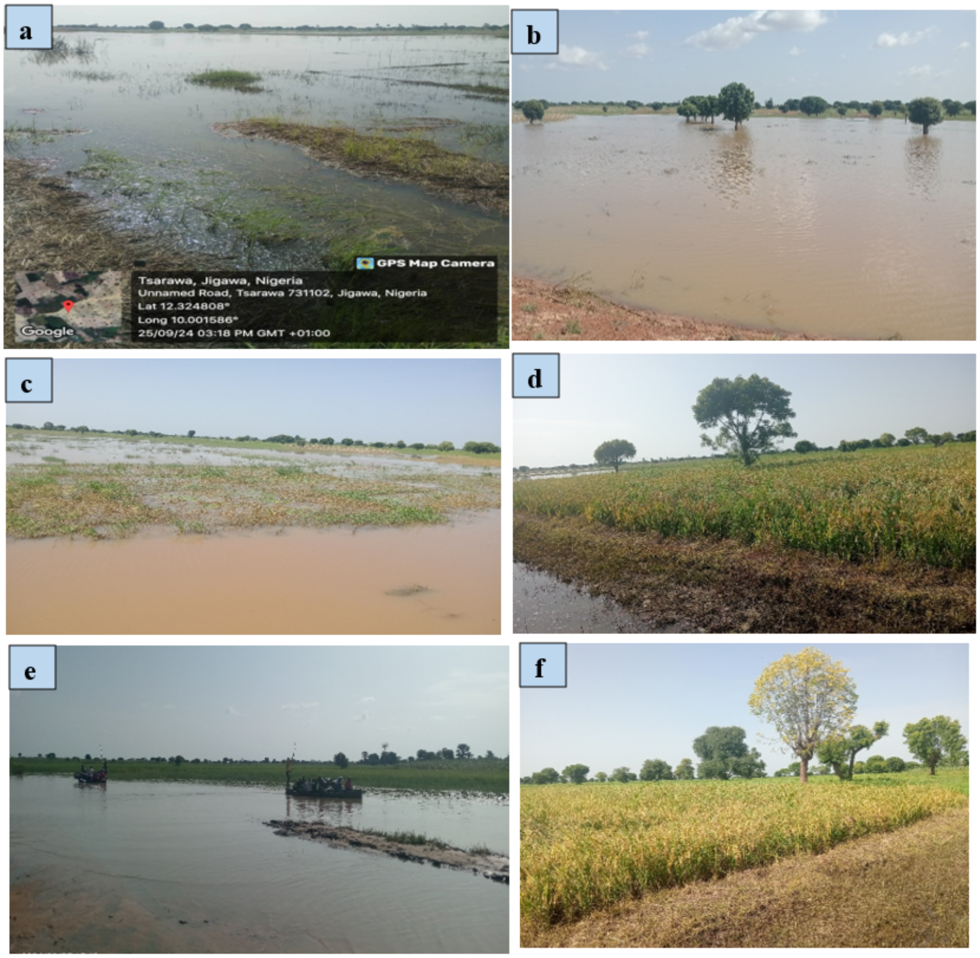


Figure 2: Snapshots of the floodplains with submerged rice and the adjoining rice farms at Tsarawa suburb of Hadejia town, Jigawa State.

study area. Particular attention was given to submerged rice farmlands where floodwaters had sufficiently receded to permit access to potentially contaminated surface soil. Background radiation measurements were obtained by recording the instantaneous dose rate at a height of 1 m above the ground surface. At each measurement location, five readings were taken and averaged to obtain a representative background radiation level (Figure 3).

### 2.4. *Sample collection*

A stratified random sampling approach was adopted to ensure adequate spatial coverage of the selected farmlands located along the floodplain. The study area was divided into five strata based on distance from the floodplain. Successive strata were established at 100 m intervals from the floodplain, and five sampling locations were randomly selected within each stratum, resulting in 25 sampling locations. At each location, a topsoil sample (1–5 cm depth) and the corresponding rice-grain sample were collected, yielding 25 soil samples and 25 rice samples for radiological analysis. With the aid of the plastic hand shovel, surface soil at a maximum depth of 5 cm was scooped at each sampling position and emptied into a plastic sample-collection bag, which was zipped to avoid cross-contamination. Rice grains at the same location were also collected. Both samples were marked with a unique sample identification number using masking tape and indelible ink for easy separation in the laboratory, and the sample identifications were recorded in an exercise book for reference. At each sampling location, GPS coordinates were also recorded for follow-up studies. The collected soil and rice samples were transported to the gamma-spectrometry laboratory at the Centre for Energy Research and Training (CERT), Ahmadu Bello University (ABU), Zaria.

### 2.5. *Selection of control area*

The control samples were collected from an adjacent rice farm located approximately 5 km outside the floodplain, at a sufficiently higher elevation, and free from seasonal inundation. This location shares similar geological and agricultural characteristics with the flooded area and was selected to provide representative background concentrations. The samples were collected and marked with unique identifications, while the GPS coordinates were recorded accordingly.


Figure 3: Radiation survey exercise in the study area conducted by members of the research team.

### 2.6. *Sample preparation*

At the CERT laboratory, the soil and rice-grain samples were air-dried, cleaned to remove impurities, and pulverized into fine powder before being sieved using a 2 mm mesh. The processed samples were subsequently transferred into cylindrical plastic containers measuring 6.5 × 6.0 cm. This dimension provides an optimal sample mass of 350 g for efficient gamma-spectrometric analysis, as described in Ref. [19]. With the aid of masking tape, the plastic containers' screw caps were sealed tightly to minimize the ingress and egress of ambient air. The containers were then stored for 28 days to attain secular equilibrium between radium and its progenies, as described in Refs. [19–21]. To ensure quality assurance, International Atomic Energy Agency (IAEA)-certified reference materials (RGK-1, RGU-1, and RGTh-1) were packaged in identical sample containers, properly sealed, and maintained under the same storage conditions.

### 2.7. *Gamma-spectrometry analysis*

As described in Ref. [19], the gamma-spectrometry system at CERT comprises a 7.62 × 7.62 cm NaI(Tl) scintillation detector (Model 727 series, Canberra Inc.) connected through a preamplifier to a Canberra Series 10 computer-based multichannel analyzer (MCA) (Model 1104). To minimize background interference, the detector is housed within a shielding assembly made of 6 cm thick lead, internally lined with cadmium and reinforced with copper sheets. The activity concentrations of the naturally occurring radionuclides $^{226}$Ra, $^{232}$Th, and $^{40}$K were evaluated using the gamma-emission peaks at 352 and 609 keV for $^{214}$Pb/$^{214}$Bi, 583 and 911 keV for $^{208}$Tl/$^{228}$Ac, and 1460 keV for $^{40}$K, respectively. The analytical procedure followed established methodologies reported in previous studies [19, 20, 22]. For accurate determination of specific activity, each prepared sample was measured for a counting duration of 28,800 s (8 h) to ensure adequate spectrum acquisition.

### 2.8. *Quality assurance and quality control*

Quality assurance and quality control (QA/QC) procedures were implemented throughout the analytical procedure to ensure the accuracy, precision, and reliability of the radionuclide activity measurements. Before sample analysis, the NaI(Tl) gamma-ray spectrometry system was calibrated for both energy and efficiency using IAEA-certified reference materials, namely RGU-1, RGTh-1, and RGK-1, representing $^{238}$U-, $^{232}$Th-, and $^{40}$K-bearing standards, respectively. Energy calibration was performed by establishing the relationship between channel number and gamma-ray energy using characteristic photopeaks of known energies. Efficiency calibration was carried out using the same reference materials prepared in geometries identical to those of the analyzed samples. The generated efficiency curve was subsequently used to convert net count rates to activity concentrations.

Background spectra were acquired periodically using an empty sealed counting container under identical counting conditions and subsequently subtracted from the sample spectra before activity determination. The performance of the spectrometry system was verified using IAEA-certified reference materials. The measured activities of the reference materials agreed with the certified values within the acceptable range of ±10%, confirming the reliability and stability of the measurement system throughout the study.

Table 1: Minimum detectable activity and uncertainty of the spectrometry system.

| Radionuclide | Energy peak (keV) | MDA (Bq kg$^{-1}$) | Counting uncertainty (%) |
|---|---|---|---|
| $^{226}$Ra (via $^{214}$Bi) | 609.00 | 1.20 | 5.00 |
| $^{232}$Th (via $^{208}$Tl) | 583.00 | 1.10 | 5.00 |
| $^{40}$K | 1460.80 | 4.50 | 3.00 |

The minimum detectable activity (MDA) was determined following the method proposed by Currie (1968), as captured in Eq. (1) [23, 24]:

$$\text{MDA} \approx \frac{4.65\sqrt{B}}{\epsilon P_\gamma m t}, \tag{1}$$

where $B$ is the background counts in the region of interest, $\epsilon$ is the detector efficiency, $P_\gamma$ is the gamma-emission probability, $t$ is the counting time (s), and $m$ is the sample mass (kg).

Only activity concentrations above the corresponding MDA values were considered detectable and used for subsequent radiological assessments (Table 1).

Throughout the analytical period, the performance of the spectrometry system was verified periodically by analyzing background and reference materials to ensure system stability and measurement reliability.

### 2.9. *Radiological health risk assessment*

The health-risk assessment was performed using established risk-assessment models in the literature [10, 13, 14, 19, 20, 25, 26]. These models are presented in Eqs. (2)–(11).

Terrestrial gamma-radiation dose rates in microsieverts per hour ($\mu$Sv $h^{-1}$) were converted to absorbed dose rate (ADR) in nanograys per hour (nGy $h^{-1}$) using Eq. (2) [25]:

$$1\,\mu\text{Sv}\,h^{-1} = 1\,\mu\text{Gy}\,h^{-1} = 1000\,\text{nGy}\,h^{-1}. \tag{2}$$

The ADR from external exposure to natural radionuclides in soil and rice was estimated using Eq. (3):

$$ADR\left(\text{nGy}\,h^{-1}\right) = 0.427C_{\text{Ra}} + 0.623C_{\text{Th}} + 0.043C_{\text{K}}, \tag{3}$$

where $C_{\text{Ra}}$, $C_{\text{Th}}$, and $C_{\text{K}}$ are the activity concentrations (Bq kg$^{-1}$) of $^{226}$Ra, $^{232}$Th, and $^{40}$K, respectively.

The annual effective dose equivalent (AEDE) was determined from Eq. (4):

$$AEDE\left(\text{mSv}\,y^{-1}\right) = ADR\left(\text{nGy}\,h^{-1}\right) \times 8760\,h \times 0.7\,\text{Sv}\,\text{Gy}^{-1} \times 0.25. \tag{4}$$

In Eq. (4), 8760 $h$, 0.7 Sv Gy$^{-1}$, and 0.25 are the total hours in a year, the dose-conversion factor from absorbed dose rate to effective dose, and the outdoor occupancy factor, respectively.

The radium equivalent ($Ra_{\text{eq}}$) was estimated using Eq. (5):

$$Ra_{\text{eq}} = A_{\text{Ra}} + 1.43A_{\text{Th}} + 0.077A_{\text{K}}, \tag{5}$$

where $A_{\text{Ra}}$, $A_{\text{Th}}$, and $A_{\text{K}}$ are the activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in Bq kg$^{-1}$, respectively.

The external hazard index ($H_{\text{ex}}$) due to external exposure gives the gamma yield from $^{226}$Ra, $^{232}$Th, and $^{40}$K in the samples and is given by Eq. (6):

$$H_{\text{ex}} = \frac{A_{\text{Ra}}}{370} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1. \tag{6}$$

The internal hazard index ($H_{\text{in}}$) was estimated using Eq. (7):

$$H_{\text{in}} = \frac{A_{\text{Ra}}}{185} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1. \tag{7}$$

The annual gonadal dose equivalent (AGDE) quantifies the yearly radiation dose received by the reproductive organs and other radiosensitive tissues, with the potential to cause genetic and hereditary effects in exposed individuals. This index was estimated using Eq. (8):

$$AGDE = 3.09A_{\text{Ra}} + 4.18A_{\text{Th}} + 0.314A_{\text{K}}. \tag{8}$$

The gamma index ($I_\gamma$) was calculated using Eq. (9):

$$I_\gamma = \frac{A_{\text{Ra}}}{300} + \frac{A_{\text{Th}}}{200} + \frac{A_{\text{K}}}{3000} \leq 1. \tag{9}$$

Table 2: Background-radiation estimated risk.

| Quantity | Min | Max | Mean | SD | SE | Mean ± SE | UNSCEAR/ICRP |
|---|---|---|---|---|---|---|---|
| Mean DR ($\mu$Sv $h^{-1}$) | 0.08 | 0.13 | 0.11 | 0.014 | 0.003 | 0.11 ± 0.003 | 0.11 |
| ADR (nGy $h^{-1}$) | 87.50 | 127.50 | 102.90 | 10.14 | 2.03 | 102.90 ± 2.03 | 84 |
| AEDE (mSv $y^{-1}$) | 0.13 | 0.20 | 0.16 | 0.016 | 0.003 | 0.16 ± 0.003 | 0.30 |
| ELCR ($\times 10^{-4}$) | 4.29 | 6.98 | 5.73 | 0.74 | 0.15 | 5.73 ± 0.15 | 2.9 |

Min: minimum; Max: maximum; SD: standard deviation; SE: standard error.

The excess lifetime cancer risk (ELCR) was estimated using Eq. (10):

$$ELCR = AEDE \times DL \times RF, \quad (10)$$

where $DL$ is the average life expectancy, typically taken as 70 years [25], and $RF$ is the cancer risk factor recommended by the International Commission on Radiological Protection (ICRP), given as 0.05 Sv$^{-1}$.

The annual effective dose (AED) due to rice consumption was estimated from Eq. (11):

$$AED\left(\mathrm{mSv}\, yr^{-1}\right) = \left(2.8 \times 10^{-4} A_{\mathrm{Ra}} + 2.3 \times 10^{-4} A_{\mathrm{Th}} + 6.2 \times 10^{-6} A_{\mathrm{K}}\right) A_{\mathrm{ig}}. \quad (11)$$

The values $2.8 \times 10^{-4}$, $2.3 \times 10^{-4}$, and $6.2 \times 10^{-6}$ are the ingestion dose-conversion factors for $^{226}$Ra, $^{232}$Th, and $^{40}$K in mSv Bq$^{-1}$, respectively [27]. $A_{\mathrm{ig}}$ is the annual intake of rice (kg y$^{-1}$); the per capita consumption of rice in Nigeria is 32 kg $y^{-1}$ [28, 29].

### *2.10. Spatial interpolation procedure*

Spatial distribution heatmaps of radionuclide activity concentrations were generated using the inverse distance weighting (IDW) interpolation method. This technique estimates values at unsampled locations based on the weighted influence of surrounding sampled points, with closer observations exerting greater influence on predicted values than distant observations. The interpolation was implemented in Python using the spatial coordinates of the sampling locations and the measured radionuclide activity concentrations. The resulting interpolated surfaces were visualized as heatmaps to identify spatial trends and potential hotspots of radionuclide accumulation across the study area.

## 3. Results and discussion

### *3.1. Background radiation risk estimation*

The measured background radiation dose rates at each sampling location were evaluated, and the mean values are presented in Table 2. Using Eqs. (2), (4), and (10), the absorbed dose rate, annual effective dose equivalent, and excess lifetime cancer risk corresponding to each measurement were evaluated. The range, mean, standard deviation, and standard error are also presented in Table 2. The mean values were compared with the world average values (WAVs) provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [30] and with ICRP recommendations [31].

As shown in Table 2, the mean ± SE ADR and ELCR were estimated to be 102.90 ± 2.03 nGy $h^{-1}$ and (5.73 ± 0.15) × $10^{-4}$, respectively, and were above the world average values of 84 nGy $h^{-1}$ and 2.9 × $10^{-4}$, respectively [30]. However, the AEDE was 0.16 ± 0.003 mSv $y^{-1}$, which is lower than the dose constraint of 0.3 mSv $y^{-1}$ recommended by the ICRP for public exposure from any single exposure situation [31]. Although ADR and ELCR were above the WAVs, the results suggest that the risk from exposure to background radiation in the flooded rice field remains essentially low because the dose constraint was not exceeded. Further investigation with wider area coverage and a larger sample size is recommended. Similar trends in background-radiation data have been observed in studies conducted in different parts of Nigeria and elsewhere [25, 32–35]. These publications reported ADR and ELCR values slightly higher than the WAVs, but none suggested an imminent radiological threat to public health because the AEDE values remained within acceptable limits, thereby corroborating the inferences from this study.

### *3.2. Radionuclide concentrations in soil and associated radiological risk*

The concentrations of the naturally occurring radionuclides $^{226}$Ra, $^{232}$Th, and $^{40}$K in soil samples collected from the flooded rice field in Hadejia were determined, and the associated radiological risks were estimated using Eqs. (2)–(10). The results are summarized in Table 3 and Figures 4 and 5.

From Table 3, the mean ± SE activity concentrations in the soil samples were 11.58 ± 0.41, 16.32 ± 1.28, and 470.24 ± 25.13 Bq/kg for $^{226}$Ra, $^{232}$Th, and $^{40}$K, respectively, and the mean radium equivalent was estimated to be 71.13 ± 2.69 Bq/kg. Compared with the WAVs reported by UNSCEAR [30], which are 30, 35, and 400 Bq/kg for $^{226}$Ra, $^{232}$Th, and $^{40}$K, respectively, and with the radium-equivalent limit of 370 Bq/kg, the mean radionuclide concentrations and radium equivalent obtained in this study were below the average values, except for $^{40}$K, which was slightly higher than its WAV. This increase in $^{40}$K may partly reflect the use of

Table 3: Summary of the activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in soil and the radiological hazard indices.

| Quantity | Min | Max | Mean | SD | SE | Mean ± SE | CTR mean | EF | UNSCEAR |
|---|---|---|---|---|---|---|---|---|---|
| $^{226}$Ra (Bq/kg) | 7.85 | 15.26 | 11.58 | 2.03 | 0.41 | 11.58 ± 0.41 | 10.65 | 1.09 | 30.00 |
| $^{232}$Th (Bq/kg) | 5.78 | 27.28 | 16.32 | 6.40 | 1.28 | 16.32 ± 1.28 | 15.73 | 1.04 | 35.00 |
| $^{40}$K (Bq/kg) | 265.95 | 705.87 | 470.24 | 125.67 | 25.13 | 470.24 ± 25.13 | 374.45 | 1.26 | 400.00 |
| $Ra_{eq}$ (Bq/kg) | 47.81 | 96.51 | 71.13 | 13.46 | 2.69 | 71.13 ± 2.69 | – | – | 370.00 |
| ADR (nGy/h) | 24.52 | 48.60 | 35.34 | 6.74 | 1.35 | 35.34 ± 1.35 | – | – | 84.00 |
| AEDE (mSv/y) | 0.04 | 0.07 | 0.05 | 0.01 | 0.01 | 0.05 ± 0.01 | – | – | 0.30 |
| AGDE (mSv/y) | 0.18 | 0.35 | 0.25 | 0.05 | 0.01 | 0.25 ± 0.01 | – | – | 0.30 |
| ELCR ($\times 10^{-4}$) | 1.32 | 2.61 | 1.90 | 0.36 | 0.07 | 1.90 ± 0.07 | – | – | 2.90 |
| $H_{in}$ | 0.15 | 0.30 | 0.22 | 0.04 | 0.01 | 0.22 ± 0.01 | – | – | 1.00 |
| $H_{ex}$ | 0.13 | 0.26 | 0.19 | 0.04 | 0.01 | 0.19 ± 0.01 | – | – | 1.00 |
| $I_{\gamma}$ | 0.19 | 0.38 | 0.28 | 0.05 | 0.01 | 0.28 ± 0.01 | – | – | 1.00 |

EF: enrichment factor; SD: standard deviation; SE: standard error; CTR: control sample.

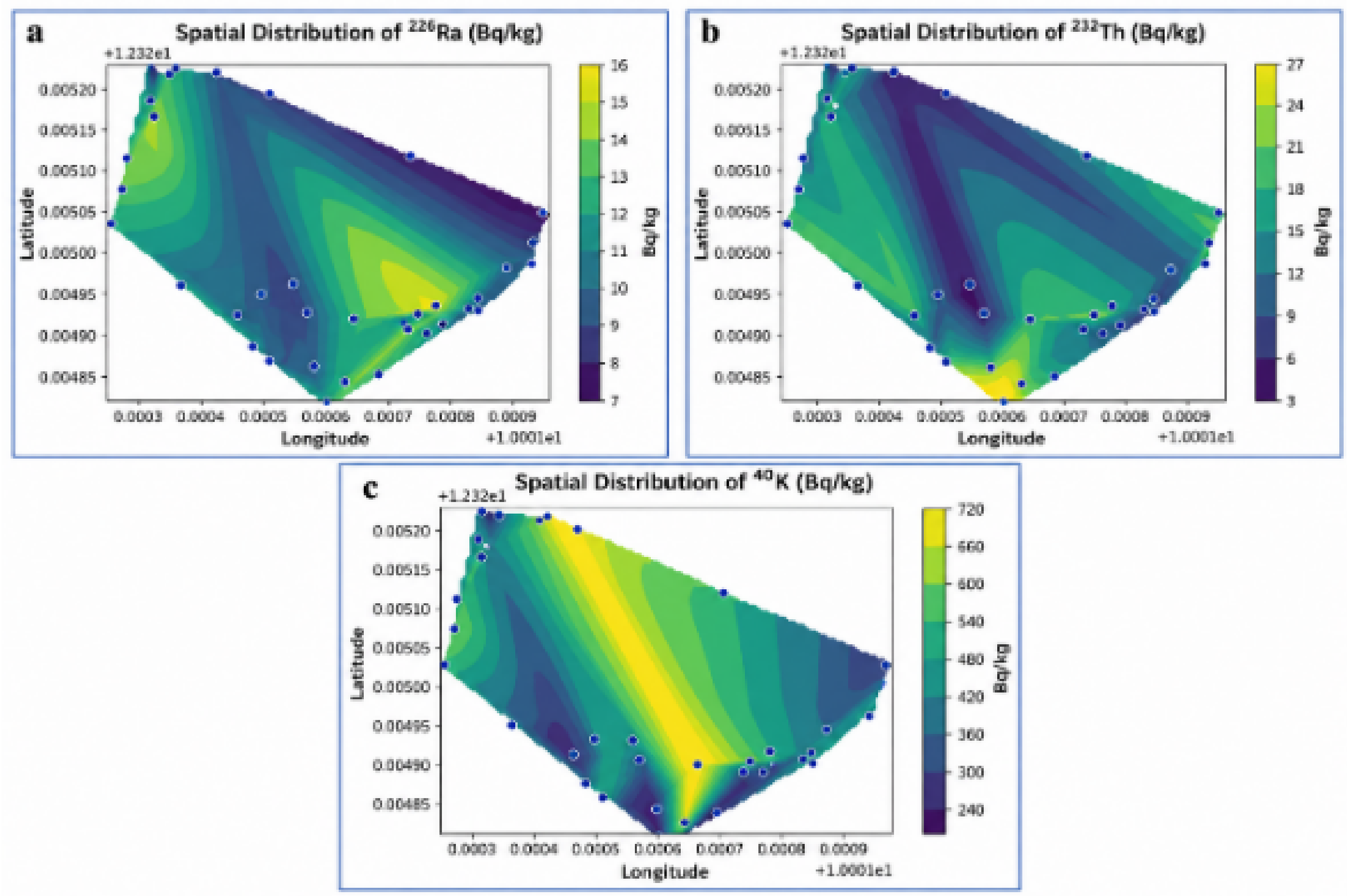


Figure 4: Heatmaps indicating the interpolated spatial distribution of $^{226}$Ra, $^{232}$Th, and $^{40}$K in the study area.

potassium-containing fertilizers commonly applied in rice cultivation, although fertilizer inputs were not directly quantified in this study. The radionuclide enrichment factors in the soil samples, presented here as indicators of relative enhancement of concentration, were computed by dividing the radionuclide concentrations in the study area by those of the control sample. From Table 3, the enrichment factors for $^{226}$Ra (1.09), $^{232}$Th (1.04), and $^{40}$K (1.26) were marginally greater than unity, indicating slight enhancement relative to the control site. The observed enrichment was most pronounced for $^{40}$K, whereas $^{232}$Th exhibited the least deviation from background conditions. Hence, the enrichment factors suggest limited radionuclide accumulation within the flood-affected soils. Further research is required in the area to corroborate the findings of this study.

Figure 4 depicts the interpolated spatial distribution of radionuclide concentrations in the sampled area. Spatial interpolation was

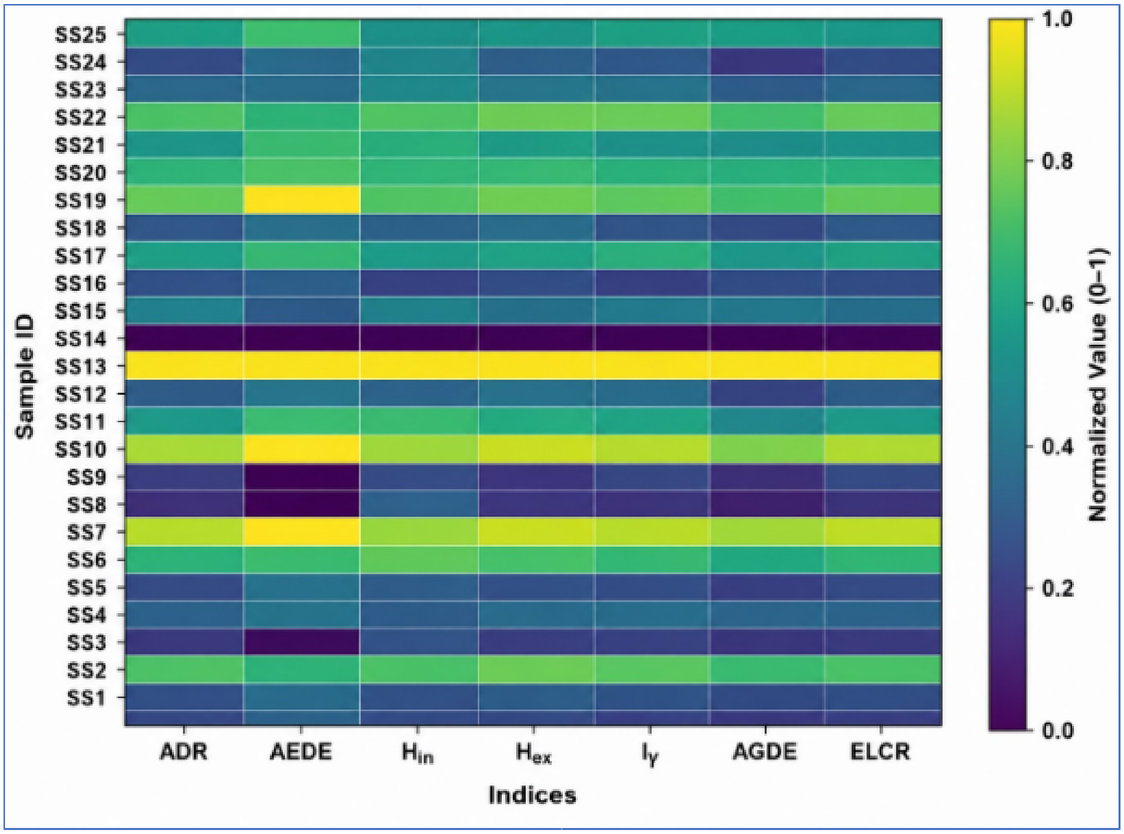


Figure 5: Heatmap of the normalized radiological hazard indices associated with exposure to $^{226}$Ra, $^{232}$Th, and $^{40}$K in soil from the study area.

performed using IDW implemented in Python. The spatial heatmaps of $^{226}$Ra, $^{232}$Th, and $^{40}$K reveal a heterogeneous distribution of radionuclide concentrations across the study area. The interpolated surfaces highlight localized zones of elevated activity, indicating that radionuclide concentrations are not uniformly distributed. This heterogeneous distribution could be attributed to irregular deposition on the surface soil as floodwaters receded. The concentrations obtained in this study were compared with those reported in a similar study conducted in the Mekong Delta region of Vietnam [7]. A similar trend was observed, although the concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K reported by Nguyen *et al.* [7] were slightly higher than those reported in this study. Both studies reported an increase in the concentration of $^{40}$K in the topsoil of rice fields. Compared with another study conducted using topsoil from rice farms in three selected areas in Nigeria [36], the concentrations of natural radionuclides in this study were higher, possibly because the selected area in this study is inundated by perennial floods that may deposit sediments and enrich the radionuclide profile of the topsoil.

Figure 5 presents a heatmap of normalized radiological hazard indices computed to reveal the risk level from direct and continuous exposure to soil around the flooded rice farmlands. The heatmap shows the radiological hazards and highlights both the spatial heterogeneity and the interrelated nature of radiological risk indices. Clear spatial variability and inter-parameter relationships are evident across the sampled locations. Samples SS7, SS10, SS13, and SS19 consistently exhibited higher normalized values across multiple indices, including AED, $H_{in}$, $H_{ex}$, $I_{\gamma}$, and ELCR. This convergence correlates strongly with localized areas of enhanced radionuclide accumulation, which may be associated with sediment deposition following recurrent flooding events in the study area. Although all calculated hazard indices remain below the WAVs reported by UNSCEAR [30] and the safety limits recommended by the ICRP [31], the relative elevation observed in specific samples indicates areas where radiological exposure is comparatively higher. These findings suggest that, while the study area does not pose significant radiological health risks at present, broader monitoring and robust risk assessment would be prudent for comparative purposes.

### *3.3. Radionuclide concentrations in rice and associated radiological risk*

The concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in the collected rice samples were analyzed, and the results are presented in Table 4 and Figure 6.

From Table 4, the mean ± SE concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in rice samples were 2.01 ± 0.15, 2.24 ± 0.17, and 130.22 ± 2.19 Bq/kg, respectively, while the soil-rice transfer factors (TFs) were 0.18, 0.17, and 0.30, respectively. Although there is

Table 4: Summary of activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in the rice samples.

| Quantity | Min | Max | Mean | SD | SE | Mean ± SE | TF | ICRP |
|---|---|---|---|---|---|---|---|---|
| $^{226}$Ra (Bq/kg) | 0.96 | 3.17 | 2.01 | 0.74 | 0.15 | 2.01 ± 0.15 | 0.18 | – |
| $^{232}$Th (Bq/kg) | 0.65 | 3.95 | 2.24 | 0.86 | 0.17 | 2.24 ± 0.17 | 0.17 | – |
| $^{40}$K (Bq/kg) | 117.03 | 169.58 | 130.22 | 10.95 | 2.19 | 130.22 ± 2.19 | 0.30 | – |
| AED (mSv/y) | 0.04 | 0.08 | 0.06 | 0.01 | 0.01 | 0.06 ± 0.01 | – | 0.30 |

TF: transfer factor.

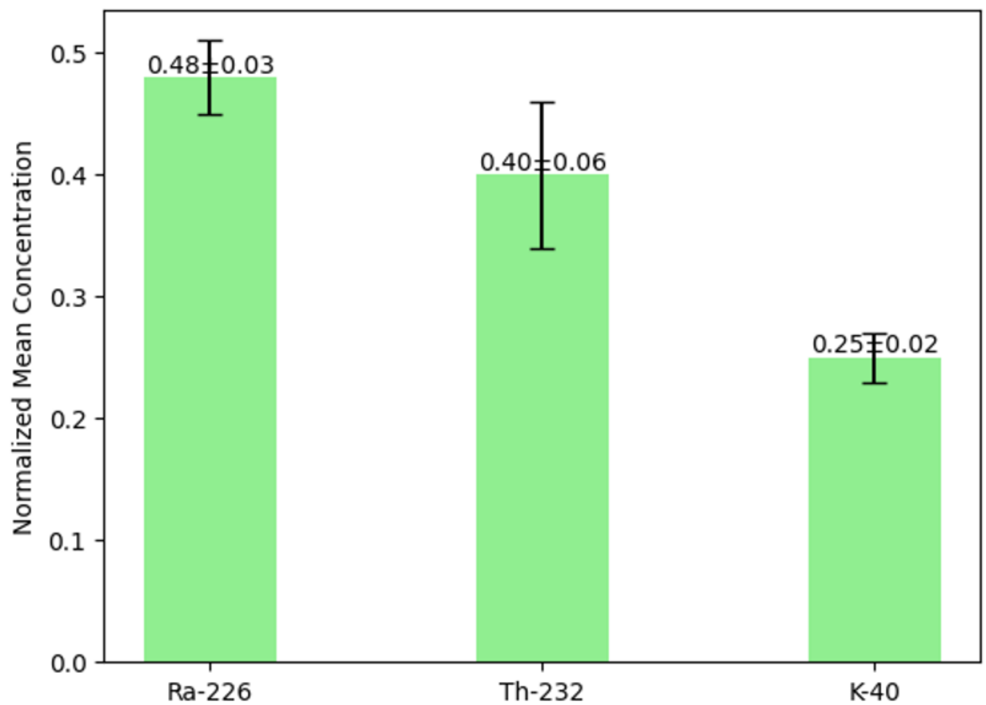


Figure 6: Bar chart of normalized concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in rice samples.

no standard recommended concentration of natural radionuclides in food crops, the annual effective dose depends on the consumption rate in a given population and is the value compared with the global recommended limit for the public [10, 37, 38]. The concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K obtained in this study are consistent with those reported in a similar study conducted in Jigawa State [39]. The slight variations in concentration values can be attributed to inundation in the present study area.

The transfer factors varied in the order $^{40}$K > $^{226}$Ra > $^{232}$Th across all samples, and this variation is consistent with findings reported by Asaduzzaman *et al.* [40], Miyama and Alkali [41], and Hossain *et al.* [42]. The TF values reported in this study were higher than those published by the IAEA for clay soil-to-rice for $^{226}$Ra, $^{232}$Th, and $^{40}$K, averaged at 0.00057, 0.00014, and 0.220, respectively [12, 42]. The mean annual effective dose due to rice consumption was 0.06 ± 0.01 mSv $y^{-1}$, which is lower than the ICRP recommended limit of 0.30 mSv $y^{-1}$ [31]. Similar studies conducted in Nigeria and other parts of the world reported variable data. For example, the annual effective doses due to rice consumption in Bangladesh, Malaysia, and Vietnam, reported by Hossain *et al.* [42], Asaduzzaman *et al.* [40], and Nguyen *et al.* [7] as 0.75, 0.29, and 0.56 mSv $y^{-1}$, respectively, are higher than those reported in this study. This difference can be attributed to higher per capita rice consumption in those locations than in Nigeria [7, 29, 40, 42]. The annual effective doses reported in some studies conducted in Nigeria are consistent with the findings of this study, while others are exceptionally higher. For example, the annual effective doses due to rice consumption in Ebonyi and Jigawa States were reported as 0.06–0.12 and 0.07–0.29 mSv $y^{-1}$, respectively [5, 39]. However, a study conducted by Arije *et al.* [29] in Ondo and Ekiti States reported an annual effective dose of 1.44–1.53 mSv $y^{-1}$, which is exceptionally higher than that found in this study. This discrepancy could be attributed to the fact that the study was conducted in mining-stressed locations, where potential contamination from mine tailings, overburden rocks, and water from mine pits may occur. Although the radiological risk in this study was low, repeated flooding events may alter radionuclide distribution patterns over time. Therefore, continuous monitoring is important to ensure long-term food safety and sustainable rice production in flood-prone agroecosystems.

To simplify the understanding of the concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in rice samples, a bar chart of the normalized mean concentrations with associated standard deviations was plotted (Figure 6). The data were scaled using min–max normalization to allow direct comparison across radionuclides with different concentration magnitudes. The results show that $^{226}$Ra exhibited the

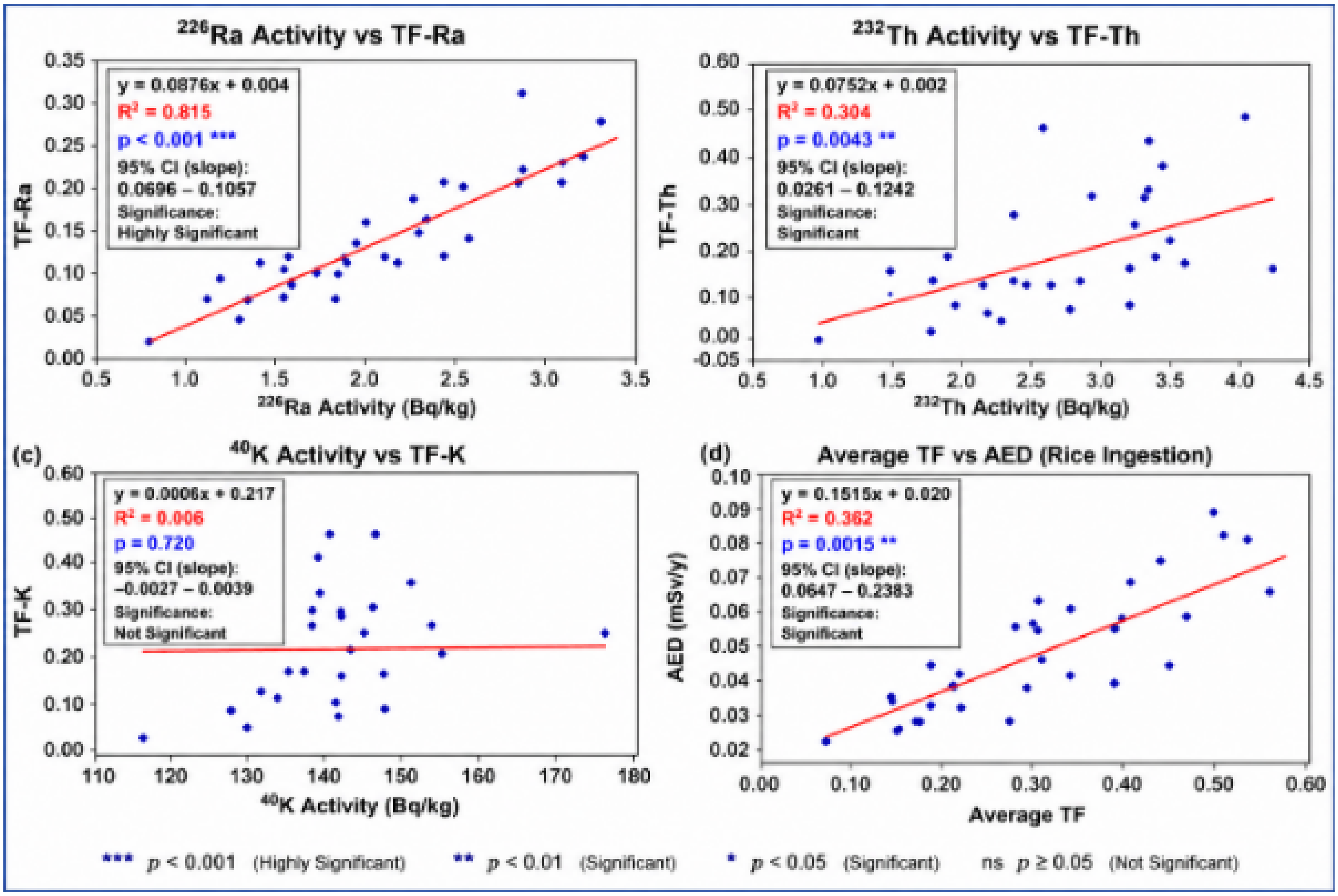


Figure 7: Relationships between soil-to-rice transfer factors and activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K, and the annual effective dose.

highest normalized mean concentration (0.48 ± 0.03), indicating relatively consistent and elevated uptake across the samples, while $^{232}$Th showed a moderate normalized mean (0.40 ± 0.06) with greater variability, indicating heterogeneous distribution influenced by flood-induced changes in bioavailability. In contrast, $^{40}$K showed the lowest normalized mean concentration (0.25 ± 0.02) and minimal variability, reflecting more stable and regulated uptake because it is a macroelement that plays an essential role in plant physiology.

Figure 7 presents regression analyses comparing the activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K with their respective TFs and the annual effective dose computed from the activity concentrations and TFs. The analysis aimed to reveal the relationship between radionuclide activity concentration and its TF and whether the annual effective dose due to rice consumption is linearly related to the average radionuclide TFs. A strong positive correlation was observed between $^{226}$Ra activity concentration and its transfer factor ($R^2 = 0.815$, $p < 0.001$), indicating that rice uptake of $^{226}$Ra is largely controlled by its activity concentration in the soil, with a 95% confidence interval of 0.070–0.106. For $^{232}$Th (Figure 7b), a moderate but statistically significant positive relationship was observed ($R^2 = 0.304$, $p = 0.004$), with a regression slope of 0.075 and a 95% confidence interval of 0.026–0.124. This relationship reflects the limited mobility of $^{232}$Th in the soil-rice system, a condition largely influenced by soil pH, as reported by Ankapong *et al.* [6], Ugbede and Osahon [12], and Hossain *et al.* [42]. In contrast, the activity concentration of $^{40}$K showed no significant correlation with its transfer factor ($R^2 = 0.006$, $p = 0.720$). This finding indicates that the uptake of $^{40}$K by rice plants is governed primarily by biological processes such as nutrient homeostasis rather than by soil concentration. This assertion has also been reported in several studies [40, 42]. Furthermore, a significant positive relationship was observed between the average transfer factor and annual effective dose ($R^2 = 0.362$, $p = 0.0015$), with a 95% confidence interval of 0.065–0.238. This finding indicates that increased radionuclide transfer from soil to rice will likely contribute to elevated radiological exposure through rice consumption.

### *3.4. Multivariate correlation analysis of radionuclide transfer and radiological exposure*

A multivariate analysis exploring relationships among radionuclides in soil and rice grains, transfer factors, and annual effective dose was performed using the Pearson correlation matrix presented as a correlation heatmap in Figure 8. The Pearson correlation

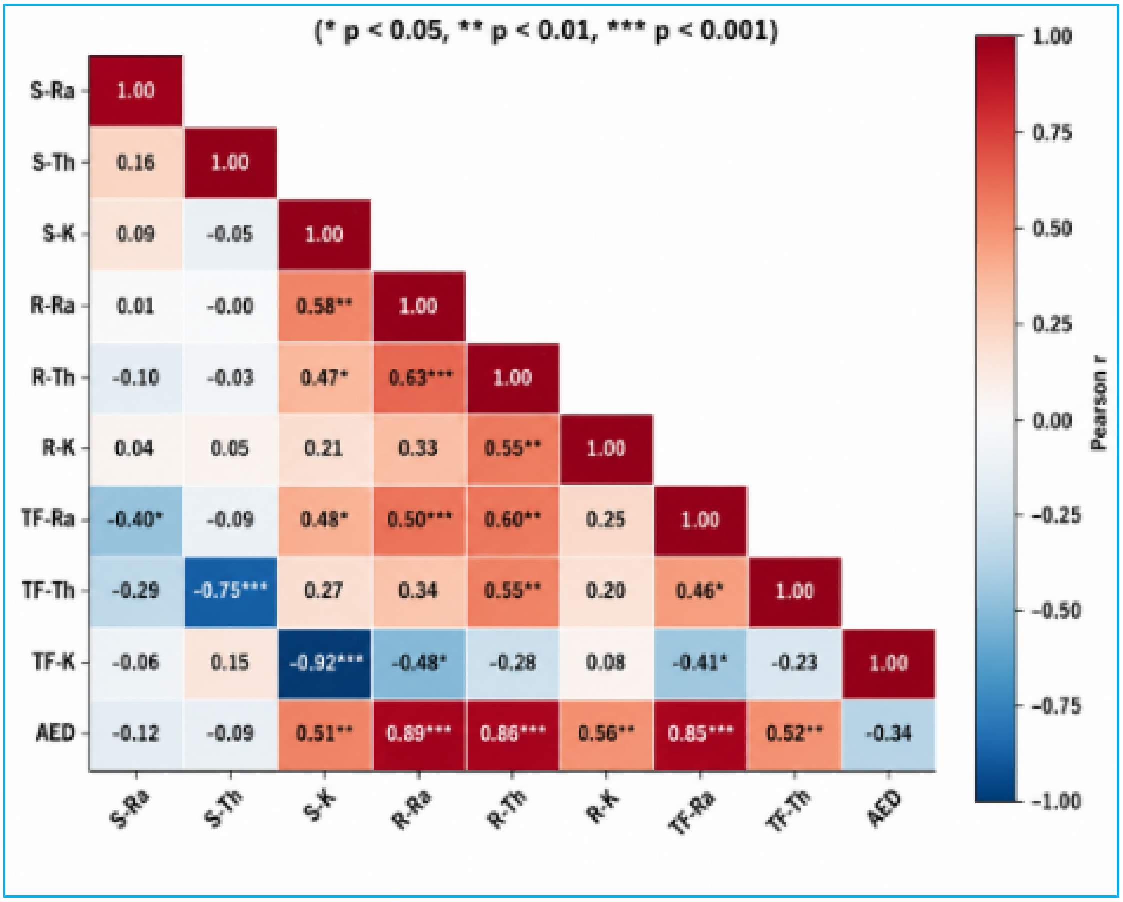


Figure 8: Pearson correlation matrix of radionuclide concentrations in soil and rice, transfer factors, and annual effective dose.

matrix was selected mainly for its simple presentation and convenience.

In Figure 8, the radionuclide activity concentrations in soil are represented by S-Ra, S-Th, and S-K for $^{226}$Ra, $^{232}$Th, and $^{40}$K, respectively, and by R-Ra, R-Th, and R-K for the same radionuclides in rice grains. The soil-to-rice transfer factors are presented as TF-Ra, TF-Th, and TF-K for the three radionuclides, respectively. Correlation coefficients ($r$) are displayed within the cells, while asterisks indicate statistical significance ($p < 0.05$, $p < 0.01$, and $p < 0.001$). Positive correlations are represented by red shades and negative correlations by blue shades, with color intensity reflecting the strength of association.

The analysis revealed a very strong positive correlation between the concentration of $^{226}$Ra in rice and TF-Ra ($r = 0.90$, $p < 0.001$), indicating that variations in $^{226}$Ra accumulation in rice were strongly influenced by transfer efficiency from soil. Similarly, strong positive correlations were observed between AED and $^{226}$Ra in rice ($r = 0.89$, $p < 0.001$), $^{232}$Th in rice ($r = 0.86$, $p < 0.001$), and TF-Ra ($r = 0.85$, $p < 0.001$), demonstrating that radionuclide uptake by rice is a major determinant of radiation exposure through rice consumption. A significant positive relationship was also observed between $^{232}$Th in rice and TF-Ra ($r = 0.60$, $p < 0.01$), suggesting similarities in the environmental factors influencing the uptake of these radionuclides.

In contrast, TF-K exhibited a strong negative correlation with the concentration of $^{40}$K in soil ($r = -0.92$, $p < 0.001$), indicating that potassium transfer to rice is not solely governed by soil concentration but is likely regulated by physiological nutrient-uptake mechanisms. Likewise, TF-Th showed a strong negative correlation with $^{232}$Th concentration in soil ($r = -0.75$, $p < 0.001$), suggesting a likely reduction in transfer efficiency at slightly elevated soil-thorium levels. Therefore, this correlation analysis corroborates the regression results and highlights the need for further robust investigation to support these findings.

### 3.5. Food safety implications

The findings of this study corroborate the fact that radionuclides present in soils are transferred to edible plant tissues, thereby constituting a potential pathway for human exposure. The results indicate that rice produced within the study area does not currently pose a significant radiological health risk to consumers. However, given the recurrent flooding events experienced within the Hadejia floodplain, stakeholders in environmental and food safety should establish a continued monitoring program for radionuclide levels in agricultural soils and food crops to ensure the long-term safety of locally produced rice amid climate-related hydrological variations.

## 4. Conclusion

This study assessed the radionuclides concentration in topsoil samples and rice grains collected from farmlands that are inundated by perennial flooding in Hadejia, Jigawa State, Nigeria. The concentration of natural radionuclides namely; $^{226}$Ra, $^{232}$Th, and $^{40}$K in soil and rice samples were found to be lower than their World's average values, indicating less radiological risk associated with study area. However, variations in the concentrations of the radionuclides with sample locations revealed some hotspots and underscore the heterogeneous nature of the distribution of the natural radionuclides in the topsoil, which was largely attributed to the sediment deposition following recurrent flooding events in the study area. Radiological hazard indices showed a similar pattern with values well below the recommended limits by UNSCAER and ICRP. The soil-rice transfer factors were found to vary in the order $^{40}K >^{226} Ra >^{232} Th$ in all the samples analyzed. The values of the transfer factors were found to be higher than those published by the IAEA for clay soil-to-rice, and consistent with those reported in several literatures. While the overall findings of this study did not highlight any significant radiological health risk to the members of public in the study area, it is however considered to be a valuable source of baseline data and it is further recommended that an expanded spaciotemporal radiological monitoring and robust risk assessment should be carried out in this study location to corroborate the findings of this study or otherwise.

## Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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## Declaration of competing interest

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

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