IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 18, Issue 5 Ser. 1 (Sep. – Oct. 2026), PP 07-18
www.iosrjournals.org

Public Health Risks of Soil Radionuclide Contamination from Scrap Metal Yards and Flooding in Maiduguri, Nigeria

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Abstract: *Naturally occurring radionuclides such as ^{40}K, ^{226}Ra and ^{232}Th are present in soils and sediments, with concentrations influenced by geology and human activities. Scrap metals, which may contain orphan radioactive sources, and flood events, which redistribute contaminated sediments, represent potential environmental pathways of exposure. This study evaluates the concentrations of ^{40}K, ^{226}Ra and ^{232}Th in soils from scrap yards and flood-affected areas in Maiduguri, Nigeria, to determine associated radiological risks to the public. A total of 32 soil samples were collected and analyzed using NaI(Tl) gamma spectrometry. Activity concentrations were quantified, and radiological hazard indices—including absorbed dose rate, D_γ, annual effective dose, A_E, radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), internal hazard index (H_{in}), and excess lifetime cancer risk, ELCR—were calculated following UNSCEAR and ICRP guidelines. Results were compared with recommended safety limits. The results showed the average concentrations of 47.55 Bq/kg for ^{232}Th, 35.49 Bq/kg for ^{226}Ra, and 66.81 Bq/kg for ^{40}K, which are comparable to the UNSCEAR reference values of 30 Bq/kg for ^{232}Th, 35 Bq/kg for ^{226}Ra, and 400 Bq/kg for ^{40}K. While the mean concentrations remained within recommended safety limits, there were instances of elevated ^{232}Th levels exceeding UNSCEAR benchmarks in particular hotspots. Furthermore, the mean R_{aeq} calculated was 108.49 Bq/kg, which is below the established safety limit of 370 Bq/kg. The average A_E was measured at 0.03032 mSv/year, falling below the ICRP public dose limit of 1 mSv/year. However, the estimated ELCR values ($0.576–1.599 \times 10^{-4}$; average 1.059×10^{-4}) lie within the global acceptable risk range ($10^{-6} – 10^{-3}$) recommended by ICRP and USEPA, though the upper value indicates potential localized risks requiring targeted monitoring. The findings underscore the need for regulatory monitoring of scrapyards and flood-prone areas in Maiduguri to prevent chronic exposure risks.*

Keywords: *Radionuclides, Scrap metals, Flooding, Gamma spectrometry, Radiological risk, Maiduguri.*

Date of Submission: 28-08-2026 Date of Acceptance: 07-09-2026

I. Introduction

The growing demand for metal recycling and the expansion of informal scrap metal activities in many urban centers have led to increased concerns about environmental safety and public health. In cities such as Maiduguri, North-Eastern Nigeria, scrap metal yards often operate without strict regulatory oversight, creating potential hotspots for environmental contamination from orphan radioactive sources—uncontrolled or lost radioactive materials embedded in industrial or medical equipment (IAEA, 2007). The improper handling and disposal of such sources can result in the release of radionuclides into the environment, contaminating soils and contributing to external and internal radiation exposures among both workers and nearby residents (Ogboeli et al., 2025; International Journal of Science for Global Sustainability, 2023; Ohimain, 2013; Ogwueleka et al., 2021). Simultaneously, Maiduguri and its environs experience seasonal flooding, which may exacerbate the spread and redistribution of contaminants in soil. Floodwaters can mobilize and deposit radionuclide-laden sediments across wider areas, especially in low-lying zones around scrap metal yards. Naturally occurring radionuclides such as potassium-40 (^{40}K), radium-226 (^{226}Ra), and thorium-232 (^{232}Th) are commonly found in soils; however, their concentrations can increase significantly due to anthropogenic activities (Hassan et al. 2020; Uba, 2024; Umar et al., 2025; Hassan et al., 2025). Elevated exposure to these radionuclides may pose chronic health risks, including increased cancer incidence, cellular mutations, and organ-specific radiation damage (WHO, 2005).

Naturally occurring radioactive materials (NORMs) such as ^{40}K, ^{226}Ra, and ^{232}Th are ubiquitous in the environment and originate primarily from the Earth's crust. These radionuclides are present in varying concentrations in soils, rocks, and sediments, and contribute significantly to background gamma radiation levels. Their presence and concentration in the environment are influenced by both geological formations and anthropogenic activities such as mining, waste disposal, and scrap metal recycling (Popoola et al., 2025). In many

developing countries, including Nigeria, inadequate control over waste disposal and informal handling of scrap metals has raised concerns about environmental contamination and public exposure to ionizing radiation. Orphan radioactive sources—radioactive materials that are not under regulatory control—can be inadvertently incorporated into scrap metals and distributed widely through informal recycling networks (IAEA, 2005). When such materials are present in scrap yards or are deposited into the environment due to flooding or improper waste handling, they may contribute to elevated levels of NORMs in the soil (Oni et. al., 2011; Irunkwor et al., 2022).

Maiduguri, the capital of Borno State in North-Eastern Nigeria, is a fast-growing urban center experiencing increased scrap metal activities and recurrent seasonal flooding. These factors heighten the risk of environmental contamination through the redistribution of soil-bound radionuclides and the potential introduction of orphan radioactive sources (Ohakwere-Eze et al., 2024; Algattawi et al., 2019). Floodwaters may transport contaminants from informal scrap yards to residential or agricultural zones, thereby increasing the potential for human exposure through external radiation, inhalation of dust, or ingestion of radionuclide-contaminated food and water (Mbonu et al., 2025; Ibigbami et al., 2025).

Exposure to ionizing radiation from ^{226}Ra and ^{232}Th is particularly concerning due to their long half-lives and the production of highly radiotoxic decay products, such as ^{222}Rn. These decay chains pose both internal and external radiation hazards, which can lead to long-term health effects including lung cancer, organ damage, and genetic mutations if exposure levels exceed recommended safety limits (ICRP, 1991; WHO, 2017). Assessing the concentration of these radionuclides in soils helps estimate the radiological dose individuals may receive and informs risk management strategies for environmental health (Dione et al., 2025). Several studies have reported on natural radioactivity levels in Nigerian soils; however, there is limited localized data for Maiduguri, particularly in areas affected by scrap metal activities and seasonal flooding (Abdulmalik et al., 2024). Understanding the spatial distribution and intensity of radionuclide contamination in such areas is critical for developing evidence-based policies and interventions. It also helps in aligning with international safety standards such as those established by the UNSCEAR and the International Commission on Radiological Protection (ICRP).

This study, therefore, seeks to evaluate the environmental and health risks posed by radionuclide contamination in scrap metal–impacted and flood-affected soils of Maiduguri. Specifically, the research will determine the activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th, estimate radiological dose parameters such as absorbed gamma dose rate and annual effective dose, and assess hazard indices in accordance with international radiological protection standards. The findings are expected to support evidence-based recommendations for environmental monitoring, public health safeguards, and radiation risk management in vulnerable urban communities.

II. Methodology

2.1 Study Area

This study was conducted in Maiduguri and its environs in Borno State, Nigeria. The region is characterized by the presence of informal scrap metal yards and seasonal flooding, both of which contribute to potential environmental contamination. Sites were selected based on evidence of scrap metal activities, history of flooding, and accessibility. Geographic coordinates for each sampling point were recorded using a handheld GPS device for spatial reference and analysis. The study was conducted in Maiduguri, the capital of Borno State, which is situated in northeastern Nigeria at an elevation of 354 meters above sea level and at latitude 11.85°N and longitude 13.08°E. The neighboring local government areas of Jere, Magumeri, Konduga, and Mafa were also included in the probe. A semi-arid climate with annual rainfall between 300 and 800 *mm* and mean temperatures between 25 and 32 °C—which frequently rise above 40 °C during the hottest part of the dry season—defines the area, which is part of the Sudano-Sahelian ecological zone. Seasonal flooding has become more prevalent in Maiduguri and the adjacent villages, which may lead to the contamination of surface soils and groundwater and promote the dispersal of waste metals. Thirty-two (32) sampling locations were carefully chosen for this study in order to represent important scrap yards and areas that are vulnerable to flooding in Maiduguri and the surrounding area. Table 1 lists all of the sampling sites' geographic coordinates, and Figure 1 shows how they are distributed spatially.

Table 1: The soil samples are from some Local Government Areas of Borno State, Nigeria

Sample ID	Sample Site	Latitude	Longitude
SL00	Njimtilo	11.862778	13.032222
SL01	Opp. BOSU	11.845000	13.031944
SL02	Gambari	11.829444	13.060833
SL03	Gambari II	11.826944	13.051111
SL04	Custom Area	11.850278	13.179444
SL05	Custom Mashamari	11.844444	13.178056

SL06	Simari	11.849300	13.195300
SL07	Gidan Dambe London	11.845556	13.180278
SL08	Moramti	11.835556	13.083889
SL09	Ayafe Junction Old Airport	11.840000	13.088056
SL10	Abba Street Gwange	11.833611	13.163611
SL11	Gwange Layin Gida Kifi	11.825278	13.162222
SL12	Gwange Barrack	11.808889	13.166944
SL13	Zanna Bukar Dipchari St.	11.828056	13.166111
SL14	Usman Tobacco Samaila Idris St.	11.843056	13.159722
SL15	Layin Kantin Yara	11.829167	13.177222
SL16	Gwange III Ward	11.826667	13.151667
SL17	Gwange II Ward Layin City Buba	11.828611	13.237500
SL18	Goni Kachallari	11.863056	13.207500
SL19	Gwange II Ward Layin Makaranta	11.833056	13.167222
SL20	Gwange I Ward Maijir St. Pom-Pom Zafi	11.834444	13.174722
SL21	Kasuwan Shanu	11.858056	13.174444
SL22	Gamboru	11.850278	13.172222
SL23	Gamboru Liberty	11.850278	13.172222
SL24	Post Office Bola	11.837222	13.147500
SL25	Baga Road Mechanical Workshop	11.863056	13.133611
SL26	Baga Road	11.863889	13.131667
SL27	West-End	11.853056	13.142778
SL28	Lamisula	11.855000	13.148611
SL29	Abbaganaram	11.857222	13.152500
SL30	Kajari	12.113611	12.166111
SL31	Opp. Vocational Center	12.110833	12.828333

2.2 Soil Sample Collection and Preparation

Soil samples were collected from 32 locations across Maiduguri and its environs, focusing on areas affected by scrap metal activities and seasonal flooding. Sampling points were geo-referenced, and approximately 1 *kg* of surface soil (0–10 *cm* depth) was obtained at each location using a stainless-steel auger to minimize contamination and clean plastic tools to avoid cross-contamination.

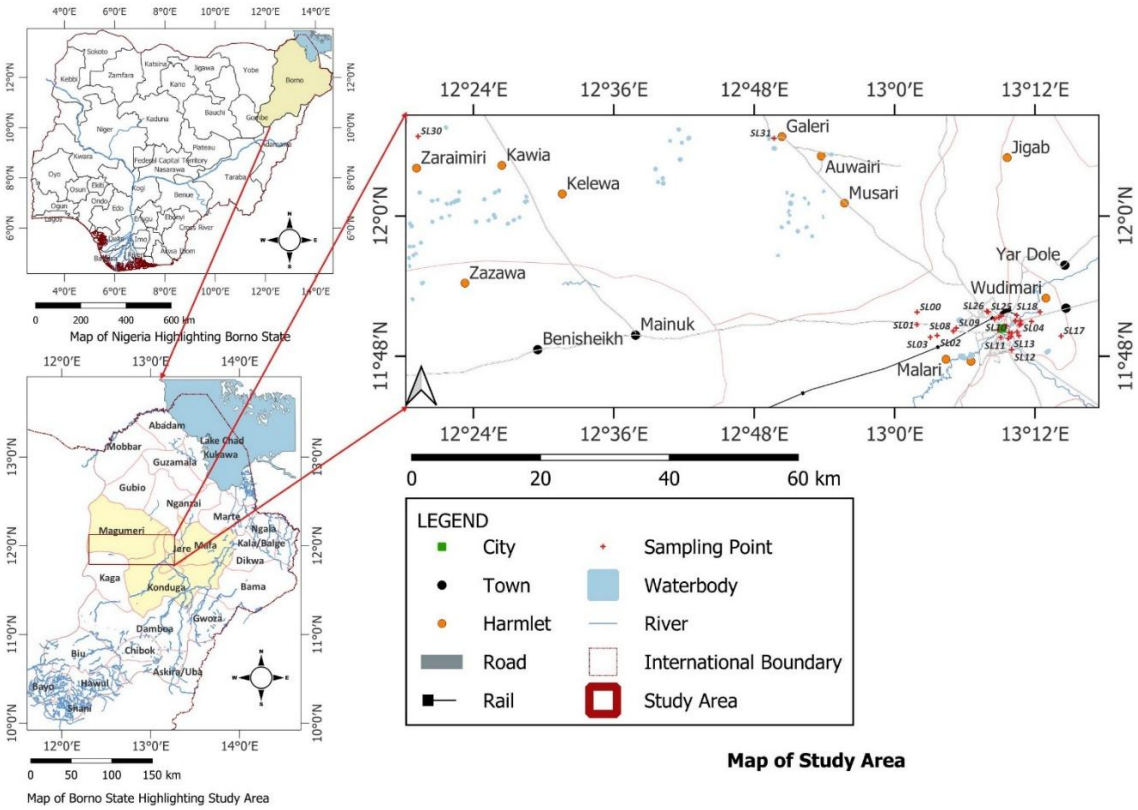

Figure 1. Geographical map of Maiduguri showing the sampling locations

The samples were air-dried for 72 *hours*, pulverized, crushed, homogenized, and sieved through a 2 *mm* mesh. Each sample (approximately 500 *g*) was then sealed in 1-liter Marinelli beakers with parafilm to prevent radon escape and stored for at least 28 *days* to allow for secular equilibrium between ^{226}Ra and its short-lived progeny (^{214}Pb, ^{214}Bi) before radiometric analysis.

2.3 Gamma-Ray Spectrometry

Using a 3" × 3" *NaI(Tl)* gamma-ray spectrometer, the activity concentrations of naturally occurring radionuclides (^{40}K, ^{226}Ra, and ^{232}Th) were measured. For spectral acquisition and analysis, the detector was connected to a 1,024-channel multichannel analyzer (MCA). The detection assembly was placed inside a 10 *cm* thick lead shield lined with copper and cadmium sheets to reduce background interference and effectively reduce ambient and scattered radiation. The International Atomic Energy Agency (IAEA) provided standard reference materials that were used to calibrate the spectrometer for energy and efficiency. During the course of the measurement campaign, calibration stability was frequently checked. The prepared samples were counted for 36,000 *seconds* (10 *hours*) in a 1 *L* Marinelli beaker in order to minimize statistical uncertainty and obtain accurate counting data. An empty Marinelli beaker was used to measure background radiation under the same circumstances. To account for cosmic and environmental effects, the background spectrum was deducted from each sample spectrum. For every radionuclide, the specific activity concentration C (in $Bq{\cdot}kg^{-1}$) was calculated using the following relation:

$$C = \frac{N}{\varepsilon P_\gamma M t}$$

where N is the net count under the photopeak, ε is the detector efficiency at the specific gamma energy, $P\gamma$ is the gamma emission probability, M is the mass of the sample (kg), and t is the counting time (s). The International Atomic Energy Agency's (IAEA, 1989) guidelines were adhered to in the analysis and computation processes.

2.4 Energy and Efficiency Calibration

The system was calibrated using standard gamma-ray sources (^{137}Cs, ^{60}Co, ^{152}Eu) covering the energy range of 200–2000 *keV*. The calibration curve was generated by plotting channel number against gamma-ray energy. Efficiency calibration was performed by measuring standard reference materials (IAEA-RGU-1, IAEA-RGTh-1, and IAEA-KCl) in identical geometry to soil samples. The absolute efficiency, ε for each energy peak was obtained by,

$$\varepsilon(E) = \frac{N}{AI_\gamma t}$$

where *N* is the net peak area, A is the source activity, Bq, I_γ is the gamma emission probability, and *t* is the live time, *s*. The efficiencies of the radionuclide peaks in the samples were then ascertained by fitting the resulting efficiency–energy data with a polynomial regression function to produce a smooth calibration curve. The calibration results were frequently validated to assure system stability and dependability.

2.5 Identification of Radionuclides

Radionuclides were identified using their characteristic gamma peaks: ^{226}Ra from the 351 *keV* (^{214}Pb) and 609 *keV* (^{214}Bi) peaks, ^{232}Th from the 583 *keV* (^{208}Tl) and 911 *keV* (^{228}Ac) peaks, ^{40}K from the 1460 *keV* peak. The minimum detectable activity (MDA) was calculated using,

$$MDA = \frac{2.71+4.65\sqrt{B}}{\varepsilon I_\gamma t m}$$

where *B* is the background count in the region of interest, ε is the detector efficiency, I_γ is the gamma emission probability, *t* is the counting time, and m is the sample mass (kg). MDAs were typically ~5 *Bq/kg* for ^{226}Ra, 7 *Bq/kg* for ^{232}Th, and 10 *Bq/kg* for ^{40}K under the present conditions.

2.6 Quality Assurance and Uncertainty Analysis

Strict quality assurance and quality control (QA/QC) protocols were used throughout the analytical process to guarantee the gamma spectrometric measurements' correctness, precision, and dependability. To determine the system's energy and efficiency response, the *NaI*(*Tl*) detector was calibrated using IAEA-standard reference materials with known activity concentrations. Plotting the observed efficiency values against matching gamma energies allowed for the creation of efficiency calibration curves, and the correctness of the calibration was confirmed when the correlation coefficients (R^2) were found to be more than 0.99. To ensure uniformity, every sample was examined using the same geometry and counting parameters. All obtained spectra were adjusted for background counts, and background radiation levels were routinely checked to take environmental variations into consideration. To evaluate reproducibility, duplicate measurements were made on randomly chosen samples; the findings indicated variances of less than 5%. A ~ ^{137}Cs reference source was regularly used to verify the stability of the spectrometric apparatus. The total uncertainty in the measured activity concentration (ΔC) was calculated

by propagating the individual errors associated with efficiency calibration, emission probabilities, and counting statistics. The following was the total of the uncertainties:

$$\frac{\Delta C}{C} = \sqrt{\left(\frac{\Delta N}{N}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2 + \left(\frac{\Delta P_\gamma}{P_\gamma}\right)^2}$$

where the corresponding uncertainties in net count, efficiency, and emission probability are denoted by ΔN, $\Delta \varepsilon$, and ΔP_γ. As advised by the IAEA (1989) and UNSCEAR (2020), the overall propagated uncertainty in activity determination was generally within ±10%, which is acceptable for environmental gamma spectrometry measurements.

2.7 Radiological Risk Assessment

A series of well-known radiological risk assessment models were used to estimate the radiological risks associated with naturally occurring radionuclides (^{40}K, ^{226}Ra, and ^{232}Th) in the environmental samples that were gathered. The United Nations Scientific Committee on the Effects of Atomic Radiation and other credible organizations endorse these models (Abdulmalik et al., 2024). The techniques use measured activity concentrations to estimate exposures, both internal and external.

2.7.1 Absorbed Gamma Dose Rate (D_γ)

The following formula was used to get the absorbed gamma dose rate in air at a height of one meter above ground (Wong, 1999; Ajayi, 2008; Śródka, 2012; Ojo & Gbadegesin, 2013; Orosun et al., 2016; Ibraheem et al., 2018):

$$D_\gamma(nGy \cdot h^{-1}) = C_{Ra}A_{Ra} + C_{Th}A_{Th} + C_K A_K \quad (1)$$

The activity concentrations of ^{226}U, ^{232}Th and ^{40}K (in *Bq/kg*) are denoted by A_{Ra}, and A_{Th}, A_K; the dose conversion coefficients (in *nGy/h* per *Bq/kg*) are represented by C_{Ra} = 0.427, C_{Th} = 0.662, and C_K = 0.0432; these values were taken from UNSCEAR (2000). The gamma dose rate directly related to the terrestrial radionuclides in the samples is estimated by this model.

2.7.2 Annual Effective Dose Rate (A_E)

Equation (2) was used to determine the annual effective dose (A_E) from exposure to outdoor gamma radiation.

$$A_E(\mu Sv\ y^{-1}) = D\gamma \times T \times O \times Q \times 10^{-3} \quad (2)$$

The outdoor occupancy factor for rural settings is O = 0.3 (based on 365.25 *days per year*), the dose conversion factor from absorbed dose in air to effective dose is Q = 0.7 *Sv/Gy*, and 10^{-3} converts from *nSv* to *μSv*. For rural populations like those in the study area, an outdoor occupancy factor of 0.3 (approximately 8 *hours* daily exposure) was adopted based on lifestyle and climate considerations (Ajekiigbe et al., 2017; Rahman et al., 2018; Najam et al., 2016; Karim et al., 2016). Thus, the annual effective dose is given by

$$A_E = D_\gamma \times 8766 \times 0.7 \times 0.3 \times 10^{-3} \quad (3)$$

where D_γ is defined by equation (1). This equation accounts for time spent outdoors and converts absorbed dose into effective dose for radiological protection purposes.

2.7.3 The Excess Lifetime Cancer Risk

The Excess Lifetime Cancer Risk (ELCR) is used to estimate the probability of developing cancer over a lifetime due to exposure to ionizing radiation. It is derived as

$$ELCR = A_E \times DL \times RF \quad (4)$$

where AE is the Annual Effective Dose Equivalent (*Sv/y*), *DL* is the duration of life (years), often taken as 70 *years* (average human lifespan), and *RF* is the Risk factor for stochastic effects (Sv^{-1}), recommended by ICRP as 0.05 for the general public (Gyuk et al., 2025).

2.7.4 Radium Equivalent Activity (Ra_{eq})

The radium equivalent activity (R_{aeq}) was calculated using (5) in order to represent the gamma output from a mixture of radionuclides with a single index (Yinusa et al., 2017; Abu-Samreh et al., 2014).

$$Ra_{eq}(Bq \cdot kg^{-1}) = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (5)$$

The hazard contributions of ^{40}K and ^{232}Th are normalized to that of ^{226}Ra in this equation. The public exposure limit of 1 *mSv/year* is equivalent to a R_{aeq} value ≤ 370 *Bq/kg* (Najam et al., 2016).

2.7.5 Gamma representative index (I_γ)

A screening method for assessing possible radiological danger from gamma-emitting radionuclides is the gamma representative index, I_γ (Rahman et al., 2018):

$$I_\gamma = \frac{A_K}{1500} + \frac{A_{Th}}{100} + \frac{A_{Ra}}{150} \quad (6)$$

where each radionuclide's maximum allowable activity concentrations (*Bq/kg*) are represented by the denominators. A gamma dose that falls within the acceptable exposure limits for the general population is indicated by an index value of $I_\gamma \leq 1$ (Assefa & Bhardwaj, 2019; Kolo et al., 2016).

2.7.6 External Hazard Indices (H_{ex})

To evaluate the possibility of exposure to external radiation, the external hazard index (H_{ex}) was computed:

$$H_{ex} = \frac{A_K}{4810} + \frac{A_{Th}}{259} + \frac{A_{Ra}}{370} \quad (7)$$

H_{ex} should not be more than unity for radiological safety, guaranteeing that the annual external exposure stays below 1 *mSv* (Yinusa et al., 2017; Harikrishnan et al., 2017).

2.7.7 Internal Hazard Indices (H_{in})

The possible internal exposure by the internal hazard index, H_{in} given by equation (8).

$$H_{in} = \frac{A_K}{4810} + \frac{A_{Th}}{259} + \frac{A_{Ra}}{185} \quad (8)$$

An H_{in} value ≤ 1 guarantees that internal exposures, particularly through inhalation pathways, do not present serious health hazards (El-Araby et al., 2021; Sombo et al., 2021).

2.8 Data Analysis

Descriptive statistics such as mean, minimum, maximum, and standard deviation were used to summarize the activity concentrations and radiological indices. The results were compared with global average values and safety limits set by UNSCEAR (2000) and WHO, (2004). Where applicable, spatial analysis was conducted using GIS tools to identify contamination hotspots and their potential impact zones.

III.Results

The soil samples from Maiduguri and the surrounding area had a mean content of 66.81 *Bq/kg* of ^{40}K), with a range of 32.45 to 99.84 *Bq/kg*. This average is far below than the 400 *Bq/kg* global reference value that UNSCEAR (2000) recommends. This discrepancy suggests that, in comparison to other radionuclides, ^{40}K contributes very little to the total gamma dose in the research area and has little radiological importance in environmental risk evaluations. A number of factors could be responsible for the unusually low levels of ^{40}K, such as the local soil's mineralogical makeup, the lack of potassium-rich rock formations, or potential dilution effects from floodwaters and human activities like urbanization and the deposition of scrap materials. These results support the impact of regional geochemistry and land use on radionuclide dispersion, as they are in line with other studies carried out in Nigeria that found below-average ^{40}K values.

The ^{226}Ra activity concentrations in the research region ranged from 12.05 to 59.43 *Bq/kg*, with a mean of 35.49 *Bq/kg*. This average indicates a relatively natural background level of ^{226}Ra in the area, as it roughly matches the worldwide reference value of 35 *Bq/kg* published by UNSCEAR (2000). Nevertheless, several samples showed higher concentrations than the global average, especially SL31 and SL20, suggesting localized abnormalities that were probably brought on by human activity. The increased levels seen in some areas could be the consequence of residual industrial pollutants commonly found in scrap metal yards or contamination by orphan radioactive sources. As a result of the degradation of ^{226}Ra to ^{222}Rn, a radioactive gas that can cause lung cancer when inhaled, these results underscore the necessity of public health monitoring and control. It is crucial to put in place suitable radiation protection measures in the impacted areas because prolonged exposure to such high concentrations, especially in residential or commercial settings, could result in considerable internal radiation doses.

The mean concentration of ^{232}Th in the research area is 47.55 *Bq/kg*, with a range of 22.81 to 83.24 *Bq/kg*. There is a noticeable thorium enrichment in the local soils, as this average is far greater than the UNSCEAR (2000) suggested global reference level of 30 *Bq/kg*. Samples SL23, SL24, SL28, SL29, and SL31 had especially high values that were more than twice as high as the global average. These elevated levels indicate localized accumulation that may be related to geogenic impacts or the deposition of thorium-containing minerals from scrap metal activities. Elevated concentrations in surface soils present a potential threat through increased external exposure, particularly in locations with protracted human presence, due to the relatively large gamma radiation emissions associated with ^{232}Th decay products. Since this kind of exposure can eventually lead to cumulative radiation doses, it's critical to evaluate land use in these areas and take mitigating measures into account. These results highlight the significance of public health interventions and environmental monitoring in thorium-contaminated areas, especially in locations where residential developments or informal recycling are located adjacent to contaminated soils.

In the study area, the average absorbed gamma dose rate (D_γ) was 49.33 *nGy/h*, with a range of 26.82 to 74.46 *nGy/h*. This mean figure indicates moderate external exposure in most places, as it is lower than the UNSCEAR (2000) recommended global average of 59 *nGy/h*. However, values far above this threshold were reported at some sites, including SL23, SL24, SL29, and SL31, suggesting localized radiation amplification most

likely caused by flood redistribution or radioactive accumulation from scrap metal. With a mean of 30.26 $\mu Sv/y$, the estimated A_E ranged from 16.46 to 45.69 $\mu Sv/y$. This indicates that there is no imminent health risk from gamma radiation in the soils examined because it is much below the 1,000 $\mu Sv/y$ (1 mSv/y) public exposure limit established by the ICRP and WHO. However, the high A_E values in some samples point to the necessity of routine monitoring, particularly in places where people have been present for extended periods of time.

The Excess Lifetime Cancer Risk (ELCR) values for soils in Maiduguri range from 0.576×10^{-4} to 1.599×10^{-4}, averaging 1.059×10^{-4}, which is within the globally acceptable risk range of 10^{-6} to 10^{-3} as recommended by the International Commission on Radiological Protection (ICRP, 1991) and the United States Environmental Protection Agency (USEPA). This suggests that the overall radiological risk from soil exposure in Maiduguri does not present a significant long-term public health threat according to international standards. However, the highest ELCR value of 1.599×10^{-4} indicates certain localized areas of concern, particularly near scrapyards and flood-deposited sediment zones, likely influenced by human activities such as the handling of orphan radioactive sources and the redistribution of radionuclides due to flooding. These hotspots could elevate the risk of cancers among nearby populations. Thus, while the average ELCR values indicate that the radiological risks are generally manageable, the detection of localized higher risks underscores the need for targeted environmental monitoring and regulatory action. Enhanced surveillance of scrapyard areas and initiatives to raise public awareness, along with improved waste management practices, are crucial for mitigating potential radiological hazards and protecting vulnerable communities in the region.

The average Ra_{eq} was 108.49 Bq/kg, with a range of 57.85 to 163.59 Bq/kg. All measured values fell within the UNSCEAR-established safety threshold of 370 Bq/kg, demonstrating adherence to radiological safety regulations for general land use and building materials. With average values of 0.28 and 0.37, respectively, the H_{ex} and H_{in} were both far below the allowable limit of 1. This implies that the radiation hazards from these soils, both internal and external, are currently below acceptable bounds. A couple sites (SL24 and SL31) have a mean value of 1.0 for I_γ, a rapid screening tool for radiological risk. An $I_\gamma > 1$ suggests that the gamma dose may be higher than the advised public exposure limit, necessitating additional research or potential action in those particular areas. While the majority of sites are under globally recognized radiological safety limits, some hotspots (most notably SL24, SL29, and SL31) show high dose rates and hazard indices that could present long-term exposure risks with extended occupancy. These results highlight the necessity of focused environmental management, public awareness campaigns, and regulatory supervision, especially in regions contaminated by flooding or used for unofficial scrap metal handling.

Table 2: The radiological risk assessment from soil samples and the activity concentrations of radionuclides in soil samples from flood-affected and scrap metal-impacted sites in Maiduguri and environs.

Sample ID	Concentrations (Bq/Kg± Error)			$D\gamma$	A_E	ELCR	R_{eq}	I_γ	H_{ex}	H_{in}
	^{40}K	^{226}Ra	^{232}Th	(nGy/h)	($\mu Sv/y$)	$\times 10^{-4}$	(Bq/kg)			
SL00	84.448±3.5769	35.2178±2.4328	51.4253±3.0786	52.73	32.36	1.133	115.26	0.81	0.30	0.39
SL01	57.6983±2.6438	23.5171±2.2011	40.8209±2.5085	39.56	24.27	0.849	86.33	0.60	0.22	0.29
SL02	71.3841±2.7993	40.6626±3.8229	28.2782±2.1664	39.17	24.03	0.841	86.60	0.60	0.22	0.33
SL03	61.7574±3.4370	31.6265±4.0546	38.3124±4.3329	41.54	25.49	0.892	91.17	0.64	0.23	0.32
SL04	97.8383±2.7993	12.0482±1.4365	49.1448±3.8768	41.91	25.71	0.900	89.86	0.64	0.22	0.26
SL05	86.7807±3.2659	44.4856±2.2011	35.9179±2.9646	46.52	28.55	0.999	102.53	0.71	0.26	0.38
SL06	84.4479±3.5769	35.2178±2.4328	51.4253±3.0786	52.73	32.36	1.133	115.26	0.81	0.30	0.39
SL07	75.9300±9.7153	14.9421±1.8291	25.9179±2.7525	26.82	16.46	0.576	57.85	0.41	0.14	0.18
SL08	77.9160±3.7325	23.1696±2.4328	39.2246±2.7366	39.23	24.07	0.842	85.26	0.60	0.22	0.28
SL09	84.1415±3.3545	43.3039±2.6764	46.3580±3.7480	52.81	32.41	1.134	116.07	0.81	0.30	0.41
SL10	88.4914±3.8880	38.5774±4.7497	50.8552±4.4469	53.96	33.11	1.159	118.11	0.82	0.30	0.41
SL11	87.4028±3.2659	25.4865±1.1584	49.9429±2.3945	47.72	29.28	1.025	103.64	0.73	0.26	0.33
SL12	69.3623±2.7993	28.6144±2.4328	38.7685±1.8244	40.88	25.08	0.878	89.39	0.62	0.23	0.31
SL13	50.6221±4.2146	39.1566±2.2011	43.3295±2.0524	47.59	29.20	1.022	105.02	0.73	0.27	0.38
SL14	55.0544±4.9875	25.8341±1.2743	22.8050±1.3683	28.51	17.49	0.612	62.68	0.44	0.16	0.23
SL15	96.5785±2.3328	38.6932±2.5139	43.0331±2.1664	49.18	30.18	1.056	107.67	0.75	0.27	0.38
SL16	51.0109±2.6594	33.3758±2.7224	52.0638±2.7480	50.92	31.25	1.094	111.76	0.78	0.29	0.38
SL17	78.0715±3.2659	37.9981±2.8382	49.6009±2.5427	52.43	32.17	1.126	114.94	0.80	0.30	0.40
SL18	32.4463±3.4681	37.8304±2.1177	48.5644±3.0623	49.70	30.50	1.068	109.78	0.76	0.29	0.39
SL17	52.0995±2.0062	43.2344±3.7187	42.9874±1.6875	49.17	30.17	1.056	108.72	0.75	0.28	0.40
SL20	40.1244±3.5769	45.0648±2.6181	55.7582±3.8198	57.89	35.52	1.243	127.89	0.88	0.34	0.46
SL21	52.2706±3.5769	41.8211±1.6218	58.3808±2.7366	58.76	36.06	1.262	129.33	0.90	0.34	0.45
SL22	66.8740±4.8833	37.6506±4.4022	53.4777±2.5085	54.37	33.36	1.168	119.27	0.83	0.31	0.41
SL23	59.2535±2.5194	42.6320±2.2127	62.5997±1.6989	62.20	38.17	1.336	136.71	0.95	0.36	0.47
SL24	32.4883±2.3328	42.0528±1.5407	83.2383±3.7628	74.46	45.69	1.599	163.59	1.13	0.44	0.55
SL25	99.8444±4.8833	45.1807±4.9814	41.9612±2.2919	51.38	31.53	1.104	112.87	0.79	0.29	0.41
SL26	54.8989±3.9191	33.3642±1.7377	39.6807±2.3603	42.89	26.32	0.921	94.330	0.66	0.24	0.33
SL27	65.4743±3.4210	42.7479±1.9115	53.8198±2.3375	56.71	34.80	1.218	124.75	0.87	0.32	0.44
SL28	60.3421±3.6081	30.3521±3.5913	60.8894±2.8848	55.88	34.29	1.200	122.07	0.85	0.32	0.40
SL29	65.0077±3.2659	41.7052±4.7497	66.8187±2.0866	64.85	39.79	1.393	142.26	0.99	0.37	0.48
SL30	84.6034±2.3172	44.1381±2.3169	56.5564±3.7856	59.94	36.78	1.287	131.53	0.92	0.34	0.46
SL31	47.5894±3.2348	59.4300±1.1932	64.5382±3.8882	70.16	43.05	1.507	155.38	1.07	0.41	0.57
Min	**32.44635±3.4681**	**12.0482±1.436515**	**22.8050±1.3683**	**26.82**	**16.46**	**0.576**	**57.85**	**0.41**	**0.14**	**0.18**
Ave	**66.80909**	**35.49033**	**47.55458**	**49.33**	**30.26**	**1.059**	**108.49**	**0.75**	**0.28**	**0.37**
Max	**99.84448±4.883359**	**59.43003±1.19323**	**83.23831±3.762828**	**74.46**	**45.69**	**1.599**	**163.59**	**1.13**	**0.44**	**0.57**

IV.Discussion of the Results

The study's findings revealed that soil samples taken from flood-affected and scrap metal-impacted regions in Maiduguri and the surrounding area had different quantities of naturally occurring radionuclides (^{40}K, ^{226}Ra, and ^{232}Th). The average activity concentration of ^{40}K was 66.81 *Bq/kg*, with a range of 32.45 to 99.84 *Bq/kg*. ^{232}Th varied from 22.81 to 83.24 *Bq/kg*, with a mean of 47.55 *Bq/kg*, while ^{226}Ra ranged from 12.05 to 59.43 *Bq/kg*, with an average of 35.49 *Bq/kg*. These values varied considerably between sites, with certain sites (SL24, SL29, and SL31) showing noticeably higher quantities of radium and thorium. The data show that ^{40}K concentrations were substantially lower than the global average levels given by UNSCEAR (2000), which were 400 *Bq/kg* for ^{40}K, 35 *Bq/kg* for ^{226}Ra, and 30 *Bq/kg* for ^{232}Th. This suggests that potassium contributed very little to the external gamma dose. Though certain locations, like SL31 (59.43 *Bq/kg*) and SL20 (45.06 *Bq/kg*), exceeded the standard, the ^{226}Ra mean value is quite near to the global average. With multiple samples (SL24: 83.24 *Bq/kg*, SL29: 66.82 *Bq/kg*, SL31: 64.54 *Bq/kg*) more than twice the global average, ^{232}Th is of special concern. This suggests that there may be thorium enrichment, presumably from man-made sources like scrap contamination.

This conclusion is further supported by the computed radiological characteristics. With a mean of 49.33 *nGy/h*, the absorbed D_γ fell short of the global average of 59 *nGy/h*, but values in high-thorium regions were higher. The range of D_γ was 26.82 to 74.46 *nGy/h*. The average A_E, which was below the ICRP public dose limit of 1000 *μSv/y*, was 30.26 *μSv/y*, with a range of 16.46 to 45.69 *μSv/y*. Far below the 370 *Bq/kg* safety criterion, the Ra_{eq} ranged from 57.85 to 163.59 *Bq/kg* (mean: 108.49 *Bq/kg*). Furthermore, radiation levels are not now dangerous because H_{ex} and H_{in} hazard indices were both within safe bounds (average H_{ex}: 0.28, H_{in}: 0.37). However, in several places (SL24: 1.13, SL31: 1.07), the I_γ) was greater than unity, indicating that the annual allowable dose of gamma radiation in these areas may be higher than the public's tolerance.

In Maiduguri, North-Eastern Nigeria, soils were collected from scrap metal yards and flood-affected areas. The results of this study offer a comprehensive understanding of the spatial distribution and radiological health implications of naturally occurring radionuclides (^{40}K, ^{226}Ra, and ^{232}Th). Both geogenic and anthropogenic factors can be responsible for the observed variation in activity concentrations between sampling locations. Although the local geology, which is dominated by lateritic deposits and sedimentary formations, controls the background radiation levels in most locations, several hotspots showed high radioactive levels, especially close to active scrap metal recycling yards and flood sediment accumulation zones.

The higher levels of ^{226}Ra, and ^{232}Th found at particular research areas are in line with findings from other parts of Nigeria where increased environmental pollution has been connected to intense scrap metal activity. According to Aisien et al., (2013), the long-term buildup and corrosion of metallic wastes is the cause of the noticeably elevated amounts of heavy metals found in and around a scrap car dumpsite at Uwelu. In a similar vein, Efunwole et al. (2020) noted high levels of heavy metals in the soils near an Ile-Ife scrap metal recycling business, highlighting the significant role that industrial emissions and waste from metal recycling activities play in soil pollution. High quantities of heavy metals in Gombe Metropolis were explicitly linked to scrap yard operations in a related study by Abdulsalam et al., (2024), suggesting that these locations serve as localized sources of contamination. Thus, the pattern seen in Maiduguri is consistent with these results, indicating that natural radionuclides like ^{226}Ra, and ^{232}Th may have been released into the environment as a result of the handling, storage, and disassembly of scrap materials. The fact that these findings hold true across several Nigerian regions highlights the wider environmental effects of unregulated scrap metal operations as a source of heavy metal and radiological enrichment in soil matrices.

The activity concentrations' geographic distribution pattern, in particular the high value clustering around SL23, SL24, SL29, and SL31, suggests localized contamination that may be related to the past buildup of metallic wastes or flood-deposited sediments that are radionuclide-rich. It is commonly known that floodwater affects radionuclide migration; during floods, soil particles and metal fragments containing radionuclides from the uranium and thorium decay series can be removed, carried, and redeposited downstream. Thus, the results draw attention to the environmental dynamics of radionuclide dispersion in metropolitan areas that are vulnerable to flooding, a developing concern in Northern Nigeria due to shifting climatic and hydrological circumstances.

The study's estimated yearly effective doses and absorbed dose rates were, on the whole, below the global average limits suggested by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) and the International Commission on Radiological Protection (ICRP, 1991). This suggests that the background radiation levels that are currently present in the areas under investigation fall within acceptable ranges for the general public's radiological safety. However, the discovery of regional hotspots with absorbed dose rates slightly higher than the global average of 60 *nGy/h* raises the possibility of radiological hazards for people who live or work in such areas. Similar localized exceedances have been documented by Olowookere et al. (2022) in Nigerian institutional facilities and Eze et al. (2025) at major dumpsites in Calabar. In both cases, elevated dose rates were associated with marginally higher excess lifetime cancer risk (ELCR) values in comparison to international standards. Additionally, Igomah et al. (2025) showed that even mild spatial variation in environmental gamma radiation could affect patterns of long-term exposure, especially in areas with

high population density or high occupational activity, like scrap metal yards and markets. Relatedly, Musa et al. (2011) and Otwoma et al. (2013) pointed out that long-term exposure to slightly higher background radiation levels, even if they are within acceptable bounds, may eventually lead to a cumulative increase in stochastic health risks and chronic low-dose radiation effects. Therefore, the trends found in this study support the need for ongoing environmental monitoring, dose optimization, and radiological risk assessment to guarantee early identification of localized abnormalities and to protect the public and occupationally exposed workers from possible long-term radiogenic effects.

The estimated Excess Lifetime Cancer Risk (ELCR) values in this study ranged from 0.576×10^{-4} to 1.599×10^{-4}, which fall within the global reference range of $10^{-4} – 10^{-3}$ reported by UNSCEAR and are comparable to values documented in other parts of Nigeria and beyond. For instance, Gyuk et al. (2025), in their assessment of environmental exposures in Kaduna, reported similar ELCR magnitudes, indicating moderate radiological risk levels associated with background radiation. Likewise, Ononugbo and Bubu (2017) recorded comparable ELCR values for coastal soils in Bonny Island, while Biere et al. (2025) found close estimates for indoor and outdoor exposures in Yenagoa, suggesting that typical Nigerian environments exhibit broadly similar radiological patterns. Internationally, Oktamuliani and Sabila (2023) observed analogous ELCR values in Solok Selatan, Indonesia, and Alkufi et al. (2022) demonstrated comparable risk levels across different age groups in their ingestion-based study. These consistent findings reinforce that while the carcinogenic risk associated with soil radionuclide exposure in Maiduguri is generally low, prolonged or localized exposure, particularly in areas influenced by human activity such as scrap metal accumulation and flood-affected soils, could elevate risk slightly above background levels. This pattern underscores the importance of continuous monitoring, environmental remediation after flooding, and regulatory oversight of industrial and recycling activities to prevent long-term stochastic health effects.

In this regard, the obtained radiation metrics show that Maiduguri's general environmental condition stays below acceptable radiological safety standards. However, the evidence of localized radionuclide enrichment close to flood-prone areas and scrap metal yards emphasizes the significance of ongoing monitoring and preventive policy measures. To reduce long-term threats to public health, it is highly advised that municipal authorities set up radiation monitoring units, enforce safety regulations in metal recycling operations, and conduct ongoing environmental surveillance.

V.Conclusions

The activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th were assessed in this study in soil samples taken from scrap metal yards and flood-affected areas in Maiduguri and the surrounding area in northeastern Nigeria. The results showed that the radionuclide concentrations, along with the associated absorbed dose and annual effective dose rates, were generally within the safe limits suggested by the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). There may be increased radioactive exposure in certain locations, though, as evidenced by the identification of a number of localized hotspots with increasing thorium and radium activities, especially around scrap metal storage and flood sediment zones. The findings highlight how the spatial pattern of soil radioactivity in Maiduguri is shaped by both natural processes, such as flood-driven sediment redistribution, and anthropogenic activities, including scrap metal recycling and the potential existence of orphan radioactive sources. The need for focused site assessments as opposed to broad regional averages is highlighted by these processes, which also contribute to diverse contamination profiles. Even while the increased lifetime cancer risks and overall radiological hazard indices are below international safety standards, the localized abnormalities that have been detected raise the prospect of chronic low-dose exposure, particularly for surrounding households and occupationally exposed workers in metal recycling yards. These results emphasize the significance of putting preventive and mitigating measures into place to lower long-term exposure risks from the standpoint of public health. The implementation of community-based radiation safety awareness initiatives, stringent regulation and screening of scrap metal imports and recycling facilities, and routine environmental radioactivity monitoring are all examples of such efforts. The redistribution and accumulation of radionuclides during flood events—a persistent problem in Maiduguri's low-lying areas—will also be reduced with the incorporation of radiological monitoring into flood management and urban planning frameworks. To give a more thorough evaluation of human exposure pathways, future studies should concentrate on supplementary analyses, such as radionuclide speciation, bioavailability, and transfer factors into vegetation and water sources. Understanding the dynamics of radionuclide dispersion will be further enhanced by the application of spatial geostatistical modeling and high-resolution gamma spectrometry. All things considered, this study offers a solid scientific basis for environmental management regulations and public health initiatives meant to guarantee radiological safety and sustainable growth in Northern Nigerian cities that are vulnerable to flooding.

Acknowledgements: The authors would like to express their gratitude to the Tertiary Education Trust Fund (TETFund), Nigeria, for funding this work with an Institutional-Based Research (IBR) Grant. We sincerely

appreciate the financing, which enabled this project to be completed successfully. We also thank the community residents and local officials for their cooperation and assistance throughout the fieldwork phase. We are grateful to the University of Maiduguri's Department of Physics for providing institutional support and granting us access to the lab equipment required for our investigation. We also want to express our gratitude to the postgraduate students, field assistants, and laboratory technologists whose dedication and technical assistance were crucial in the gathering and examination of soil samples from the flood-affected and scrap metal-contaminated districts of Maiduguri.

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