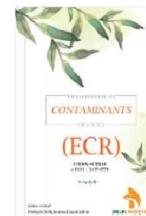


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RESEARCH ARTICLE

NATURAL OCCURRING RADIONUCLIDES ACTIVITY CONCENTRATIONS AND DERIVED RADIOLOGICAL RISK ASSESSMENT OF SOILS IN SOUTHWESTERN NIGERIA

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ABSTRACT

Radiation exposure from terrestrial sources mainly due to natural occurring radionuclides comprises significant portions of environmental radiation exposure. Activity concentrations of U-238, Th-232 and K-40, spatial distribution, contamination assessment and estimation of radiological health risk indices of surface soil samples were carried out in Ondo Town southwestern Nigeria. Twenty surface soil samples were collected and prepared as per the recommended procedure by the International Atomic Energy Agency (IAEA). Activities of U-238, Th-232 and K-40 in these samples were determined using wavelength-dispersive X-ray fluorescence spectrometry (WDXRF). Results showed that the activity concentrations of ²³⁸U, ²³²Th and ⁴⁰K in soil samples obtained ranged from 52.70–113.34 Bq kg⁻¹, 26.66–196.34 Bq kg⁻¹ and 1292.69–2087.71 Bq kg⁻¹, respectively. The calculated mean radium equivalent activity (R_{eq}) value of the soils was found to be 343.12 Bq kg⁻¹. Pollution indices (I_{geo}, CF, CD and PLI) showed low enrichment with background contributions from K-40 and U-238. Radiological hazard assessment revealed that average indoor and outdoor AEDE of 1.68 mSv/y and 0.143 mSv/y, respectively. The average excess lifetime cancer risk values were highest for indoor pathway affecting the testes and bone marrow. Pearson correlation coefficient and principal component analysis revealed that the dominant contributor to external gamma radiation exposure was K-40, while Th-232 was the controlling nuclide for gonadal dose exposure. Spatial distribution maps showed localized hotspots associated with heterogeneous lithological and geochemical characteristics. The soil in this study vicinity is not highly contaminated but indoor exposures from building materials containing these radionuclides can pose a potential health risk upon long-term exposure.

KEYWORDS

Naturally Occurring Radionuclides; U-238; Th-232; K-40; Radiological Risk; Southwest Nigeria.

1. INTRODUCTION

Primordial radionuclides have existed since the formation of Earth and can be found throughout nature. Radioactive isotopes are present in the environment including soil, sediments, water bodies, plants, and air. The most common reason for their presence in the environment is geochemical cycling such as radioactive decay chains of primordial radionuclides found naturally in the Earth's crust. These are quantitatively U-238 and Th-232 decay series and to a lesser extent K-40 account for natural radiation levels (Idrisheva et al., 2025). Their terrestrial concentrations are uneven and depend largely on regional lithology. Because different rocks have different abundances of U-238, Th-232, and K-40, these contribute to the overall amount of gamma radiation on the Earth's surface.

By weathering processes, these radionuclides leach into daughter soils and surface water bodies from their parent rocks (Gaspar et al., 2021). Regions with rocks containing radioactive minerals consequently have high levels of background radiation (Habib et al., 2024). Therefore, the distributions of these radionuclides help to understand regional background levels and possible exposure effects on biotic receptors in that region. Activity concentrations of naturally occurring radionuclides in the environment are typically reported in units of Becquerels per kilogram (Bq/kg) of air, soil or water (UNSCEAR 1993; Joel et al., 2021). Activity

concentration of soils is often used to determine changes in environmental radiation conditions (Idriss et al., 2018; Zuccarini et al., 2023). Exposure pathways to radiation come from external exposure and internal exposure. External exposure doses received from outside the body can be estimated by thermos-luminescent dosimeters (TLDS), or dose rate measurements, atmospheric dispersion modeling approaches have also been used to assess external exposure (Yoshida-Ohuchi et al., 2013; Yasutaka et al., 2013; Evangelidou et al., 2013).

Ingestion and inhalation are predominant intake pathways responsible for internal exposure from radionuclides. Inhalation exposure assessments have also been done using air sampling methods and atmospheric transport modeling techniques (Rabi and Oufni, 2025; Bartol et al., 2024). Inhabitants living in mining areas who receive chronic radiation doses over long periods may develop radiological concerns. Radon Rn-222 and daughters being short-lived radio nuclides contribute the most to the total dose (UNSCEAR 1993; Popoola et al., 2025a).

Naturally occurring radioactivity is enhanced by mining and mineral processing activities leading to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORMs) found in the environment (Adeola et al., 2023). Extraction of ores from the Earth increase concerns about radioactivity worldwide. The mining industry produces large amounts of radioactive contaminated dust which accumulates near mine

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tailings along with mining wastes that elevate radioactivity levels in the environment (Popoola et al., 2025b). Activities such as burning of fuels also contribute to radioactive exposure because rocks and sediments used for building activities contain measurable activities concentration of radionuclides. Most people around the world live in homes built with rocks and sediments close to them. In Nigeria, activity concentrations of these building materials have been found to be high (Yoshida-Ohuchi et al., 2013; Evangeliou et al., 2013). People spend about 80% of their time indoors; therefore, inhalation of radon gas emitted from these building materials can increase the risk of lung cancer.

The distribution of radionuclides in urban soils has been reported by several studies across the world (Jibiri and Okeyode, 2011; Isinkaye et al., 2015; Taqi et al., 2018; Wang et al., 2023; Li et al., 2024). Within Nigeria, studies have been carried out by most of researchers which determined concentrations and radiological impact of radionuclides found in soils on human health (Jegade et al., 2025; Laniyan and Adewumi, 2021; Ajaero et al., 2025). A group researcher studied activity concentrations found in the Southern-West region of Nigeria (Akpan et al., 2020). In other hand, some researchers assessed distribution and environmental impact of naturally occurring radionuclides in soil samples around gold deposits in Nigeria (Popoola et al., 2025a).

However, there is still a lack of research in regards to radionuclide contamination and potential health implications in some cities of Nigeria like the study area. This work seeks to determine the distribution, environmental contamination and radiological health effects of U-238, Th-232 and K-40 radionuclides naturally found in soil samples from Ondo. The objectives are to: determine the activity concentrations of U-238, Th-232 and K-40 radionuclides found in the soil samples, ascertain the level of environmental contamination compared to other parts of the world and determine the potential radiological health risks of inhabitants using the appropriate dose-response indices.

2. MATERIALS AND METHODS

2.1 Study Area

Ondo Town lies in southwestern Nigeria and is the second-largest city in Ondo State. It is located at latitude, $7^{\circ}05'20''\text{N}$; longitude, $4^{\circ}47'57''\text{E}$ with an elevation, 287 m above mean sea level (MSL) (Figure 1). Ondo Town is located inland from the Gulf of Guinea, which allowed early settlement to develop from coast through trading activities to become an economic and administrative regional centre over time (Eke et al., 2017; Asowata and Adisa, 2022). It plays host to different business sectors and produces goods such as cassava, yams and grains. Locally brewed tobacco and cotton textiles called Aso Oke fabrics are produced here. Nigeria is one of the largest producers of cocoa and Ondo state is one of the largest producers in the country.

The climate of the study area can be described as tropical rainforest with two seasons: rainy season (April–October) and dry season (November–March). Average rainfall is very high due to which rainforest vegetation dominates the area alongside crops such as oil palm, rubber trees, mahogany and fruit trees which can be used for economic purposes (Eke et al., 2017). Ondo Town drains its surface water through Ala and Owena Rivers and their tributaries. Groundwater resources are recharged mainly by meteoric water and perennial discharges through springs and along the streams provide baseflow during dry season. Geomorphologically, the study area is located within the Precambrian Basement Complex of southwestern Nigeria (Asowata and Adisa, 2022). The lithology of the area comprises mainly of migmatite – gneiss, granite, granite- gneiss and quartzite. Rocks have experienced poly-phase deformations which has resulted in formation of faults, fractures, intrusions and various types of folds folds in the study area (Epuh et al., 2020). These discontinuities are responsible for groundwater movement and mineralization of various rock structures.

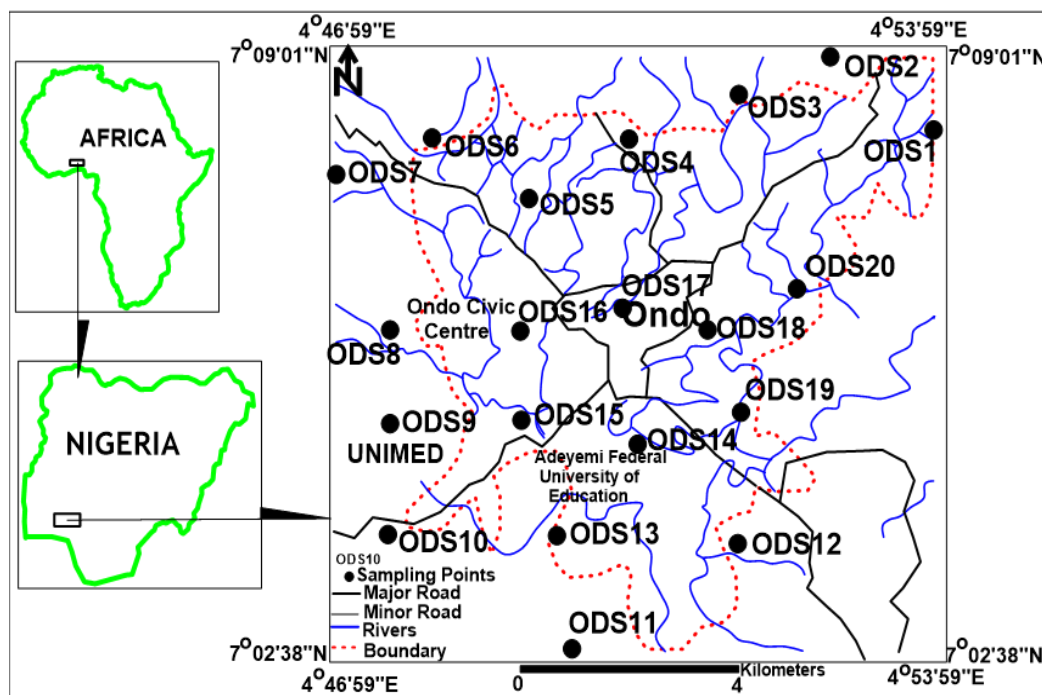


Figure 1: Location map showing Ondo town and the sampling area

2.2 Sampling Technique

Random sampling method was employed during collection of soil and stream sediment samples for geochemical background assessment from known sources/target sites and control points selected across the study area. The selected sampling points were widely spread out to encompass natural lithogenic changes and allow the inclusion of different geochemical zones in order to obtain a random and representative baseline of local environment and contaminant distributions. Twenty (20) samples were randomly collected in January, 2024 for analysis. Samples were collected with stainless steel spoons to avoid contamination and cross contamination during collection process. Soil samples were collected from surface horizon (5–10 cm) of the study area. Collected samples were placed in labeled polyethylene zip-lock bags immediately after collection. All samples were properly labeled, without contamination from external sources, stored properly to avoid alteration and preserved in a sealed container ready for laboratory analysis.

2.3 Sample Processing and Preparation

The methods adopted for sample preparation prior to laboratory analyses were done strictly according to the International Atomic Energy Agency (IAEA) guideline. The soil and stream sediment samples were left to dry (air-dry) at room temperature for twenty-four (24) hours immediately they were brought to the laboratory to eliminate top moisture on them. Thereafter, they were heated in a furnace at 110°C until they reached constant mass. This will enable them to become free from interstitial water prior to grinding and relevant analysis for their radioactivity concentrations. After drying, the samples were ground to fine powders using a grinder. Grinding of the samples to fine powder will ensure homogeneity of the samples as taken for analysis and provide appropriate geometry for measurement. Finely ground materials will give homogenous sub-sample for analysis and allow radon daughters to escape easily from the bulk material. The prepared samples were placed in labeled, clean, air tight cylindrical bottles which were sealed properly to

avoid the loss of radon through the bottles. The samples were kept for at least twenty-eight (28) days before the counting begins to allow secular equilibrium between parents (uranium-238 and thorium-232) and their daughters (radon-222 and thoron-220).

2.4 Instrument Calibration

For quality assurance and quality control purposes, matrix matched Certified Reference Materials (CRMs) with known concentrations of U-238, Th-232 and K-40 were analyzed using WDXRF spectrometer to ascertain any instrumental bias. Certified Reference Materials (CRMs) were used as primary analytical standard to evaluate the calibration curve's sensitivity and detection limits as well as performance capability of the instrument. Counting rates due to the presence of each target radionuclides (U-238, Th-232 and K-40) were determined by measuring the fluorescence intensity of the respective major characteristic X-ray peaks of these elements present in each CRM.

The peak intensities were plotted against the certified concentrations of these elements to obtain a calibration curve. The calibration curve was determined by fitting a straight line to the plot points using linear regression method. Each of the obtained calibration curves were used to calculate the activity concentrations of the unknown samples and also provided acceptable high correlation coefficient values which in turn ensures good precision and high degree of confidence to the geochemical data obtained (Isinkaye et al., 2015).

2.5 Analytical Methods

Activity concentrations of uranium-238, thorium-232 and potassium-40 isotopes in the samples were determined using Wavelength dispersive X-ray fluorescence (WDXRF) spectrometer. The spectrometer was optimized to detect only energy region of interest of each element. An optimized voltage and current value were used in the X-ray tube according to (Bashier et al., 2012). The excitation voltage and current used were 40–60 kV and 30–60 mA respectively. The voltage and current values were optimized to obtain suitable excitation of all elements in the matrix of the sample. Counting time was fixed at two hundred seconds for each nuclide to obtain reasonable Signal to Noise Ratio (SNR). Sample pellets were placed in the multi-sample changer holder. Characteristic fluorescence intensity for each element in every sample was read.

Duplicate samples were analyzed for each sample following the recommendation (Jibiri et al., 2011). Spectra were obtained for each sample, then the characteristic peaks of interest were isolated. Peak intensities of each element were deconvoluted using the attached software of the instrument to solve for any interfering peaks and background contribution. The measured intensities were used along the respective calibration curves to obtain the concentrations of each element present in the samples.

2.6 Quality Assurance and Data Conversion

Quality Assurance/Quality Control (QA/QC) were employed during analysis to ensure good accuracy, precision and reproducibility of the data obtained. Certified Reference Materials (CRM), blanks and duplicate samples were analyzed. The CRMs were used to validate that the analytical procedure employed gives accurate analysis, blanks were used to check for any cross contamination during analyses while duplicates served as a reproducibility check. Relative Standard Deviation (RSD) value obtained for the dataset was less than 5% for both soil and stream sediment samples as a criterion for accepting the data. For both soil and sediment samples.

The concentrations of uranium-238, thorium-232 were expressed in mg/kg while those of potassium-40 was expressed in %. The measured concentrations in mass were converted to activity concentrations expressed in Bq/kg using the respective factors from the constant specific activity of each radionuclide following the procedures recommended by the International Atomic Energy Agency (IAEA, 2003). The conversion factors are 1 mg/kg^{238U} = 12.35Bq/kg; 1 mg/kg^{232Th} = 4.06 Bq/kg and 1%K = 313.00 Bq/kg (or 1mg/kg K ≈ 0.031Bq/kg).

2.7 Indices of Environmental Pollution

Four indices of pollution namely, geo-accumulation index (I_{geo}), contamination factor (CF), contamination degree (CD), and pollution load index (PLI) were used to determine the magnitude of radionuclide enrichment and the anthropogenic influence on the study area.

2.7.1 Geo-accumulation index (I_{geo})

Geo-accumulation index (I_{geo}) was used to determine the level of metal or radionuclide enrichment in the environment relative to the background. Müller (1969) suggested I_{geo} accounting for lithological effects using the

constant of 1.5 as correction factor in the equation. I_{geo} was calculated as follows;

$$I_{geo} = \log_2 \frac{C_n}{1.5 \times B_n}$$

Where C_n and B_n are the activity concentration of the radionuclide of interest and the geochemical background values, respectively. Activity concentration value was corrected by the natural background matrix (Popoola et al. 2025a). The geo-accumulation index classes are presented as follows; I_{geo} ≤ 0 (unpolluted), I_{geo} > 0 -< 1 (unpolluted to moderately polluted), I_{geo} ≥ 1 -< 2 (moderately polluted), I_{geo} ≥ 2 -< 3 (moderately to heavily polluted), I_{geo} ≥ 3 -< 4 (heavily polluted), I_{geo} ≥ 4 -< 5 (heavily to extremely polluted) and I_{geo} ≥ 5 (extremely polluted)

2.7.2 Contamination Factor (CF)

Contamination factor (CF) was used as a single-element based index to describe contamination level of the radionuclide of interest with respect to its crustal abundance or local background value (Popoola et al., 2025).

$$Contamination\ Factor = \frac{C_{sample}}{C_{background}}$$

Where C_{sample} and C_{background} are the activity concentrations in the analyzed sample and the reference background sample, respectively. The contamination categories are described as follows; CF < 1: Low contaminated, 1 ≤ CF < 3: Moderately contaminated 3 ≤ CF < 6: Considerably contaminated CF > 6: Very high contaminated

2.7.3 Contamination Degree (CD)

The degree of contamination (CD) of all radionuclides analyzed at each sampling site was determined to evaluate the overall enrichment factor. CD is an integrated parameter that described the summation of all CFs recorded at each sampling location (Popoola et al., 2025a):

$$C_d = \sum_{i=1}^n C_f^i$$

Where n is the total number of radionuclides analyzed. The classes of CD are described as follows; CD < 8: Low contamination, 8 ≤ CD < 16: Moderate contamination, 16 ≤ CD < 32: Considerable contamination and CD ≥ 32: Very high contamination.

2.7.4 Pollution Load Index (PLI)

Pollution Load Index (PLI) was computed to give a relative index of pollution level between sampling sites. PLI is simply the nth root of the product of individual CFs. (Popoola et al., 2025a)

$$Pollution\ Load\ Index\ (PLI) = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \dots \times CF_n}$$

A PLI score < 1.0 suggests that the environment under study is unpolluted or at baseline quality. Values > 1.0 indicate progressive deterioration and contamination of the study area.

2.8 Indices of Radiological Hazard and Health Risk Assessment

2.8.1 Radium Equivalent Activity (Raeq)

The gamma dose contribution from naturally occurring radionuclides in soil samples was estimated using radium equivalent activity (Raeq). Raeq provided a single index which accounts for U-238, Th-232, and K-40 contribution to overall gamma exposure through terrestrial radiation (Dike et al., 2019). Raeq was calculated using Equation (5) and expressed as Becquerel per kilogram (Bq kg⁻¹);

$$Raeq\ Bq\ Kg^{-1} = A_U + 1.43A_{Th} + 0.077A_K$$

This approach is based on the assumption that activity concentration of 370Bq kg⁻¹ for U-238, 259 Bq kg⁻¹ for Th-232, and 4810Bq kg⁻¹ for K contribute equivalent gamma dose rates. Raeq was used to account for external exposure from gamma radiation and additional internal exposure from alpha particle emission following inhalation of radon gas. According to international guidelines, the recommended upper limit value of Raeq in building materials is 370Bq kg⁻¹ (Dike et al., 2019).

2.8.2 External Hazard Index (Hext) and Internal Hazard Index (Hint)

Radiological hazard assessment due to exposure to natural radionuclides found in terrestrial materials necessitates the determination of external and internal hazard indices.

2.8.2.1 External Hazard Index

2.8.2.2 Estimation of External Hazard Index (Hext)

External hazard index (Hext) was determined using two equations. The first equation Hext₁ assumes that the inhalation occupied space has infinitely thick walls with no openings such as doors or windows. This suggested an indoor scenario with no ventilation leading to maximum intake of gamma rays, hence worst-case condition. Equation Hext₁ was calculated using Equation (6) (Dike et al., 2019);

$$H_{ext1} = \frac{A_{Ra}}{370B_q} + \frac{A_{Th}}{250B_q} + \frac{A_K}{4810B_q} \leq 1$$

Hext₂ was based on the situation where buildings have doors and windows which allow ventilation of radon gas into the surrounding atmosphere. Hext₂ was computed using Equation (7) (Zhang et al., 2018);

$$H_{ext2} = \frac{A_{Ra}}{740B_q} + \frac{A_{Th}}{518B_q} + \frac{A_K}{9620B_q} \leq 1$$

Comparing equations (7) with (6) shows that the denominators in equation (7) were multiplied by two. This is because the inhalation space is assumed to have adequate ventilation which halves the dose intake from gamma radiation exposure. Either of the above criteria should be less than unity to indicate insignificant external radiation hazard to inhabitants (Mejía-Piña et al., 2016).

2.8.3 Internal Hazard Index

2.8.3.1 Estimation of Internal Hazard Index (Hint)

Internal hazard index (Hint) was determined to assess radiological risk due to ingestion of alpha particles from short-lived progenies of radon gas (Rn-222) emitted from Ra-226 and thoron (Rn-220) emitted from Ra-224. Hint was calculated using Equation (8) (Mejía-Piña et al., 2016);

$$H_{int} = \frac{A_{Ra}}{185B_q} + \frac{A_{Th}}{259B_q} + \frac{A_K}{4810B_q} \leq 1$$

The recommended maximum permissible value of Hint before any building material or natural environmental sample can be declared safe for residential buildings must be less than unity.

2.8.4 External Level Index(I_γ) due to gamma-ray (γ-radioactivity) and Internal Level Index(I_α) due to alpha-particle (α-radioactivity) emissions.

2.8.4.1 External gamma radiation level index (I_γ)

External gamma radiation hazard was evaluated using representative level index (I_γ). Index I_γ takes into account contribution from human activities and natural gamma radiation sources. I_γ was calculated using Equation (9) (Mejía-Piña et al., 2016):

$$I_{\gamma} = \frac{A_{Ra}}{300B_q} + \frac{A_{Th}}{200B_q} + \frac{A_K}{3000B_q} \leq 1$$

A representative level index (I_γ) value < 1 suggest the study area complies with the international recommended safe limits for γ-radioactivity exposure.

2.8.4.2 Internal alpha radiation level index (I_α)

Internal alpha level index (I_α) considers additional alpha dose people are subjected following inhalation of radon gas emitted from building materials and soil. I_α was calculated as follows (Mejía-Piña et al., 2016);

$$I_{\alpha} = \frac{A_{Ra}}{200} \leq 1$$

Radiologically safe building materials must have an I_α value < 1 which equates to a maximum allowable activity concentration of Ra-226 at 200Bq kg⁻¹.

2.8.5 Exposure Rate (ER) and Dose Rate (DR)

Radiation exposure depends on individual environmental interactions and activities carried out daily. Radiation exposure due to activity concentration of naturally occurring radionuclides was calculated as follows (Mejía-Piña et al., 2016);

$$ER (\mu R h^{-1}) = 1.90A_{Ra} + 2.82A_{Th} + 0.179A_K$$

Dose rate (DR) representing the energy absorbed by an individual was calculated based on the obtained exposure rate using Equation (12) (Mejía-Piña et al., 2016).

$$DR (mSv yr^{-1}) = 0.0833 ER (\mu R h^{-1})$$

2.8.6 Air Absorbed dose rate (ADR)

Absorbed dose rate in air at a height of 1 meter above the ground level due

to presence of Ra-226, Th-232, and K-40 were calculated as follows (Zhang et al., 2018);

$$D \left(\frac{nGy}{h} \right) = 0.462A_U + 0.621A_{Th} + 0.0417A_K$$

The unit conversion factors (nGy h⁻¹ per Bq kg⁻¹) used were 0.462 for Ra-226, 0.621 for Th-232 and 0.0417 for K-40. The world average outdoor absorbed dose rate in air is 57nGy h⁻¹.

2.8.7 Annual Effective Dose Equivalent (AEDE)

Annual effective dose equivalent both outdoor (AEDEout) and indoor (AEDEin) were determined using Equations (14) and (15) respectively (Zhang et al., 2018);

$$D_{out} (mSv/y) = D (nGy/h) \times 24(h) \times 365.25(day) \times OF \times 0.7 \times 10^{-3}$$

$$D_{in} \left(\frac{mSv}{y} \right) = D \left(\frac{nGy}{h} \right) \times 24(h) \times 365.25(day) \times 0.8 \times 0.7 \times 10^{-3}$$

where; (D) absorbed dose rate air in nGy h⁻¹. 0.7 Sv Gy⁻¹ is the dose conversion coefficient based on ICRP publication 103, and OF is the occupancy factors, which is taken as 0.20 for outdoor and 0.80 for indoor exposures. International recommended maximum allowable value for AEDE is 0.48mSv yr⁻¹ and combined indoor and outdoor exposures not be greater than 1 mSv yr⁻¹.

2.8.8 Effective dose to specific organs and tissues

Effective dose received by specific organs and tissues was calculated using Equation (16) (Evangelidou et al., 2013);

$$D_{organ} (mSv/y) = AEDE \times f$$

where; (f) is the dose conversion coefficient based on air to organ. The mean value conversion coefficients from air to other organs were taken as f=lungs= 0.64, ovaries = 0.58, bone marrow= 0.69, testes= 0.82 and whole body= 0.68.

2.8.9 Annual Gonadal Dose Equivalent (AGDE)

Annual gonadal dose equivalent measures radiological significance on organs such as gonads, active bone marrow, and bone surface fluid/skin cells. AGDE due to Ra-226, Th-232, and K-40 were calculated as follows (Michalik, 2017);

$$AGDE (\mu Sv/y) = 3.09A_{Ra} + 4.18A_{Th} + 0.013A_K$$

The world-wide mean annual AGDE value due to Ra-226, Th-232 and K-40 were obtained as; 35, 35 and 370 μSv yr⁻¹, respectively. UNSCEAR recommends mean AGDE ≤300 μSv yr⁻¹.

2.8.10 Excess Life Time Cancer Risk (ELCR)

Excess lifetime cancer risk gives an indication of the likelihood of cancer due to exposure to terrestrial radionuclides. ELCR was calculated as follows (Michalik, 2017);

$$ELCR (mSv/yr) = AEDE \times DL \times RF$$

where DL is the lifespan which is assumed to be 56 years (Adewumi and Laniyan, 2020) and RF is risk factor for stochastic effects, which is taken as 0.05 Sv⁻¹ for the general public (IAEA).

2.9 Statistical Analysis

Statistical analyses were performed using Microsoft Excel (MS Excel) and Statistical Package for the Social Sciences (SPSS). Microsoft Excel was used for calculation of radiological hazard indices while descriptive statistical analysis, bivariate correlation analysis, hierarchical cluster analysis, and principal component analysis were carried out using SPSS software.

3. RESULTS

3.1 Activity concentrations of U-238, Th-232, K-40 and Radium equivalent activity concentration index (Raeq)

Table 1 shows activity concentrations of U-238, Th-232 and K-40 present in soils of the study area. The range of U-238, Th-232 and K-40 present in soils is 52.70 Bq kg⁻¹ to 113.34 Bq kg⁻¹, 26.66 Bq kg⁻¹ to 196.34 Bq kg⁻¹ and 1292.69 Bq kg⁻¹ to 2087.71 Bq kg⁻¹ with corresponding mean value of 88.74 Bq kg⁻¹, 66.86 Bq kg⁻¹ and 1750.86 Bq kg⁻¹ respectively (Table 1). Range of Raeq is 236.64 Bq kg⁻¹ to 465.43 Bq kg⁻¹ and 319.36 Bq kg⁻¹ to 344.41 Bq kg⁻¹ with average value of 317.56 Bq kg⁻¹ and 343.12 Bq kg⁻¹ respectively. Results reveal that radionuclides follow the order K-40 > Raeq > U-238 > Th-232 in soils and stream sediments of the study area in general (Table 1).

The spatial distribution map of naturally occurring radionuclides present in the soils and stream sediments of the study area are shown in Figure 2. Figure 2a reveals that the U-238 concentration is more dominant in northeast-southwest direction of the study area. The highest concentration of U-238 was observed in sample collection location S20 while the least amount occurred in locations S3 and S6 (Figure 2a). Figure 2b reveals that the concentration of Th-232 was maximum in location S7 which lie towards northwestern part of the

study area while the minimum concentration was found in location S3 which also lie towards northern part of the study area. Figure 2c reveals that maximum concentrations of K-40 occurred in locations S3 and S6 which lie towards northern part of the area while the least concentration was observed in location S20 lie towards east of the study area. Figure 2d reveals that maximum Raeq was found in location S7 while locations S3 and S6 which lie towards northern part of the area showed least concentrations.

Table 1: Activity concentration and radium equivalent of radionuclides in soils				
Radionuclides	U-238 (Bq/kg)	Th-232 (Bq/kg)	K-40 (Bq/kg)	R _{aeq} (Bq/kg)
Minimum	50.47	41.53	250.04	148.46
Maximum	80.97	60.84	2259.86	284.49
Average ± STD	66.01±15.53	50.35±36.18	1296.51±193.63	236.97±10.18
CV (%)	23.53 %	71.85 %	14.93 %	4,29 %
P-Value	p<0.001	p<0.001	p<0.001	p<0.001
Reported Average/Global Average	2.06	1.11	3.09	-
Reported Average/Global Average (%)	206.28 %	111.89 %	308.69 %	-
Anka ¹	34.74	66.59	1067.93	212.19
Ota ²	18.85	67.22	373.65	143.75
Abuja ³	34.00	61.00	573.00	165.35
Emure-Ekiti ⁴	121.69	47.62	1659.45	317.56
Idanre ⁵	73.29	44.03	1614.65	260.58
Sudan ⁶	25.95	35.56	685.38	129.58
Algeria ⁷	41.00	27.00	422.00	112.10
Ghana ⁸	16.02	20.31	195.01	60.08
Ethiopia ⁷	64.00	70.00	330.00	189.51
Global Average UNSCEAR (2000)	32.00	45.00	420.00	-

1: Adewumi and Laniyan, 2021; 2: Usikalu et al., 2020; 3: Omeje et al., 2013; 4: Popoola et al., 2025; 5: Popoola et al., 2025; 6: Idriss et al., 2018; 7: Amrani and Tahat, 2001; 8: Adukpó et al., 2014; 9: Abate, 2022

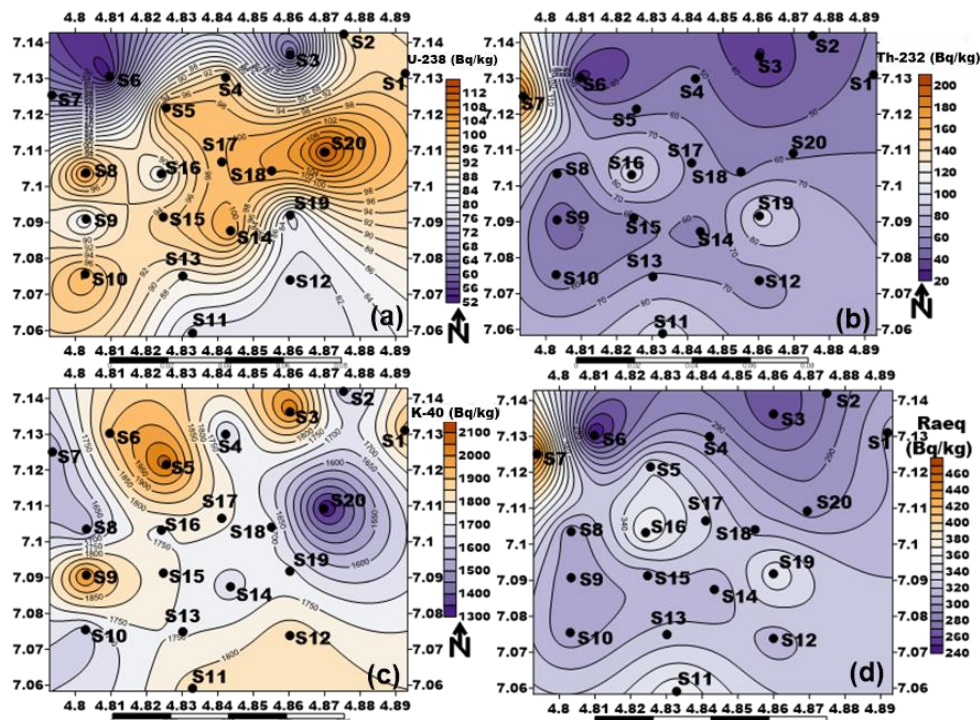


Figure 2: Spatial distribution of U-238, Th-232, K-40 and Raeq in soils

3.2 Pollution Evaluation of Radionuclides in Soils

Geo-accumulation index (I_{geo}) of radionuclides in soils is presented in Table 2. Geo-accumulation (I_{geo}) of U-238, Th-232 and K-40 in soils varied from 0.07-0.75, -0.70-0.15 and -1.33-1.84 with means of 0.44, -0.43 and 0.83 respectively.

Contamination factor of U-238, Th-232 and K-40 in soils ranged from 1.58-2.53, 0.92-1.35 and 0.59-5.38 with means of 2.06, 1.12 and 3.09 respectively (Table 2). Degree of contamination (CD) of radionuclides in soils ranged from 4.04 and 7.90 with mean value of 6.27 (Table 2) whereas pollution load index varied from 1.16 to 2.22 with average of 1.85 (Table 2).

Table 2: Pollution Assessment of Radionuclides in Soils

		U-238 (Bq/kg)	Th-232 (Bq/kg)	K-40 (Bq/kg)	Contamination Degree (CD)	Pollution Load Index (PLI)
Geo-accumulation Factor (I _{geo})	Minimum	0.07	-0.70	-1.33	-	-
	Maximum	0.75	-0.15	1.84	-	-
	Average	0.44	-0.43	0.84	-	-
Contamination Factor (CF)	Minimum	1.58	0.92	0.59	4.04	1.16
	Maximum	2.53	1.35	5.38	7.90	2.22
	Average	2.06	1.12	3.09	6.27	1.85

3.3 Radiological hazard effects

3.3.1 Internal level index (I_α)

The internal level index (I_α), radiological index frequently applied when estimating potential inhalation/internal exposure to radionuclides is presented in Table 3. Radon gas inhalation and ingrowth products primarily cause internal exposure dose to natural radionuclides. When considering inhalation hazard posed by U-238 and Th-232 series radionuclides in soils, I_α is essential. The arithmetic mean value of I_α for soils in the area under investigation was determined as 0.27 mSv/yr and varied between 0.08 mSv/yr and 0.62 mSv/yr.

3.3.2 External level index (I_γ)

Gamma γ-radioactivity level index (I_γ) used to estimate potential external exposure from naturally occurring radionuclides (U-238, Th-232, and K-40) present in soils materials is presented in Table 3. The γ-radioactivity level index offers a way to evaluate the radiological security of an environment that contains these radionuclides by providing a numerical estimate of the gamma dose rate that these radionuclides contribute. The arithmetic mean value of γ-radioactivity level index for soils samples obtained from the area under investigation was determined as 0.33 mSv/yr and ranged from 0.10 mSv/yr to 0.74 mSv/yr.

3.3.3 Exposure/Dose Rates (ER)

Dose rate (radiation absorption rate) is defined as the rate at which ionizing radiation energy is absorbed per unit mass of an object or organism over a given period of time (USNRC, 2017). It provides information about the possible impacts of radionuclides on the environment by examining the transfer of energy from radionuclides to matter. The dose rate data for soil samples obtained from the area under investigation is presented in Table 3.

Soil samples show dose rate ranging from 4.89 μR/h to 35.15 μR/h with an average value of 15.52 μR/h. These variations may be due to variation in activity concentrations of radionuclides spatially across the study area. Constant dose rate values across the mediums suggest that radiological exposure potential across areas under investigation is uniformly distributed. The average exposure rate of soil samples was found to be 186.31 μR/h and ranged from 58.67 μR/h to 421.91 μR/h.

3.4 External hazard index (H_{ext})

The measured activities of building materials are used to estimate radiation doses that may be expected to be delivered externally if a building constructed using these materials. (Arman and Gumuş 2018). H_{ext} was determined based on assumption of infinitely thick walls without windows and doors as a standard (Krieger, 1981). According to radiological impact criteria, the acceptable limit for H_{ext} is 1.

Table 3 showed the mean of H_{ext} for soils that used to build a room with infinitely thick walls without windows and doors and soils used to build a room with windows and doors within the study area. Average value of H_{ext} for soils that used to build a room with infinitely thick walls without windows and doors is 1.10 mSv yr⁻¹ while H_{ext} for soils that used to build a room with windows and doors is 0.55 mSv yr⁻¹, respectively.

3.5 Internal hazard index (Hint)

Radon (Rn-222) is radioactive gaseous and short-lived decay product of Ra-226, damage to respiratory organs could occur as a result of exposure (Table 3). Hint that is used to quantify internal exposure due to radon and daughter products in equilibrium with radon is presented. Hint will be less than unity if the maximum permissible concentration of Ra-226 is only half of the acceptable limit (Ravisankar et al., 2012). Hint < 1 is used as standard for safety consideration during use of materials for construction of buildings (Ravisankar et al., 2012). According to radiological impact criteria, the acceptable limit for Hint for radiological impact is 1. Table 3 displays the range and mean Hint for soils collected from within the area. Within this area the Hint was found to range while the mean Hint was 1.74 mSv yr⁻¹, respectively.

3.6 Air absorbed gamma dose rate (D_{air})

Terms like total gamma radiation absorbed dose rate in air, D_{air} are typically used to characterize the effects of gamma radiation emitted from radioactive materials found in the atmosphere (Samreh et al., 2015). Terrestrial gamma radiation and radionuclide concentrations have a close relationship (Ravisankar et al., 2012). The observed air-absorbed gamma radiation dose rates were found to range from 67 nGy h⁻¹ to 144 nGy h⁻¹ with an average value of approximately 114 nGy h⁻¹ (Table 3). The wide variation between the minimum and maximum observed values indicates noticeable spatial distribution of natural radionuclides in the study area.

3.7 Annual effective dose equivalent (AEDE)

Annual Effective Dose Equivalent rates ranged from 0.083 mSv y⁻¹ as minimum value and 0.178 mSv y⁻¹ as maximum value with 0.143 mSv y⁻¹ as mean value obtained for outdoor sampling locations (Table 3). The indoor AEDE ranged from 0.95 mSv y⁻¹ as minimum and 2.10 mSv y⁻¹ as maximum with mean value of 1.68 mSv y⁻¹ (Table 3). Total AEDE ranged from 1.05 mSv y⁻¹ as minimum to 2.18 mSv y⁻¹ as maximum with mean value of 1.88 mSv y⁻¹ (Table 3).

3.8 Annual Gonadal Dose Equivalent (AGDE)

Annual Gonadal Dose Equivalent (AGDE) is defined as a radiological index that is used to estimate annual radiation dose absorbed by gonads due to environmental gamma radiation exposure. AGDE was calculated from 18.31 mSv/year to 28.22 mSv/year with average value of 21.82 mSv/year (Table 3).

3.9 Excess Lifetime Cancer Risk (ELCR)

Estimated outdoor ELCR (ELCR_{out}) values across sampling locations ranged from 0.23 mSv yr⁻¹ to 0.49 mSv/year (Table 3). Indicated non-significant health risk presented by outdoor γ-radiation exposure. Indoor excess lifetime cancer risk (ELCR_{in}) values were higher in all sampling locations ranging from 2.76 mSv yr⁻¹ to 5.92 mSv yr⁻¹ (Table 3). Total excess lifetime cancer risk values (ELCR_{total}) across the sampling locations in the study area show high spatial variation ranging from 2.99 mSv/year to 6.42 mSv/year (Table 3).

3.10 Effective Dose Rate (D_{organ}) to different body organs and tissues

Values of outdoor excess lifetime cancer risk (ELCR_{out}) were consistent across the study area. Testes showed the maximum ELCR among all samples i.e., from 0.72 mSv yr⁻¹ and 1.54 mSv yr⁻¹ (Table 3). Bone marrow

is on the second place (0.51 mSv yr⁻¹ - 1.09 mSv yr⁻¹) followed by lungs and ovaries having values between 0.05 mSv yr⁻¹ - 0.11 mSv yr⁻¹ and 0.05 mSv yr⁻¹ - 0.10 mSv yr⁻¹ respectively. Dose assessed to whole-body lies between 0.49 mSv yr⁻¹ - 1.06 mSv/year for all datasets (Table 3). Total ELCR ranged from 1.82 mSv yr⁻¹ - 3.90 mSv yr⁻¹. Indoor highest ELCR values were observed in testes at all sampling locations reflecting its high radiosensitivity (0.81 mSv yr⁻¹ - 1.73 mSv yr⁻¹) (Table 3). This trend was followed by bone marrow with indoor ELCR values ranging from 0.69 mSv

yr⁻¹ to 1.46 mSv yr⁻¹ (Table 3). Lung and ovary values followed with indoor ELCR ranging from 0.63 mSv yr⁻¹ - 1.35 mSv yr⁻¹ and 0.57 mSv yr⁻¹ - 1.23 mSv yr⁻¹, respectively (Table 3). These elevated levels are above recommended benchmark globally acceptable levels. Whole-body indoor ELCR values range from 0.67 mSv yr⁻¹ - 1.44 mSv yr⁻¹ (Table 3). Total indoor ELCR values ranged widely from 3.36 mSv yr⁻¹ - 7.21 mSv yr⁻¹ (Table 3). Values obtained from most sampling locations ranged from 5.40 - 6.70 mSv yr⁻¹.

Table 3: Radiological parameters in soils

Radiological Parameters	Organs	Minimum	Maximum	Average
Internal Level, I _α (mSv yr ⁻¹)		0.08	0.62	0.27
External Level, I _γ (mSv yr ⁻¹)		0.10	0.74	0.10
Dose Rate (μR/h)		4.89	35.15	15.52
Exposure Rate (μR/h)		58.67	421.91	186.31
^a H _{ext}		0.59	1.40	1.10
^b H _{ext}		0.30	0.70	0.55
H _{int}		1.00	2.17	1.74
D _{air} (nGy h ⁻¹)		67.00	144.00	114.00
AEDE _{outdoor} (mSv yr ⁻¹)		0.083	0.178	0.143
AEDE _{indoor} (mSv yr ⁻¹)		0.95	2.10	1.68
AEDE _{Total} (mSv yr ⁻¹)		1.05	2.18	1.88
AGDE		18.31	28.22	21.82
ELCR _{outdoor}		0.23	0.49	0.40
ELCR _{indoor}		2.76	5.92	4.76
ELCR _{total}		2.99	6.42	5.15
ELCR _{outdoor}	Lungs	0.05	0.11	0.09
	Ovaries	0.05	0.10	0.08
	Bone Marrow	0.51	1.09	0.88
	Testes	0.72	1.54	1.24
	Whole Body	0.49	1.06	0.85
	Total	1.82	3.90	3.14
ELCR _{indoor}	Lungs	0.63	1.35	1.09
	Ovaries	0.57	1.23	0.95
	Bone Marrow	0.68	1.46	1.17
	Testes	0.81	1.73	1.39
	Whole Body	0.67	1.44	1.15
	Total	3.36	7.21	5.79

^aH_{ext}: a room with infinitely thick walls without windows and doors

^bH_{ext}: a room with windows and doors

3.11 Bivariate correlation

Pearson correlation matrix was utilized to interpret possible correlations between studied radionuclides (U-238, Th-232 and K-40) with the evaluated radiological hazard indices (Raeq, Hext and Hint), D, AEDE, ELCR, AGDE, I_γ and I_α. The correlations obtained revealed that U-238 has weak to moderate positive correlations with all radiological indices obtained in this study revealing its insignificant contribution to radiation hazard as depicted by the bivariate correlation plot (Figure 3a). Radiological hazard assessment-based thoron shows very strong positive correlations with AGDE (r=0.998; p<0.01), suggesting thoron as the main contributor to gonadal dose commitment which might be due to high gamma emission from its daughters. Potassium 40 has very strong positive correlations with Raeq (r=0.943; p<0.01), Hext (r=0.969; p<0.01), Hint (r=0.962; p<0.01), D (r=0.974; p<0.01), AEDE (r=0.960; p<0.01) and ELCR (r=0.960; p<0.01) revealing that K-40 is the main radionuclide contributing to external gamma radiation exposure. Additionally, a significant negative correlation was observed between K-40 and U-238 (r=-0.457; p<0.05) implying different geochemical behavior or mineralogical origin (Figure 3a). Raeq has very strong relationship with

Hint (r=0.996), D (r=0.990), AEDE (r=0.998), ELCR (r=0.998) and I_α (r=1.000), suggesting that Raeq can serve as a good estimator of radiological hazard assessment due to natural radioactivity. Hext and Hint revealed almost perfect positive correlations (r=0.999; p<0.01) confirming their interdependency and effectiveness as reliable hazard indices since they are controlled by the same radionuclide inputs (Akpan, 2011). Both Hext and Hint showed perfect positive correlations with D (r=0.990 and 0.994 respectively) and AEDE (r=0.998 and 0.999 respectively) indicating external gamma exposure as dominant factor influence in the study area. Perfect to very strong positive correlations were also observed between D and I_γ (r=1.000), Hext (r=1.000), and AEDE (r=0.995) suggesting consistency in their responses to changes in concentrations of natural radionuclides present in the study area soils. Similarly, very strong positive correlation was observed between AEDE and ELCR (r=1.000; p<0.01) suggesting that exposure to radiation through inhalation and ingestion as presented by AEDE controls lifetime cancer risk. Strong positive correlation was also observed between ELCR and Raeq (r=0.998), further confirming Raeq as a good estimator of potential long-term stochastic effects. AGDE revealed very strong positive correlations with Th-232 (r=0.998; p<0.01) but only moderate correlations with K-40 and other radiological hazard indices (Figure 3a). This might suggest that thorium bearing minerals dominate gonadal dose

commitment since gonads are radiosensitive organs in terms of genetic effects. The dendrogram (Figure 3b) shows various sample partitions which indicate clustering of items that share common sources, exposure pathways and relative radiological significance. From the dendrogram (Figure 3b), two main clusters were formed at higher rescaled distances before subdividing into smaller subclusters at lower rescaled distances. Cluster I which is the first and bigger cluster consists of K-40, Raeq, Hext, Hint, D, Iy, Iα, AEDE and ELCR (Figure 3b). These items cluster at very small rescaled distances (<3) indicating that they share strong similarities and are possibly controlled by the same factor(s).

This cluster represents external gamma radiation and radiological risk since K-40 was observed to be the dominant natural radionuclide influencing the soils. Cluster purity was also confirmed by associating Raeq with Hext and Hint; D and AEDE as well as ELCR with AEDE. This confirms that these indices are interdependent mathematically hence describing the same radiological exposure pathway. Close association between Iy and Iα with D and AEDE respectively further supports their usefulness as screening indices since they are controlled by gamma radiation exposure obtained from radiation measurements. Cluster II consists of Th-232 and AGDE (Figure 3b).

AGDE associates very closely with Th-232 at a relatively small rescaled distance before clustering with cluster I at a relatively high rescaled distance. Close association of Th-232 with AGDE suggests common source or controlling factor between the two and since they cluster at the end of dendrogram far from cluster I, this implies that their relationship is different from those in Cluster I. From interpretation of dendrogram, Th-232 and AGDE form a cluster separate from Cluster I made up of parameters representing external gamma radiation and radiological risk (Table 3b). The close association between Th-232 and AGDE supports previous conclusions made from bivariate correlations (Figure 3b). Here thorium bearing minerals are suggested to have major control over gonadal dose commitment. Separation of this cluster from Cluster I at a relatively high rescaled distance suggest different source and exposure pathway. Different exposure pathway implies that thorium contributes to radiation possible influence on genetic and reproductive health unlike the other radionuclides which influence radiological risk through external gamma irradiation. Uranium-236 registers the highest rescaled distance before joining any cluster (Figure 3b). This might imply that U-236 share weak similarities with other radionuclide activities and radiological indices obtained since it neither belongs to cluster I nor cluster II.

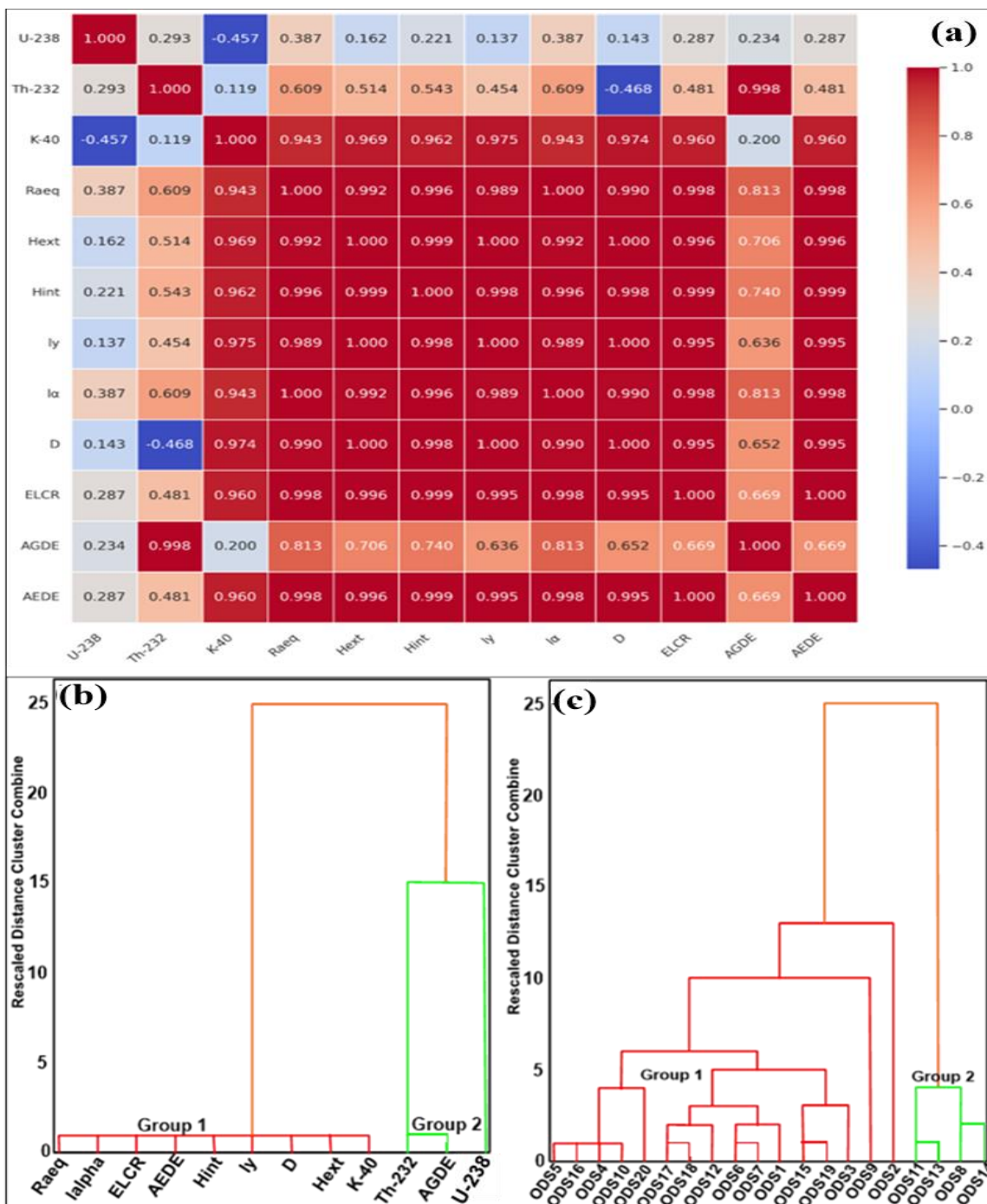


Figure 3: Bivariate correlation and hierarchical clusters of radionuclides in soils

Principal component analysis (PCA) was performed to determine the main factors governing the spatial variability of natural radionuclides and different radiological hazard indices in the study area. Two components with eigenvalues greater than unity were extracted. These two components cumulatively explain 93.02% of the total variance in the dataset, suggesting an excellent dataset representation (Table 4). PC1 accounts for 75.57% of the total variance, and it has very high positive loadings with K-40 (0.983), Raeq (0.987), Hext (0.997), Hint (0.996), I_γ (0.999), I_α (0.987), D (0.998), AEDE (0.995) and ELCR (0.995). All these parameters have very high communalities (≥ 0.99), suggesting that PC1 represents them well. Therefore, PC1 can be interpreted as gamma radiation-dose-risk factor governed by K-40. External gamma exposure is known to be mostly controlled by K-40 content since K is abundant in crustal materials.

The strong association of Raeq with different hazard indices, dose parameters and different cancer risk metrics reiterate their common dependence on external gamma radiation and validate their use as effective combined measures of radiological risk from gamma radiation. The marginal negative loadings of U-238 (-0.342) and Th-232 (-0.228) on PC1 infer that U-238 and Th-232 have lesser contributions to external gamma dose than potassium in the study area (Table 4).

It could also be an indication of lithological control/mineralogical composition/mobility of U-238 and Th-232 relative to K-40 bearing minerals in this area. PC2 explained 17.45% of the total variance in the data set and has high positive loadings with Th-232 (0.952) and AGDE (0.966) with high communalities (0.958 and 0.960 respectively). U-236 has moderate positive loading with PC2 (0.407), while K-40 and most of the dose indices have negligible loadings (Table 2).

PC2 thus can be considered as a thorium-driven internal and gonadal dose factor controlled by abundance of Th-232 bearing minerals and their subsequent daughter products that contribute significantly to radiation dose to sensitive organs like gonads. The strong positive association between Th-232 and AGDE suggest genetic reproductive radiation risks can be approximated using Th-232 contents; similar interpretations have been made in earlier radiological studies of the area. Also, the segregation of Th-232 and AGDE from K-40 and external dose indices suggests that they may have been controlled by different source materials/routes of exposure.

Communality values range from 0.283 (U-236) to 1.000 (Hext and Hint). Values close to unity indicate that extracted components explain those variables well. However, the relatively low communality of U-236 indicates that the variability in U-236 activities may be partly controlled by other processes not incorporated in the PCA model, such as redox conditions and interactions with water.

Table 4: Principal component analysis of natural radionuclides and radiological parameters in soils

-	Component 1	Component 2	Communalities
U-238	-0.342	0.407	0.283
Th-232	-0.228	0.952	0.958
K-40	0.983	-0.158	0.991
Raeq	0.987	0.128	0.991
Hext	0.997	0.072	1.000
Hint	0.996	0.091	1.000
I_γ	0.999	0.047	0.999
I_α	0.987	0.128	0.991
D	0.998	0.053	0.999
ELCR	0.995	0.077	0.995
AGDE	-0.163	0.966	0.960
AEDE	0.995	0.077	0.995
Total	9.068	2.093	-
% of Variance	75.571	17.445	-
Cumulative %	75.571	93.016	-

4. DISCUSSION

Activity concentrations of the naturally occurring radionuclides revealed soils in Ondo were enriched in U-238 and K-40 than several comparison sites. Average activity concentrations of U-238 and K-40 were higher than values obtained for Anka, Nigeria soils, Ota, Nigeria soils, Abuja, Nigeria soils, Sudan soils, Algeria soils, Ghana soils and Ethiopia soils (Table 1) (Adewumi and Laniyan, 2021; Usikalu et al., 2020; Omeje et al., 2013; Idriss et al., 2018; Amrani and Tahat, 2001; Adukpo et al., 2014; Abate, 2022). In comparison with other study areas in Southwestern Nigeria, soils from Ondo town had lower activities of U-238 than those reported for Emure-Ekiti and Idanre (Popoola et al., 2025). Ondo soils had greater activity concentrations of U-238 and K-40 than the world average values of 35 Bq kg⁻¹ and 420 Bq kg⁻¹, respectively (UNSCEAR, 2000).

This result suggests that the soils possess higher uranium and potassium contents than the world average soils and, therefore, more naturally occurring radioactivity attributed to geological nature in the area. Activity concentrations of Th-232 in soils sampled across Ondo city are lower than the values reported for Anka soil, Ota soil, Abuja soil and Ethiopia soil and higher than those reported for Emure-Ekiti soil, Idanre soil, Sudan soils, Algeria soils and Ghana soils. Mean activity concentration of Th-232 in Ondo town soils (121.13±86.35 Bq kg⁻¹) exceeded the world average value of 45 Bq kg⁻¹ reported by (UNSCEAR 2000). Differences in activity concentrations of radionuclides observed within this study area compared to other regional sites and the world average may be due to variation in parent materials, degree of weathering, and geochemical fractionation effects.

Coefficients of variation was computed to normalized standard deviation so it can be compared across radionuclides with different means. Thorium-232 displayed the highest degree of variability compared to uranium and potassium which had lower variability coefficients (CV; Th-232 = 71.85%, U-238 = 23.53%, K-40 = 14.93%). Raeq was least variable among radionuclides (CV; 4.29%). The heterogeneous distribution of Th-232 implies thorium has a localized geochemical control perhaps due to its lithological association with minerals that are highly resistant to weathering (Christidis et al., 2019). Thorium-232 distribution is uneven therefore; the highest CV is observed for Th-232. U-238 displayed some degree of variability probably due to its higher mobility compared to Th-232 and K-40. This moderate variability could be attributed to mobilization processes like leaching or removal from soils. K-40 had the lowest variability suggesting a relatively uniform distribution throughout the study area. This is not surprising given that K-40 is ubiquitous in potassium-bearing minerals. Spatial distribution maps of radionuclides activity concentrations show that uranium activities are high in most sampled locations except a few outliers where activities were low. This pattern implies redistribution has occurred in these areas, possibly due to enhanced uranium leaching caused by dissolution or perhaps migration to other areas with better favorable conditions. Activities of Th-232 and K-40 were low in most locations except certain points where activities were relatively high (for Th-232) or low (for K-40 at S1, S5, S6, S9, S11, S12, S15, S16, and S19). Distribution maps of Raeq showed moderately uniform distribution throughout the study area (Figure 2d).

The geo-accumulation index revealed soils from Ondo town were unpolluted to moderately polluted by U-238 and K-40 activities and not polluted by Th-232 activities. Moderate contamination from uranium distributed across all sampled locations. While 10% of soils were found to be within the low contamination class by Th-232, about 90% of samples were within moderate contamination class. Low, moderate and considerable contamination categories were shared equally by 10%, 20%, and 70% of samples analyzed for potassium contamination respectively. In general, soils in Ondo town were within the low contamination index class for radiological contamination and moderate pollution load index class. Although 60% of samples were within the medium range of PLI index category.

Internal alpha index values suggested an overall moderate internal exposure likely due to moderate activities of U-238 and Th-232 observed in most sampled locations. However, some locations with high mean internal alpha index values experienced potential internal exposure from radionuclides. This relationship was observed for U-238 and Th-232 activities as these increased with increasing average I_α values. Elements might become enriched in soils at these locations through mineral dissolution and release of these elements into the atmosphere where they can become entrained and transported over long distances before depositing in/on these areas. Soil samples with high internal exposure potentials are found especially if occupants spend extended periods of time indoors or come from locations where soil is used domestically or for construction purposes such as brick-making.

Most buildings are constructed with local soil materials. Indoor inhalation exposure can easily exceed the reference levels of 200 Bq m⁻³ because of increased alpha and gamma emission from radionuclides found within building materials (El-Galy et al., 2008). Inhalation of indoor radon leads to the significant accumulation of radiation dose which can cause residents of these buildings to receive higher doses than the openair outdoor dose rates. Increased radiological risk are likely to occur along selected locations where soils are used domestically or undergo excavation when compared to areas where soils are not used for brick manufacturing or agricultural purposes.

Alpha particles have low penetration depth and high linear energy light compared to beta particles, inducing denser ionization in living tissues. Exposure to alpha particles could lead to DNA damage, mutation and cancer particularly to lungs, bones and liver following inhalation or ingestion of alpha emitting radionuclides or dust containing alpha emitters (Verma et al., 2025; Roy et al., 2022). At high doses, alpha particles have direct biological effects such as cell damage and necrosis (Pouget and Constanzo, 2021). Infertility might occur due to alpha particle exposure depending on location and duration spent (Obrador et al., 2022).

Gamma radioactivity concentrations are considered low therefore external gamma exposure are low. Small variations in gamma activity indices shows gamma emitting radionuclides within study area are distributed relatively uniformly. Deposited radionuclides suggest similar lithological units, pedogenic processes, and mineralogy were involved in soil formation within study area. Hence, degree of weathering within study area is assumed uniform. Gamma indices are comparable to that obtained for soils within lithologically similar regions. Gamma radiation levels within study area are not high and therefore dominated by natural gamma radiation. Under existing environmental conditions and usage patterns, soils are considered radiologically safe for agricultural production and living. Variations in exposure rate is due to geology and geochemical factors within the study area. Study area experienced high exposure rate indicating few locations within study area with higher-than-normal natural radiation exposure. Based on USNRC (2017) definition of exposure rate, inhabitants of these areas experience high radiation levels from atmospheric sources.

Mean external hazard index exceeded unity suggesting potential radiological concerns. UNSCEAR (2000, 2008) used external hazard index as a conservative screening tool that accounts for the exposure of infinitely thick building materials to ensure annual effective doses are below 1mSv yr⁻¹. This standard does not apply to soils within study area since mean Hext values exceeds 1 indicating that soils within study area needs to undergo further radiological assessment and possible remediation. Mean internal hazard index exceeded unity indicating higher potential risk to breathing organs due to inhalation of radon progenies. Results compare with study conducted in Egypt and Nigeria (Darwish et al., 2015; Laniyan and Adewumi, 2021).

Air absorbed dose rates and AEDE varied spatially due to difference in lithology and parent materials that make up soils within study area. Mean outdoor and indoor AEDE are higher than world average reported by UNSCEAR but fall below internationally recommended dose limit of 1mSv yr⁻¹ set by ICRP for public. Higher indoor values were expected due to increased occupancy hours spent indoors coupled with minimal ventilation compared to outdoors. Indoor values were the main contributor to total (>85-90%) absorbed dose values received by individuals within study area. Mean annual gonadal dose equivalent follows similar trend with higher doses at specific locations where soils were enriched with radioactive elements causing high AGDE values.

ELCR values were estimated to be above the recommended acceptable range of 10⁻⁶-10⁻⁴ indicating long term cancer risks associated with residing within study area are high. Specific locations (ODS6, ODS7, ODS9, ODS18 and ODS19) were radiological hotspots due to enrichment of uranium and thorium-based rocks occur within these spots. The use of soil as construction material for buildings and domestic usage of soils may lead to intensified human illness. Testes and bone marrow received higher risk doses followed by whole body, lungs, ovaries. Higher doses to lungs show the significance of inhalation exposure particularly indoors where poor ventilation allow for easy accumulation of radon and dust. High testes doses could be linked to infertility issues among males residing within study area. Gonads (ovaries) are highly radiosensitive therefore exposure could lead to damage of reproductive cells affecting fertility of women leading to reproductive health issues within study area. Radioactivity increases chances of male and female infertility which has been confirmed as major issue within Nigeria (Georgakopoulos et al., 2024; Fukunaga et al., 2022). Bone marrow showed increased exposure. Radiation affects hematopoietic tissues therefore significant doses could lead to bone marrow failure leading to anemia, leukemia, and suppression of immune

system (Zhang et al., 2024). Higher indoor radionuclide activities translate to poor ventilation in houses compared to outdoors meaning Nigerians residing within study area are at risk if consistently exposed indoors (Zhang et al., 2024). Mean whole body radiation doses received indoors were almost twice that of outdoors suggesting higher radiation doses associated with indoor exposure than outdoor. Radiation doses to different organs received indoors were higher than outdoors except ovaries (Table 3). Reasons adduced for higher radiation doses indoors are longer occupancy hours coupled with poor ventilation. Individuals residing within study area are at more risk indoors than outdoors therefore attention should be given to improving house ventilation as well as limiting time spent indoors in high radon emission areas.

5. CONCLUSION

Natural radioactivity in soils from Ondo town, southwestern Nigeria were investigated for their spatial distribution, contamination assessment and radiological health risks assessment due to naturally occurring radionuclides of U-238, Th-232 and K-40. Results revealed that investigated soils have high activity concentrations of U-238 and K-40 above the global average and several Nigerian regional background reference sites, while activity concentrations of thorium were moderate above global mean background values. Geochemical behaviour of natural radionuclides of U-238, Th-232 and K-40 series observed in the study area are controlled by Precambrian Basement Complex lithology, mineralogy, enrichment, weathering process and redistribution of these radionuclides in soils within the study area near-surface horizon. Maps showed heterogeneous distributions of radionuclides and radium equivalent activity which may be attributed to localized influence of lithology of the area and geochemical distribution of uranium-, thorium- and potassium-bearing minerals.

The Igeo, CF, CD and PLI indices showed soils in Ondo town area have low to moderate pollution levels with enrichment dominated by uranium and potassium radionuclides. Radiological risk assessments of indoor exposure through soils used as building materials indicated increased radiological hazards due to exceeding recommended values of several dose indices like AGDE, AEDE and ELCR against worldwide average soil background reference. Radiological hazards were dominated by internal exposure pathways. Testes and bone marrow are the most radiosensitive organs when organ specific risks were considered. Correlation matrix and principal component analysis indicated dominance of K-40 in contributing towards external gamma radiation exposure and dose quantities while Th-232 was found to be dominant in gonadal and internal exposure pathways. Influence of uranium in radiation exposure quantities observed were generally low in Ondo town area soils.

Recommendations from the study included; systematic sampling within the study area considering micro-scale heterogeneity of radionuclides due to small sampling spots used during investigation. Seasonal variation of radioactivity concentrations and radon emanation were also recommended for future investigations. Samples from water, air and other possible exposure matrices such as locally produced building materials from Ondo town area should also be considered during future investigations. This study provides baseline dataset on environmental radiation exposure assessment for human health protection and sustainable environmental management within Ondo town and Southwestern Nigeria region.

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Disclosure Statement

The authors declare that there is no conflict of interest whatsoever

REFERENCES

- Abate, S. Y., 2022. Assessment of natural radioactivity levels and associated radiological hazards in soils from Ethiopia. *Journal of Environmental Radioactivity*, 240, 106750. <https://doi.org/10.1016/j.heliyon.2023.e19476>
- Adamopoulou, M., Makrynioti, D., Fouras, A., Koutsojannis, C., 2024. Human radiation-induced eye diseases: A scoping review towards in-silico experimental studies. *Ophthalmology Research Reports*, 8, 159.
- Adeola, A. O., Iwuozor, K. O., Akpomie, K. G., Adegoke, K. A., Oyedotun, K. O., Ighalo, J. O., Conradie, J., 2023. Advances in the management of radioactive wastes and radionuclide contamination in environmental compartments: A review. *Environmental Geochemistry and Health*,

- 45(6), 2663–2689. <https://doi.org/10.1007/s10653-022-01378-7>
- Adewumi, A. J., Laniyan, T. A., 2020. Contamination, sources and risk assessments of metals in media from Anka artisanal gold mining area, Northwest Nigeria. *Science of the Total Environment*, 718, 137235. <https://doi.org/10.1016/j.scitotenv.2020.137235>
- Adukpo, O. K., Tettey-Larbi, L., Darko, E. O., Kpeglo, D. O., 2014. Natural radioactivity levels and associated radiological hazards in soils from Ghana. *Journal of Radioanalytical and Nuclear Chemistry*, 301(2), 473–479.
- Ajaero, C. C., Madu, C. N., Okafor, C. C., Nnadi, V. E., Otunomo, F. A., 2025. Activity concentration levels of natural radionuclides in soils of Anambra State, South-East Nigeria. *Physics Open*, 100361. <https://doi.org/10.1016/j.physo.2025.100361>
- Akpan, A. E., Ebong, E. D., Ekwok, S. E., Eyo, J. O., 2020. Assessment of radionuclide distribution and associated radiological hazards for soils and beach sediments of Akwa Ibom coastline, southern Nigeria. *Arabian Journal of Geosciences*, 13(15), 753. <https://doi.org/10.1007/s12517-020-05727-7>
- Amrani, D., Tahtat, M., 2001. Natural radioactivity in Algeria building materials. *Applied Radiation and Isotopes*, 54, 687–689. [https://doi.org/10.1016/S0969-8043\(00\)00304](https://doi.org/10.1016/S0969-8043(00)00304)
- Asowata, I. T., Adisa, A. L., 2022. Trace element characterization of soils and rocks in agricultural areas of Labunwa, near Idanre, SW Nigeria. *Ife Journal of Science*, 24(2), 377–398. DOI: 10.21203/rs.3.rs-1219401/v1
- Bartol, I. R., Graffigna Palomba, M. S., Tano, M. E., Dewji, S. A., 2024. Computational multiphysics modeling of radioactive aerosol deposition in diverse human respiratory tract geometries. *Communications Engineering*, 3(1), 152. <https://doi.org/10.1038/s44172-024-00296-z>
- Bashier, E. H., Salih, I., Sam, A. K., 2012. GIS predictive mapping of terrestrial gamma radiation in the Northern State, Sudan. *Radiation Protection Dosimetry*, 151(3), 500–510. <https://doi.org/10.1093/rpd/ncs022>
- Darwish, D. A. E., Abul-Nasr, K. T. M., El-Khayatt, A. M., 2015. The assessment of natural radioactivity and associated radiological hazards in granite samples from South Sinai, Egypt. *Journal of Radiation Research and Applied Sciences*, 8(1), 17–25. <https://doi.org/10.1016/j.jrras.2014.10.003>
- Dike, R. S., Oni, O. M., Adeyemo, D. J., 2019. Assessment of natural radioactivity and associated radiological hazards in soil samples from mining areas in Nigeria. *Journal of Radiation Research and Applied Sciences*, 12(1), 1–8.
- Eke, E. E., Oyinloye, M. A., Olamiju, I. O., 2017. Analysis of urban expansion for Akure, Ondo State, Nigeria. *International Letters of Social and Humanistic Sciences*, 75, 41–55. DOI: 10.18052/www.scipress.com/ILSHS.75.41
- Epuh, E. E., Joshua, E. O., Elesho, A. O., Orji, M. J., Damilola, O. M., Adetoro, P. T., 2020. Groundwater potential mapping in Ondo State using multi-criteria analysis and hydrogeophysics. *Journal of Geology and Geophysics*, 9(4), 471. DOI: 9:471. 10.35248/2381-8719.20.9.471
- Evangelidou, N., Balkanski, Y., Cozic, A., Møller, A. P., 2013. Simulations of the transport and deposition of ¹³⁷Cs over Europe after the Chernobyl accident. *Atmospheric Chemistry and Physics*, 13(14), 7183–7198. <https://doi.org/10.5194/acp-13-7183-2013>
- Fukunaga, H., Yokoya, A., Prise, K. M., 2022. Radiation-induced effects on spermatogenesis and oncofertility: A brief overview. *Cancers*, 14(3), 805.
- Gaspar, L., Lizaga, I., Navas, A., 2021. Spatial distribution of fallout and lithogenic radionuclides controlled by soil carbon and water erosion. *Geoderma*, 391, 114941. <https://doi.org/10.1016/j.geoderma.2021.114941>
- Georgakopoulos, I., Kouloulas, V., Ntoumas, G. N., Desse, D., Koukourakis, I., Kougoumtzopoulou, A., Zygogianni, A., 2024. Radiotherapy and testicular function: Radiation-induced effects with emphasis on spermatogenesis. *Biomedicine*, 12(7), 1492. <https://doi.org/10.3390/biomedicines12071492>
- Habib, M. A., Akhi, S. Z., Khan, R., Phoungthong, K., Basir, M. S., Anik, A. H., Idris, A. M., 2024. Elevated environmental radioactivity in fluvial sediment: Origin and health risk assessment. *Environmental Science: Processes & Impacts*, 26(3), 555–581. <https://doi.org/10.1039/D3EM00493A>
- Idrisheva, Z., Uvaliyeva, I., Khassenova, Z., Amenova, F., Toktaganov, T., Daumova, G., 2025. Spatial and in-depth analysis of soil radioactivity using borehole gamma-ray surveys. *ES Energy and Environment*, 29, 1691. <https://doi.org/10.30919/esee1691>
- Idriss, H., Salih, I., Alaamer, A. S., Al-Rajhi, M. A., Osman, A., Adreani, T. E., Ali, N. I., 2018. Health risk profile for terrestrial radionuclides around artisanal gold mining areas, Sudan. *Acta Geophysica*, 66(4), 673–681. <https://doi.org/10.1007/s11600-018-0155-2>
- International Atomic Energy Agency (IAEA), 2003. Guidelines for radioelement mapping using gamma ray spectrometry data. IAEA-TECDOC-1363.
- Isinkaye, M. O., Emelue, H. U., Olatunji, M. A., 2015. Natural radioactivity measurements and dose rate assessment in soils from Ekiti State, Nigeria. *Journal of Radiation Research and Applied Sciences*, 8(3), 411–416. <https://doi.org/10.1016/j.jrras.2015.02.003>
- Jegede, D. O., Afolabi, T. A., Agunbiade, F. O., Ogundiran, O. O., Gbadamosi, M. R., Varanusupakul, P., 2025. Spatial distribution and radiological hazards of NORM in soils from quarry sites, Ogun State, Nigeria. *Environmental Monitoring and Assessment*, 197(5), 575. <https://doi.org/10.1007/s10661-025-13275-9>
- Jibiri, N. N., Okeyode, I. C., 2011. Assessment of natural radionuclides and radiological hazards from tiles made in Nigeria. *Radiation Protection Dosimetry*, 147(4), 555–560. <https://doi.org/10.1093/rpd/ncr307>
- Joel, E. S., Omeje, M., Olawole, O. C., Adeyemi, G. A., Akinpelu, A., Embong, Z., Saeed, M. A., 2021. In-situ assessment of terrestrial radioactivity and health implications in a coastal urban environment. *Scientific Reports*, 11(1), 17555. <https://doi.org/10.1038/s41598-021-96516-z>
- Laniyan, T. A., Adewumi, A. J., 2021. Health risk profile of natural radionuclides in soils, sediments, tailings and rocks around mining sites in Nigeria. *Environmental Earth Sciences*, 80(10), 375. <https://doi.org/10.1007/s12665-021-09674-8>
- Li, H., Wang, Q., Zhang, C., Su, W., Ma, Y., Zhong, Q., Xiao, T., 2024. Geochemical distribution and environmental risks of radionuclides in a uranium mining area, South China. *Toxics*, 12(1), 95. <https://doi.org/10.3390/toxics12010095>
- Mejía-Piña, K. G., Huerta-Díaz, M. A., González-Yajimovich, O., 2016. Calibration of handheld XRF equipment for sediment analysis. *Talanta*, 161, 359–367. <https://doi.org/10.1016/j.talanta.2016.08.061>
- Michalik, B., 2017. NORM contaminated area identification using radionuclide activity patterns in soil. *Journal of Environmental Radioactivity*, 173, 102–111. <https://doi.org/10.1016/j.jenvrad.2017.03.012>
- Obrador, E., Salvador-Palmer, R., Villaescusa, J. I., Gallego, E., Pellicer, B., Estrela, J. M., Montoro, A., 2022. Nuclear and radiological emergencies: Biological effects and countermeasures. *Antioxidants*, 11(6), 1098. <https://doi.org/10.3390/antiox11061098>
- Omeje, M., Olusegun, A. O., Joel, E. S., PraiseGod, E. C., Akinwumi, S., Saeed, M. A., 2018. Natural radioactivity in commercial building materials and lifetime cancer risk. *Human and Ecological Risk Assessment*, 24(8), 2036–2053. <https://doi.org/10.1080/10807039.2018.1458593>
- Popoola, O. J., Olubi, O. E., Adewalure, O. S., 2025. Elevated natural radionuclides in soils and stream sediments: Pollution and cancer risks in Emure-Ekiti, SW Nigeria. *Discover Soil*, 2, 70. <https://doi.org/10.1007/s44378-025-00074-z>
- Popoola, O. J., Olubi, O. E., Bamidele, S. E., Adepoju, A. O., 2025a. Geochemical distribution and radiological health hazards of radionuclides in Idanre area, SW Nigeria. *Discover Geoscience*, 3(1), 1–29. DOI: 10.1007/s44288-025-00243-1
- Pouget, J. P., Constanzo, J., 2021. Revisiting the radiobiology of targeted alpha therapy. *Frontiers in Medicine*, 8, 692436. DOI: 10.3389/fmed.2021.692436
- Rabi, R., Oufni, L., 2025. CFD modeling of radon progeny transport in the human respiratory tract. *European Physical Journal Plus*, 140(4), 292. <https://doi.org/10.1140/epjp/s13360-025-06128-z>
- Ravisankar, R., Chandramohan, J., Chandrasekaran, A., Jebakumar, P. P. P., Vijayalakshmi, L., Vijayagopal, P., Venkatraman, B., 2012. Natural radioactivity in soils of Yelagiri Hills, Tamil Nadu, India and the associated radiation hazards. *Radiation Physics and Chemistry*, 81(12),

- 1789–1795. <https://doi.org/10.1016/j.radphyschem.2012.07.003>
- Roy, I., Krishnan, S., Kabashin, A. V., Zvestovskaya, I. N., Prasad, P. N., 2022. Transforming nuclear medicine with nanoradiopharmaceuticals. *ACS Nano*, 16(4), 5036–5061. DOI: 10.1021/acsnano.1c10550
- Samreh, M. M., Al-Awad, F. A., 2015. Natural radioactivity levels and radiation hazards in soils from Jordan. *Journal of Radiation Research and Applied Sciences*, 8(4), 459–465.
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000. Sources and effects of ionizing radiation. United Nations, New York.
- United States Nuclear Regulatory Commission (USNRC), 2017. Radiation protection: Dose limits. USNRC, Washington DC.
- UNSCEAR, 1993. Sources and effects of ionizing radiation. United Nations, New York.
- UNSCEAR, 2008. Sources and effects of ionizing radiation report. United Nations, New York.
- Usikalu, M. R., Achuka, J. A., Babalola, A. D., Adewoyin, O. O., 2020. Natural radioactivity levels and radiological hazards in soils from Ota, Nigeria. *Journal of Radiation Research and Applied Sciences*, 13(1), 1–8.
- Verma, D. K., Rameshwari, R., Meena, J., 2025. Health and environmental risk of alpha emitter radium. In: *Hazardous Chemicals*, 713–722. Academic Press. <https://doi.org/10.1016/B978-0-323-95235-4.00015-3>
- Wang, Q., Wang, H., Ma, Y., Wang, J., Su, W., Xiao, E., Zhong, Q., 2023. Geochemical distributions of radionuclides impacted by Pb-Zn mining. *Ecotoxicology and Environmental Safety*, 263, 115210. <https://doi.org/10.1016/j.ecoenv.2023.115210>
- Yang, J., Sun, Y., Wang, Z., Gong, J., Gao, J., Tang, S., Duan, Z., 2022. Heavy metal pollution in agricultural soils of a volcanic area. *Chemosphere*, 304, 135340. <https://doi.org/10.1016/j.chemosphere.2022.135340>
- Yasutaka, T., Naito, W., Nakanishi, J., 2013. Cost and effectiveness of decontamination strategies in Fukushima. *PLoS One*, 8(9), e75308. <https://doi.org/10.1371/journal.pone.0075308>
- Yoshida-Ohuchi, H., Matsuda, N., Saito, K., 2019. Review of reduction factors by buildings for gamma radiation from radiocaesium fallout. *Journal of Environmental Radioactivity*, 210, 105810. <https://doi.org/10.1016/j.jenvrad.2018.02.006>
- Zhang, Y., Chen, X., Wang, X., Chen, J., Du, C., Wang, J., Liao, W., 2024. Insight into ionizing radiation-induced bone marrow hematopoietic stem cell injury. *Stem Cell Research & Therapy*, 15(1), 222. doi: 10.1186/s13287-024-03853-7
- Zhang, Y., Li, X., Wang, Z., 2018. Environmental sampling and analysis techniques for soil and sediment studies. *Environmental Science & Technology*, 52(15), 8456–8464.
- Zuccarini, P., Sardans, J., Asensio, L., Peñuelas, J., 2023. Altered activities of extracellular soil enzymes under global environmental change. *Global Change Biology*, 29(8), 2067–2091. DOI: 10.1111/gcb.16604

