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Distribution of Natural Radionuclides and Associated Radiological Risks in Soils and River Sediments from Ibeno, Niger Delta, Nigeria

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ABSTRACT
Determination of natural radioactivity level in environmental media is necessary to evaluate the possible sources of radiation exposure to man in an environment dominated by industrial activities. In present investigation, soil and sediment samples were collected within Ibeno Local Government Area, Akwa Ibom State, Nigeria and analysed for the concentrations of natural radionuclides (^{40}K, ^{238}U, ^{232}Th).The activity concentrations of the natural radionuclides were determined by gamma-ray spectrometry with a NaI[Tl] detector. Knowledge of the radiological health hazards of natural radionuclides was obtained by calculating different health hazard indices The mean activity concentrations were 43.08 ± 8.19, 3.71 ± 3.30 and 17.98 ± 10.75 Bq/kg for ^{40}K, ^{238}U, and ^{232}Th respectively, in sediments while the activity concentrations were 121.04 ± 30.11, 8.79 ± 5.39, 43.31 ± 17.48 Bq/kg respectively in soils. The activity of ^{40}K and ^{238}U were found to be lower than the worldwide mean values recommended by UNSCEAR in both media. ^{232}Th on the other hand revealed some degrees of enrichment at some locations for soils samples relative to those of sediments. The recorded dose rates of 7.58 - 28.22 nGy/h in sediments and 16.19 - 47.85 nGy/h in soils were also found to be lower than the world mean value of 59 nGy/h. AED, ELCR, Ra_{eq}, H_{ex} and H_{in} all showed lower values below acceptable safety levels. The results indicate that soils exhibited higher radionuclide concentrations and radiological burdens than sediments, with thorium contributing most significantly to the observed dose rates. The study demonstrates that the current levels of natural radioactivity in the Ibeno environment pose negligible radiological risks to the public, although continued environmental monitoring is recommended due to ongoing oil and gas activities.
Keywords; Soil and sediment samples, natural radionuclide, radiological risk, Ibeno LGA,

1.0 INTRODUCTION

The Niger Delta region of Nigeria is one of the most productive hydrocarbon producing provinces in the world, and has been the target of decades of heavy oil and gas exploration, production, transportation and processing activities. These activities have been linked to the generation and redistribution of Naturally Occurring Radioactive Materials (NORMs), especially the uranium and thorium decay series radionuclides (Omorotionmwan & Ighariemu, 2022; Okoro et al., 2025). Radionuclides can be released from oil extraction and production activities into the production water, drilling wastes, scales, sludge and sediments, and become more mobile and available for human exposure. A number of studies have reported that the natural radioactivity concentration in oil-producing environments could be higher than in

non-industrial environments, and therefore, continuous radiological monitoring is needed to guarantee environmental safety and regulatory compliance (Akpan et al., 2020; Omorotionmwan & Ighariemu, 2022; Okoro et al., 2025).

Deterministic and stochastic health effects may be caused by exposure to high doses of ionizing radiation. Deterministic effects only occur at relatively high dose thresholds, while stochastic effects like induction of cancer or hereditary genetic alterations can occur at low radiation doses and increase with radiation dose (ICRP, 2020; UNSCEAR, 2020). Chronic exposure to environmental radionuclides has been linked to higher risk of leukemia, lung cancer, bone cancer and other radiation-induced diseases. Uranium and thorium are also sources of internal radiation exposure via the inhalation and ingestion routes, and their decay products, such as radon and its progeny, are also sources of health concern (UNSCEAR, 2020; Eyibio et al., 2024). Hence, the assessment of radionuclide concentrations in soils and sediments is crucial to estimate the radiation doses and to assess if the environmental conditions are below the internationally accepted safety limits (Eyibio et al., 2023; Ekanem et al., 2025).

International organizations, including the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) have developed radiation protection frameworks and dose limits (ICRP, 2020; UNSCEAR, 2020) to protect humans and the environment from the harmful effects of ionizing radiation. One of the fundamental principles of radiation protection is the As Low As Reasonably Achievable (ALARA) principle, which is to keep radiation exposures as low as reasonably possible, taking into account economic and social considerations. The ALARA philosophy is achieved by three basic principles: justification of practices that involve radiation exposure, optimization of protection and dose limitation (ICRP, 2020). Environmental radioactivity assessments are thus the scientific basis for assessing compliance with these principles and for supporting evidence-based environmental management decisions (UNSCEAR, 2020).

The models and indices used for the assessment of radiological health risks from environmental radionuclides are generally accepted internationally, such as absorbed dose rate, annual effective dose equivalent, radium equivalent activity, external and internal hazard indices, annual gonadal equivalent dose, gamma representative index and excess lifetime cancer risk (UNSCEAR, 2020; Akpan et al., 2020). These models offer quantitative estimates of the potential radiological impact from environmental exposure and allow comparison with internationally recommended reference values. These indices can be used together to assess the radiation hazards caused by the naturally occurring radionuclides in soils and sediments (Amodu et al., 2024; Omorotionmwan & Ighariemu, 2022; Okoro et al., 2025).

In addition to the traditional radiological risk assessment, the contemporary environmental radioactivity studies increasingly use advanced statistical and multivariate analytical methods to enhance the interpretation of radionuclide data. Descriptive statistics, correlation analysis, principal component analysis, hierarchical cluster analysis and uncertainty-based approaches have been useful in determining the relationship between radionuclides, possible sources and factors affecting the distribution of radionuclides in the environment (Amodu et al., 2024; Omorotionmwan & Ighariemu, 2022; Okoro et al., 2025). The use of statistical methods plays an important role in the understanding of the factors controlling radionuclide distribution and the relative contribution of various radionuclides to the total health risk.

The distribution and the associated radiological risks of the natural radionuclides in the coastal and oil producing areas of southern Nigeria have been subject to several studies. Akpan et al. (2020) found that the activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the soils and beach sediments of the study area were generally within the international safety limits, but there were some local variations which were explained by the geological and depositional conditions. In a similar vein, Esi et al. (2024) analysed sediment samples from the southern coastal area of Delta State and found that some of the samples had high radiological hazard indices, which were attributed to hydrocarbon exploration activities, hence the need for regular monitoring.

The transfer of radionuclides, environmental exposure pathways and health risks in agricultural soils and riverine environment in other Nigerian studies have confirmed that uranium-, thorium- and potassium-

series radionuclides are still the main contributors to natural radiation exposure. In addition, recent investigations have increasingly been based on multivariate statistical methods and collectively, these investigations have provided valuable baseline information; but, comprehensive assessment of soils and river sediments in the oil-producing communities of Ibeno has been limited and is therefore needed for the present investigation.

The distribution of natural radionuclides and the associated radiological risks in the coastal and oil producing environment of Southern Nigeria have been the subject of several studies (Osiga Aibangbee et al., 2025). For instance, Omeje et al. (2023) reported high gamma dose rates in the Unumherin community and Iwetan et al. (2015) evaluated radionuide concentrations in sediments of Delta State. Omeje et al. (2024) also studied the distribution of radioactivity and biohazard risks in coastal marine environments. Agbalagba and Oghenevovwero Emmanuel (2023) and Olise et al. (2013) have assessed the naturally occurring radioactive materials (NORMs) and radionuclides and trace metals in soils and shale samples from the Niger Delta, respectively.

The transfer of radionuclides, the environmental exposure pathways, and the health effects of radionuclides in agricultural soils and riverine environments have been assessed in other Nigerian studies, which showed that uranium, thorium, and potassium series radionuclides are the most dominant contributors to natural radiation exposure (Omeje et al., 2023; Iwetan et al., 2015).

The radiological properties of soils and river sediments in the oil-producing communities of Ibeno are still not well known, despite a number of investigations that have been conducted in the region on environmental radioactivity in various locations in the Niger Delta. Most of the existing studies have concentrated on the wider coastal area or on a single environmental medium, with a lack of focus on the integrated assessment of radionuclide distribution, radiological hazards and statistical relationships in soils and sediments from this environmentally sensitive area (Akpan et al., 2020; Eyibio et al., 2024). Considering the strategic economic importance of Ibeno and the potential influence of petroleum-related activities on environmental quality, there is a need for updated baseline data to support environmental monitoring and radiological protection programs.

The current study aims to determine the concentrations of natural radionuclides (^{238}U, ^{232}Th and ^{40}K) in soil and sediment samples from Ibeno, Akwa Ibom State, Nigeria and to evaluate the radiological health risks associated with these radionuclides. In particular, the study aims at quantifying the activity concentration of radionuclides, assessing the radiological hazard parameters, comparing the results with the internationally accepted safety limits and using statistical analysis to find the relationship between radionuclides, distribution patterns and possible sources. The results of this study will give baseline radiological information to the area, improve environmental radiation monitoring, aid in the regulation decision making and contribute to the sustainable management of oil-producing environments in Ibeno Local Government Area (Omorotionmwan & Ighariemu, 2022; Okoro et al., 2025).

2.0 MATERIALS AND METHOD

Description of the study area

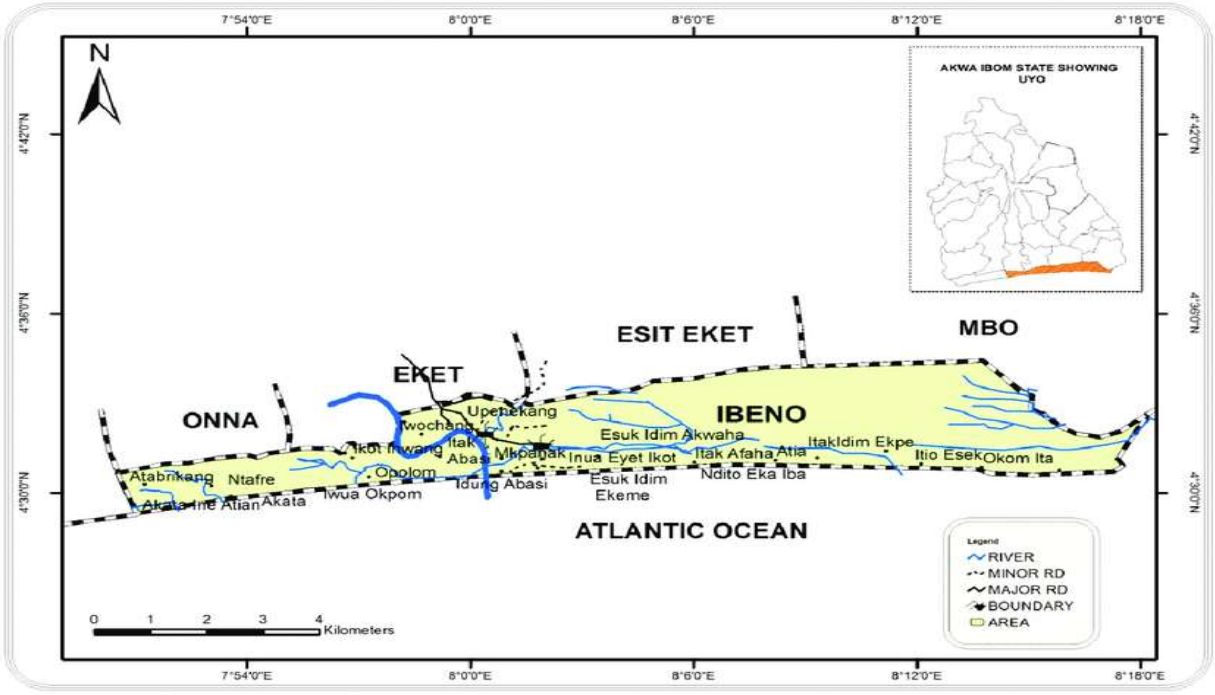

Figure 1. Map of the Ibeno LGA showing communities and rivers (Abraham et al., 2021)

Ibeno Local Government Area of Akwa Ibom State is strategically located along the south eastern coast of Nigeria and has the largest petroleum exploration and production facilities in the state such as the Qua Iboe Terminal and associated oil infrastructure. It is a region of large coastal plains, mangrove swamps, river systems, estuaries and sedimentary deposits that can serve as reservoirs for naturally occurring radionuclides and industrial contaminants. The Ibeno River and its sediments are important environmental compartments where radionuclides can be introduced via erosion, sedimentation, weathering of geological formations and oil-related activities. Fishing, agriculture, transportation and domestic activities are all dependent on the surrounding environment of local communities and any rise in radioactivity in the environment could impact the ecological integrity and public health of the communities (Akpan et al., 2020; Esi et al., 2024).

Collection, preparation and analysis of samples.

Eight surface soil samples (0-15 cm) were taken from the communities along the Ibeno River, Akwa Ibom State, Nigeria. A stainless steel grab sampler was also used to collect sediment samples from the riverbed. Each sample (approx. 2 kg) was bagged in polythene, labeled and sent to the laboratory. Samples were air dried at room temperature for 72 hours and then oven dried at 105 °C until a constant weight was reached (Weyrich et al., 2019). Each sample was ground and sieved through a 2 mm mesh and 250 g of each sample was placed in a Marinelli beaker and allowed to stand for 30 days to allow secular equilibrium. A thallium-activated sodium iodide (NaI(Tl)) detector was used to measure the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K.

The activity concentration (Ac) of a radionuclide in a sample of mass m(s) is determined from the net count rate using (Axelsson and Ringbom, 2014):

$$A_c = \frac{C_n}{\varepsilon(E) P_\gamma m(s)} \quad (1)$$

where ε(E) is the detector efficiency at the gamma-ray energy of interest (counts/Bq), P_γ is the gamma emission probability of the radionuclide, and C_n is the net count rate

Calculation of radiological health indices

Radiological hazard indices were computed from the measured activity concentrations of radionuclides using standard models recommended by international bodies (UNSCEAR, 2000; ICRP, 2007). These indices provide quantitative measures of potential radiation exposure and associated health risks.
The following parameters were derived using standard formulations.

Absorbed dose rate ($\dot{D}$, nGy h^{-1}):

$\dot{D} = 0.462A_{ra} + 0.604A_{th} + 0.0417A_k$ (Darko et al., 2015) (2)

where A_{ra}, A_{th}, and A_k are activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Bq kg^{-1}).

Annual effective dose (AED, mSv y^{-1}):

$AED = \dot{D} \times 8760 \times OF \times 0.7 \times 10^{-6}$ (AL-abrdi, 2023) (3)

Occupancy factor (OF) = 0.2 (outdoor).

Annual gonadal dose (AGD, µSv y^{-1}):

$AGD = 3.09A_{ra} + 4.18A_{th} + 0.314A_k$ (UNSCEAR, 2000) (4)

Excess lifetime cancer risk (ELCR, $\times 10^{-3}$):

$ELCR = AED \times 55 \times 0.05$ (ICRP, 2007) (5)

where 55 y is average lifespan (Nigeria) and 0.05 Sv^{-1} is the risk factor.

Radium equivalent activity ($R_{ae}q$, Bq kg^{-1}):

$R_{ae}q = A_{ra} + 1.43A_{th} + 0.077A_k$ (Beretka & Mathew, 1985) (6)

External hazard index (H_{ex}):

$H_{ex} = A_{ra}/370 + A_{th}/259 + A_k/4810$ (UNSCEAR, 2000) (7)

Internal hazard index (H_{in}):

$H_{in} = A_{ra}/185 + A_{th}/259 + A_k/4810$ (UNSCEAR, 2000) (8)

For H_{ex} and H_{in}, values less than inity indicate acceptable hazard levels.

All statistical analyses were performed using MATLAB (version R2023b). Descriptive statistics were computed for activity concentrations of ^{40}K, ^{238}U, and ^{232}Th in sediment (IST1–8) and soil (ISL1–8) samples, as well as for the corresponding absorbed dose rates (D, nGy/h). Normality of the data was assessed using Shapiro–Wilk tests ($p > 0.05$ considered normal) and visual inspection of Q-Q plots; non-normal variables were log-transformed where appropriate

3.0 RESULTS AND DISCUSSION

The activity concentrations of ^{40}K, ^{238}U, and ^{232}Th measured in sediment samples collected from the Ibeno River are presented in Table 1. The mean activity concentrations were 43.08 ± 8.19, 3.71 ± 3.30, and 17.98 ± 10.75 Bq kg^{-1} for ^{40}K, ^{238}U, and ^{232}Th, respectively. These values are considerably lower than the worldwide average values of 400, 35, and 30 Bq kg^{-1} recommended by UNSCEAR (2000), indicating that the river sediments are characterized by relatively low natural radioactivity levels.

Among the investigated radionuclides, ^{40}K exhibited the highest mean activity concentration, although its values remained substantially below the global average. The observed potassium concentrations are markedly lower than those reported by Osiga-Aibangbee et al. (2025) for Niger Delta sediments, where ^{40}K ranged from 294.29 to 774.40 Bq kg^{-1}, and considerably lower than the mean value of 1586.80 Bq

kg^{-1} reported by Esi et al. (2026) for coastal sediments in the Niger Delta. Similarly, the mean ^{232}Th concentration obtained in the present study (17.98 Bq kg^{-1}) was lower than the 46.90 Bq kg^{-1} reported by Esi et al. (2026), while the mean ^{238}U concentration (3.71 Bq kg^{-1}) was substantially lower than the 27.25 Bq kg^{-1} observed in the same study. These differences may reflect variations in geological settings, sediment mineralogy, hydrodynamic sorting processes, and the degree of influence from petroleum-related activities across different parts of the Niger Delta.

The present results are, however, comparable to those reported by Sombo et al. (2017) for shore sediments from River Benue, where average concentrations of 1.17, 3.31, and 405.95 Bq kg^{-1} were reported for ^{238}U, ^{232}Th, and ^{40}K, respectively. While uranium concentrations in both studies are similar, the Ibeno sediments exhibited higher thorium concentrations but substantially lower potassium levels. Such differences highlight the influence of local geological formations and depositional environments on radionuclide distribution.

Although the thorium concentration at sampling location IST4 (42.03 ± 2.42 Bq kg^{-1}) exceeded the global reference value, the overall sediment profile suggests limited radiological enrichment. The spatial variability observed across sampling points may be attributed to sediment transport processes, differential accumulation of heavy minerals, weathering of parent materials, and localized anthropogenic inputs associated with oil exploration and transportation activities. Overall, the low radionuclide concentrations indicate that significant accumulation of technologically enhanced naturally occurring radioactive materials (TENORMs) has not occurred within the river sediments despite decades of petroleum operations in the area.

Table 1. Mean activity concentration assessed radionuclides in Sediment samples from different locations in the Ibeno River

Sample code	**K-40 Bq/kg**	**U-238 Bq/kg**	**Th-232 Bq/kg**
IST1	35.70 ± 1.81	1.74 ± 0.23	9.32 ± 0.54
IST2	32.28 ± 1.56	0.02 ± 0.00	10.31 ± 0.58
IST3	45.03 ± 2.17	6.00 ± 0.45	15.81 ± 0.88
IST4	38.23 ± 1.93	2.69 ± 0.33	42.03 ± 2.42
IST5	53.41 ± 2.70	3.17 ± 0.40	20.88 ± 1.21
IST6	35.70 ± 1.81	1.74 ± 0.23	9.32 ± 0.54
IST7	54.65 ± 2.64	2.96 ± 0.22	25.97 ± 1.45
IST8	49.66 ± 2.53	11.36 ± 1.25	10.37 ± 5.79
Mean	43.08 ±8.19	3.71 ± 3.30	17.98 ± 10.75
Recommended standard	400	35	30

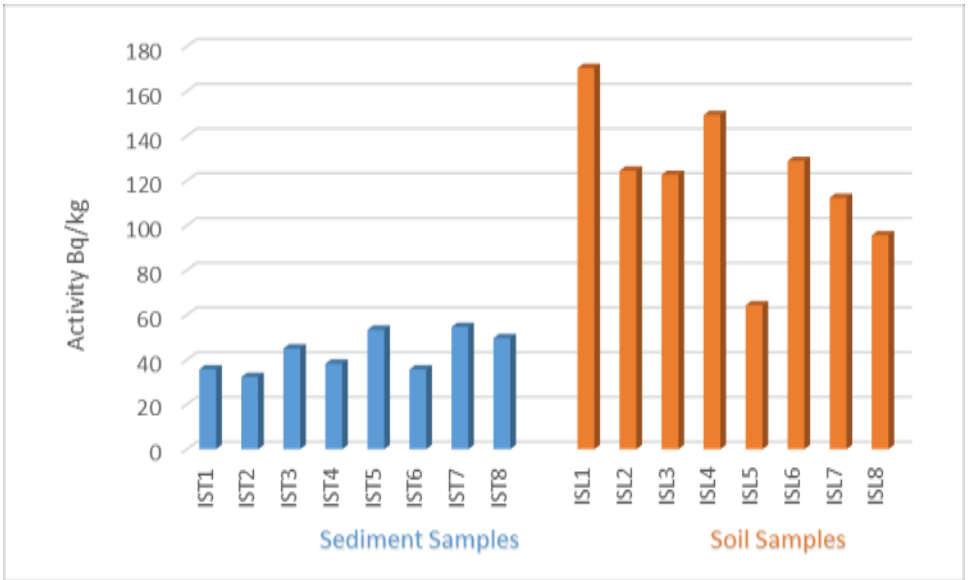

Figure 2. Comparison of activity concentration of ^{40}K in sediment and soil samples from Ibeno LGA

The activity concentrations of naturally occurring radionuclides in soil samples collected from communities within Ibeno Local Government Area are presented in Table 2. The mean activity concentrations of ^{40}K, ^{238}U, and ^{232}Th were 121.04 ± 30.11, 8.79 ± 5.39, and 43.30 ± 17.48 Bq kg^{-1}, respectively. Similar to the sediment samples, the mean concentrations of ^{40}K and ^{238}U were below the corresponding world average values of 400 and 35 Bq kg^{-1}. However, the mean ^{232}Th concentration exceeded the global reference value of 30 Bq kg^{-1}, suggesting moderate thorium enrichment within some locations of the study area.

The elevated thorium concentrations observed in ISL1, ISL2, ISL4, and ISL8 indicate localized accumulation of thorium-bearing minerals, possibly arising from geological controls, weathering processes, and anthropogenic disturbances linked to oil exploration activities. The predominance of thorium is consistent with the statistical analysis, which identified ^{232}Th as the principal contributor to external gamma dose rates in the study area. A visual of the activity of radionuclides present in soil are depicted in Figure 2 to Figure 4..

Compared with other studies, the mean ^{40}K concentration obtained in the present work is lower than the values reported by Chetty and Ilori (2024), who observed ^{40}K concentrations ranging from 357.46 to 504.25 Bq kg^{-1} in agricultural soils of southwestern Nigeria. Similarly, the mean ^{238}U concentration recorded in this study is lower than the values reported by Ghazal et al. (2024) for Iraqi soils (26.19 Bq kg^{-1}) and by Ba et al. (2019) for soils from Ho Chi Minh City, Vietnam (23–33 Bq kg^{-1}). In contrast, the mean thorium concentration of 43.30 Bq kg^{-1} is higher than the 18.66 Bq kg^{-1} reported by Ghazal et al. (2024) and the 22–25 Bq kg^{-1} reported by Ba et al. (2019), but lower than the values ranging from 81.15 to 147.23 Bq kg^{-1} reported by Adebayo et al. (2026) for agricultural soils in southwestern Nigeria.

The observed radionuclide concentrations also compare favorably with those reported by Legasu and Chaubey (2022) for soils in Dessie City, Ethiopia, where mean concentrations of 26.59, 26.59, and 115.65 Bq kg^{-1} were reported for 226Ra, ^{232}Th, and ^{40}K, respectively. The similarity in potassium levels but higher thorium concentration in the present study further highlights the influence of local geological characteristics on radionuclide distribution. The generally higher radionuclide concentrations observed in soils compared with sediments may be attributed to prolonged weathering, adsorption onto clay minerals, organic matter retention, and reduced radionuclide mobility within terrestrial environments.

Table 2. Mean activity concentration of assessed radionuclides in soil samples from different communities along the Ibeno River

Sample code	K-40 Bq/kg	U-238 Bq/kg	Th-232 Bq/kg
ISL1	170.43 ± 8.57	14.46 ± 1.48	56.40 ± 3.25
ISL2	124.53 ± 6.30	12.11 ± 1.31	61.09 ± 3.52
ISL3	122.65 ± 6.14	5.57 ± 0.62	37.33 ± 2.15
ISL4	149.41 ± 7.52	11.41 ± 1.31	59.23 ± 3.42
ISL5	64.34 ± 3.26	1.28 ± 0.17	21.39 ± 1.24
ISL6	128.87 ± 6.48	9.76 ± 1.01	14.87 ± 0.86
ISL7	112.40 ± 5.69	15.37 ± 1.48	35.09 ± 2.03
ISL8	95.65 ± 4.82	0.35 ± 0.04	60.97 ± 3.51
Mean	121.04 ± 30.11	8.79 ± 5.39	43.30 ± 17.48
Recommended standard (UNSCEAR, 2000)	400	35	30

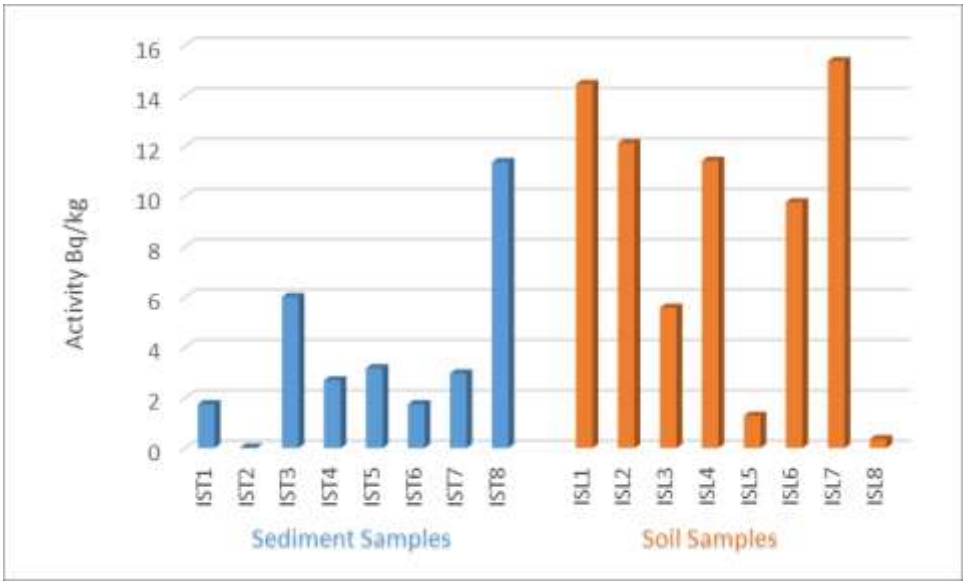

Figure 3. Comparison of activity concentration of ^{238}U in sediment and soil samples from Ibeno LGA

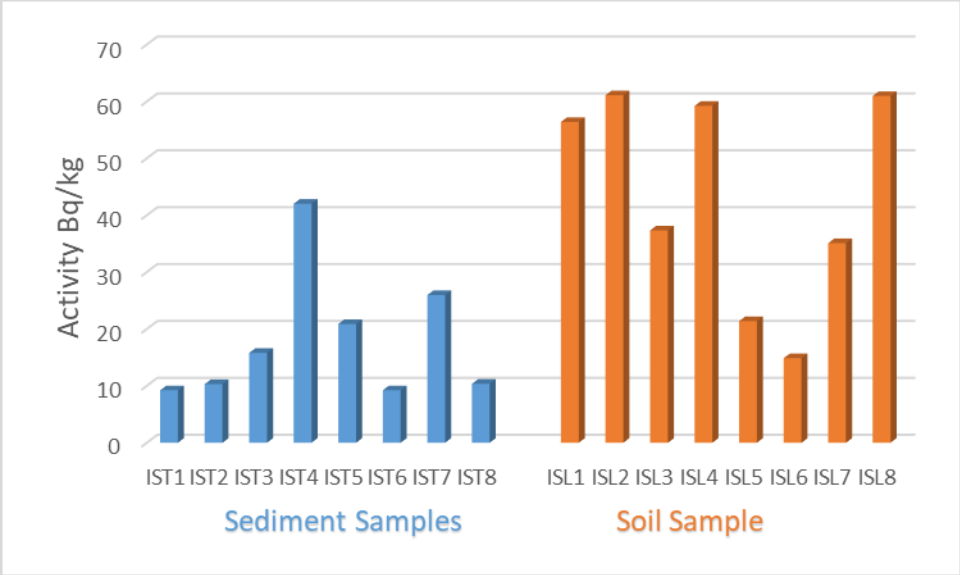

Figure 4. Comparison of activity concentration of ^{232}Th in sediment and soil samples from Ibeno LGA

Radiological Health Risk Assessment

The radiological health risk parameters estimated from the measured radionuclide activities provide an integrated assessment of the potential exposure pathways and health implications associated with environmental radioactivity in the study area. In general, all evaluated indices indicate low radiological risk despite the moderate enrichment of thorium observed in some soil locations.

The absorbed dose rate ranged from 7.58 to 28.22 nGy h^{-1} in sediments and from 16.19 to 47.85 nGy h^{-1} in soils. These values are below the global average value of 59 nGy h^{-1} recommended by UNSCEAR (2000). The mean dose rates are also substantially lower than those reported by Ankapong et al. (2024) for Ghanaian mining and non-mining districts, where absorbed dose rates ranged from 198 to 224 nGy h^{-1}. Similarly, the obtained values are lower than the mean dose rate of 107.80 nGy h^{-1} reported by Esi et al. (2026) for Niger Delta coastal sediments. The relatively low dose rates suggest limited external gamma exposure to residents of the study area.

The annual effective dose equivalent (AEDE) values ranged from 0.01–0.03 mSv y^{-1} in sediments and 0.02–0.06 mSv y^{-1} in soils, remaining well below the public exposure limit of 1 mSv y^{-1}. These values are comparable to the 0.08 mSv y^{-1} reported by Legasu and Chaubey (2022) and lower than the 0.13 mSv y^{-1} reported by Esi et al. (2026). The results therefore indicate that annual radiation exposure from natural radionuclides in the study area is unlikely to result in significant adverse health effects.

The annual gonadal equivalent dose (AGED) ranged from 53.29 to 196.00 µSv y^{-1} for sediments and from 113.57 to 333.95 µSv y^{-1} for soils. These values are comparable to the range of 162.33–350.97 µSv y^{-1} reported by Ghazal et al. (2024). Although AGED at ISL1 slightly exceeded the reference value of 300 µSv y^{-1}, the majority of locations remained within acceptable limits, suggesting minimal hereditary and genetic risks to the exposed population.

The excess lifetime cancer risk (ELCR) values varied from 0.03×10^{-3} to 0.10×10^{-3} in sediments and from 0.05×10^{-3} to 0.16×10^{-3} in soils. These values are below the recommended world average value of 0.29×10^{-3} and substantially lower than the approximately 4.6×10^{-3} reported by Esi et al. (2026). The low ELCR values indicate that the probability of developing radiation-induced cancer due to long-term environmental exposure in the study area is negligible.

Radium equivalent activity (Raeq) values ranged from 17.25 to 65.74 Bq kg^{-1} in sediments and from 36.82 to 109.06 Bq kg^{-1} in soils. These values are significantly below the recommended safety limit of 370 Bq kg^{-1} and lower than the mean value of 396.21 Bq kg^{-1} reported by Osiga-Aibangbee et al. (2025) for Niger Delta sediments. Similarly, the values fall within or below the range of 48.20–105.49 Bq kg^{-1} reported by Ghazal et al. (2024). The low Raeq values confirm that the combined contribution of the investigated radionuclides does not constitute a significant radiological hazard.

The external hazard index (H_ex) and internal hazard index (H_in) remained below unity for all samples, with H_ex ranging from 0.05 to 0.29 and H_in ranging from 0.05 to 0.33. These values are comparable to those reported by Ghazal et al. (2024), who observed H_ex and H_in values ranging from 0.13–0.28 and 0.17–0.38, respectively. Since both indices are considerably less than the recommended threshold value of one, the risks associated with external gamma exposure and internal radon inhalation are considered insignificant.

Overall, the radiological assessment indicates that the soils and sediments of Ibeno exhibit low to moderate levels of natural radioactivity. Although thorium concentrations in some soil locations exceeded the global average, the resulting radiological hazard indices remained well within internationally accepted limits. Compared with several studies conducted in other parts of Nigeria, Ghana, Iraq, Ethiopia, and Vietnam, the radiological burden observed in the present study is generally lower, indicating a relatively safe environmental condition. Nevertheless, the dominance of thorium as the primary contributor to dose rate and radiological risk highlights the need for continued environmental surveillance, particularly in view of ongoing petroleum exploration and production activities within the region.

Table 3. Health risks estimated from the activity of soil and sediment samples in Ibeno LGA

Sample code	D (nGy/h)	AEDE (mSv/y)	AGED (uSv/y)	ELCR X10-3	Raeq Bq/Kg	Hex (mSv/y)	Hin (mSv/y)
				Sediments			
IST1	7.87	0.01	55.17	0.03	17.69	0.05	0.05
IST2	7.58	0.01	53.29	0.03	17.25	0.05	0.05
IST3	14.20	0.02	98.77	0.05	32.08	0.09	0.10
IST4	28.22	0.03	196.00	0.10	65.74	0.18	0.18
IST5	16.30	0.02	113.84	0.05	37.14	0.10	0.11
IST6	7.87	0.01	55.17	0.03	17.69	0.05	0.05
IST7	19.33	0.02	134.86	0.07	44.31	0.12	0.13
IST8	13.58	0.02	94.04	0.05	30.01	0.08	0.11
				Soil			
ISL1	47.85	0.06	333.95	0.16	108.24	0.29	0.33
ISL2	47.69	0.06	331.88	0.16	109.06	0.29	0.33
ISL3	30.24	0.04	211.76	0.10	68.40	0.18	0.20
ISL4	47.28	0.06	329.75	0.16	107.61	0.29	0.32
ISL5	16.19	0.02	113.57	0.05	36.82	0.10	0.10
ISL6	18.86	0.02	132.78	0.06	40.95	0.11	0.14
ISL7	32.98	0.04	229.46	0.11	74.20	0.20	0.24
ISL8	40.98	0.05	285.97	0.14	94.90	0.26	0.26
Recommended standard (UNSCEAR, 2000)	59	1	300	0.29	370	1	1

Statistical analysis

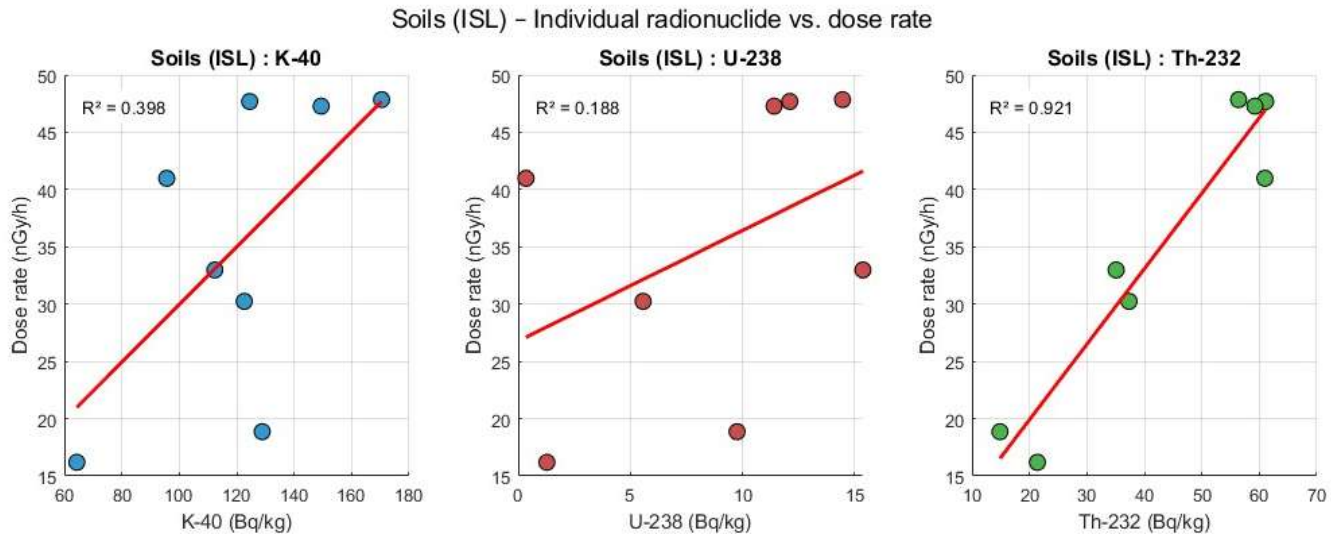

Figure 5. Scatter plots from multiple regression analysis of radionuclides in sediment against dose rate.

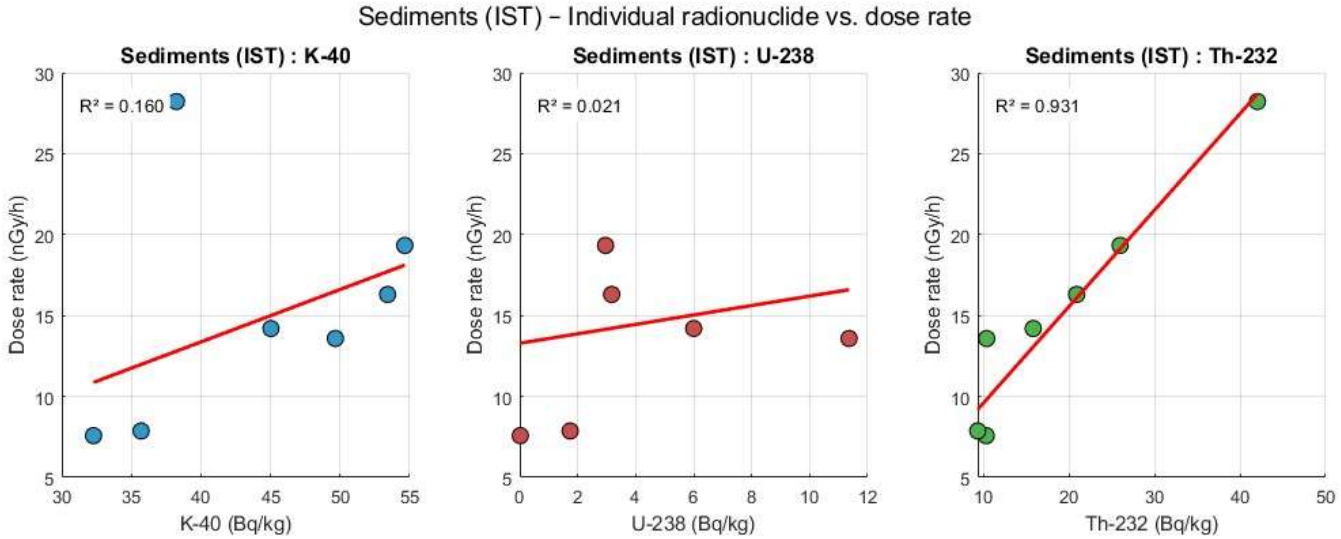

Figure 6. Scatter plots from multiple regression analysis of radionuclides in soil against dose rate.

To further elucidate the relative contribution of individual radionuclides to the observed gamma dose rates, multiple linear regression analysis was performed using ^{40}K, ^{238}U, and ^{232}Th activity concentrations as predictor variables and absorbed dose rate as the response variable. The analysis was conducted separately for sediment and soil samples to account for differences in radionuclide distribution between the two environmental media.

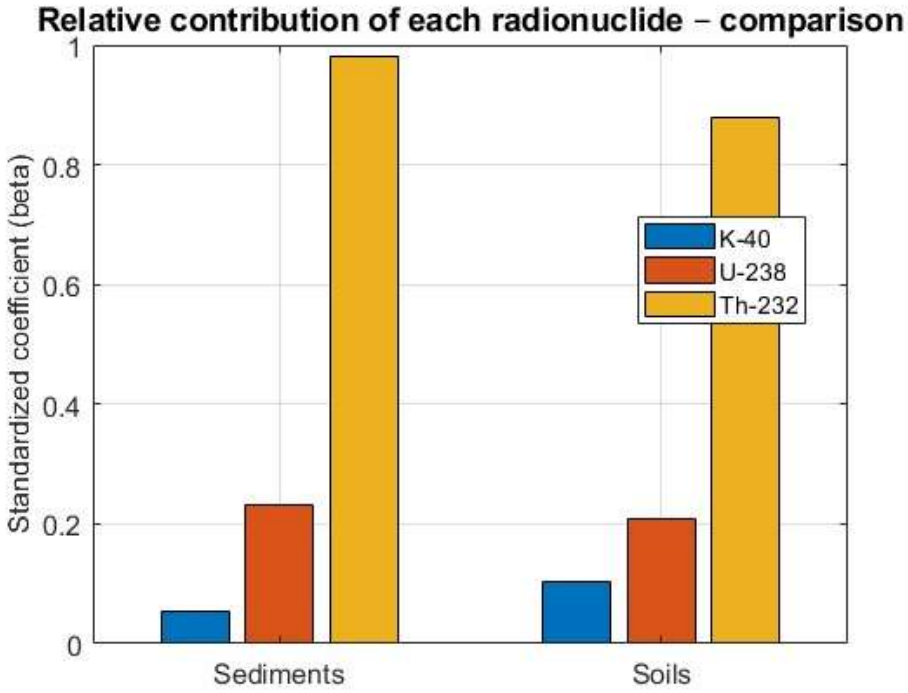

Figure 7. Individual contribution of radionuclides to dose rate obtained from beta coefficiets in multiple regression analysis.

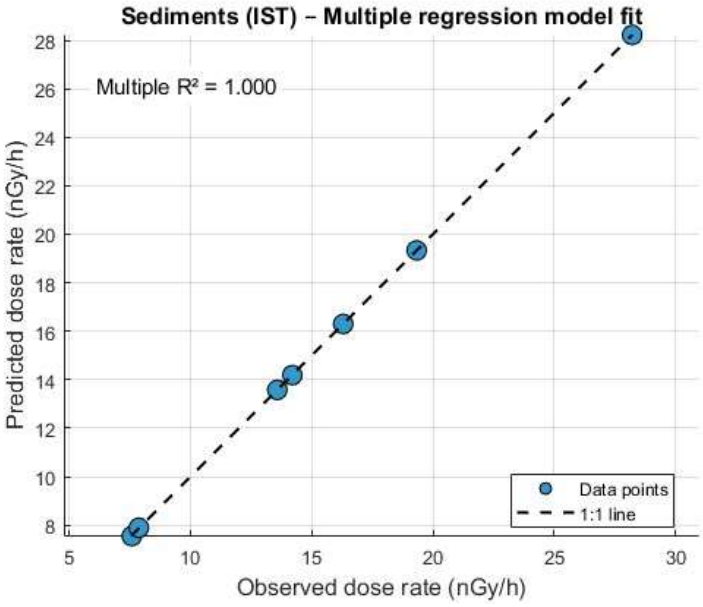

Figure 7. Model fit for observed dose rate againts predicted dose rate in sediments .

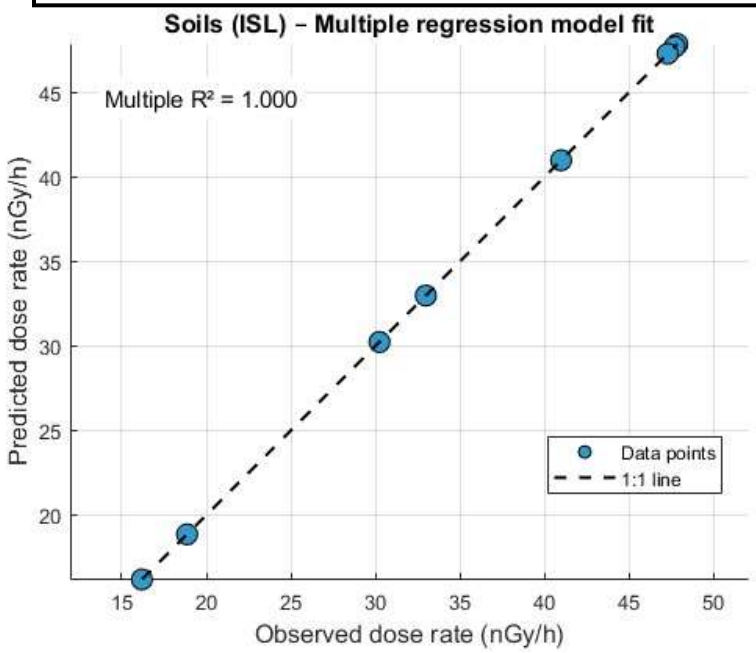

Figure 8. Model fit for observed dose rate againts predicted dose rate in soils.

For the sediment samples, the regression model had a very good agreement with the measured radionuclides (R^2 = 1.00) and all the radionuclides explained nearly all of the variation in the absorbed dose rate. The standardized regression coefficients showed that the dose rate was most strongly affected by ^{232}Th with a coefficient of β = 0.980, which is significant when compared to the coefficient of the other radionuclides, ^{238}U (β = 0.231) and ^{40}K (β = 0.052). This was confirmed by Pearson correlation analysis as there is a very strong positive relationship between ^{232}Th activity concentration and absorbed dose rate (r = 0.965, p < 0.001). The correlation between ^{40}K and ^{238}U, however, was not statistically significant (p>0.05) and small, suggesting that the spatial variations in radiation dose caused by the variations of these radionuclides were not significant.

This was also observed for the soil samples. The coefficient of determination (R^2 = 1.00) for the regression model also showed that the combined activity of the three radionuclides accounted for the variation of the dose rate along the study locations well. The most important predictor variables were ^{232}Th (β = 0.880) and ^{238}U (β = 0.207), with the coefficient of the former being much higher than the coefficient of the latter and of the ^{40}K (β = 0.105). Likewise, high and statistically significant correlation was found between ^{232}Th and absorbed dose rate (r = 0.960, p < 0.001), while the correlation between ^{40}K and absorbed dose rate (r = 0.631, p = 0.093) and between ^{238}U and absorbed dose rate (r = 0.433, p = 0.283) were relatively low and not statistically signifiThe uniformity of the results between both matrices confirms that thorium is the main contributor in the study area to the external gamma radiation level. The relatively high activity concentrations of ^{232}Th, in some cases, especially in soil samples, and the higher dose conversion coefficient of ^{232}Th than that of ^{238}U and ^{40}K, are responsible for this domination. Therefore, the change in thorium concentration is having an unduly high impact on the absorbed dose rates and related radiological risk indices. This is also confirmed by the high concentrations of thorium in some sampling locations and is the reason for the high correlation between the spatial distribution of the radiological hazard parameters and thorium activity. The results as a whole indicate that the radiological parameters of both the soil and sediment environment in Ibeno is mainly controlled by thorium component of the natural radionuclides, while the contribution of uranium and potassium is relatively small. This information is necessary to identify the most important sources of radiation exposure and is a

scientific basis for ranking radionuclides for future environmental monitoring and radiological risk management programmes.

Conclusion

This study aimed to evaluate the concentration of the naturally occurring radionuides (^{40}K, ^{238}U and ^{232}Th) and the radiological health risk associated with the soil and sediment samples of Ibeno Local Government Area, Akwa Ibom State, Nigeria. The average activity concentration of both ^{40}K and ^{238}U were found to be below the recommended average worldwide activity concentrations by UNSCEAR for both environmental media, while moderate enrichment was noted for ^{232}Th in some of the soil sites. The high thorium concentrations did not affect all the radiological hazard parameters, including absorbed dose rate, annual effective dose equivalent, excess lifetime cancer risk, radium equivalent activity and radium equivalent hazard index, as they were all found to be below the international safety standards. The results suggest that the study area is now radioactively safe and is not a health risk to the local people. Radiological monitoring is recommended to be done periodically to monitor for any potential changes that may occur due to continued oil and gas operations. Additional research is needed to better understand radionuclide transfer to water, plants, and aquatic life to measure the environmental and public health effects.

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