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Radiological risk assessment and bioaccumulation of natural radionuclides in sediments and mackerel from oil-impacted coastal areas of Akwa Ibom State, Nigeria

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ABSTRACT: This study evaluates the activity concentrations of naturally occurring radionuclides (^{40}K, ^{238}U, and ^{232}Th) in sediments and mackerel fish collected from Eastern Obolo, Mbo, and Ibeno in Akwa Ibom State, Nigeria, with emphasis on radiological health risks and transfer dynamics. Samples were collected, processed, and analysed using a NaI(Tl) gamma-ray spectrometry system. Radiological indices including absorbed dose rate (D), annual effective dose (AED), annual gonadal dose (AGD), excess lifetime cancer risk (ELCR), radium equivalent activity (Raeq), and hazard indices (Hex and Hin) were computed using standard models. Results indicate that ^{40}K exhibited the highest activity concentration (304.28 ± 140.32 Bq/kg), while ^{232}Th (62.19 ± 11.10 Bq/kg) exceeded global reference values, suggesting enrichment. Most radiological indices remained within world averages and international safety recommendations; however, elevated values observed in Ibeno indicate localised radiological concern. Transfer factor analysis revealed enhanced bioaccumulation, particularly for ^{238}U and ^{232}Th, indicating increased radionuclide mobility. Although sediment-associated risks are low to moderate, elevated transfer into fish suggests a potential pathway for human exposure via seafood consumption. Average excess lifetime hereditary risk (ELHR) was 60.65×10^{-6}, equivalent to 61 cases per million people. Although these values are low, stochastic effects cannot be ruled out, and therefore continuous monitoring and regulation of oil-related activities are recommended.

Keywords: Activity concentration, bioaccumulation, mackerel, Niger Delta, radiological risk, TENORM, transfer factor.

INTRODUCTION

Intrinsic radioactive elements like potassium-40, uranium-238 and thorium-232 (^{40}K, ^{238}U, and ^{232}Th) are commonly found in the Earth's crust and constantly cycle through environmental systems. These radionuclides constitute a significant component of natural background radiation and occur at different concentrations in soils, sediments, water, and biological organisms (UNSCEAR, 2000). The movement and concentration of radionuclides are primarily regulated by intrinsic forces such as mineralogy, weathering processes, and hydrodynamics. Nonetheless, certain anthropogenic processes, especially those involved in industrial activities, can alter natural concentrations and bioavailability of radionuclides in the environment (Balonov, 2010).

Oil exploration and extraction processes are among such anthropogenic activities that contribute greatly to environmental pollution, specifically in marine environments. Oil extraction requires extensive drilling, extraction, and processing stages during which considerable amounts of waste are produced. Waste products from oil extraction contain increased concentrations of natural radionuclides, thus forming Technologically Enhanced Naturally Occurring

Radioactive Materials (TENORMs) (Abbasi *et al*., 2022). Discharge of such materials into aquatic environments leads to increased mobility and concentration of radionuclides in marine sediments and waters (El-Taher *et al*., 2018).

Oil spills, whether accidental or deliberate, also form a part of environmental pollution in regions where oil extraction occurs. There are various dangerous pollutants associated with oil spills, including hydrocarbons, heavy metals, and radionuclides, which are released into the aquatic environment, undergoing numerous physicochemical transformations such as dissolution, dispersion, sedimentation, and degradation (Naser, 2013). Their persistence makes them bioavailable; therefore, the chances of accumulating them in living tissue become high. Pollutant-sediment interactions play an important role in determining the ultimate fate of oil spill pollutants, particularly radionuclides. Sediment acts as a sink but can also act as a secondary source of radionuclides (Ulyantsev *et al*., 2011).

Sediments are crucial in radiological evaluation of pollutants since the accumulation of these contaminants in sediments is considerably higher than the concentration found in the overlying water (Bell, 2024). It, therefore, increases the risk of radionuclides transferring into benthic organisms, resulting in the pollution of the whole marine ecosystem (Bell, 2024). Consequently, accumulation of radionuclides in fishes and other marine organisms makes them useful indicators of pollutants in the environment. The extent of accumulation depends on the features of the organisms, the nature of the radionuclides, and environmental factors.

Fish are part of the foods consumed by humans. Coastal people who rely on seafood as a source of proteins and other nutrients will benefit most from fish. Mackerel, one type of marine fish popular among many, provides high levels of omega-3 fats, vitamins, and essential minerals. Fish with radionuclides as contaminants pose potential internal radiation risks to humans (Isinkaye and Emelue, 2015). According to Abbasi *et al*. (2022), radionuclides absorbed in the body of fish could be passed over to the consumer when ingesting such fish.

An important principle associated with the transportation of radionuclides in aquatic ecosystems is bioaccumulation. In simple terms, bioaccumulation can be defined as the accumulation of contaminants in the body tissues of aquatic organisms at greater concentrations than in their surrounding environment (Freije, 2015; Amin and Almahasheer, 2022). Bioaccumulation happens in many ways, such as by ingestion of food containing contaminants, from sediments in the water and directly by absorption from the water. Biomagnification is another phenomenon that may result from bioaccumulation, especially in cases where there are several trophic levels (Chernysh *et al*., 2024).

The Transfer Factor (TF) is one of the main parameters utilised for measuring the effectiveness of transferring the radionuclide from the environmental media into organisms. The parameter represents a ratio of the activity concentration of a particular radionuclide in organisms and the surrounding medium, such as water or sediments (Gautam *et al*., 2024; Balonov, 2010). The transfer factor is highly informative in terms of revealing the degree of bioavailability and mobility of radionuclides. Therefore, the evaluation of this parameter plays a vital role in the process of assessing environmental and public health risks. Large values of transfer factors mean higher chances for organisms to accumulate the studied radionuclides, which can negatively impact the safety of using the foods in question (Isinkaye and Emelue, 2015). Sediment-based TFs often better reflect long-term exposure because many radionuclides strongly adsorb to particulates and enter benthic food chains, whereas water-based TFs capture more immediate, dissolved-phase availability (IAEA, 2010; UNSCEAR, 2000). However, TFs are limited by assumptions of equilibrium, species-specific variability, and environmental heterogeneity (e.g., pH, salinity). They also neglect trophic interactions and temporal fluctuations, potentially leading to over- or underestimation of bioaccumulation (Wang and Fisher, 1999).

It is also necessary to perform the analysis of radiological health risks by means of evaluating specific indices. Some of the indices that are frequently used include the absorbed dose rate, the annual effective dose equivalent, radium equivalent activity, and the hazard index (UNSCEAR, 2000). All the above indices reflect the degree of exposure to ionising radiation and are used as an informative measurement in environmental radiation studies. International organisations such as the World Health Organisation (WHO) and the International Atomic Energy Agency (IAEA) have established recommended limits for these indices to ensure public safety (IAEA, 2010).

One of the major oil-producing regions in the world is the Niger Delta region of Nigeria, which has undergone intense oil exploration and production activities over many decades. There has been environmental degradation in the form of oil spillage, gas flaring, and discharge of wastes from industries in the water systems (Tsamos *et al*., 2025). Akwa Ibom State falls within this region of Nigeria, and because of its wide coast, it is more affected by the environmental degradation caused by oil exploration. Some of the areas affected within Akwa Ibom State include Eastern Obolo, Mbo, and Ibeno Local Government Areas.

Even though the environment is highly degraded in these areas, there are no records available regarding the level of radionuclides in the marine biota such as edible fishes. Even though there are several research works related to heavy metal contamination in the Niger Delta, fewer have addressed the levels of radionuclides, health risks of radiation, and their transfer factors in fish (Abbasi

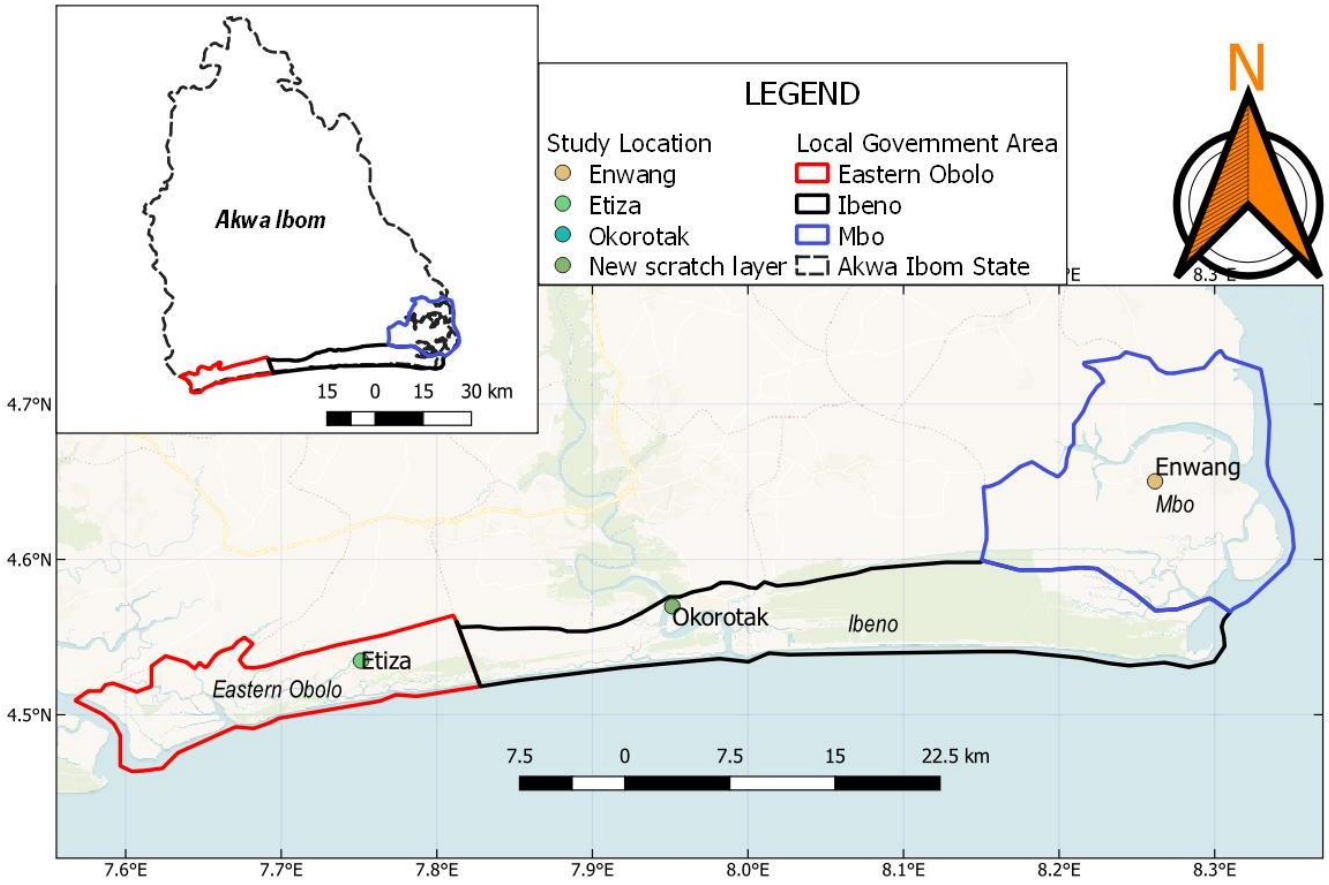

Figure 1. Map of the study area in Akwa Ibom State showing the study communities and their corresponding river.

and Mirekhtiary, 2025). Additionally, the research work conducted focuses more on environmental media such as soil and sediments without addressing radionuclides in the aquatic food chain.

A gap in this area highlights the importance of interdisciplinary research that would involve measurement of radionuclide levels in marine organisms and their relationship with indices of radiological health. Such an investigation is important because it would allow scientists to estimate the radiation risk related to the use of contaminated fish. Evaluation of the transport processes of radionuclides from water to fish species is especially relevant to the issue under discussion. This study therefore seeks to examine the activity concentrations of such elements as ^{40}K, ^{238}U, and ^{232}Th in mackerel fish in selected coastal zones in Akwa Ibom State of Nigeria. Besides, it is important to assess the indices of radiological health and calculate the values of transfer factors in order to obtain complete information about the process of radionuclide bioaccumulation in fish and their implications for human health. Focusing on the oil-polluted coastlines in this region, the study will contribute to the existing scientific literature.

MATERIALS AND METHODS

Study area

Sampling was conducted in three coastal communities in Akwa Ibom State, Nigeria. Stratified random sampling was chosen to capture within-location variability. This method ensures equal presentation across all three strata, enabling robust comparison of radionuclide levels between locations. The communities are Etiza, which is located in the Eastern Obolo Local Government Area (LGA) (4°32′05.71″N, 7°45′04.26″E), Enwang, which is located in Mbo LGA (4°39′01.44″N, 8°15′41.08″E), and Okorotak, which is located in Ibeno LGA (4°34′37.45″N, 7°55′51.29″E) as indicated in Figure 1. All the locations are situated in the Niger Delta Coastal ecosystem, which comprises mangrove swamps, estuaries, and high hydrodynamics as a result of the proximity to the Atlantic Ocean, as shown in Figure 1. This particular ecosystem is sensitive from an ecological point of view as well as exposed to the impacts of environmental pollution caused by long-term petroleum exploration and production (UNSCEAR, 2000; Naser, 2013).

In addition, Eastern Obolo LGA is known for fishing settlements located near the mouth of the Imo River estuary. Economic activities in the village mainly include artisanal fishing, which supplies subsistence and commercial activities in the village. However, offshore oil drilling has created some environmental hazards for the region, including radionuclide contamination caused by discharged produced water and oil spillage (IAEA, 2010). Another village, which serves as the administrative centre of Mbo LGA, is Enwang. Similar to the previous village, Enwang is located in the vicinity of offshore oil facilities.

Ibeno, together with Okorotak, forms one of the largest oil-producing coastal regions in Nigeria, with important offshore oil installations located here. There is a considerable fishery community in this area, where seafood constitutes an important source of nutritional supply. Nevertheless, constant oil prospecting activities and releases raise fears of pollution and subsequent accumulation of radioactive elements in marine organisms (Isinkaye and Emelue, 2015).

Generally, all three sites mentioned are good candidates for studying the distribution of radionuclides in aquatic ecosystems and their bioaccumulation by fish. Moreover, since these areas depend considerably on fisheries, there is a need to investigate possible effects on humans as well (WHO, 2023).

Sample collection and preparation

The study was conducted in three coastal locations in Akwa Ibom State, Nigeria: Etiza (Eastern Obolo LGA), Enwang (Mbo LGA), and Okorotak (Ibeno LGA). 10 sediment samples were collected in each location, bringing the total to 30 sediment samples. Also, 4 samples of mackerel fish were collected from each of the 3 locations, bringing the total to 12 samples of mackerel fish. These locations were selected due to their proximity to oil exploration activities and their ecological importance as fishing communities. Sampling was conducted following established environmental sampling procedures to ensure representativeness and minimise contamination (IAEA, 2010).

Fish samples were obtained directly from local fishermen at landing sites, immediately placed in clean polyethylene containers, and transported to the laboratory under cold conditions. Surface sediment samples were collected from the riverbed at each location using a stainless steel grab sampler at a depth of 0–5 cm, representing recently deposited materials most relevant to contaminant interaction with aquatic organisms (UNSCEAR, 2000). The sediment samples were also stored in labelled polyethylene bags to prevent cross-contamination. In the laboratory, fish samples were thoroughly rinsed with distilled water to remove adhering impurities, and edible muscle tissue was carefully dissected. Both fish tissues and sediment samples were oven-dried at 105 °C for 24 hours to remove moisture. The dried samples were then crushed, homogenised, and sieved to obtain uniform particle size distribution.

Approximately 500 g of each prepared sample (fish and sediment) was sealed in airtight Marinelli beakers and stored for a period of 28–30 days. This storage period allows for the re-establishment of secular equilibrium between ^{226}Ra and its short-lived decay products in the ^{238}U decay series, and between ^{228}Ra and its short-lived decay products in the ^{232}Th decay series, prior to gamma spectrometric analysis (IAEA, 2010; UNSCEAR, 2000). Quality assurance and quality control measures included calibration with certified reference sources, routine background subtraction, and duplicate sample analyses to ensure precision and accuracy (Munno, 2023). Blanks were processed to check contamination, while standardised procedures for sampling, preparation, and counting were strictly followed to maintain data reliability (Weyrich *et al*., 2019).

Gamma-ray spectrometric analysis

The activity concentrations of naturally occurring radionuclides in both fish and sediment samples were determined using a Sodium Iodide activated with Thallium [NaI(Tl)] gamma-ray detector (3″ × 3″ crystal) coupled to a multichannel analyser (MCA). The detector was housed within a 10 cm thick lead shield lined internally with copper to minimise background radiation interference.

Energy and efficiency calibration of the system were carried out using certified reference sources such as ^{137}Cs and ^{60}Co (IAEA, 2010). Each sample was counted for 86,400 seconds to ensure high statistical reliability, and background measurements were recorded under identical conditions and subtracted from the sample spectra. The activity concentrations (Bq/kg^{-1}) of ^{238}U, ^{232}Th, and ^{40}K were determined based on their characteristic gamma emission peaks. Specifically, ^{226}Ra was quantified through its progeny ^{214}Pb (351.9 keV) and ^{214}Bi (609.3 keV), ^{232}Th through ^{228}Ac (338.4 keV and 911.2 keV) and ^{208}Tl (583.1 keV), while ^{40}K was determined using its prominent 1460.8 keV photopeak (UNSCEAR, 2000). The same analytical procedure was consistently applied to both fish and sediment samples to ensure comparability.

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.

The estimated number that may be used to determine the

Table 1. The conversion factors and weighting coefficients for radiological hazard models (ICRP, 2007)

Coefficient	Meaning
0.462	Dose conversion factor for Ra-226 (nGy h^{-1} per Bq kg^{-1}
0.604	Dose conversion factor for Th-232
0.0417	Dose conversion factor for K-40
3.09	Gonadal dose coefficient for Ra-226
4.18	Gonadal dose coefficient for Th-232
0.314	Gonadal dose coefficient for K-40
1.43	Relative hazard factor of Th-232 compared with Ra-226 ((370/259))
0.077	Relative hazard factor of K-40 compared with Ra-226 ((370/4810))
370	Reference Ra-226 activity yielding the accepted gamma dose limit
259	Equivalent Th-232 activity producing the same dose as 370 Bq kg^{-1} Ra-226
4810	Equivalent K-40 activity producing the same dose as 370 Bq kg^{-1} Ra-226
185	Ra-226 reference value for internal exposure due to radon inhalation

least quantity of radioactivity that can be detected with a particular degree of confidence is called the minimal detection limit, or MDA

$$MDA = \frac{L_D}{\varepsilon * t * I_\gamma} \quad (2)$$

Where ε is the absolute detector efficiency, I_γ is the gamma emission probability, and t is the counting time.

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. A table of the coefficients used in the models is shown in Table 1.

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

The absorbed gamma dose rate in air at 1 m above ground level was calculated using (Darko *et al*., 2015):

$$\dot{D} = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (3)$$

Where: A_{Ra}, A_{Th}, and A_K represent the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

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

The annual effective dose equivalent was estimated using occupancy factors and a dose conversion coefficient (AL-abrdi, 2023; Ahmadu, 2025):

$$AED = D \times 8760 \times OF \times 0.7 \times 10^{-6} \quad (4)$$

Where *OF* represents the occupancy factor (0.25 for outdoor exposure and 0.75 for indoor exposure). The 0.25 (outdoor) and 0.75 (indoor) factors follow standard recommendations by the UNSCEAR for global comparability and capture villagers who spend more time indoors, unlike fishermen. However, they may underestimate exposure for fishermen, who spend more time outdoors.

Annual gonadal dose (AGD, μSv y^{-1})

The gonadal dose equivalent was calculated using:

$$AGD = (3.09A_{Ra} + 4.18A_{Th} + 0.314A_K) \quad (5)$$

This parameter evaluates the potential radiation impact on reproductive organs (UNSCEAR, 2000).

Excess lifetime cancer risk (ELCR ×10^{-3})

The excess lifetime cancer risk was determined as:

$$ELCR = AEDE \times 55 \times 0.05 \quad (6)$$

Where 55 years represents the average lifespan for Nigeria (Macrotrends, n.d) and 0.05 Sv^{-1} is the risk factor (ICRP, 2007).

Radium equivalent activity (Raeq, Bq/kg^{-1})

The radium equivalent activity was calculated as:

$$Raeq = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (7)$$

This index provides a single parameter for comparing the

radiological hazard of different samples (Beretka and Mathew, 1985).

External hazard index (Hex)

$$Hex = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (8)$$

Internal hazard index (Hin)

$$Hin = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (9)$$

For both indices, values less than unity indicate that the radiation hazard is within safe limits (UNSCEAR, 2000).

Transfer factor is calculated using the relation (Asaduzzaman *et al*., 2022).

$$TF = \frac{Activity\ concentration\ in\ fish\ (Bq.kg^{-1}\ dry\ weight\ of\ fish)}{Activity\ concentration\ in\ sediment (Bq.kg^{-1}\ dry\ weight\ of\ sediment)} \quad (10)$$

Excess lifetime hereditary risk due to consumption of fish is given by;

$$ELHR = CED \times DL \times RF_H$$

Where *DL* is the duration of life, and RF_H is the hereditary risk coefficient. *CED* is the committed effective dose (Sv y^{-1}) given by

$$CED_{total} = \sum_{i=1}^{n} (Ai \times CR \times DCFi)$$

Where A_i is the activity concentration (Bq kg^{-1}) of the contributing radionuclides, *CR* is the consumption rate of fish (kg y^{-1}), and $DCFi$ is the ingestion dose conversion factor (Sv Bq^{-1})

RESULTS AND DISCUSSION

The results obtained are outlined in Tables 2 to 4 for activity concentration of sediments culled from rivers within Eastern Obolo, Mbo, and Ibeno, respectively. These tables show the concentration of ^{40}K, ^{238}U, and ^{232}Th. The mean values for the activity of sediments are shown in Table 5 in comparison to the reported world average according to UNSCEAR (2000). Table 6 shows the radiological health hazard indices estimated from the activity concentration of the analysed radionuclides in the respective study locations. Table 7 shows the mean activity concentration of mackerel fish obtained from different rivers in the study locations and their corresponding transfer factor to humans in relation to the sediments taken from the rivers. Figures 2 to 4 show the radionuclide activity concentration in comparison to their respective world average, while Figure 5 depicts a graphical representation of the mean activities of ^{40}K, ^{238}U, and ^{232}Th in the respective communities.

The ^{40}K, ^{238}U, and ^{232}Th activity concentrations in the sediment samples showed clear variations with location, as is evidenced by sediments from Ibeno showing consistently higher concentrations in comparison to the other locations (Tables 2 to 4). However, the mean ^{40}K concentration of 304.28 ± 140.32 Bq/kg is still below the average worldwide value reported by UNSCEAR (2000) to be 400 Bq/kg, suggesting no significant enhancement at the regional level. However, the elevated ^{40}K activity of 463.83 ± 150.52 Bq/kg at Ibeno is higher than this average. ^{238}U concentrations at all locations are significantly lower than the global average of 35 Bq/kg, and the ^{232}Th values are higher than the globally recommended average of 30 Bq/kg.

In comparison with other studies, the current ^{40}K and ^{238}U values lie between the ranges of ^{40}K (294-774 Bq/kg) and ^{238}U (3.91-14.13 Bq/kg) found by Osiga-Aibangbee *et al*. (2025) in Niger Delta sediments, but not their ^{232}Th values. The ^{40}K values reported by Esi *et al*. (2026) are significantly higher than the values observed in this study. The comparatively higher ^{232}Th activity found in this study may have been attributed to sedimentation processes that led to the concentration of heavy minerals from oil exploration.

Table 6 shows that the values of the radiological health indices obtained in this study have similar variation as the activity concentrations and the absorbed dose rate varied from 43.77 to 68.86 nGy/h, with the average value being slightly lower than that from UNSCEAR (2000), which is 59.00 nGy/h. However, Ibeno recorded values exceeding this average, whereas the corresponding values for the other locations remained below it. This observation is consistent with findings reported by Ghazal *et al*. (2024), where absorbed dose rates ranged from 22.91 to 49.76 nGy/h. In contrast, the study by Ankapong *et al*. (2024) reported significantly higher values, with peak absorbed dose rates exceeding 200 nGy/h.

Values for Raeq range from 66.53 to 100.11 Bq/kg, which are much lower than the internationally accepted value of 370 Bq/kg, suggesting no serious radiological hazard. This is different from the results obtained by Osiga-Aibangbee *et al*. (2025) where the values for Raeq exceeded the dose limit; this was due to geological variation and anthropogenic contribution. Similarly, the values for hazard indices (Hex and Hin) in the present study are all less than unity, which translates to no significant radiological hazard. This compares to results reported for a study conducted in Vietnam by Ba *et al*. (2019).

Table 2. Activity concentration of sediments collected from rivers within Eastern Obolo LGA.

S/N	Sample code	Radiation content for sediments (Bq/kg^{-1})		
		^{40}K	^{238}U	^{232}Th
1	ETZ1	199.97	9.53	12.55
2	ETZ2	149.31	3.53	15.98
3	ETZ3	84.83	3.66	63.51
4	ETZ4	263.54	2.41	38.88
5	ETZ5	120.56	Bdl	58.58
6	ETZ6	245.37	Bdl	110.26
7	ETZ7	141.11	2.80	34.91
8	ETZ8	211.35	Bdl	82.30
9	ETZ9	384.34	14.78	68.77
Mean		200.04 ± 90.70	6.12 ± 4.98	53.97 ± 31.73

* Bdl = below detectable limit.

Table 3. Activity concentration of sediments collected from rivers within Mbo LGA.

S/N	Sample code	Radiation content for sediments (Bq/kg^{-1})		
		^{40}K	^{238}U	^{232}Th
1	ENW1	243.17	7.43	47.45
2	ENW2	278.63	1.30	40.82
3	ENW3	458.73	7.24	72.88
4	ENW4	170.46	20.19	129.12
5	ENW5	226.97	1.91	13.36
6	ENW6	32.83	1.48	72.53
7	ENW7	329.45	2.53	52.59
8	ENW8	200.10	2.93	39.58
9	ENW9	285.26	2.83	34.14
10	ENW10	264.03	0.31	75.28
Mean		248.96 ± 109.89	4.82 ± 5.91	57.78 ± 31.84

Table 4. Activity concentration of sediments collected from rivers within Ibeno LGA.

S/N	Sample code	Radiation content for sediments (Bq/kg^{-1})		
		^{40}K	^{238}U	^{232}Th
1	OKT1	793.42	Bdl	102.49
2	OKT2	351.61	4.36	76.93
3	OKT3	432.87	6.96	43.43
4	OKT4	506.05	18.32	62.11
5	OKT5	613.08	8.42	49.61
6	OKT6	275.75	17.31	121.70
7	OKT7	379.11	1.92	98.12
8	OKT8	366.75	8.45	83.48
9	OKT9	406.59	6.68	45.88
10	OKT10	513.06	11.88	64.39
Mean		463.83 ± 150.52	9.37 ± 5.53	74.81 ± 26.49

* Bdl = below detectable limit.

Tables 7, 8, and 9 show the activity concentration measured from fish in the respective communities. The results show clear spatial variation in radionuclide accumulation. Okorotak (Ibeno) recorded the highest ^{40}K (532.91 Bq/kg), reflecting natural potassium abundance in aquatic systems. Enwang (Mbo) exhibited the highest

Table 5. Mean activity concentration of sediments collected from rivers within the study communities.

Location	Radiation content for sediments (Bq/kg^{-1})		
	^{40}K	^{238}U	^{232}Th
Eastern Obolo	200.04 ± 90.70	6.12 ± 4.98	53.97 ± 31.73
Mbo	248.96 ± 109.89	4.82 ± 5.91	57.78 ± 31.84
Ibeno	463.83 ± 150.52	9.37 ± 5.53	74.81 ± 26.49
Overall mean	304.28 ± 140.32	6.77 ± 2.34	62.187 ± 11.10
World Average (UNSCEAR, 2000)	400.00	35.00	30.00

Table 6. Radiological health hazard estimated from the measured activity concentration of sediment samples.

Location	D (nGy/h)	AED (mSv/y)	AGD (uSv/y)	ELCR X10-3	Raeq Bq/Kg	Hex (mSv/y)	Hin (mSv/y)
Eastern Obolo	43.77	0.07	53.65	58.08	66.53	0.27	0.28
Mbo	47.50	0.07	57.93	62.65	71.78	0.29	0.30
Ibeno	68.86	0.11	81.16	87.26	100.11	0.41	0.44
Mean	53.38	0.08	64.25	69.33	79.47	0.32	0.34
World average UNSCEAR (2000)	59.00	0.10	300.00	0.29	370.00	1.00	1.00

Table 7. Activity concentration of mackerel fish collected from rivers within Etiza, Eastern Obolo LGA.

Sample code	^{40}K (Bq/kg-1)	^{238}U (Bq/kg-1)	^{232}Th (Bq/kg-1)
EOM1	371.84	28.36	85.54
EOM2	291.17	31.24	69.74
EOM3	336.45	25.13	65.93
EOM4	325.70	13.75	83.51
Mean	331.29	24.62	76.18

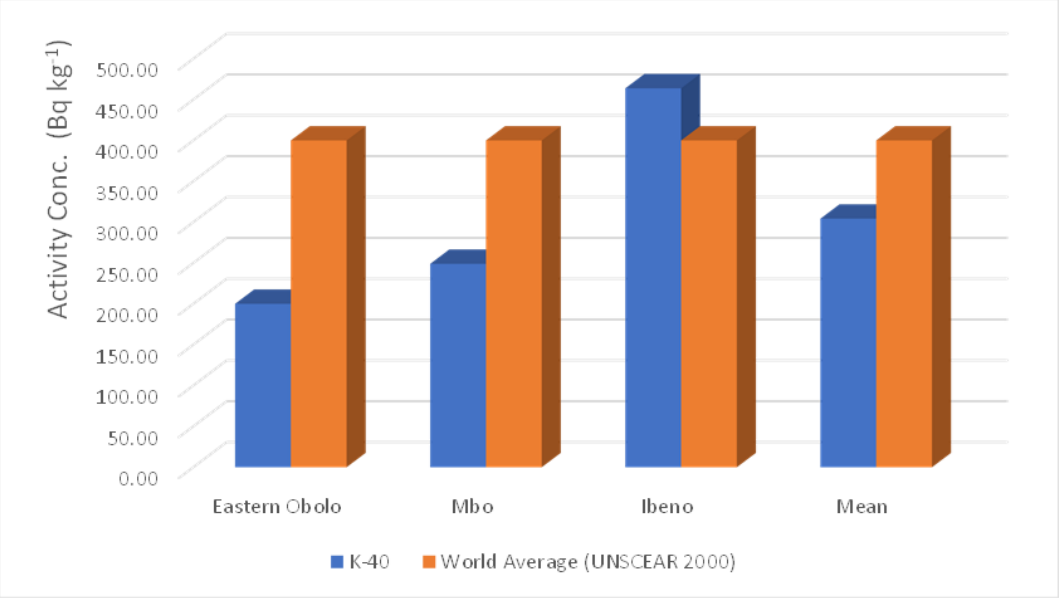

Figure 2. Comparison of activity concentration of K-40 to obtained in the respective study areas to the world average.

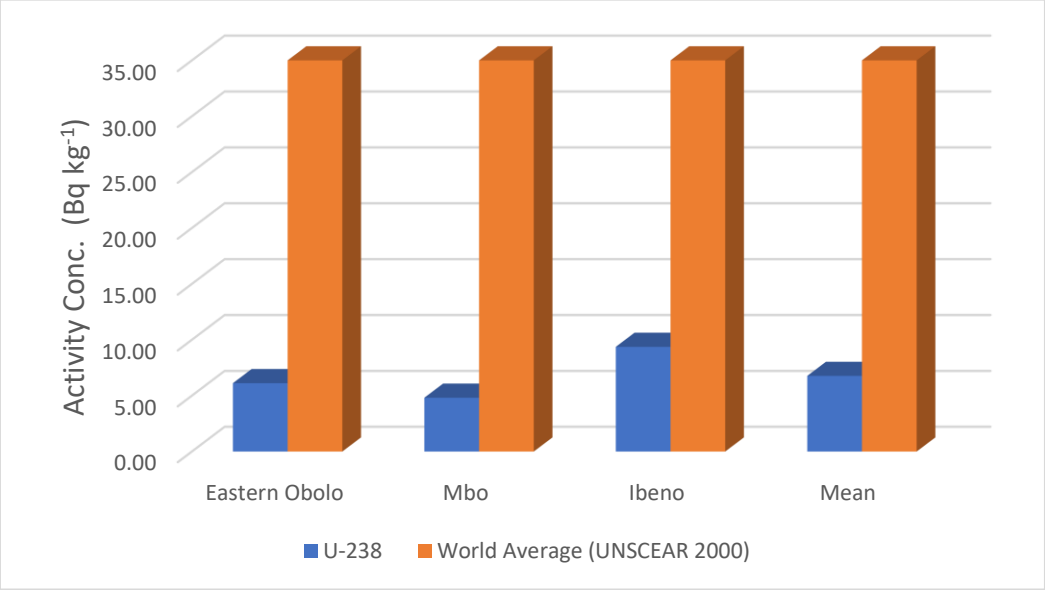

Figure 3. Comparison of activity concentration of U-238 obtained in the respective study areas to the world average.

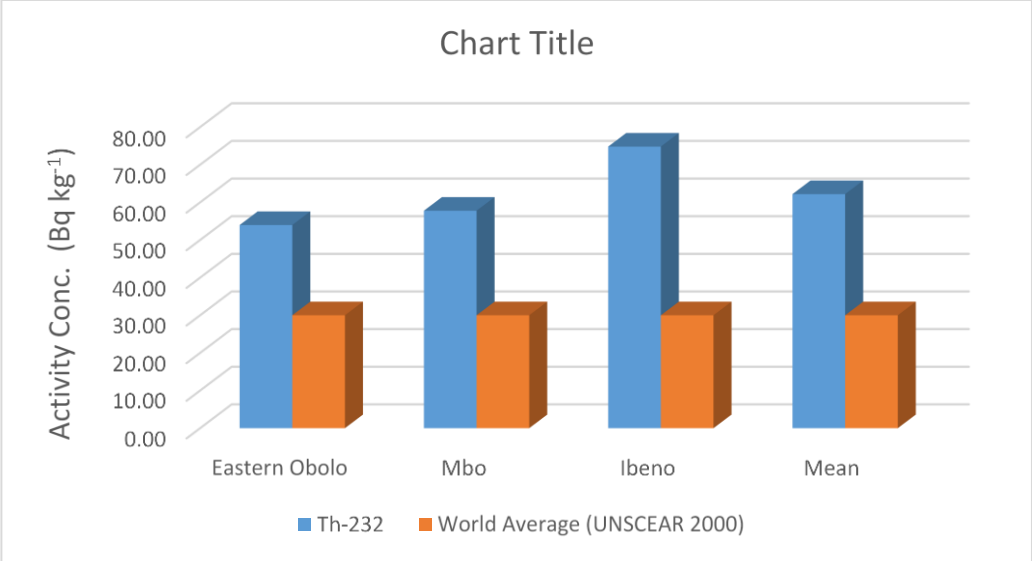

Figure 4. Comparison of activity concentration of Th-232 obtained in the respective study areas to the world average.

^{232}Th (118.09 Bq/kg), suggesting sediment-associated enrichment likely linked to anthropogenic inputs. Conversely, Etiza (Eastern Obolo) showed the highest ^{238}U (24.62 Bq/kg), indicating enhanced uranium mobility and bioavailability. The low uranium levels in Ibeno imply stronger sediment binding.

Activity concentrations in mackerel fish and transfer factor (TF) are shown in Table 10. The ^{40}K concentrations (331.29-532.91 Bq/kg) in fish were found to be in similar ranges as ^{40}K concentrations reported by Asaduzzaman *et al*. (2022), which range from 171-513 Bq/kg. However, the concentrations of ^{238}U and ^{232}Th in fish were higher than world averages reported by IAEA (2010). The results of the transfer factor (TF) show that there is a significant rise in bioaccumulation of ^{238}U and ^{232}Th in fish, specifically in Eastern Obolo and Mbo. Interestingly, the TF of 238U was

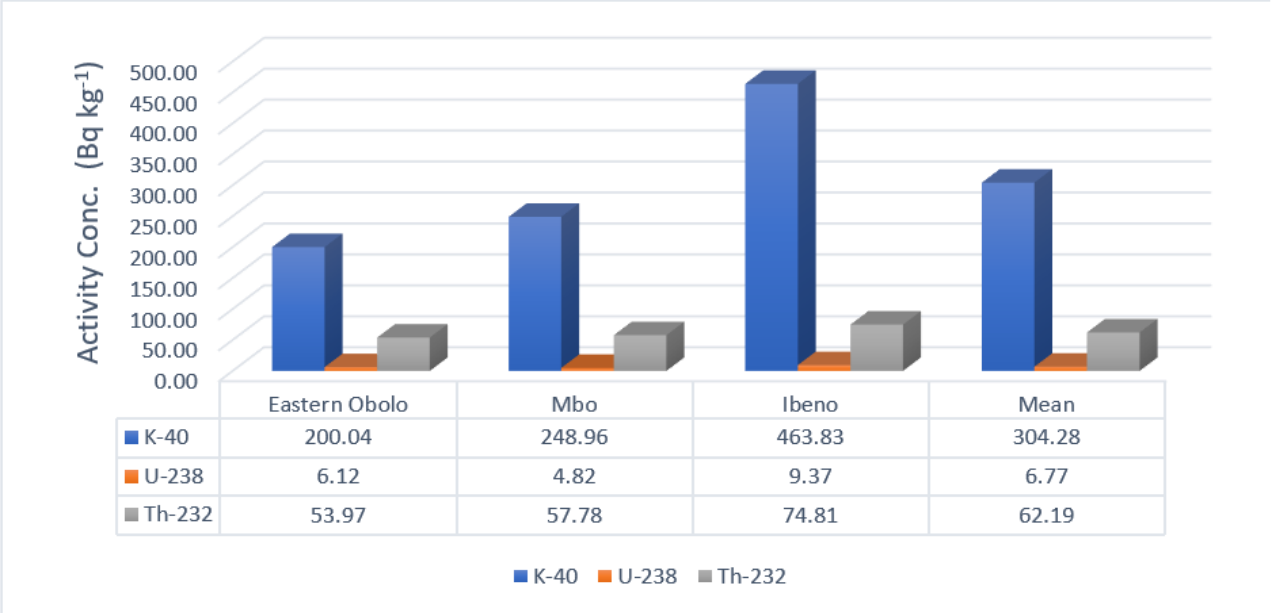

Figure 5. Graphical representation of activity concentration of the analysed radionuclides.

Table 8. Activity concentration of mackerel fish collected from rivers within Enwang, Mbo LGA

Sample code	^{40}K (Bq/kg-1)	^{238}U (Bq/kg-1)	^{232}Th (Bq /kg-1)
MBO1	431.25	17.57	85.54
MBO2	503.64	7.23	131.81
MBO3	497.31	11.79	110.93
MBO4	443.32	6.61	144.08
Mean	468.88	10.8	118.09

Table 9. Activity concentration of mackerel fish collected from rivers within Okorotak, Ibeno LGA.

Sample code	^{40}K (Bq/kg-1)	^{38}U (Bq/kg-1)	^{232}Th (Bq /kg-1)
EOM1	611.35	1.33	72.47
EOM2	338.25	2.11	43.87
EOM3	507.38	1.72	37.31
EOM4	674.66	1.44	47.11
Mean	532.91	1.65	50.19

Table 10. Mean activity concentration in mackerel fish and the calculated transfer factor from using activity concentration of sediments.

Location	Radiation content for Mackerel fish (Bq/kg^{-1})			Transfer Factor		
	^{40}K	^{238}U	^{232}Th	^{40}K	^{238}U	^{232}Th
Eastern Obolo	331.29	24.62	76.18	1.656	4.024	1.411
Mbo	468.88	10.8	118.09	1.883	2.243	2.044
Ibeno	532.91	1.65	50.19	1.149	0.176	0.671
World average (IAEA, 2010)	200.00	1.00	0.50	10.00	0.01	0.001

Table 11. Committed effective dose due to the radionuclides and their resulting lifetime hereditary risk.

Sample Code	Committed effective dose (CED) mSv/y			CED_{Total}	ELHR ($X10^{-6}$)
	^{40}K	^{238}U	^{232}Th		
EOM1	57.64	31.91	491.86	581.4	63.95
EOM2	45.13	35.15	401.01	481.28	52.94
EOM3	52.15	28.27	379.1	459.52	50.55
EOM4	50.48	15.47	480.18	546.13	60.07
MBO1	66.84	19.77	491.86	578.47	63.63
MBO2	78.06	8.13	757.91	844.11	92.85
MBO3	77.08	13.26	637.85	728.19	80.10
MBO4	68.71	7.44	828.46	904.61	99.51
EOM1	94.76	1.50	416.70	512.96	56.43
EOM2	52.43	2.37	252.25	307.06	33.78
EOM3	78.64	1.94	214.53	295.11	32.46
EOM4	104.57	1.62	270.88	377.07	41.48
Mean	68.88	13.90	468.55	551.33	60.65

up to 4.024, which is significantly higher than the common International Atomic Energy Agency reference value of about 0.01 for aquatic systems. These high TF values are a good indication of increased uptake and retention of radionuclides by aquatic biota. Conversely, in terrestrial farming settings, including those by Adebayo *et al*. (2026) and Chetty and Ilori (2024), the TF values tend to be lower than unity, indicating less extensive transfer in soil-plant systems. This difference highlights the inherent differences between aquatic and terrestrial systems, with physicochemical factors in water bodies usually favouring increased radionuclide mobility and bioavailability.

Under natural conditions, the transfer factor of ^{238}U in Ibeno, which is approximately 0.176, could be attributed to its geochemical properties. Uranium is mostly found in the hexavalent oxidation state (U^{6+}) as uranyl ion (UO_2^{+2}), a form that forms soluble carbonate and bicarbonate complexes in water. These complexes increase its mobility and make it be absorbed by aquatic organisms by gill absorption and ingestion of contaminated particulates (Alam and Cheng, 2014). Nevertheless, in spite of this relative mobility, uranium too has the propensity to adsorb onto sediments and organic matter, restricting its bioavailability in natural environmental conditions and thereby maintaining TF values comparatively low. The significantly increased TF values in this experiment thus suggest an imbalance in these equilibrium processes, which are probably caused by anthropogenic inputs.

The high levels of thorium in Eastern Obolo and Mbo can be reasonably attributed to technologically enhanced naturally occurring radioactive materials (TENORM) that relate to oil and gas operations. The drilling, production, and pipeline transport operations are capable of concentrating radionuclides in produced water, drilling muds, and mineral scales. Thorium is relatively insoluble, and it is associated preferentially with particulate matter and sediments, indicating that its higher occurrence in biota could be due to sediment resuspension and ingestion, and not necessarily to direct dissolution in water. This indicates an anthropogenic increase in radionuclides in excess of natural contributions.

Moreover, the elevated TF values in fish may be ascribed to constant exposure and uptake of the radionuclides, as indicated by the activity concentrations measured and also trophic transfer in the aquatic food web. The mobility of radionuclides and environmental availability are enhanced in areas where there is a high rate of oil exploration like Eastern Obolo and Ibeno, due to the release of produced water and other waste streams. This leads to a further increase in bioaccumulation in fish, and this creates a concern about human exposure when people consume fish. Similar results are also provided by Darko *et al*. (2015), but the values obtained in the current study are somewhat greater, probably because of the site-specific environmental factors and variations in radionuclide speciation.

Notably, the greater TF in Eastern Obolo indicates greater bioavailability and not necessarily greater environmental concentrations. Uranium in this region would be in more soluble and bioavailable chemical forms, whilst in Ibeno it seems to be more firmly bound to sediments, inhibiting its uptake despite high levels in the environment. This underlines the importance of radionuclide speciation, water chemistry (e.g., pH, redox conditions, and carbonate content), and sediment interactions in regulating transfer processes.

From Table 11, the average committed effective dose (CED) of 551.33 μSv y^{-1} shows that eating fish is an important route through which people may be exposed to radiation. Most of this dose came from ^{232}Th, which

contributed more than 85% of the total dose. This is because thorium has a greater ability to cause radiation dose when ingested than the other radionuclides. The average excess lifetime hereditary risk (ELHR) was 60.65 × 10^{-6}, equivalent to 61 cases per million people (0.0061%). Although this risk is low, it indicates a low possibility of genetic effects from long-term exposure.

Conclusion

The activity concentrations of naturally occurring radionuclides (^{40}K, ^{238}U and ^{232}Th) in sediments and mackerel fish collected from some coastal localities of Akwa Ibom State were measured along with associated health hazard indices and transfer factors. All activity concentrations were higher in the sediments collected at Ibeno, and the level of ^{40}K activity concentrations in sediments was highest across all locations, and ^{238}U activity concentration values were all lower than the world average. ^{232}Th concentrations were higher than the world average, and this suggests some enrichment. The observed values showed variation in the distribution within these locations, and this was primarily due to anthropogenic sources (oil exploration, drilling).

The results from radiological health indices like absorbed dose rate (D), annual effective dose (AED), annual gonadal dose (AGD) and radium equivalent activity (Raeq) are all within world dose limits, although the dose rate for Ibeno was above the world average. The values for hazard indices (Hex and Hin) are within limits, and they all indicate negligible risk.

The results for the transfer factor show significant bioaccumulation of radionuclides (especially ^{238}U and ^{232}Th) in mackerel fish, as transfer factors of up to 4.024 were recorded, far higher than the IAEA reference value of 0.01, implying a high tendency to be accumulated into the environment, and suggesting human exposure via diet as a way of uptake of these radionuclides into the food chain. The activity concentrations of radionuclides in the fish samples are higher than those of the sediments; this is due to the high mobility and bioavailability of these radionuclides as a result of increased oil and gas activity.

With the hereditary risk being 60.65 cases per million, it is recommended that the Nigeria Nuclear Regulatory Authority rise to the occasion and ensure close monitoring of the environment and the seafood consumed in the area. This would ensure that regulatory policies are adhered to and oil and gas operations that could exacerbate exposure are minimised.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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