

ASSESSMENT OF NATURALLY OCCURRING RADIOACTIVE MATERIALS AND RADIOLOGICAL RISKS IN SOILS AROUND THE KADUNA REFINING AND PETROCHEMICAL COMPANY, NIGERIA

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ABSTRACT

Industrial activities, particularly petroleum refining, have been identified as significant contributors to the enrichment of Naturally Occurring Radioactive Materials (NORMs) in surrounding environments. This study assessed the radiological impact of the Kaduna Refining and Petrochemical Company (KRPC) on the local soil environment. Soil samples were collected from 10 sampling points within the refinery operational area and one control site located approximately 2 km away. Activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K were determined using Thallium-activated Sodium Iodide [NaI(Tl)] gamma spectrometry. Results revealed that the mean activity concentrations of ²²⁶Ra (25.94 ± 14.97 Bq/kg) and ⁴⁰K (171.85 ± 63.27 Bq/kg) were below the UNSCEAR global averages of 35 Bq/kg and 400 Bq/kg, respectively. However, ²³²Th exhibited significant enhancement, with a mean concentration of 66.23 ± 27.32 Bq/kg, substantially exceeding both the control site (36.12 Bq/kg) and the UNSCEAR global average of 30 Bq/kg. Radiological hazard indices, including Absorbed Dose Rate (59.15 nGy/h), Annual Effective Dose Equivalent (0.0725 mSv/y), Radium Equivalent Activity (133.88 Bq/kg), and hazard indices ($H_{ex} = 0.362$, $H_{in} = 0.432$, $I_{\gamma} = 0.950$), all remained within internationally recommended safety limits. However, the Excess Lifetime Cancer Risk (1.140×10^{-3}) exceeded the global average of 0.29×10^{-3} , indicating a cumulative long-term health risk. Pearson correlation analysis revealed weak to negative correlations among the radionuclides, confirming anthropogenic interference through Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) from refinery operations. The study concludes that while no acute radiation hazard exists, sustained industrial exposure poses a latent public health vulnerability that requires regulatory intervention.

Keywords: NORMs, Kaduna Refinery, gamma spectrometry, radiological hazard, TENORM, Excess Lifetime Cancer Risk, ²³²Th

INTRODUCTION

The rapid industrialisation of developing nations has brought significant economic benefits alongside environmental challenges. Among these challenges is the release of Naturally Occurring Radioactive Materials (NORMs) into the environment through various industrial processes. Petroleum refining operations, in particular, have been recognised as significant contributors to the enrichment of NORMs in surrounding soils, water bodies, and biota (Agbalagba & Esi, 2022; Suleiman *et al.*, 2021). NORMs encompass primordial radionuclides such as ²²⁶Ra (Uranium-238 decay series), ²³²Th (Thorium-232 decay series), and ⁴⁰K, which are ubiquitously distributed in the Earth's crust.

While these radionuclides occur naturally, industrial activities can concentrate them to levels that pose radiological risks to both workers and the public. Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) result from industrial processes that alter the natural distribution and concentration of these radionuclides, potentially leading to elevated radiation exposure (Singh *et al.*, 2024).

The petroleum industry has been identified as a major source of TENORM, as the extraction, processing, and refining of crude oil tend to concentrate radionuclides in production equipment, waste streams, and surrounding soils. Scale deposits in pipelines, sludge from storage tanks, and produced water often contain elevated levels of ²²⁶Ra and ²²⁸Ra, which can eventually enter the environment through spills, leaks, and improper waste disposal (Njinga *et al.*, 2022).

Nigeria, Africa's largest oil producer, has numerous petroleum facilities, with the Kaduna Refining and Petrochemical Company (KRPC) serving as a major processing hub in the northern region. The refinery processes crude oil from the Niger Delta, producing various petroleum products and generating significant quantities of waste materials. Despite the facility's established presence and the potential for radiological contamination, comprehensive assessments of NORMs around this industrial site remain limited. Previous studies across Nigeria have documented elevated NORM concentrations in industrial and mining areas. Agbalagba and Esi (2022) reported mean activity concentrations of ⁴⁰K (1586.82 Bq/kg), ²³⁸U (27.26 Bq/kg), and ²³²Th (37.67 Bq/kg) in soil samples from the Niger Delta, with total effective doses exceeding safety limits. Oluyide *et al.* (2019) found elevated NORM levels around an iron and steel smelting facility in Osun State, with mean ²³²Th concentrations of 23.23 Bq/kg. More recently, Jegede *et al.* (2025) reported that 70% of sampled locations at quarry sites in Ogun State exceeded the world average limits for NORMs.

Specifically in Kaduna, Suleiman *et al.* (2021) evaluated NORM activity concentrations in soil and rock specimens from a superphosphate fertilizer plant, finding that phosphate rock processing significantly influenced radionuclide accumulation. However, a comprehensive assessment of NORMs around the Kaduna Refining and Petrochemical Company has not been previously conducted.

This study aims to fill this gap by assessing the radiological impact of the Kaduna Refining and Petrochemical Company on the local soil environment. The specific objectives are: (1) to determine the activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K in soil samples from the refinery operational area, (2) to evaluate the radiological hazard posed by these NORMs through the calculation of various hazard indices and dose parameters, (3) to assess the Excess Lifetime

Cancer Risk associated with environmental exposure, and (4) to determine the sources of radionuclide enrichment through statistical correlation analysis.

MATERIALS AND METHODS

Study Area

The Kaduna Refining and Petrochemical Company is located in Kaduna Metropolis, northwestern Nigeria, at approximately 10°26'N latitude and 7°26'E longitude. The refinery, commissioned in 1980, has a processing capacity of 110,000 barrels per day and is the primary petroleum processing facility in the northern region. A mix of industrial, residential, and agricultural land uses characterizes the surrounding area.

Sampling Design and Collection

Soil samples were collected from 11 sampling locations within and around the KRPC facility. Ten sampling points (D1-D10) were established within the refinery operational area, including locations near processing units, storage tanks, and waste disposal areas, as well as along the perimeter boundaries. One control site (DC) was selected approximately 2 km away from the refinery, in an area with minimal industrial influence.

At each sampling location, approximately 1 kg of surface soil (0-5 cm depth) was collected using a hand auger and shovel. A handheld Global Positioning System (GPS) was used to record the geographical coordinates of each sampling point (Table 1). Samples were placed in clean polyethylene bags, sealed to prevent cross-contamination, labelled with unique identification codes, and transported to the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, for processing and analysis.

Table 1: Geographical Coordinates of Sampling Locations at KRPC

SAMPLE ID	LATITUDE (N)	LONGITUDE (E)
DC (CONTROL)	10.43673	7.43789
D1	10.43734	7.43851
D2	10.43734	7.43825
D3	10.43714	7.43818
D4	10.43703	7.43801
D5	10.43690	7.43787
D6	10.43673	7.43765
D7	10.43658	7.43750
D8	10.43644	7.43743
D9	10.43632	7.43731
D10	10.43621	7.43705

Sample Preparation

Soil samples were oven-dried at 105°C for 10-12 hours to remove moisture. The dried samples were ground using a ceramic mortar and pestle, then passed through a 2 mm sieve to achieve a homogeneous particle size suitable for gamma spectrometry. Approximately 200 g of each homogenised sample was weighed and packed into airtight cylindrical plastic containers. The containers were hermetically sealed and stored for 30 days to allow secular radioactive equilibrium to be established between the long-lived parent radionuclides and their short-lived decay products, particularly between ²²⁶Ra and its daughter products, ²¹⁴Pb and ²¹⁴Bi (Yachiso, 2022).

Gamma Spectrometry Analysis

The activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K were determined using a Thallium-activated Sodium Iodide [NaI(Tl)] gamma spectrometry system located at CERT. The detector system consisted of a 3" × 3" NaI(Tl) crystal coupled to a photomultiplier tube, with associated electronics for signal processing and data acquisition.

The gamma spectrometer was calibrated using standard reference materials (e.g., IAEA-375, RGU-1, RGTh-1, and RGK-1) with known activity concentrations. Samples were counted for 10,000 seconds to achieve acceptable statistical precision. The spectrum analysis was performed using an appropriate software package, with peaks identified at the following energy windows:

- ²²⁶Ra: 609.3 keV (²¹⁴Bi) and 351.9 keV (²¹⁴Pb)
- ²³²Th: 583.1 keV (²⁰⁸Tl) and 911.1 keV (²²⁸Ac)
- ⁴⁰K: 1460.8 keV (single gamma line)

Radiological Hazard Assessment

Absorbed Dose Rate (D)

The absorbed dose rate in air at 1 meter above ground level was calculated using the conversion factors provided by UNSCEAR (2000):

$$D \text{ (nGy/h)} = 0.0417C_{\text{Ra}} + 0.462C_{\text{Th}} + 0.604C_{\text{K}} \quad (1)$$

Where C_{Ra} , C_{Th} , and C_{K} are the activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K in Bq/kg, respectively.

Annual Effective Dose Equivalent (AEDE)

The outdoor annual effective dose equivalent was calculated using the dose conversion factor of 0.7 Sv/Gy and the outdoor occupancy factor of 0.2:

$$\text{AEDE}_{\text{outdoor}} \text{ (mSv/y)} = D \text{ (nGy/h)} \times 8760 \text{ h/y} \times 0.2 \times 0.7 \text{ Sv/Gy} \times 10^{-6} \quad (2)$$

Radium Equivalent Activity (R_{eq})

The radium equivalent activity, which provides a weighted sum of the three radionuclides, was calculated using the formula:

$$R_{\text{eq}} \text{ (Bq/kg)} = C_{\text{Ra}} + 1.43C_{\text{Th}} + 0.077C_{\text{K}} \quad (3)$$

Where C_{Ra} , C_{Th} , and C_{K} are the activity concentrations in Bq/kg.

External and Internal Hazard Indices (H_{ex} , H_{in})

The external and internal hazard indices were calculated as:

$$H_{\text{ex}} = C_{\text{Ra}}/370 + C_{\text{Th}}/259 + C_{\text{K}}/4810$$

(4)

$$H_{\text{in}} = C_{\text{Ra}}/185 + C_{\text{Th}}/259 + C_{\text{K}}/4810$$

(5)

Both indices should be less than unity for the materials to be considered safe.

Representative Gamma Level Index (I_{γ})

The gamma level index was calculated using:

$$I_{\gamma} = C_{\text{Ra}}/150 + C_{\text{Th}}/100 + C_{\text{K}}/1500$$

(6)

Excess Lifetime Cancer Risk (ELCR)

The ELCR for external gamma radiation was calculated using:

$$\text{ELCR} = \text{AEDE}_{\text{outdoor}} \times \text{DL} \times \text{RF}$$

(7)

Where DL is the average duration of life (55 years), and RF is the risk factor for stochastic effects at low doses (0.05 per Sievert), as recommended by ICRP.

Statistical Analysis

Pearson correlation analysis was performed to determine the relationships among the three radionuclides. The analysis was conducted using standard statistical software, with significance set at $p < 0.05$.

RESULTS

Activity Concentrations of NORMs

The specific activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K measured in soil samples from the KRPC operational area and the control site are presented in Table 2.

Table 2: Activity Concentrations of NORMs in Soil Samples from KRPC

SAMPL E ID	^{40}K (BQ/KG)	ERR OR (±)	^{226}RA (BQ/KG)	ERR OR (±)	^{232}TH (BQ/KG)	ERR OR (±)
DC (CONT ROL)	253.3	3.25	32.66	2.64	36.12	3.43
D1	148.7	3.59	13.15	1.71	75.79	3.40
D2	244.2	4.54	12.20	1.59	69.96	2.29
D3	284.4	4.80	44.20	3.91	38.40	3.43
D4	175.9	3.02	10.46	1.51	93.47	3.98
D5	179.8	4.19	15.35	1.58	22.48	2.46

	18	91	3	1	0	3
D6	58.58	3.87	16.53	1.82	61.44	3.60
D7	131.7	3.30	34.18	3.21	88.56	3.92
D8	155.6	4.76	21.42	2.21	100.3	4.79
D9	207.0	4.68	47.62	3.53	81.28	3.64
D10	132.3	3.46	44.20	3.46	30.56	3.67

Table 3: Summary Statistics for Activity Concentrations at KRPC

PARAMETER	^{40}K (BQ/KG)	^{226}RA (BQ/KG)	^{232}TH (BQ/KG)
CONTROL (DC)	253.31	32.67	36.12
SAMPLE MEAN (D1-D10)	171.85	25.94	66.23
STANDARD DEVIATION	±63.27	±14.97	±27.32
MINIMUM	58.59	10.47	22.48
MAXIMUM	284.42	47.62	100.33
UNSCEAR WORLD AVERAGE	400	35	30

FIGURE 1: Spatial Distribution of ^{232}Th Activity Concentrations at KRPC

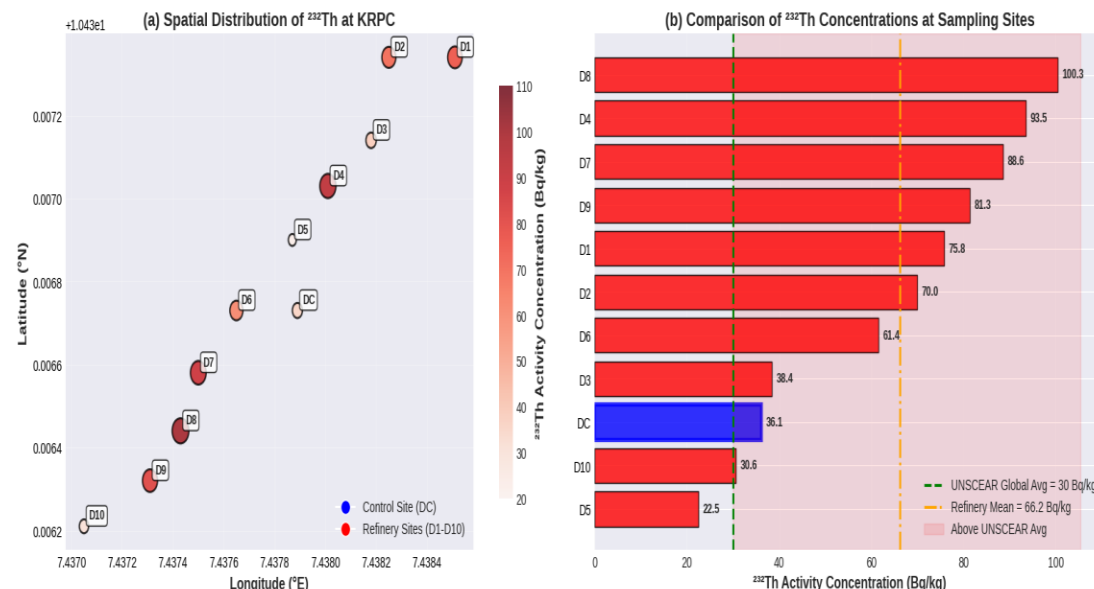


Figure 1: Spatial distribution and comparison of ^{232}Th activity concentrations in soils around Kaduna Refining and Petrochemical Company. (a) Bubble map showing the spatial distribution of ^{232}Th at sampling locations, with bubble size and colour intensity representing activity concentration (Bq/kg). The control site (DC) is marked in blue. (b) Horizontal bar chart comparing ^{232}Th concentrations at all sampling sites against the UNSCEAR global average of 30 Bq/kg (dashed green line). Red bars indicate refinery samples exceeding the global average.

Potassium-40 (^{40}K)

The activity concentration of ^{40}K in the refinery soil samples ranged from 58.59 to 284.42 Bq/kg, with a mean of 171.85 ± 63.27 Bq/kg. The control site (DC) recorded 253.31 Bq/kg, which was higher

than the refinery mean. All values remained well below the UNSCEAR world average of 400 Bq/kg.

Radium-226 (²²⁶Ra)

The ²²⁶Ra activity concentrations ranged from 10.47 to 47.62 Bq/kg, with a mean of 25.94 ± 14.97 Bq/kg. While the mean was below the UNSCEAR global average of 35 Bq/kg, certain locations (D3, D9, D10) exhibited elevated concentrations above this threshold. The control site recorded 32.67 Bq/kg, slightly above the refinery mean.

Thorium-232 (²³²Th)

The ²³²Th activity concentrations ranged from 22.48 to 100.33 Bq/kg, with a mean of 66.23 ± 27.32 Bq/kg. Critically, this mean value was significantly higher than both the control site (36.12 Bq/kg) and the UNSCEAR global average (30 Bq/kg). Nine out of ten sampling locations exceeded the global average, with the highest concentrations found at D8 (100.33 Bq/kg), D4 (93.47 Bq/kg), and D7 (88.56 Bq/kg).

Absorbed Dose Rate (D)

The calculated absorbed dose rates are presented in Table 4. The mean absorbed dose rate for the refinery samples was 59.15 nGy/h, slightly exceeding the UNSCEAR world average of 59 nGy/h. Values ranged from 28.17 nGy/h (D5) to 79.73 nGy/h (D9). The control site recorded 47.47 nGy/h.

Table 4: Absorbed Dose Rates and Annual Effective Dose Equivalent

SAMPLE ID	ABSORBED DOSE (D) (NGY/H)	AEDE_OUTDOOR (MSV/Y)
DC (CONTROL)	47.47	0.0582
D1	58.06	0.0712
D2	58.08	0.0712
D3	55.48	0.0680
D4	68.63	0.0842
D5	28.17	0.0345
D6	47.19	0.0579
D7	74.78	0.0917
D8	76.99	0.0944
D9	79.73	0.0978

D10	44.40	0.0545
MEAN (D1-D10)	59.15	0.0725

Annual Effective Dose Equivalent (AEDE)

The outdoor annual effective dose equivalent ranged from 0.0345 mSv/y to 0.0978 mSv/y, with a mean of 0.0725 ± 0.0199 mSv/y. The highest AEDE was recorded at D9 (0.0978 mSv/y), while the control site recorded 0.0582 mSv/y. All values were well below the ICRP recommended limit of 1.0 mSv/y for the general public.

Radium Equivalent Activity (Ra_{eq})

The radium equivalent activity ranged from 61.35 to 179.80 Bq/kg, with a mean of 133.88 ± 37.01 Bq/kg (Table 5). The control site recorded 103.83 Bq/kg. All values remained substantially below the maximum permissible limit of 370 Bq/kg.

Hazard Indices

The calculated external and internal hazard indices, along with the representative gamma level index, are presented in Table 5.

Table 5: Radiological Hazard Indices and ELCR

SAMPLE ID	H_EX	H_IN	I_Γ	ELCR (×10 ⁻³)
DC (CONTROL)	0.280	0.369	0.749	0.915
D1	0.359	0.395	0.944	1.119
D2	0.354	0.387	0.944	1.119
D3	0.327	0.446	0.867	1.069
D4	0.426	0.454	1.122	1.322
D5	0.166	0.207	0.449	0.543
D6	0.294	0.339	0.765	0.909
D7	0.462	0.554	1.203	1.441
D8	0.478	0.536	1.251	1.483
D9	0.486	0.614	1.267	1.536
D10	0.265	0.384	0.687	0.855
MEAN (D1-D10)	0.362	0.432	0.950	1.140
SAFETY LIMIT	≤1	≤1	≤1	---

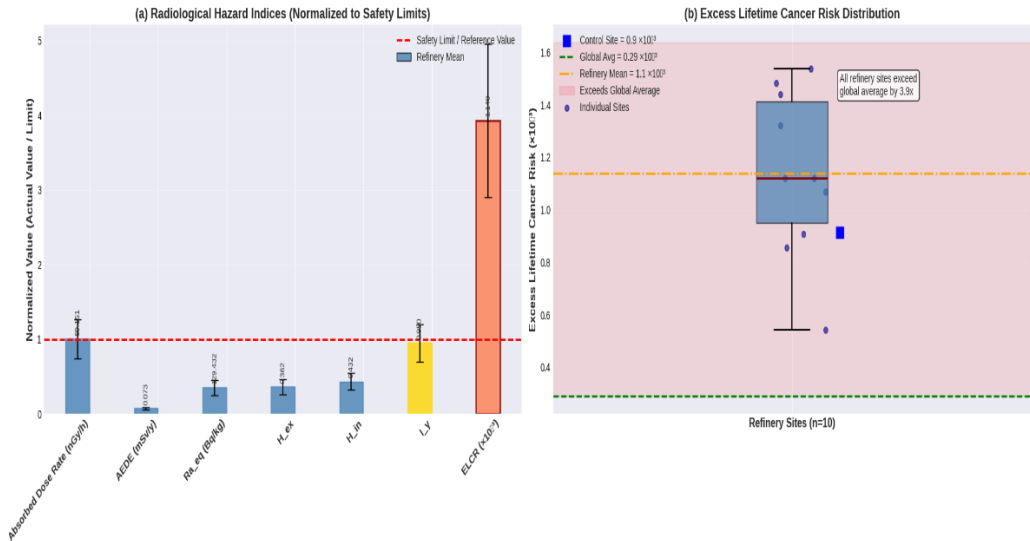


FIGURE 2: Comparative Assessment of Radiological Hazard Indices

Figure 2: Radiological hazard assessment for soils around KRPC. (a) Bar chart showing radiological hazard indices normalized to their respective safety limits or reference values. Values above 1.0 (dashed red line) indicate exceedance of the safety limit. The ELCR shows the most significant exceedance. (b) Boxplot of Excess Lifetime Cancer Risk (ELCR) distribution across refinery sampling sites, with individual site values (dark blue dots) and the control site (blue square). The dashed green line represents the global average (0.29×10^{-3}), while the dashed orange line shows the refinery mean. All refinery sites exceed the global average.

External Hazard Index (H_{ex})

The external hazard index ranged from 0.166 to 0.486, with a mean of 0.362. This is well below the unity threshold (≤ 1), indicating that the external gamma radiation from the soils does not constitute a significant hazard.

Internal Hazard Index (H_{in})

The internal hazard index ranged from 0.207 to 0.614, with a mean of 0.432. All values were below the unity threshold.

Representative Gamma Level Index (I_γ)

The gamma level index ranged from 0.449 to 1.267, with a mean of 0.950. While the mean was slightly below unity, four sampling locations (D4, D7, D8, D9) exceeded this threshold, suggesting that these specific areas require further attention.

Excess Lifetime Cancer Risk (ELCR)

The calculated ELCR ranged from 0.543×10^{-3} to 1.536×10^{-3} , with a mean of 1.140×10^{-3} (Table 5). All refinery samples exceeded the global average ELCR of 0.29×10^{-3} , and the mean was approximately four times higher than this reference value. The control site recorded an ELCR of 0.915×10^{-3} , also exceeding the global average.

Correlation Analysis

Pearson correlation coefficients among the three radionuclides are presented in Table 6.

Table 6: Pearson Correlation Matrix for Primordial Radionuclides

VARIABLE	^{226}Ra	^{232}Th	^{40}K
^{226}Ra	1.000		
^{232}Th	-0.265	1.000	
^{40}K	-0.326*	0.033	1.000

*Correlation is statistically significant at the 0.05 level (2-tailed)

A statistically significant negative correlation was observed between ^{226}Ra and ^{40}K ($r = -0.326$, $p < 0.05$). A weak negative correlation existed between ^{226}Ra and ^{232}Th ($r = -0.265$), while virtually no correlation was observed between ^{232}Th and ^{40}K ($r = 0.033$). The absence of strong positive correlations among these naturally co-occurring radionuclides indicates disruption of the natural geochemical equilibrium.

DISCUSSION

Activity Concentrations and Anthropogenic Enhancement

The most significant finding of this study is the pervasive elevation of ^{232}Th in soils around the KRPC facility. With a mean concentration of 66.23 Bq/kg, the refinery samples exceeded both the control site (36.12 Bq/kg) and the UNSCEAR global average (30 Bq/kg). This enhancement is consistent with the concept of Technologically Enhanced Naturally Occurring Radioactive

Materials (TENORM), where industrial processes concentrate naturally occurring radionuclides (Singh et al., 2024).

The elevated ^{232}Th concentrations can be attributed to refinery activities. Crude oil processing often results in the accumulation of radionuclides in scale deposits, sludge, and produced water (Njinga et al., 2022). The refining process can concentrate thorium by precipitating and settling solids in various processing units. Moreover, the refinery's storage tanks, pipelines, and wastewater treatment systems may accumulate NORM-bearing deposits over time, which can eventually enter the surrounding environment through spills, leaks, or improper waste management.

The spatial variability of ^{232}Th concentrations across the refinery site is noteworthy. Sample D8 (100.33 Bq/kg) and D4 (93.47 Bq/kg) exhibited the highest concentrations, suggesting localized contamination hotspots. These locations likely correspond to areas of intense industrial activity, such as waste-disposal sites, processing areas, or effluent discharge points. The high variability (standard deviation of 27.32 Bq/kg) indicates that contamination is not uniformly distributed but rather concentrated in specific zones. In contrast, ^{226}Ra concentrations (mean 25.94 Bq/kg) remained below the global average, with only three locations exceeding the 35 Bq/kg threshold. Interestingly, the control site (32.67 Bq/kg) showed a higher ^{226}Ra level than the refinery mean, suggesting that petroleum refining may not be a significant source of radium at this location, or that radium's behaviour in the refinery environment differs from that of thorium. This differential enrichment pattern is consistent with findings by Agbalagba and Esi (2022), who observed similar variations in NORM distributions in the Niger Delta.

Potassium-40 concentrations (mean 171.85 Bq/kg) were generally lower than the control site and well below the global average. The negative correlation between ^{226}Ra and ^{40}K (discussed in section 4.4) provides evidence of anthropogenic interference, as natural geological processes would typically maintain positive correlations among these radionuclides.

Radiological Hazard Assessment

Despite the elevated ^{232}Th concentrations, the calculated radiological hazard parameters indicate that the soils from the KRPC area do not pose an immediate acute radiation hazard. The mean Absorbed Dose Rate (59.15 nGy/h) was marginally above the UNSCEAR global average (59 nGy/h), while the maximum recorded value of 79.73 nGy/h falls within acceptable limits. This finding aligns with the broader NORM assessment literature, in which absorbed dose rates in industrial areas often exceed global averages yet remain below threshold levels (Jegade et al., 2025; Oladejo et al., 2025).

The Annual Effective Dose Equivalent (AEDE) values (mean 0.0725 mSv/y, maximum 0.0978 mSv/y) are well below the ICRP recommended limit of 1.0 mSv/y for the general public. This suggests that short-term exposure to the soils poses minimal immediate health risks. However, it is important to note that these values represent only outdoor exposure, and the use of an outdoor occupancy factor of 0.2 standardizes this conservative estimate. Indoor AEDE values would be approximately four times higher, though still below the 1.0 mSv/y limit.

The Radium Equivalent Activity (Ra_{eq}) values (mean 133.88 Bq/kg) were all below the 370 Bq/kg safety limit. Similarly, the hazard indices ($H_{ex} = 0.362$, $H_{in} = 0.432$) remained well below unity. These findings are comparable to those reported by Ganiyu et al. (2026) for soils from industrial fabrication and welding sites in

Abeokuta, and by Ohakwere-Eze et al. (2024) for mining sites in North-Eastern Nigeria. They indicate that from a radiation protection perspective, the soils meet safety standards for unrestricted use.

Excess Lifetime Cancer Risk (ELCR)

The ELCR results present a more nuanced picture of the public health implications. With a mean ELCR of 1.140×10^{-3} (approximately 1.14 additional cancers per 1,000 people exposed over a lifetime), the refinery area shows an elevated cancer risk compared to the global average of 0.29×10^{-3} . This represents an approximately four-fold increase in lifetime cancer risk.

The ELCR values from this study are comparable to those reported by Akuo-ko et al. (2025) for artisanal gold-mining regions in Nigeria, where ELCR levels exceeded 2.9×10^{-4} . Similarly, the values align with findings from other industrial sites, such as the superphosphate fertilizer industry in Kaduna Metropolis (Suleiman et al., 2021) and quarry sites in Ogun State (Jegede et al., 2025). The ELCR exceeding global averages, even when AEDE values remain within safety limits, is a critically important finding. It highlights the distinction between acute and chronic radiation effects and emphasizes the need for risk-based rather than dose-based regulatory approaches. As Singh et al. (2024) noted, chronic exposure to NORMs, even at low doses, can contribute to cumulative health effects over a lifetime, particularly in industrialized areas where exposure is continuous.

Statistical Source Apportionment

The observed weak and negative correlations among certain radionuclides suggest distinct geochemical processes or sources may influence them. In unperturbed geological environments, primordial radionuclides typically exhibit strong positive correlations because they co-exist within the same lithogenic parent rocks and follow similar weathering and transport pathways (Njinga et al., 2022). The absence of such positive correlations in this study may suggest that external inputs have disrupted the natural equilibrium.

The statistically significant negative correlation between ^{226}Ra and ^{40}K ($r = -0.326$, $p < 0.05$) is particularly revealing. This inverse relationship suggests that the sources contributing to ^{40}K enhancement (such as potassium-containing chemical additives or construction materials) are distinct from those responsible for ^{226}Ra enrichment. Moreover, the weak negative correlation between ^{226}Ra and ^{232}Th ($r = -0.265$) indicates that these radionuclides are being deposited independently, possibly from different industrial streams or at different times, rather than as part of a natural co-deposition process.

The near-zero correlation between ^{232}Th and ^{40}K ($r = 0.033$) further supports the conclusion that contamination originates from multiple isolated point sources rather than a single homogeneous source. These statistical findings are consistent with the interpretation that petroleum refining operations, with their multiple waste streams, effluent discharges, and accidental releases, create a complex contamination signature that deviates from natural patterns.

Comparison with Global Standards and Previous Studies

The elevated ^{232}Th concentrations observed in this study (mean 66.23 Bq/kg) exceed those reported by Oluyide et al. (2019) for an iron and steel smelting facility (23.23 Bq/kg) and by Adegbulugbe et al. (2024) for Kwara State soils (generally below 30 Bq/kg). However, they are comparable to values reported by Agbalagba

and Esi (2022) for the Niger Delta (37.67 Bq/kg) and by Jegede et al. (2025) for quarry sites in Ogun State (exceeding world averages).

The ELCR values from this study (1.140×10^{-3}) are higher than those reported by Ohakwere-Eze et al. (2024) for mining sites in North-Eastern Nigeria, suggesting that petroleum refining may pose a greater long-term cancer risk than mining activities in the region. This underscores the need for dedicated attention to the petroleum sector in national radiation protection frameworks.

Limitations and Recommendations

While this study provides radiological data for the KRPC area, several limitations should be acknowledged. First, the study focused only on surface soil samples; deeper soil profiles and groundwater samples were not analyzed, which limits understanding of vertical migration and potential groundwater contamination. Secondly, the ELCR calculations assumed continuous outdoor exposure for 55 years, which may not reflect actual exposure patterns for all population groups.

Future research should investigate the soil-to-plant transfer factors of these radionuclides to assess internal exposure pathways through the food chain. Additionally, occupational health surveillance of refinery workers, including personal dosimetry and health screening, would provide more accurate assessments of worker risk. Radon exhalation rates from soil and waste materials should also be measured to evaluate inhalation dose contributions.

Conclusion

This study assessed the radiological impact of the Kaduna Refining and Petrochemical Company on the local soil environment using gamma spectrometry to analyze ^{226}Ra , ^{232}Th , and ^{40}K . The results demonstrate that petroleum refining operations have significantly enhanced the concentration of ^{232}Th in surrounding soils, with the mean concentration (66.23 Bq/kg) substantially exceeding both local control values and the UNSCEAR global average of 30 Bq/kg. This enhancement represents a clear case of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) from industrial activities.

Despite this elevation, the calculated radiological hazard indices, including Annual Effective Dose Equivalent (0.0725 mSv/y), Radium Equivalent Activity (133.88 Bq/kg), and hazard indices ($H_{\text{ex}} = 0.362$, $H_{\text{in}} = 0.432$), remain within internationally recommended safety limits, confirming that there is no immediate acute radiation hazard to workers or the public.

However, the Excess Lifetime Cancer Risk (1.140×10^{-3}), which exceeds the global average of 0.29×10^{-3} by approximately fourfold, reveals a significant cumulative, long-term health risk associated with continuous exposure to the refinery environment. The statistical correlation analysis, which identified weak to negative correlations among the radionuclides, provides quantitative proof that anthropogenic inputs from isolated industrial point sources have disrupted the natural geochemical equilibrium. The study concludes that while the Kaduna Refining and Petrochemical Company area remains radiologically safe for short-term operations, prolonged, unmitigated industrial exposure presents a latent public health vulnerability. This finding carries important implications for environmental management and public health policy in the region.

Acknowledgements

The authors express sincere gratitude to the Nigerian Defence Academy for providing the platform for this research. Special thanks are due to the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, for technical assistance during the analytical phase of this study. The cooperation of the management and staff of the Kaduna Refining and Petrochemical Company is also gratefully acknowledged.

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