FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 16, June, 2026, pp 420 – 427
DOI: https://doi.org/10.33003/fjs-2026-1016-5530

Impact of Industrial Activities on the Distribution of Naturally Occurring Radioactive Materials in Soils from Dantata Road Construction Site in Kaduna State, Nigeria

***[1]Jude Okemsinachi Anaegbu, [2]Agomuo John Chidowerem, [2]Ige Olumide Oluwasanmi and [2]Hauwau Kulu Shuaibu**

[1]Department of Physics, Greenfield University Kaduna, Kaduna State, Nigeria.
[2]Department of Physics, Nigerian Defence Academy, Kaduna State, Nigeria.

*Corresponding authors' email: jude.anaegbu@gmail.com

Received: 15 Jul. 2026
Accepted: 27 Aug. 2026
Published: 01 Aug. 2026

ABSTRACT
This study assessed the distribution of naturally occurring radioactive materials (NORMs) in soils from the Dantata Road Construction Site, Kaduna State, Nigeria, to evaluate potential industrial influence. Soil samples (n=10) were collected from active operational areas, with one reference sample from a location approximately 500 m away. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were measured using a thallium-activated sodium iodide [NaI(Tl)] gamma spectrometer. In the active zone, mean activity concentrations were 206.80 ± 81.04 Bq/kg (^{40}K), 22.78 ± 10.82 Bq/kg (^{226}Ra), and 61.91 ± 22.02 Bq/kg (^{232}Th). The reference sample yielded 165.99 Bq/kg, 40.25 Bq/kg, and 22.18 Bq/kg respectively. The elevated ^{232}Th mean exceeds both the reference value and the UNSCEAR worldwide reference mean of 30 Bq/kg. Calculated annual effective dose equivalents ranged from 0.044 to 0.094 mSv/y, below the 1.0 mSv/y public limit. Excess lifetime cancer risk estimates ranged from 0.155×10^{-3} to 0.328×10^{-3}, with some locations exceeding the global average of 0.29×10^{-3}. Weak to moderate negative correlations among radionuclides suggest possible disruption of natural geochemical equilibrium. However, the limited sample size (n=10) and single reference measurement preclude definitive source attribution. The observed ^{232}Th enrichment warrants further investigation with expanded sampling and mineralogical analysis.

Keywords: Naturally occurring radioactive materials, gamma spectrometry, Dantata Road Construction, radiological hazard, excess lifetime cancer risk, TENORM

INTRODUCTION

Kaduna Metropolis, a prominent industrial hub in northern Nigeria, hosts diverse industrial activities that drive economic growth and urban development. However, the ecological impacts of these activities are often underestimated (Ujuagu et al., 2025). Among the environmental concerns associated with industrialization is the potential redistribution and concentration of Naturally Occurring Radioactive Materials (NORMs), which are ubiquitous in the environment, originating from primordial radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K present in soils, rocks, and water (Suleiman et al., 2021; Adebiyi et al., 2021).

While NORMs occur naturally, industrial activities particularly those involving large-scale earthworks, aggregate handling, imported fill, and mineral-bearing construction materials—can significantly enhance their concentrations, leading to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). The Dantata Road Construction Site represents a significant industrial operation where such activities may redistribute and concentrate radionuclides in soils. The processes through which this may occur include excavation of deeper soil horizons, processing of construction materials containing thorium-bearing minerals, and deposition of industrial by-products. The Dantata site functions primarily as a road-construction materials processing and earthworks facility, involving stockpiling of aggregates, soil movement, and preparation of construction materials rather than a multi-industry zone.

Previous Nigerian studies have measured NORM concentrations in various environmental settings (Agbalagba & Oghenevovwero, 2023; Jegede et al., 2025; Ohakwere-Eze et al., 2024), but few have focused on the specific processes through which road construction activities might affect radionuclide distribution, nor have they adequately resolved the question of whether observed enrichments represent natural variability or anthropogenic enhancement. This study addresses this gap by providing a radiological assessment of the Dantata Road Construction Site using gamma spectrometry to quantify activity concentrations of primordial radionuclides and evaluate associated health risks.

The central hypothesis of this study is that if industrial activities at the site have significantly altered NORM distribution, then activity concentrations particularly ^{232}Th would be elevated in active operational areas relative to reference locations, and radionuclide correlations would deviate from those expected in undisturbed geological settings.

MATERIALS AND METHODS

Study Area and Sampling Design

The research was conducted at the Dantata Road Construction Site, located within Kaduna Metropolis, Kaduna State, Nigeria. The site coordinates range from latitude 10.63098°N to 10.63539°N and longitude 7.39194°E to 7.39659°E. The study area represents a significant industrial operation involving large-scale construction and earthworks. A scaled site map was prepared showing all sampling locations, operational features (stockpiles, drainage patterns, material processing areas), and prevailing wind direction.

A reference site was established at coordinates 10.63503°N, 7.39515°E, approximately 500 meters from the active operational zone, to provide a baseline representing the natural background radiation of the region. It is acknowledged that a single reference measurement, while providing some contextual information, does not provide sufficient statistical power for definitive background

comparison. Future studies should incorporate multiple reference samples from geologically comparable, demonstrably unaffected locations.

Sample Collection and Preparation

Soil samples were collected from eleven locations within and around the Dantata Road Construction Site. Ten sampling points (B1–B10) were established within the active operational areas, and one reference sample (BC) was collected from a location away from direct industrial influence.

The geographic coordinates of each sampling point were recorded using a handheld Global Positioning System (GPS) with an accuracy of ±3 meters. Each sample represented a composite of three sub-samples collected within a 5 m radius at each location, homogenized to account for local spatial variability. At each location, approximately one kilogram of soil was collected from the surface layer (0–10 cm depth) using a hand auger and shovel. Samples were stored in clean polyethylene bags, labeled with unique identification codes, and transported to the laboratory for processing.

In the laboratory, samples were oven-dried at 105°C for approximately 10–12 hours to remove moisture. This temperature was selected to ensure complete moisture removal within a practical timeframe; however, it is acknowledged that standard environmental-soil protocols sometimes recommend lower temperatures (e.g., 40–60°C) to avoid potential alteration of certain sample properties, though for gamma spectrometric analysis of radionuclides, the drying temperature is not expected to significantly affect activity concentrations.

The dried samples were ground and passed through a 2 mm sieve to achieve uniform particle size and ensure sample homogeneity. The homogenized samples were then weighed and placed into airtight cylindrical plastic containers of standard geometry (450 mL Marinelli beakers). The containers were hermetically sealed and stored for approximately 30 days to allow attainment of secular radioactive equilibrium between the long-lived parent radionuclides and their short-lived decay products, ensuring reliable gamma spectrometric measurements (Yachiso, 2022).

Gamma Spectrometry Analysis

Activity concentrations of primordial radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) were measured using a thallium-activated sodium iodide [NaI(Tl)] gamma spectrometer coupled to a multi-channel analyzer at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria.

The detector system comprised a 7.62 cm × 7.62 cm NaI(Tl) crystal coupled to a photomultiplier tube, housed in a 10 cm thick lead shield with a copper inner lining to reduce background radiation. The system provided an energy resolution of approximately 7.5% at the 662 keV photopeak of ^{137}Cs.

The detector system was calibrated using certified reference materials (IAEA-375, IAEA-447, and RGU-1) with known activity concentrations, ensuring measurement accuracy and traceability. The efficiency calibration curve was generated using a mixed radionuclide standard source (^{226}Ra, ^{232}Th, and ^{40}K) in the same geometry as the samples. The efficiency (ε) as a function of energy (E) was fitted using:

$$\log \varepsilon\,(E) = a_0 + a_1 \log E + a_2 (\log E)^2$$

Each sample (approximately 350 g) was counted for periods of 10,000–20,000 seconds to achieve acceptable counting statistics with uncertainties below 10%. The sample geometry was standardized using identical 450 mL Marinelli beakers placed directly on the detector end-cap.

Background spectra were acquired for 100,000 seconds using an empty Marinelli beaker and were subtracted from each sample spectrum using the formula:

$$C_{net} = C_{gross} - C_{background}$$

Minimum detectable activity concentrations (MDACs) were calculated using the Currie method (Currie, 1968) and were 1.2 Bq/kg for ^{226}Ra, 1.5 Bq/kg for ^{232}Th, and 5.0 Bq/kg for ^{40}K.

Measurement uncertainties were calculated by propagation of errors, accounting for counting statistics (1σ), calibration uncertainty, and sample mass uncertainty using:

$$\sigma_{total} = \sqrt{\sigma_{counting}^2 + \sigma_{calibration}^2 + \sigma_{mass}^2}$$

The characteristic gamma-ray energies used for quantification were:

i. ^{40}K: 1460.8 keV (single photopeak)
ii. ^{226}Ra: 1764.5 keV (via ^{214}Bi from the decay series)
iii. ^{232}Th: 2614.5 keV (via ^{208}Tl from the decay series)

Peak selection was performed using the software's automatic peak-search algorithm, with manual verification of all peaks.

Radiological Hazard Assessment

The following radiological hazard parameters were calculated to evaluate the potential health risks associated with exposure to NORMs in the soil samples, following standard protocols established in the literature (Beretka & Mathew, 1985; UNSCEAR, 2000; ICRP, 2007).

Absorbed Dose Rate (D)

The absorbed dose rate (D) in air at 1 meter above the ground was calculated using the formula (UNSCEAR, 2000):

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

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

Annual Effective Dose Equivalent (AEDE)

The annual effective dose equivalent (AEDE) was calculated from the absorbed dose rate using:

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

Where 0.7 is the conversion coefficient from absorbed dose in air to effective dose, 0.2 is the outdoor occupancy factor, and 8760 is the number of hours per year (UNSCEAR, 2000). The occupancy factor of 0.2 assumes 20% outdoor occupancy; sensitivity analysis indicates that varying this factor between 0.1 and 0.4 changes AEDE values proportionally, and results should be interpreted with this uncertainty in mind.

Radium Equivalent Activity (Ra_{eq})

The radium equivalent activity (Ra_{eq}) was calculated to represent the weighted sum of the three radionuclides as a single quantity (Beretka & Mathew, 1985):

$$Ra_{eq} \text{ (Bq/kg)} = C_{Ra} + 1.43C_{Th} + 0.077C_K$$

The Ra_{eq} must remain below the safe limit of 370 Bq/kg for the radiation hazard to be considered insignificant (OECD, 1979).

External Hazard Index (H_{ex})

The external hazard index (H_{ex}) was calculated using (Beretka & Mathew, 1985):

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

For safe use, H_{ex} must be less than unity.

Internal Hazard Index (H_{in})

The internal hazard index (H_{in}) accounts for the internal exposure to radon and its progeny (Beretka & Mathew, 1985):

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

For safe use, H_{in} must be less than unity.

Gamma Level Index (I_γ)

The gamma level index (I_γ) was calculated as (UNSCEAR, 2000):

$$I_\gamma = \frac{C_{Ra}}{150} + \frac{C_{Th}}{100} + \frac{C_K}{1500}$$

A value of $I_\gamma \leq 1$ corresponds to an annual effective dose of ≤ 1 mSv/y.

Excess Lifetime Cancer Risk (ELCR)

The excess lifetime cancer risk (ELCR) was calculated using the standard ICRP 103 formula (ICRP, 2007):

$$ELCR = AEDE \times DL \times RF$$

Where:

i. AEDE = Annual Effective Dose Equivalent (in Sv/y)
ii. DL = Average lifetime duration (70 years)
iii. RF = Risk factor for stochastic effects (0.05 Sv^{-1} for the public)

ELCR estimates represent theoretical screening values based on a linear no-threshold model and should be interpreted as conservative upper-bound estimates rather than definitive individual risk probabilities.

Statistical Analysis

Pearson correlation analysis was performed using IBM SPSS Statistics (Version 26) to determine the relationships among the three radionuclides (^{226}Ra, ^{232}Th, and ^{40}K). For the 10 samples in the active zone (n=10), the critical value for significance at $p < 0.05$ (two-tailed) is $r = 0.632$. Statistical significance was considered at $p < 0.05$, with exact p-values reported. The coefficient of variation (CV) was calculated to assess the variability of activity concentrations across the sampling locations. Confidence intervals (95%) for mean activity concentrations were calculated using the standard error of the mean.

It is emphasized that with only 10 samples in the active zone and a single reference sample, statistical comparisons between active and reference locations lack the necessary replication for definitive inference. The reference value is presented for contextual comparison only and does not constitute a statistical baseline.

RESULTS AND DISCUSSION

Activity Concentrations of NORMs

The geographical coordinates and specific activity concentrations of the primordial radionuclides measured across all sampled locations at the Dantata Road Construction Site are presented in Table 1.

Table 1: Geographical Coordinates and Activity Concentrations of NORMs at Dantata Road Construction Site

Sample ID	Latitude (N)	Longitude (E)	^{40}K (Bq/kg)	Error ±	^{226}Ra (Bq/kg)	Error ±	^{232}Th (Bq/kg)	Error ±
BC (Control)	10.63503	7.39515	165.99	3.14	40.25	3.30	22.18	2.49
B1	10.63539	7.39659	100.39	4.75	21.07	3.51	59.39	2.98
B2	10.63462	7.39617	190.00	3.17	39.88	3.93	48.28	4.08
B3	10.63445	7.39589	185.27	4.84	14.40	1.52	60.66	3.97
B4	10.63385	7.39515	237.64	6.84	12.98	1.74	55.09	3.42
B5	10.63391	7.39498	395.80	6.55	17.87	1.95	18.88	2.81
B6	10.63228	7.39414	184.25	3.83	17.16	1.93	85.48	4.51
B7	10.63273	7.39345	138.68	3.43	37.11	2.81	82.31	4.56
B8	10.63156	7.39243	164.54	3.63	37.28	3.08	56.58	3.48
B9	10.63189	7.39272	206.10	3.19	15.15	1.68	55.44	3.33
B10	10.63098	7.39194	265.37	3.92	14.86	1.53	96.99	4.41

Summary Statistics and Comparison with Global Standards

Table 2 presents the summary statistics for the activity concentrations of the three primordial radionuclides, comparing the active industrial zone with the reference site and global standards recommended by UNSCEAR.

Table 2: Summary Statistics for ^{40}K, ^{226}Ra, and ^{232}Th Activity Concentrations (Bq/kg) Compared with Reference Site and Global Standards

Location	Statistic	^{40}K (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)
Reference Site (BC)	Single Value	165.99	40.25	22.18
Active Zone (B1–B10)	Mean	206.80	22.78	61.91
	Minimum	100.39	12.98	18.88
	Maximum	395.80	39.88	96.99
	Standard Deviation	±81.04	±10.82	±22.02
	Coefficient of Variation (%)	39.2	47.5	35.6
UNSCEAR World Average	-	400	35	30

Discussion of Activity Concentrations

Potassium-40 (^{40}K)

The activity concentrations of ^{40}K in the active industrial zone ranged from 100.39 Bq/kg to 395.80 Bq/kg, with a mean value of 206.80 ± 81.04 Bq/kg. This mean is higher than the single reference value of 165.99 Bq/kg, suggesting possible enhancement. The maximum value of 395.80 Bq/kg at sample B5 approaches the UNSCEAR worldwide average of 400 Bq/kg. However, given the limited sample size and single reference measurement, this observation cannot be conclusively attributed to anthropogenic activity. The mean concentration remains well below the UNSCEAR average,

suggesting that while localized elevations exist, overall ^{40}K levels are not exceptionally high.

Radium-226 (^{226}Ra)

The activity concentrations of ^{226}Ra in the active industrial zone ranged from 12.98 to 39.88 Bq/kg, with a mean of 22.78 ± 10.82 Bq/kg. This mean is lower than the single reference value of 40.25 Bq/kg, and all active zone values fall below the UNSCEAR worldwide average of 35 Bq/kg (except B2 at 39.88 Bq/kg, which is close to the average). The reference value (40.25 Bq/kg) slightly exceeds the UNSCEAR average, highlighting the need for replicated reference measurements. The generally lower ^{226}Ra concentrations in the active zone compared to the reference suggest that the industrial activities at this site are not associated with elevated ^{226}Ra.

Thorium-232 (^{232}Th)

The most notable finding of this study relates to the activity concentrations of ^{232}Th. The active industrial zone recorded concentrations ranging from 18.88 to 96.99 Bq/kg, with a mean of 61.91 ± 22.02 Bq/kg. This mean is substantially higher than the single reference value of 22.18 Bq/kg and exceeds the UNSCEAR worldwide average of 30 Bq/kg. Several samples particularly B6 (85.48 Bq/kg), B7 (82.31 Bq/kg), and B10 (96.99 Bq/kg) show markedly elevated ^{232}Th concentrations relative to both the reference and global average.

This elevation of ^{232}Th is consistent with observations from other industrial sites (Agbalagba & Oghenevovwero, 2023; Jegede et al., 2025) and may be associated with industrial processes such as earthmoving, material processing, and the use of construction materials containing thorium-bearing minerals. However, without mineralogical analysis, replicated reference samples, or direct source tracing, this pattern should be interpreted as possible localized ^{232}Th enrichment requiring further investigation, rather than confirmed TENORM deposition. The elevated values suggest that thorium-containing materials may be present in the operational area, but source attribution cannot be definitively established from these data alone.

Previous studies in Nigeria have reported elevated thorium in various settings. Agbalagba and Oghenevovwero (2023) reported thorium concentrations of 35–72 Bq/kg in oil-producing areas, attributing enrichments to drilling mud residues and produced water discharges. Jegede et al. (2025) found thorium up to 89 Bq/kg in quarry sites, associated with granite crushing and dust deposition. However, these comparisons must account for differences in geology, detector type, sampling depth, and land use. The present study's values are within the range of these previous findings, but the specific geological context of the Kaduna area (primarily crystalline basement rocks) should be considered when comparing to other regions.

Figure 1: Activity concentrations (Bq/kg) of ^{40}K, ^{226}Ra, and ^{232}Th in soil samples from Dantata Road Construction Site

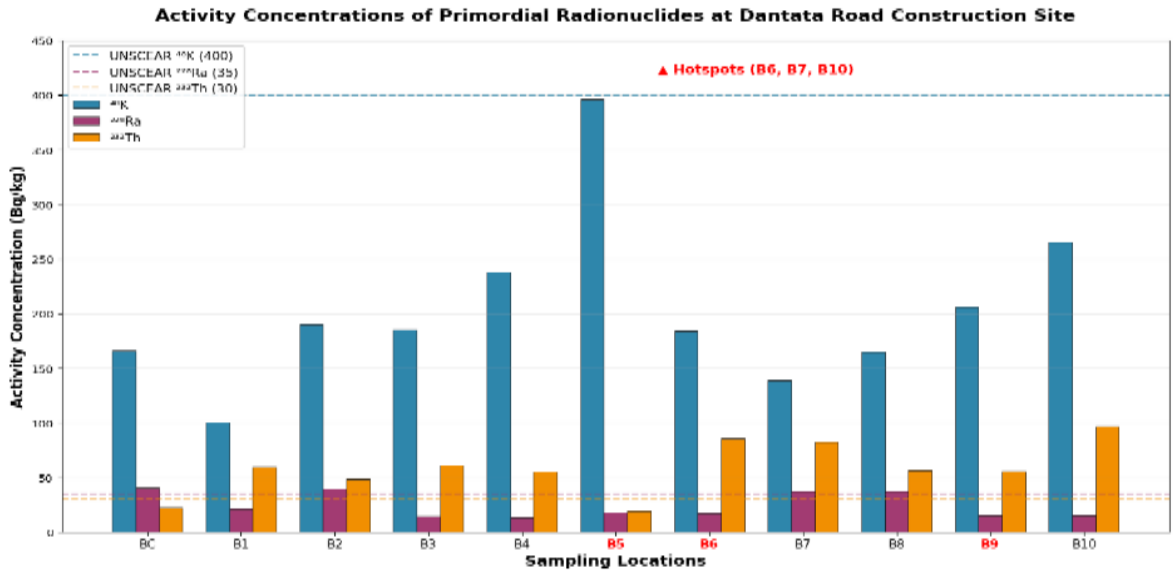

Figure 1: Activity concentrations (Bq/kg) of ^{40}K, ^{226}Ra, and ^{232}Th in soil samples from Dantata Road Construction Site compared with UNSCEAR worldwide reference means (dashed lines). The control site (BC) is shown in green. Error bars represent measurement uncertainties (1σ). Red labels indicate hotspot locations (B6, B7, B10) where ^{232}Th concentrations exceed 80 Bq/kg, substantially above the UNSCEAR worldwide reference mean of 30 Bq/kg. The elevated ^{232}Th concentrations at these hotspots suggest possible localized enrichment requiring further investigation

Radiological Hazard and Dose Assessments

To evaluate the potential health risks posed to workers and the general public by the measured NORMs, several radiological hazard indices were calculated. The results are presented in Tables 3 and 4.

Table 3: Absorbed Dose Rates, Annual Effective Dose Equivalents, and Radium Equivalent Activities at Dantata Road Construction Site

Sample ID	Absorbed Dose (D) (nGy/h)	AEDE (mSv/y)	Ra_eq (Bq/kg)
BC (Control)	38.92	0.0477	84.76
B1	49.79	0.0611	113.72
B2	55.51	0.0681	123.55
B3	51.02	0.0626	115.41

Sample ID	Absorbed Dose (D) (nGy/h)	AEDE (mSv/y)	Ra_eq (Bq/kg)
B4	49.18	0.0603	110.05
B5	36.17	0.0444	75.35
B6	67.25	0.0825	153.59
B7	72.65	0.0891	165.50
B8	58.26	0.0714	130.86
B9	49.08	0.0602	110.30
B10	76.51	0.0938	173.99
Active Zone Mean	**56.54**	**0.0693**	**127.23**

Table 4: Calculated Radiation Hazard Indices and Excess Lifetime Cancer Risk

Sample ID	H_ex	H_in	I_γ	ELCR (×10⁻³)
BC (Control)	0.229	0.338	0.601	0.167
B1	0.307	0.364	0.801	0.214
B2	0.334	0.441	0.877	0.238
B3	0.312	0.351	0.826	0.219
B4	0.297	0.332	0.796	0.211
B5	0.203	0.252	0.572	0.155
B6	0.415	0.461	1.092	0.289
B7	0.447	0.547	1.164	0.312
B8	0.353	0.454	0.925	0.250
B9	0.298	0.339	0.792	0.211
B10	0.470	0.510	1.246	0.328
Active Zone Mean	0.344	0.405	0.909	0.242

Absorbed Dose Rate (D)

The absorbed dose rates at 1 meter above ground ranged from 36.17 nGy/h (sample B5) to 76.51 nGy/h (sample B10), with a mean value of 56.54 nGy/h for the active industrial zone. This mean is notably higher than the reference site value of 38.92 nGy/h, indicating elevated gamma radiation levels in the operational areas.

The mean absorbed dose rate of 56.54 nGy/h approaches the UNSCEAR world average of 59 nGy/h. Samples B6 (67.25 nGy/h), B7 (72.65 nGy/h), and B10 (76.51 nGy/h) exceeded the global average, indicating localized elevated radiation levels within the study area.

Annual Effective Dose Equivalent (AEDE)

The calculated Annual Effective Dose Equivalent (AEDE) values ranged from 0.0444 mSv/y (sample B5) to 0.0938 mSv/y (sample B10), with a mean of 0.0693 mSv/y for the active industrial zone. The reference site recorded an AEDE of 0.0477 mSv/y.

All AEDE values are well below the International Commission on Radiological Protection (ICRP) recommended public dose limit of 1.0 mSv/y and the occupational limit of 20 mSv/y (ICRP, 2007). This indicates that the current radiation levels do not pose an immediate or acute radiation hazard to workers or residents.

Radium Equivalent Activity (Ra_eq)

The radium equivalent activity (Ra_{eq}) values ranged from 75.35 Bq/kg (sample B5) to 173.99 Bq/kg (sample B10), with a mean of 127.23 Bq/kg for the active industrial zone. The reference site recorded an Ra_{eq} of 84.76 Bq/kg.

All Ra_{eq} values are substantially below the recommended safe limit of 370 Bq/kg (OECD, 1979), confirming that the specific activity limits of the soil are radiologically safe for ongoing operations and nearby inhabitants.

Radiation Hazard Indices (H_{ex}, H_{in}, and I_γ)

The external hazard index (H_{ex}) values ranged from 0.203 to 0.470, all below the safety threshold of unity (≤ 1). The internal hazard index (H_{in}) values ranged from 0.252 to 0.547, also below unity. The gamma level index (I_γ) values ranged from 0.572 to 1.246, with a mean value of 0.909 for the active industrial zone.

While most I_γ values remained below the threshold of 1.0, samples B6 (1.092), B7 (1.164), and B10 (1.246) exceeded unity, indicating elevated gamma radiation levels at these specific locations. This suggests that while the overall site is radiologically safe, specific locations require closer monitoring and possible investigation.

These results indicate that the external gamma radiation threat and the internal threat from radon inhalation due to these soils generally fall within safe operational limits, though localized hotspots warrant attention.

Excess Lifetime Cancer Risk (ELCR)

The ELCR values, calculated using the standard ICRP 103 formula (ELCR = AEDE × 70 × 0.05), ranged from 0.155×10^{-3} (sample B5) to 0.328×10^{-3} (sample B10), with a mean of 0.242×10^{-3} for the active industrial zone. The reference site recorded an ELCR of 0.167×10^{-3}.

Several active zone samples show ELCR values above the global average of 0.29×10^{-3}, with B10 (0.328×10^{-3}) and B7 (0.312×10^{-3}) being the highest. It is important to emphasize that ELCR is a theoretical screening estimate based on a linear no-threshold model and assumes lifetime exposure at constant rates. It does not represent a deterministic prediction of cancer occurrence but rather a conservative upper-bound risk estimate for regulatory comparison purposes. The AEDE results confirm that no acute radiation hazard exists, and the elevated ELCR values at specific locations suggest that further monitoring at these hotspots would be prudent.

The ELCR values observed in this study are consistent with findings from other industrial areas. Ohakwere-Eze et al. (2024) reported elevated ELCR values in mining sites across North-Eastern Nigeria, while Ganiyu et al. (2026) observed similar results in industrial fabrication zones in Abeokuta.

Statistical Analysis and Radionuclide Relationships

To examine the geochemical relationships of the naturally occurring radioactive materials at the Dantata Road Construction Site, a Pearson Correlation analysis was conducted on the specific activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K. In unperturbed natural environments, primordial radionuclides typically exhibit strong positive correlations because they co-exist within the same lithogenic parent rocks and share similar weathering behaviors (Randhawa et al., 2024). Conversely, weak or negative correlations may indicate that the normal secular equilibrium has been disrupted by external inputs.

Table 5: Pearson Correlation Matrix for Primordial Radionuclides in Soil Samples

Radionuclides	^{226}Ra	^{232}Th	^{40}K
^{226}Ra	1	-	-
^{232}Th	-0.265	1	-
^{40}K	-0.326	0.033	1

Note: For n=10, the critical value for significance at $p < 0.05$ (two-tailed) is $r = 0.632$. None of the correlations are statistically significant at this level.

The correlation matrix reveals a striking absence of strong positive relationships among the three radionuclides across the Dantata Road Construction Site.

i. ^{226}Ra and ^{40}K Relationship:
ii. A moderate negative correlation was observed between Radium-226 and Potassium-40 ($r = -0.326$). For n=10, the critical value for significance at $p < 0.05$ (two-tailed) is $r = 0.632$. Therefore, $r = -0.326$ is not statistically significant at $p < 0.05$. This correlation should be described as weak-to-moderate and non-significant ($p > 0.05$), suggesting a possible but unconfirmed inverse relationship that may warrant further investigation with a larger sample size.
iii. ^{226}Ra and ^{232}Th Relationship:
iv. A weak negative correlation ($r = -0.265$) was observed, which is not statistically significant with the available sample size.
v. ^{232}Th and ^{40}K Relationship: Virtually no correlation ($r = 0.033$) was observed.

The weak and non-significant correlations among the three radionuclides suggest patterns that may deviate from those expected in undisturbed geological settings, where primordial radionuclides typically exhibit positive correlations due to co-occurrence in lithogenic parent rocks. However, the limited sample size (n=10) and absence of mineralogical or elemental ratio analyses mean that the correlation results alone do not provide quantitative proof of TENORM deposition. Rather, they provide preliminary evidence that warrants further investigation with expanded sampling and additional analytical techniques such as mineralogical analysis, elemental ratios, enrichment factors, or multivariate analysis to confirm source attribution.

Summary of Major Findings

This study investigated the distribution of Naturally Occurring Radioactive Materials (NORMs) at the Dantata Road Construction Site, Kaduna Metropolis. The findings are summarized as follows:

Activity Concentrations

Activity concentrations of ^{226}Ra and ^{40}K in the active operational areas were generally below or near UNSCEAR worldwide averages, with some localized elevations. The mean ^{232}Th concentration (61.91 Bq/kg) exceeded both the single reference value (22.18 Bq/kg) and the UNSCEAR worldwide average (30 Bq/kg), with several specific locations showing marked elevations (B6, B7, B10).

Radiological Hazard Indices

Calculated annual effective dose equivalents ranged from 0.044 to 0.094 mSv/y, well below the ICRP public limit of 1.0 mSv/y. Radium equivalent activity and hazard indices (H_ex and H_in) were below unity at all locations. Gamma level indices at three locations (B6, B7, B10) exceeded unity, suggesting elevated gamma radiation at these specific points.

Excess Lifetime Cancer Risk

ELCR estimates ranged from 0.155×10^{-3} to 0.328×10^{-3}. Several locations exceeded the global average of 0.29×10^{-3}, though these represent theoretical screening estimates rather than deterministic risk predictions.

Statistical Relationships

Weak-to-moderate and statistically non-significant correlations were observed among radionuclides, suggesting possible deviation from natural geochemical equilibrium patterns. However, the limited sample size (n=10) precludes definitive source attribution.

CONCLUSION

The results of this study indicate that the Dantata Road Construction Site exhibits heterogeneous NORM distribution, with notable ^{232}Th enrichment at several locations compared to a single reference value and global averages. The measured external dose estimates and most hazard indices were below selected screening values, suggesting that no acute radiation hazard exists for workers or nearby residents.

However, several critical limitations must be acknowledged. The study has no pre-industrial baseline, only a single reference measurement (which lacks replicated variance for statistical comparison), no temporal record, no mineralogical identification of the thorium-bearing materials, and no direct causal source analysis. Therefore, while the observed ^{232}Th elevations are suggestive of possible industrial influence, the findings cannot be interpreted as confirmed TENORM deposition or as undeniable evidence of anthropogenic alteration of the radiological baseline. The correlation results, while indicating patterns worthy of further study, do not provide quantitative proof of source attribution.

This study provides baseline data for future investigations at this site and highlights the need for expanded sampling, replicated reference sites, mineralogical analysis, and continued environmental monitoring. While current radiation levels appear within safe operational limits for most locations, the localized ^{232}Th elevations at specific hotspots warrant further investigation to determine their sources and potential long-term implications.

Based on the findings and acknowledging the study's limitations, the following recommendations are made:

Expanded Monitoring
Future studies should expand sampling to include multiple reference sites from geologically comparable, demonstrably unaffected locations to establish a statistically valid background. Particular attention should be paid to locations B6, B7, and B10 where elevated ^{232}Th and I_γ values were observed.

Mineralogical Analysis
Follow-up investigations should include mineralogical analysis (e.g., X-ray diffraction, scanning electron microscopy) to identify the specific mineral phases hosting thorium and to enable definitive source attribution. Elemental ratios and enrichment factors would also assist in distinguishing natural from anthropogenic sources.

Source Tracing
Investigations should be conducted to identify the specific materials (e.g., imported fill, aggregates, construction materials) that may be contributing to the observed ^{232}Th enrichments, allowing for targeted management of these materials.

Regulatory Oversight
The National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Nigerian Nuclear Regulatory Authority (NNRA) may consider periodic environmental monitoring at industrial construction sites as part of routine oversight. The NNRA, through its UNSCEAR National Contact Person, should ensure that data from this study is submitted to the UNSCEAR Global Survey for international benchmarking.

Occupational Monitoring
Given the elevated ^{232}Th at specific hotspots, dust suppression measures and routine environmental dose monitoring at these locations are prudent.

Public Awareness
Public awareness programs should be developed to educate workers about radiation safety principles, emphasizing that current exposure levels are within safe limits while promoting continued vigilance.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the technical assistance provided by the team at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, during the gamma spectrometric analysis. Special thanks are due to the Nigerian Defence Academy, Kaduna, for supporting this research. The authors also appreciate the cooperation of the management and staff of the Dantata Road Construction Site for granting access to the study area.

REFERENCES

Adebiyi, F. M., Ore, O. T., Adeola, A. O., Durodola, S. S., Akeremale, O. F., Olubodun, K. O., & Akeremale, O. K. (2021). Occurrence and remediation of naturally occurring radioactive materials in Nigeria: A review. Environmental Chemistry Letters, 19(4), 3243–3262. https://doi.org/10.1007/s10311-021-01237-4

Agbalagba, E. O., & Oghenevovwero Emmanuel, E. (2023). Occupational and public risk assessment of NORMs in soil of the Niger Delta region of Nigeria after six decades of hydrocarbon exploitation. Arabian Journal of Geosciences, 16(5). https://doi.org/10.1007/s12517-022-11151-w

Beretka, J., & Mathew, P. J. (1985). Natural radioactivity of Australian building materials, industrial wastes and by-products. Health Physics, 48(1), 87–95.
Currie, L. A. (1968). Limits for qualitative detection and quantitative determination. Analytical Chemistry, 40(3), 586-593.

Ewona, I. O., Terso, U., Keen, R. B., Udo, S. O., Eka, B. J., Okono, M. A., & Ukam, L. E. (2024). Assessment of the pollution indices of particulate matter trapped in classroom ceiling fans in a tertiary institution in southern Nigeria. International Journal of Research and Scientific Innovation (IJRSI), 11(7), 1260–1275.

Idowu, G. A. (2022). Heavy metals research in Nigeria: A review of studies and prioritization of research needs. Environmental Science and Pollution Research International, 29(44), 65940–65961. https://doi.org/10.1007/s11356-022-22174-x

International Commission on Radiological Protection (ICRP). (2007). Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Pergamon Press.

Jegede, D. O., Afolabi, T. A., Agunbiade, F. O., Afolabi, T. A., Ogundiran, O. O., Gbadamosi, M. R., Sojinu, S. O., Ojekunle, O. Z., & Varanusupakul, P. (2025). Spatial distribution and radiological hazards assessment of naturally occurring radionuclide materials in soil from quarry sites in Ogun State, Nigeria. Environmental Monitoring and Assessment, 197(5), 575. https://doi.org/10.1007/s10661-025-13988-6

Ohakwere-Eze, M. C., Nafiu, M., Singh, S. K., Rabiu, J. A., & Obingonye, I. A. (2024). Investigation into the geological radiation levels and evaluation of hazard parameters in soil and rock specimens taken from mining sites across North-Eastern Nigeria. Discover Environment, 2(1).

Organisation for Economic Co-operation and Development (OECD). (1979). Exposure to Radiation from the Natural Radioactivity in Building Materials. OECD Nuclear Energy Agency.

Randhawa, J. S., Robin, Kaur, P., & Meehnian, H. (2024). A comprehensive review on health and environmental hazards of uranium: Analytical techniques, mitigation strategies and its toxicity treatments. Journal of Radioanalytical and Nuclear Chemistry, 333(8), 3693–3711. https://doi.org/10.1007/s10967-024-09527-1

Suleiman, M. A., Abdullahi, S. S., & Dauda, M. S. (2021). Assessment of natural radioactivity levels and associated radiological hazards in soils from selected industrial areas in Nigeria. Journal of Radiation Research and Applied Sciences, 14(1), 45-58.

Ujuagu, G. I., Ejeromedoghene, O., Oladoye, P. O., Okoye, C. O., Alli, Y. A., Oladipo, M. E., & Gu, J. (2025). The ecotoxicity and social impacts of industrial pollution: Insights on intervention and bioremediation strategies in Africa. Environmental Pollution and Management, 2, 227–245.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). (2000). Sources and Effects of Ionizing Radiation. United Nations.

Yachiso, G. T. (2022). Sample preparation techniques for gamma spectrometric analysis of environmental samples: A review. Journal of Environmental Radioactivity, 245, 106–118.