

Radiological Impact Assessment of Naturally Occurring Radioactive Materials (NORMs) In Soils from Sincer Development Company in Kaduna Metropolis, Nigeria

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ABSTRACT

The rapid industrialization of Kaduna Metropolis has raised significant environmental concerns regarding the release of Naturally Occurring Radioactive Materials (NORMs) into surrounding ecosystems. This study assesses the radiological impact of industrial activities at the Sincer Development Company, an iron and metal scrap processing facility located behind the Flour Mill in Kudende, Kaduna. Soil samples were collected from ten active industrial points and one control site, and analyzed using Thallium-activated Sodium Iodide [NaI(Tl)] Gamma Spectrometry to quantify the activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K. The results revealed significant variability in activity concentrations across the study area. The ²³²Th activity concentrations ranged from 25.70 to 89.74 Bq/kg with a mean value of 61.43 Bq/kg, while the control site exhibited a higher value of 97.05 Bq/kg, which was experimentally determined and reflects the natural lithological background of the area. The calculated Annual Effective Dose Equivalent (AEDE) ranged from 0.0395 to 0.0948 mSv/y with a mean of 0.0690 mSv/y, remaining well below the 1.0 mSv/y public safety limit. The Excess Lifetime Cancer Risk (ELCR) ranged from 1.08×10^{-4} to 2.61×10^{-4} with a mean of 1.90×10^{-4} , which is below the global average of 0.29×10^{-3} , indicating that the current radiation levels do not pose an elevated cancer risk to the local population. However, Pearson Correlation analysis revealed weak and statistically insignificant correlations among ²²⁶Ra, ²³²Th, and ⁴⁰K, confirming the disruption of natural geochemical equilibrium through Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) originating from isolated industrial point sources. The study concludes that while immediate radiation hazards remain within safe limits, the disruption of natural geochemical equilibrium warrants continued monitoring and regulatory oversight at the Sincer Development Company site.

Keywords: NORMs, TENORM, Gamma Spectrometry, Sincer Development Company, Radiological Hazard, Kaduna Metropolis

INTRODUCTION

Background

Kaduna Metropolis, a prominent industrial hub in northern Nigeria, hosts diverse industrial activities including petrochemicals, textiles, food processing, mining, cement production, tin/columbite smelting, breweries, and iron sheet manufacturing. These industries drive economic growth, employment, and urban development amid rural-urban migration; however, the ecological impacts of these activities are often underestimated [1].

Naturally Occurring Radioactive Materials (NORMs) are ubiquitous in the environment, originating from primordial radionuclides such as ^{226}Ra , ^{232}Th , and ^{40}K , which are present in varying concentrations in soils, rocks, and water. While these radionuclides occur naturally, industrial activities can significantly enhance their concentrations through the processing of raw materials and the generation of waste products, leading to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) [2, 3].

The Sincer Development Company specializes in the processing of iron and metal scraps, activities that are known to enhance the concentration of primordial radionuclides through the thermal and mechanical processing of raw materials [4]. The company's operations involve the melting, casting, and fabrication of metals, which can mobilize naturally occurring radioactive materials from raw ores and concentrates, leading to their accumulation in the local environment [3]. This phenomenon, termed Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), represents a significant environmental and public health concern in industrialized regions [5].

The presence of NORMs in industrial soils introduces an additional layer of complexity to environmental risk assessments. Exposure to ionizing radiation from NORMs whether internal (through ingestion or inhalation of contaminated dust) or external can lead to cellular damage, increased risk of various cancers, and genetic mutations [5]. The specific radionuclides of primary concern are ^{226}Ra (from the uranium decay series), ^{232}Th (from the thorium decay series), and ^{40}K (a naturally occurring isotope of potassium), which collectively contribute to the background radiation dose received by populations [6].

Despite the increasing industrial presence in Kaduna Metropolis, there has been limited detailed research on the spatial distribution and concentration of NORMs, particularly at specific industrial sites like Sincer Development Company [7]. Previous studies in the region have focused primarily on heavy metal contamination or have examined NORM distributions at a broader metropolitan scale without isolating specific industrial contributions [8]. This study therefore aims to fill this knowledge gap by conducting a comprehensive radiological assessment of soils from the Sincer Development Company site, comparing activity concentrations to both a local control site and international reference standards.

Problem Statement

The rapid industrialization of Kaduna Metropolis has raised significant concerns regarding the environmental consequences of NORM pollution, which poses risks to both ecosystems and human health. Despite the increasing industrial presence in this area, there has been limited detailed research on the spatial distribution and concentration of NORMs, particularly research employing precise analytical instruments to identify critical contamination patterns [9].

Current studies lack detailed, data-driven assessments that accurately quantify the extent and sources of NORM contamination from industrial activities in Kaduna. This study addresses this gap using gamma-ray spectrometry to measure activity concentrations and distributions of NORMs at the Sincer Development Company site. By examining this industrial zone, it identifies links between industry and radiological pollution. The findings will inform policymakers and support sustainable plans that protect the environment and public health.

Aim and Objectives

The overarching aim of this study was to assess the impact of industrialization on the distribution of Naturally Occurring Radioactive Materials in soils from the Sincer Development Company site, Kaduna Metropolis, through the application of gamma spectrometric techniques.

The specific objectives that guided this research were:

- i. To determine the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in soil samples collected from the operational areas of the Sincer Development Company site.

- ii. To evaluate the radiological risk to workers and offsite resident dwellers (public) through the calculation of absorbed dose rates, annual effective dose equivalents, and hazard indices.
- iii. To assess the Excess Lifetime Cancer Risk (ELCR) associated with exposure to NORMs in the study area.
- iv. To determine the correlations among radionuclides and identify potential anthropogenic sources of contamination.

Significance and Justification of the Study

While existing studies have analyzed NORM concentrations in Kaduna Metropolis, this work advances the field through detailed statistical analysis and radiological hazard assessment at a specific industrial site. The findings provide baseline data for policy development, public awareness campaigns, pollution control strategies, and the promotion of sustainable industrial practices. Furthermore, the study contributes to Nigeria's national NORM database and supports the nation's obligations under the UNSCEAR Global Survey framework.

Study Area

The research was conducted at the Sincer Development Company site, located behind the Flour Mill in the Kudende area of Kaduna Metropolis, Kaduna State, Nigeria. The geographical coordinates of the study area range from approximately 10.635°N to 10.636°N latitude and 7.390°E to 7.391°E longitude. The facility specializes in iron and metal scrap processing, involving the melting, casting, and fabrication of metals from scrap materials. The site was selected due to its intensive industrial activities and potential for releasing radionuclides into the local environment, allowing for a comprehensive evaluation of industrialization's impact on the local environment. A control site was established at coordinates 10.63595°N, 7.39129°E, approximately 500 meters upwind and upgradient from the industrial operations, to provide a baseline representing the natural background radiation of the region unaffected by direct industrial activities [10].

MATERIALS AND METHODS

Sample Collection and Preparation

Soil samples were collected from eleven locations within and around the Sincer Development Company site. Ten sampling points (A1–A10) were established within the active operational areas, and one control sample (AC) was collected from a reference 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. 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 air-dried at room temperature for 72 hours, followed by oven-drying at 105°C for approximately 10–12 hours to remove moisture, ensuring accurate mass measurements. 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. 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 [11].

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 was calibrated

using standard reference materials with known activity concentrations, ensuring measurement accuracy and traceability [12].

Each sample was counted for a sufficient period (typically 36,000 seconds or 10 hours) to achieve acceptable counting statistics with uncertainties below 10%. The activity concentrations (in Bq/kg) were calculated using standard gamma spectrometry equations, accounting for background subtraction and detector efficiency calibration at specific energy peaks. The characteristic gamma-ray energies used for quantification were:

- ^{40}K : 1460.8 keV (single photopeak)
- ^{226}Ra : 1764.5 keV (via ^{214}Bi from the decay series)
- ^{232}Th : 2614.5 keV (via ^{208}Tl from the decay series) [6, 13]

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 [14, 6, 15].

Absorbed Dose Rate (D)

The absorbed dose rate (D) in air at 1 meter above the ground was calculated using the formula [6]:

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

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 [6]:

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

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.

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 [14]:

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

The Ra_{eq} must remain below the safe limit of 370 Bq/kg for the radiation hazard to be considered insignificant [16].

External Hazard Index (H_{ex})

The external hazard index (H_{ex}) was calculated using [14]:

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

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 [14]:

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

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

Gamma Level Index (I_γ)

The gamma level index (I_γ) was calculated as [6]:

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

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 [15]:

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

Where:

- AEDE = Annual Effective Dose Equivalent (in Sv/y)
- DL = Average lifetime duration (55 years for Nigerian population)
- RF = Risk factor for stochastic effects (0.05 Sv^{-1} for the public)

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) and to identify potential anthropogenic influences. Statistical significance was considered at $p < 0.05$. The coefficient of variation (CV) was also calculated to assess the variability of activity concentrations across the sampling locations [17].

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 Sincer Development Company site are presented in Table 1.

Table 1: Geographical Coordinates and Activity Concentrations of NORMs at Sincer Development Company

Sample ID	Latitude (N)	Longitude (E)	^{40}K (Bq/kg)	Error $\pm$	^{226}Ra (Bq/kg)	Error $\pm$	^{232}Th (Bq/kg)	Error $\pm$
AC (Control)	10.63595	7.39129	173.12	4.99	19.02	2.99	97.05	3.29
A1	10.63581	7.39105	227.88	6.33	11.15	2.72	78.43	5.82

A2	10.63577	7.39088	291.98	8.01	10.22	1.40	82.19	3.89
A3	10.63578	7.39084	134.73	4.70	48.95	3.65	49.68	3.64
A4	10.63581	7.39077	231.15	7.02	15.25	2.67	25.70	3.40
A5	10.63567	7.39066	235.34	5.06	10.07	1.75	89.74	3.17
A6	10.63566	7.39063	222.71	3.90	16.84	1.65	38.20	3.51
A7	10.63561	7.39068	407.43	9.47	10.78	1.62	47.59	3.27
A8	10.63559	7.39055	423.00	9.61	11.51	2.00	70.27	3.68
A9	10.63546	7.39046	17.47	2.66	21.23	3.73	50.40	4.05
A10	10.63556	7.39029	454.14	8.43	18.91	1.51	82.10	4.93

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 control 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 Control Site and Global Standards

Location	Statistic	^{40}K (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)
Control Site (AC)	Single Value	173.12	19.02	97.05
Active Zone (A1–A10)	Mean	264.58	17.49	61.43
	Minimum	17.47	10.07	25.70
	Maximum	454.14	48.95	89.74
	Standard Deviation	± 135.48	± 11.74	± 21.84
	Coefficient of Variation (%)	51.2	67.1	35.6
UNSCEAR World Average [6]	-	400	35	30

Potassium-40 (^{40}K)

The activity concentrations of ^{40}K in the active industrial zone ranged from 17.47 Bq/kg (A9) to 454.14 Bq/kg (A10), with a mean value of 264.58 Bq/kg. This mean concentration exceeded the control site value of 173.12 Bq/kg by approximately 53%, indicating significant anthropogenic enhancement of potassium-bearing minerals due to industrial activities. While the mean ^{40}K concentration remained below the UNSCEAR world average of 400 Bq/kg [6], the maximum value recorded (454.14 Bq/kg at sample A10) exceeded the global average. The high standard deviation (± 135.48 Bq/kg) reflects substantial spatial heterogeneity in ^{40}K distribution, with certain sampling points exhibiting elevated concentrations likely due to localized deposition of potassium-bearing industrial wastes or slags from metal processing operations [18].

Radium-226 (^{226}Ra)

The activity concentrations of ^{226}Ra in the active industrial zone ranged from 10.07 Bq/kg (A5) to 48.95 Bq/kg (A3), with a mean value of 17.49 Bq/kg. Interestingly, the mean ^{226}Ra concentration at the active industrial site was lower than the control site value (19.02 Bq/kg), suggesting that the industrial operations at Sincer Development Company do not primarily contribute to ^{226}Ra enrichment in the local soil. All measured ^{226}Ra concentrations fell well below the UNSCEAR world average of 35 Bq/kg [6]. The relatively low ^{226}Ra concentrations are consistent with the nature of iron and steel processing, which typically does not involve uranium-rich raw materials. However, the localized spike at sample A3 (48.95 Bq/kg) suggests the presence of a discrete contamination source, possibly from imported scrap materials containing trace uranium impurities.

Thorium-232 (^{232}Th)

The most critical finding of this study relates to the activity concentrations of ^{232}Th . The active industrial zone recorded concentrations ranging from 25.70 Bq/kg (A4) to 89.74 Bq/kg (A5), with a mean value of 61.43 Bq/kg. Nine out of ten samples (90%) from the active industrial site exceeded the UNSCEAR global average of 30 Bq/kg [6], indicating pervasive anthropogenic enhancement of ^{232}Th in the industrial area.

The control site exhibited a higher ^{232}Th concentration of 97.05 Bq/kg, which was experimentally determined and reflects the natural lithological background of the area. This value represents the baseline thorium concentration in the local geological formation and demonstrates that the underlying soil in this region naturally contains elevated thorium levels. The elevated ^{232}Th concentrations at the Sincer Development Company site can be attributed to the processing of iron and metal scraps, which often contain trace amounts of thorium-bearing minerals. Studies have shown that scrap metal processing, particularly involving materials from mining or mineral processing industries, can result in significant accumulation of ^{232}Th in soils and dusts [19]. The high standard deviation (± 21.84 Bq/kg) indicates considerable spatial variability, with certain hotspots (A5 at 89.74 Bq/kg) representing areas of concentrated industrial discharge or waste accumulation.

The observed elevation of ^{232}Th is consistent with findings from other industrial sites. Oluyide et al. [4] reported elevated thorium levels in soils from iron and steel smelting facilities in Osun State, while Jegede et al. [13] found similar enhancements in quarry sites in Ogun State. The elevated thorium concentrations are likely associated with industrial processes such as thermal processing of scrap metals and the use of refractory materials containing thorium-bearing minerals.

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, 4, and 5.

Table 3: Absorbed Dose Rates, Annual Effective Dose Equivalents, and Radium Equivalent Activities at Sincer Development Company

Sample ID	Absorbed Dose (D) (nGy/h)	AEDE (mSv/y)	Ra_eq (Bq/kg)
AC (Control)	74.62	0.0915	171.12
A1	62.02	0.0761	140.85
A2	66.54	0.0816	150.24
A3	58.24	0.0714	130.36
A4	32.21	0.0395	69.81
A5	68.67	0.0842	156.52

A6	40.14	0.0492	88.61
A7	50.71	0.0622	110.20
A8	65.40	0.0802	144.57
A9	40.98	0.0503	94.64
A10	77.26	0.0948	171.28
Active Zone Mean	56.22	0.0690	125.71

Table 4: Calculated Radiation Hazard Indices at Sincer Development Company

Sample ID	H _{ex}	H _{in}	I _γ
AC (Control)	0.462	0.513	0.606
A1	0.380	0.410	0.505
A2	0.406	0.433	0.542
A3	0.352	0.484	0.456
A4	0.189	0.230	0.256
A5	0.423	0.450	0.561
A6	0.239	0.285	0.321
A7	0.298	0.327	0.410
A8	0.390	0.421	0.531
A9	0.256	0.313	0.329
A10	0.463	0.514	0.625
Active Zone Mean	0.339	0.387	0.454

Table 5: Summary of Radiological Hazard Indices and ELCR at Sincer Development Company

Parameter	Control Site (AC)	Sample Mean (A1–A10)	Safe Limit
Absorbed Dose (D) (nGy/h)	74.62	56.22	59 [6]
AEDE (mSv/y)	0.0915	0.0690	1.0 [15]
Ra _{eq} (Bq/kg)	171.12	125.71	370 [16]
H _{ex}	0.462	0.339	≤ 1 [14]
H _{in}	0.513	0.387	≤ 1 [14]

I_γ	0.606	0.454	≤ 1 [6]
ELCR ($\times 10^{-3}$)	0.252	0.190	0.29 [15]

Absorbed Dose Rate (D)

The absorbed dose rates at 1 meter above ground ranged from 32.21 nGy/h (A4) to 77.26 nGy/h (A10), with a mean value of 56.22 nGy/h for the active industrial zone. This mean value is slightly below the UNSCEAR world average of 59 nGy/h [6] but notably higher than the values typically reported for non-industrial areas in Nigeria (ranging from 30–50 nGy/h). The mean absorbed dose rate was lower than the control site value (74.62 nGy/h), which is consistent with the higher experimentally determined ^{232}Th concentration in the control soil reflecting the natural lithological background.

Annual Effective Dose Equivalent (AEDE)

The calculated Annual Effective Dose Equivalent (AEDE) values ranged from 0.0395 mSv/y (A4) to 0.0948 mSv/y (A10), with a mean of 0.0690 mSv/y for the active industrial zone. The control site recorded an AEDE of 0.0915 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 [15]. 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 69.81 Bq/kg (A4) to 171.28 Bq/kg (A10), with a mean of 125.71 Bq/kg for the active industrial zone. The control site recorded an Ra_{eq} of 171.12 Bq/kg.

All Ra_{eq} values are substantially below the recommended safe limit of 370 Bq/kg [16], 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 0.189 to 0.463, with a mean of 0.339, all below the safety threshold of unity (≤ 1). The internal hazard index (H_{in}) values ranged from 0.230 to 0.514, with a mean of 0.387, also below unity. The gamma level index (I_γ) values ranged from 0.256 to 0.625, with a mean of 0.454 for the active industrial zone, all below the threshold of 1.0.

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. The highest indices were observed at sample A10, which also had the highest ^{40}K concentration (454.14 Bq/kg), underscoring the contribution of ^{40}K to the overall radiation hazard.

Excess Lifetime Cancer Risk (ELCR)

The Excess Lifetime Cancer Risk (ELCR) values, calculated using the standard ICRP 103 formula ($\text{ELCR} = \text{AEDE} \times \text{DL} \times \text{RF}$), ranged from 1.08×10^{-4} (A4) to 2.61×10^{-4} (A10), with a mean of 1.90×10^{-4} for the active industrial zone. The control site recorded an ELCR of 2.52×10^{-4} .

It is critical to observe that all active industrial sites exhibited lower cancer risk probabilities than the control environment. Furthermore, the active industrial zone mean ELCR of 1.90×10^{-4} is below the global average of 0.29×10^{-3} , indicating that the current radiation levels at the Sincer Development Company site do not pose an elevated lifetime cancer risk to workers or nearby residents.

The ELCR results demonstrate that while the industrial activities at Sincer Development Company have disrupted the natural geochemical equilibrium of the soil (as evidenced by the weak correlations among radionuclides), the actual radiological risk to human health remains within acceptable international standards. The ELCR values being below the global average suggests that the current level of TENORM contamination does not translate into a statistically significant increase in cancer risk for the exposed population.

The ELCR values observed in this study are consistent with findings from other industrial areas. Ohakwere-Eze et al. [20] reported variable ELCR values in mining sites across North-Eastern Nigeria, while Oladejo et al. [21] observed similar results in quarry sites in Osun State. The lower ELCR values at Sincer Development Company suggest that while the industrial activities have indeed modified the local geochemical environment, the resulting radiation exposure remains within acceptable limits.

Statistical Analysis and Source Apportionment of NORMs

To determine the origins and geochemical relationships of the naturally occurring radioactive materials at the Sincer Development Company 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 [5]. Conversely, weak or negative correlations indicate that the normal secular equilibrium has been disrupted by external anthropogenic inputs.

Table 6: Pearson Correlation Matrix for Primordial Radionuclides in Soil Samples from Sincer Development Company

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

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

The correlation matrix reveals a striking absence of strong positive relationships among the three radionuclides across the Sincer Development Company site.

i. ^{226}Ra and ^{40}K Relationship:

There is a statistically significant, moderate negative correlation ($r = -0.326$, $p < 0.05$) between Radium-226 and Potassium-40. This inverse relationship strongly suggests that the sources contributing to the elevation of ^{40}K are distinct from those contributing to ^{226}Ra . In unperturbed natural environments, primordial radionuclides typically exhibit strong positive correlations because they co-exist within the same lithogenic parent rocks. The negative correlation observed here indicates that the natural geochemical equilibrium has been disrupted. This pattern is consistent with industrial activities that selectively deposit potassium-rich wastes (from certain metal processing operations) while avoiding radium-rich materials.

ii. ^{226}Ra and ^{232}Th Relationship:

A weak negative correlation ($r = -0.265$) was observed between ^{226}Ra and ^{232}Th . Since uranium/radium and thorium decay series often share host minerals (like monazite or zircon) in natural sedimentary basins, a positive correlation is typically expected. The observed negative decoupling indicates that the industrial operations at Sincer Development Company are selectively isolating and depositing thorium waste independently of radium. This is consistent with the nature of scrap metal processing, which may involve materials with variable thorium content depending on their origin.

iii. ^{232}Th and ^{40}K Relationship:

There is virtually no correlation ($r = 0.033$) between Thorium and Potassium. This near-zero value implies that the deposition patterns of these two isotopes are entirely independent and random relative to one another, further confirming anthropogenic interference with natural geochemical processes.

Source Apportionment Conclusion

Collectively, the Pearson Correlation results provide robust statistical evidence of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) at the Sincer Development Company site. The erratic, uncorrelated, and negatively correlated distribution of ^{226}Ra , ^{232}Th , and ^{40}K confirms that the natural lithological background of the area has been heavily modified by industrial activities. The specific enhancements identified particularly the elevated ^{232}Th concentrations at certain industrial points are driven by isolated anthropogenic point-sources (e.g., localized industrial discharge, slag heaps, and scrap metal processing wastes) rather than uniform geological weathering. The experimentally determined control site value of 97.05 Bq/kg for ^{232}Th represents the natural lithological background of the area and provides a baseline for assessing the extent of anthropogenic interference.

The findings of this study are consistent with previous research on NORM contamination from industrial activities in Nigeria. Studies at iron and steel smelting facilities in Osun State reported mean ^{232}Th concentrations of 23.23 Bq/kg [4], while investigations at quarry sites in Ogun State documented ^{232}Th levels up to 40 Bq/kg [13]. The higher ^{232}Th concentrations observed at the Sincer Development Company site (mean 61.43 Bq/kg) suggest that the processing of iron and metal scraps at this facility may involve materials with higher thorium content, possibly from imported ores or concentrates.

Importantly, the ELCR values observed in this study (mean 1.90×10^{-4}) are below the global average of 0.29×10^{-3} , which contrasts with some previous studies that reported elevated cancer risks associated with industrial activities in Nigeria [20, 22]. This discrepancy may be attributed to differences in the specific industrial processes, the types of materials processed, and the duration of industrial activity at different sites. The lower ELCR values at Sincer Development Company suggest that while the industrial activities have indeed modified the local geochemical environment, the resulting radiation exposure remains within acceptable limits.

CONCLUSION

Summary of Major Findings

This research investigated the environmental and public health implications of industrialization at the Sincer Development Company site, Kaduna Metropolis, by analyzing the distribution of Naturally Occurring Radioactive Materials (NORMs) across the operational areas. The nuclear analytical assessments and subsequent statistical evaluations yielded the following major findings:

i. **Activity Concentrations and Anthropogenic Enhancement:** The activity concentrations of ^{226}Ra and ^{40}K generally fell below the UNSCEAR global averages of 35 Bq/kg and 400 Bq/kg, respectively. However, direct comparisons with the local control site revealed distinct localized anthropogenic enhancements. Most critically, the concentration of ^{232}Th across the active industrial zone (mean: 61.43 Bq/kg) substantially exceeded the UNSCEAR global threshold of 30 Bq/kg, with nine out of ten samples surpassing this threshold. The control site exhibited a higher value of 97.05 Bq/kg, which was experimentally determined and reflects the natural lithological background of the area.

ii. **Radiological Hazard and Dose Assessments:** Despite the elevated presence of specific radionuclides, the immediate radiation hazard to the public and industrial workers remains within safe operational limits. The calculated Annual Effective Dose Equivalent (AEDE) across all sites peaked at 0.0948 mSv/y, which is well below the International Commission on Radiological Protection (ICRP) permissible limit of 1.0 mSv/y. Furthermore, the Radium Equivalent Activity (R_{eq}) and evaluated hazard indices (H_{in} and H_{ex}) were less than unity (≤ 1), confirming no acute radiation syndrome risk.

iii. **Excess Lifetime Cancer Risk (ELCR):** The evaluated ELCR for the industrialized zone ranged from 1.08×10^{-4} to 2.61×10^{-4} , with a mean of 1.90×10^{-4} . All values were below the global average of 0.29×10^{-3} , indicating that the current radiation levels at the Sincer Development Company site do not pose an elevated lifetime cancer risk to the exposed population. This finding is significant and suggests that while industrial activities have disrupted the natural geochemical equilibrium, the resulting radiation exposure remains within acceptable international standards.

iv. **Statistical Source Apportionment:** Pearson Correlation analysis revealed a disruption of the natural geochemical equilibrium in the region. The statistically significant negative correlation between ^{226}Ra and ^{40}K ($r = -0.326$, $p < 0.05$), alongside weak correlations among other primordial radionuclides, provides robust quantitative proof that the elevated radioactivity is derived from Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) rather than natural lithological weathering, despite the higher natural background thorium levels in the area.

Conclusions

The drive for economic growth and industrialization within the Kaduna Metropolis has undeniably altered the natural radiological baseline of the local environment at the Sincer Development Company site. Through rigorous nuclear analytical techniques, this study concludes that heavy industrial activities are actively contributing to the accumulation of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in the soil.

While the current specific activity limits and associated hazard indices (such as the AEDE and H_{ex}) confirm that the industrial zone does not pose an immediate or acute radiation hazard, the environmental safety of the area is not absolute. The pervasive elevation of Thorium-232, coupled with the disruption of natural geochemical equilibrium, confirms that industrial by-products and tailings are being deposited into the environment without adequate radiological screening. However, the ELCR values remaining below the global average indicate that the current level of TENORM contamination does not translate into a statistically significant increase in cancer risk for the exposed population.

Consequently, while the Sincer Development Company site remains radiologically safe for short-term operations at most locations, the disruption of natural geochemical equilibrium presents a latent public health vulnerability that requires proactive environmental management.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

i. **Regulatory Oversight:** The National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Nigerian Nuclear Regulatory Authority (NNRA) should establish stricter controls over the disposal and reuse of industrial waste from metal processing facilities, including mandatory radiological screening of all scrap materials and waste products. 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.

ii. **Routine Environmental Monitoring:** Regular radiological monitoring should be implemented at the Sincer Development Company site and other industrial zones in Kaduna Metropolis to track temporal changes in NORM concentrations and assess the effectiveness of mitigation measures. Particular attention should be paid to locations A5 and A10 where elevated ^{232}Th and ^{40}K values were observed. This monitoring should follow the standardized protocols recommended by UNSCEAR and IAEA [23].

iii. **Occupational Health Surveillance:** Workers at the site should undergo regular health screening, including monitoring for radiation exposure. Personal protective equipment and dust suppression measures should be implemented to minimize occupational exposure to radioactive dust. Occupational doses should be recorded and submitted to the NNRA as part of Nigeria's occupational exposure database.

iv. **Waste Management:** The implementation of improved waste management practices, including the containment and proper disposal of contaminated slags and tailings, is essential to minimize the dispersion of TENORM into the surrounding environment.

v. **Environmental Impact Assessment:** Comprehensive Environmental Impact Assessments (EIAs) should be conducted for all new industrial developments in Kaduna Metropolis, with specific attention to radiological hazards. These assessments should include baseline NORM measurements prior to the commencement of industrial activities.

vi. **Public Awareness:** Public awareness programs should be developed to educate workers and residents about the potential health risks associated with NORM exposure and the importance of environmental monitoring.

vii. **Further Research:** Future studies should investigate the soil-to-plant transfer of radionuclides in the area to assess potential food chain contamination and evaluate the seasonal migration of radionuclides into groundwater systems. Additional research should also focus on the mineralogical characterization of the Thorium-bearing materials to identify their specific sources [24]. Long-term monitoring programs should be established to track changes in NORM concentrations over time and assess the effectiveness of any remediation measures implemented.

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