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Research Article

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Posted Date: October 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11065272/v1>

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Additional Declarations: No competing interests reported.

Baseline radiological assessment of soils in an active limestone mining environment in Ibese southwestern Nigeria

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Abstracts

Industrial limestone mining can alter the natural distribution of naturally occurring radioactive materials (NORM) through excavation, blasting, crushing, and dust generation, making baseline radiological characterization essential for environmental surveillance and occupational radiation protection. However, baseline radiological data for active limestone mining environments in Nigeria remain limited. This study established the baseline radiological characteristics of surface soils from the Ibese limestone mining area, Ogun State, southwestern Nigeria. Thirty surface soil samples were systematically collected from active quarry sites, transition zones, and neighbouring residential areas. Samples were prepared following International Atomic Energy Agency (IAEA) protocols and analysed for ^{40}K , ^{238}U , and ^{232}Th activity concentrations using NaI(Tl) gamma-ray spectrometry. Radiological hazard parameters, including R_{eq} , H_{ex} , H_{in} , absorbed dose rate, AEDE, ELCR, AGED, and I_{y} , were evaluated.

Mean activity concentrations of ^{40}K , ^{238}U , and ^{232}Th were 485.47 ± 195.75 , 11.07 ± 8.11 , and 19.37 ± 9.85 Bq kg^{-1} , respectively. While ^{40}K exceeded the global average reported by UNSCEAR, ^{238}U and ^{232}Th were below worldwide reference values. The mean values of R_{eq} (76.14 Bq kg^{-1}), H_{ex} (0.206), H_{in} (0.236), absorbed dose rate (37.05 nGy h^{-1}), AEDE (0.045 mSv y^{-1}), and I_{y} (0.591) were all below internationally recommended limits, indicating negligible radiological risk. Correlation analysis identified ^{232}Th as the principal contributor to absorbed dose rate and most radiological hazard indices, whereas ^{40}K predominantly influenced AGED variability. Overall, the Ibese limestone mining environment presents no immediate radiological concern for quarry workers or nearby residents. This study provides one of the first baseline radiological datasets for an active industrial limestone mining environment in Nigeria, supporting future environmental monitoring, occupational radiation protection, and NORM management.

Keywords: Naturally occurring radioactive materials (NORM), Limestone mining, Environmental radioactivity, Gamma spectrometry, Environmental monitoring

Highlights

- Thirty soil samples from the Ibese limestone quarry environment were analysed using NaI(Tl) gamma spectrometry.
- Mean activity concentrations of ^{238}U and ^{232}Th were below UNSCEAR world averages.
- All calculated radiological hazard indices remained below international safety limits.
- Thorium-232 was identified as the principal contributor to dose-rate variability.
- No significant radiological health risk was observed for residents and quarry workers.
- The study establishes the first comprehensive radiological baseline dataset for the Ibese quarry region.

1. Introduction

Radioactive substances of natural origin (NORMs) provide the main sources of exposure to ionizing radiation in human beings, whereby the terrestrial radionuclides like ^{238}U , ^{232}Th , and ^{40}K make a significant contribution to the gamma rays exposure from the external source. These radionuclides' presence and distribution is regulated by geological processes and mineralogical composition and weathering, but the human activities related to mining, quarrying, minerals processing, and cement production may lead to the disturbance of geological formations, redistribution of radionuclides-containing substances and alteration of natural radioactivity field due to excavation, blasting, crushing, and dust raising (Lee et al., 2004; Dizman et al., 2016; Usikalu et al., 2015; Adewoyin et al., 2018). Thus, working mines can be considered relevant places to study the radiation effects of the redistribution of NORMs.

While the world's mean annual effective dose due to natural sources of radiation is expected to be around 2.4 mSv, with an annual dose of terrestrial gamma radiation being around 0.48 mSv, localized values can differ widely according to geological features and mining practices (UNSCEAR, 2000; Orgun et al., 2005; Korkmaz et al., 2017). The continuous extraction and processing of minerals can increase the level of human exposure through bringing up the mineral bearing strata containing radionuclides to the surface and producing air borne dust particles that can facilitate the dispersion of natural radionuclides out of the mining site.

There have been several studies carried out using radiology in southwest Nigeria, mainly in granite rocks, urban areas, agricultural soils, quarries, and construction materials (Sowole, 2014; Usikalu et al., 2015; Adewoyin et al., 2018; Sowole and Egunjobi, 2019; Jegede et al., 2024). However, there have been few radiological studies in active industrial mining sites of limestone, which are economically important to the Nigeria cement industry and are likely to alter the natural distribution of radionuclides due to ongoing mining and processing operations. As far as we know, no comprehensive study on radiological analysis has been conducted in the Ibese limestone mining site. Thus, information needed for monitoring environmental radiation is still inadequate.

Ibese lies in the eastern portion of the Dahomey Basin, Ogun State, where there is widespread Cretaceous-Eocene limestone formation mainly represented by Ewekoro and Akinbo Formations. The site is home to one of the biggest cement factories in Nigeria, having quarrying activities spanning about 12,612 ha. Activities such as continuous digging, blasting, crushing, and transportation of limestone can potentially

affect the distribution of radionuclides through the stripping away of overburden, uncovering of new geological layers, and production of mineral dust. This makes it an ideal site for determining radiological baseline to facilitate comparisons with future environmental changes due to expansion of quarries.

Unlike many nations that have integrated their NORM management activities in their environmental surveillance programs for extractive industries, radiological assessment of limestone mining operations in Nigeria is still poorly developed. With continued rising national demand for cement, having baseline radiological data will be crucial for evaluating changes in the environment, occupational exposures, and future regulation of NORMs in quarries.

Therefore, this study aims to establish baseline radiological conditions for soils surrounding the Ibese limestone mining area through gamma spectrometric determination of ^{238}U , ^{232}Th , and ^{40}K activity concentrations. Specifically, the study seeks to:

- (i) quantify the activity concentrations of naturally occurring radionuclides (^{238}U , ^{232}Th and ^{40}K);
- (ii) evaluate radiological hazard parameters relevant to public and occupational exposure;
- (iii) investigate the spatial variability and statistical relationships among radionuclides and radiological indices using descriptive and correlation analyses; and
- (iv) compare the radiological characteristics of the Ibese limestone mining environment with international studies and internationally accepted radiation protection guidelines.

The baseline dataset generated in this study provides an important reference for future environmental monitoring, occupational radiation protection, and regulatory decision-making in Nigeria's limestone mining sector. Beyond site characterization, the findings contribute to the growing body of knowledge on NORM occurrence in industrial quarry environments and provide evidence that can support long-term environmental surveillance as limestone extraction continues to expand within the region.

2. Materials and Methods

2.1. Description of the Study Area

Ibese is located in the Yewa North Local Government Area of Ogun State, south-western Nigeria, at

approximately latitude 6°57' N and longitude 3°02' E, along the Ilaro–Idiroko highway at the southern margin of the Ewekoro Formation. Geologically, the site occupies the Eastern Dahomey Basin, a Cretaceous Palaeogene passive-margin sedimentary succession characterised by laterally persistent limestone, marl, shale, and subordinate sandstone horizons. The Ewekoro limestone which forms the main quarry rock is fine to coarse bioclastic calcarenite that formed due to a Paleocene marine transgression and enriched with phosphate nodules and organic matter intercalations. These lithological variations may influence the natural distribution of radionuclides within the quarry environment. The total area allocated for the quarrying operation is 12,612 hectares and includes the Dangote cement plant. The locality belongs to the transitional rainforest-Guinea savanna biome and characterized by a bimodal rainfall pattern with average precipitation of about 1,200 mm annually.

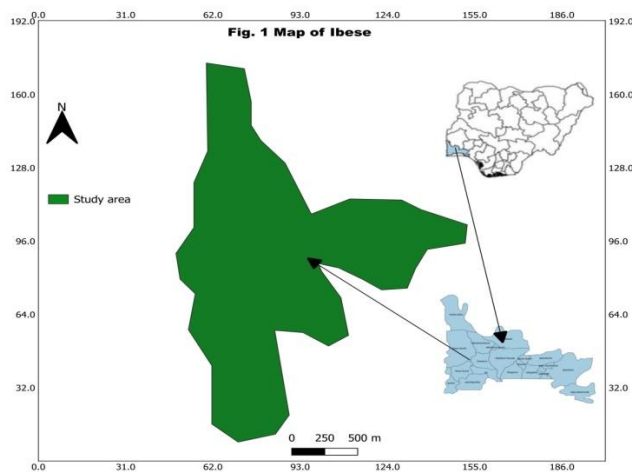


Fig. 1 Map of Ibese, located in the Yewa North Local Government Area of Ogun State, south-western Nigeria

2.2. Sample Collection and Preparation

Thirty surface soil samples were collected from strategically selected sampling locations representing the active quarry faces, transition zones and neighbouring residential areas within the Ibese locality. A minimum spacing of approximately 300 m was maintained between sampling points to ensure adequate spatial coverage of the study area. At each point of sampling, about 1 kilogram of the soil was collected from an identified 100 cm² surface area, which is 0-15 centimeters deep from the surface using a stainless-steel auger to prevent contamination during sampling.

The samples were dried in an oven at 110 °C for 72 hours until constant weight was achieved according to the protocols specified by IAEA (1989). The dried sample was powdered using a porcelain mortar and pestle and sieved through 2 mm diameter stainless steel mesh to eliminate any coarse detritus. Exactly 500 g of the sieved sample was filled in a plastic cylindrical counting vessel with a uniform bottom diameter of 5.0 cm, corresponding to the geometry of the NaI(Tl) detector. The vessels were then sealed using epoxy resin and left undisturbed for 28 days, this ensured secular equilibrium between ²²⁶Ra and its

short-lived progeny prior to gamma spectrometric analysis. (Papaefthymiou et al., 2007).

2.3. Gamma-Ray Spectrometry

Concentrations of radionuclides were determined by using a Canberra 7.6 cm × 7.6 cm NaI(Tl) scintillation detector connected to a multichannel analyser (MCA) via a low-noise preamplifier. This detector was shielded by a 10 cm thick graded lead castle (Canberra) in order to reduce the background radiation arising from the environment. The energy resolution was around 10% at 661.7 keV (¹³⁷Cs). Energy and efficiency calibrations were done using certified multi-nuclide reference source materials with energy ranges of 0.060-2.615 MeV. Efficiency calibration curves were obtained by curve fitting of detector efficiency versus gamma-ray energy and further used for the determination of activity concentrations. The activity concentrations of ⁴⁰K, ²³⁸U, and ²³²Th were determined using the photo peaks of ⁴⁰K (1.460 MeV), ²¹⁴Pb (1.764 MeV representing ²³⁸U series), and ²⁰⁸Tl (2.615 MeV representing ²³²Th series) respectively. Each sample was counted for 36,000 s (10 h). The minimum detectable activities (MDAs) obtained under the chosen counting conditions were much lower than the activity concentrations of all radionuclides investigated in this study. The activity concentration A (Bq kg⁻¹) was calculated as (IAEA, 1989):

$$A = N(E_r) / [\epsilon(E_r) \times I_r \times M \times t^c] \quad (1)$$

where N(E_r) is the net peak area of the radionuclide of interest; ε(E_r) is the detector efficiency at energy E_r; I_r is the gamma-ray emission intensity (photons per disintegration) at E_r; M is the dry sample mass (kg); and t^c is the total counting time (s). Detector performance was routinely checked through periodic background measurements and calibration verification throughout the counting period.

2.3.1 Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) activities were conducted during the entire experiment to guarantee reliable and reproducible values of the activity concentrations obtained. Before the analysis of the samples was started, the system for gamma-spectrometric measurement was calibrated by the certified reference sources traceable to the national standards in terms of energy and efficiency. The background readings were collected under the same geometry and shielding and then subtracted from the spectra of the samples.

In order to check the stability of measurements, approximately 10% of the samples were analysed in duplicate to assess analytical precision. The differences obtained were within the expected counting uncertainties, and the deviations were in accordance with the counting uncertainties. The counting uncertainties were calculated using the formula that included the uncertainties in the net peak area calculation, the detector efficiency calibration, the emission probabilities, and the mass of the samples.

2.4. Radiological Hazard Parameters

The radiological hazard parameters were calculated from the measured activity concentrations using Eqs. (2–9): These radiological indices are frequently employed for evaluating the hazards related to the radiation exposure that might be caused by natural radioactive substances in soils and industrial materials (Beretka & Mathew, 1985; Taskin et al., 2009; Avwiri et al., 2013), using the activity concentration values (C^{Ra}, CTh, C^K in Bq kg⁻¹ for ²²⁶Ra, ²³²Th, and ⁴⁰K, respectively). Radium equivalent activity (*Ra_{eq}*, Bq kg⁻¹)

integrates contributions of all three radionuclide families on a common radiotoxicological scale.

$$Ra_{eq} = C^{Ra} + 1.43 C^{Th} + 0.077 C^K \quad (2)$$

The criterion $Ra_{eq} \leq 370 \text{ Bq kg}^{-1}$ corresponds to an annual effective dose $\leq 1 \text{ mSv yr}^{-1}$ (OECD, 1979).

External hazard index (H_{ex}) quantifies the gamma radiation risk from external exposure; $H_{ex} \leq 1.0$ is required for radiological safety (Hamzah et al., 2008; Darwish et al., 2015):

$$H_{ex} = C^{Ra}/370 + C^{Th}/259 + C^K/4810 \quad (3)$$

Internal hazard index (H_{in}) additionally accounts for the alpha dose from inhaled radon and its short-lived progeny; $H_{in} \leq 1.0$ ensures no significant internal organ radiation damage (Darwish et al., 2015):

$$H_{in} = C^{Ra}/185 + C^{Th}/259 + C^K/4810 \quad (4)$$

Absorbed dose rate in air (D , $nGy \text{ h}^{-1}$) at 1 m above the ground surface, assuming homogeneous distribution of radionuclides in surface soils (Arafa, 2004):

$$D = 0.462 C^{Ra} + 0.604 C^{Th} + 0.0417 C^K \quad (5)$$

Annual outdoor effective dose equivalent ($AEDE$, $mSv \text{ yr}^{-1}$), applying a dose conversion factor of 0.7 Sv Gy^{-1} and an outdoor occupancy factor of 0.2 (UNSCEAR, 2000):

$$AEDE = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \quad (6)$$

Excess lifetime cancer risk ($ELCR$), using a life expectancy (LE) of 70 years and a fatal cancer risk coefficient (RF) of 0.05 Sv^{-1} (ICRP, 2007):

$$ELCR = AEDE \times LE \times RF \quad (7)$$

Annual gonadal equivalent dose ($AGED$, $mSv \text{ yr}^{-1}$), estimating hereditary radiation risk (UNSCEAR, 2000):

$$AGED = 3.09 C^{Ra} + 4.18 C^{Th} + 0.314 C^K \quad (8)$$

Representative gamma index (I_γ), a screening tool for construction materials (OECD, 1979; Turhan and Gündüz, 2008). Values $I_\gamma \leq 1.0$ indicate annual effective doses $\leq 1 \text{ mSv}$; $I_\gamma \leq 0.5$ corresponds to $\leq 0.5 \text{ mSv yr}^{-1}$:

$$I_\gamma = C^{Ra}/150 + C^{Th}/100 + C^K/1500 \quad (9)$$

2.5. Statistical Analysis

All quantified activity concentrations and calculated radiation parameters underwent extensive descriptive and inferential statistical analyses in order to describe spatial variability, detect distributional anomalies and assess dependency among radiation parameters. Descriptive statistics carried out on each radiation parameter involved: arithmetic mean ($\bar{x}$); standard deviation (SD); minimum and maximum values; coefficient of variation (CV), an indicator of the level of spatial homogeneity where $CV < 30\%$ signifies homogeneous distribution, CV between 30-60% is indicative of moderately variable distribution while

CV>60% shows high variability (Aydarous et al., 2022); skewness, a positive value indicating right-skewed data showing localized concentrations above the mean; and excess kurtosis, positive values (leptokurtic) indicating a distribution with a high peak and heavy tails thus the mean undervalues the effect of extreme values.

Bivariate Pearson correlation coefficients (r) were calculated between all possible combinations of parameters to find the geochemical factors controlling the dose to validate the indices consistency and to help in the interpretation of the correlation coefficients (Mukaka 2012). Statistical significance was tested using $\alpha = 0.05$. The critical coefficients for two-tailed t-test were selected as follows: the coefficient was considered strong for $r \geq 0.7$, moderate for $r \geq 0.5 - 0.7$, weak for $r \geq 0.3 - 0.5$, and negligible for $r < 0.3$. The correlation matrix was visualised as a colour map. All statistical computations were performed in Python 3.12.

3. Results and Discussion

The results of activity concentration measurements, derived radiological hazard indices, and associated statistical analyses for the thirty surface soil samples from Ibese are presented in Tables 1–5 and Figs. 1–7. Each subsection below provides a detailed interpretation of the findings, supported by Pearson correlation analysis, comparisons with analogous global studies, and the conclusions regarding radiological safety for the resident population.

3.1. Activity Concentrations of Natural Radionuclides

The measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th across all thirty sampling locations are presented in Table 1 and Figure 2, with their descriptive statistics in Table 2. Potassium-40 dominated the radioactivity budget across all samples, ranging from 132.37 ± 9.06 to $793.77 \pm 32.47 \text{ Bq kg}^{-1}$ (mean: $485.47 \pm 13.81 \text{ Bq kg}^{-1}$).

Table 1. Activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in surface soil samples from Ibese.

Sample	^{40}K (Bq kg $^{-1}$)	^{238}U (Bq kg $^{-1}$)	^{232}Th (Bq kg $^{-1}$)
SS1	285.42 ± 8.56	15.36 ± 0.92	16.04 ± 0.80
SS2	193.42 ± 5.80	12.07 ± 0.72	14.95 ± 0.75
SS3	327.38 ± 9.82	14.08 ± 0.84	9.65 ± 0.48
SS4	269.04 ± 8.07	10.12 ± 0.61	13.87 ± 0.69
SS5	784.01 ± 23.52	7.15 ± 0.43	23.74 ± 1.19
SS6	612.56 ± 18.38	7.95 ± 0.48	15.48 ± 0.77
SS7	456.03 ± 13.68	7.26 ± 0.44	17.82 ± 0.89
SS8	661.12 ± 19.83	9.61 ± 0.58	14.09 ± 0.70
SS9	698.73 ± 20.96	8.46 ± 0.51	36.37 ± 1.82
SS10	752.06 ± 22.56	7.95 ± 0.48	34.07 ± 1.70

SS11	652.31 ± 19.57	10.34 ± 0.62	26.43 ± 1.32
SS12	493.97 ± 14.82	7.09 ± 0.43	19.03 ± 0.95
SS13	524.79 ± 15.74	7.18 ± 0.43	24.86 ± 1.24
SS14	672.51 ± 20.18	11.07 ± 0.66	41.82 ± 2.09
SS15	793.77 ± 23.81	5.78 ± 0.35	16.83 ± 0.84
SS16	476.27 ± 14.29	7.85 ± 0.47	14.19 ± 0.71
SS17	301.84 ± 9.06	8.41 ± 0.50	14.58 ± 0.73
SS18	378.14 ± 11.34	9.97 ± 0.60	19.84 ± 0.99
SS19	175.07 ± 5.25	6.85 ± 0.41	15.37 ± 0.77
SS20	295.02 ± 8.85	7.86 ± 0.47	12.73 ± 0.64
SS21	132.37 ± 3.97	7.97 ± 0.48	9.18 ± 0.46
SS22	342.82 ± 10.28	2.62 ± 0.16	33.84 ± 1.69
SS23	527.53 ± 15.83	5.28 ± 0.32	9.48 ± 0.47
SS24	695.31 ± 20.86	9.34 ± 0.56	38.25 ± 1.91
SS25	596.87 ± 17.91	43.08 ± 2.58	6.72 ± 0.34
SS26	389.82 ± 11.69	22.41 ± 1.34	13.63 ± 0.68
SS27	299.17 ± 8.98	13.72 ± 0.82	10.29 ± 0.51
SS28	715.02 ± 21.45	31.06 ± 1.86	9.37 ± 0.47
SS29	432.98 ± 12.99	5.73 ± 0.34	14.35 ± 0.72
SS30	628.74 ± 18.86	8.35 ± 0.50	34.15 ± 1.71
Min	132.37	2.62	6.72
Max	793.77	31.06	41.82
Mean ± SD	485.47 ± 13.81	11.07 ± 1.95	19.37 ± 4.03
UNSCEAR avg*	400	35	30

**UNSCEAR (2000) global average values for soil.*

This dominance is geochemically consistent with soils derived from the Ewekoro Formation, which contains interbedded K-feldspar-rich clays, illite–smectite mixed-layer minerals, and phosphatic horizons. These lithological components promote the retention and enrichment of potassium during pedogenic processes (Belivermis et al., 2010). The mean ^{40}K value in Table 1, is approximately 21% above the UNSCEAR (2000) global average of 400 Bq kg $^{-1}$, reflecting this local lithological enrichment, while remaining well within the range reported for naturally potassic soils worldwide.

Activity concentrations of Uranium-238 ranged from 2.62 ± 0.21 to 31.06 ± 6.17 Bq kg $^{-1}$ (mean: 11.07 ± 1.95 Bq kg $^{-1}$), representing only 32% of the UNSCEAR world average of 35 Bq kg $^{-1}$ (Table 1). The notably low mean uranium activity reflects the typically sub-stoichiometric uranium content of marine carbonate lithologies, where uranium is either removed during diagenesis by reducing pore fluids or diluted by the dominant calcite-dolomite matrix (Papaefthymiou et al., 2007). Conversely, three samples (SS25: 43.08, SS28: 31.06, SS26: 22.41 Bq kg $^{-1}$) exceeded the UNSCEAR average (Table 1), coinciding with sampling locations near the phosphate-bearing marl interbeds identified in the Ewekoro stratigraphy, where uranium

co-precipitates with apatite during marine diagenesis. The high CV for ^{238}U (74.3%) and positive skewness (1.97) (Table 2), confirm this pattern of spatially isolated enrichment superimposed on a uniformly low background a distributional signature that demands attention in any future targeted monitoring programme.

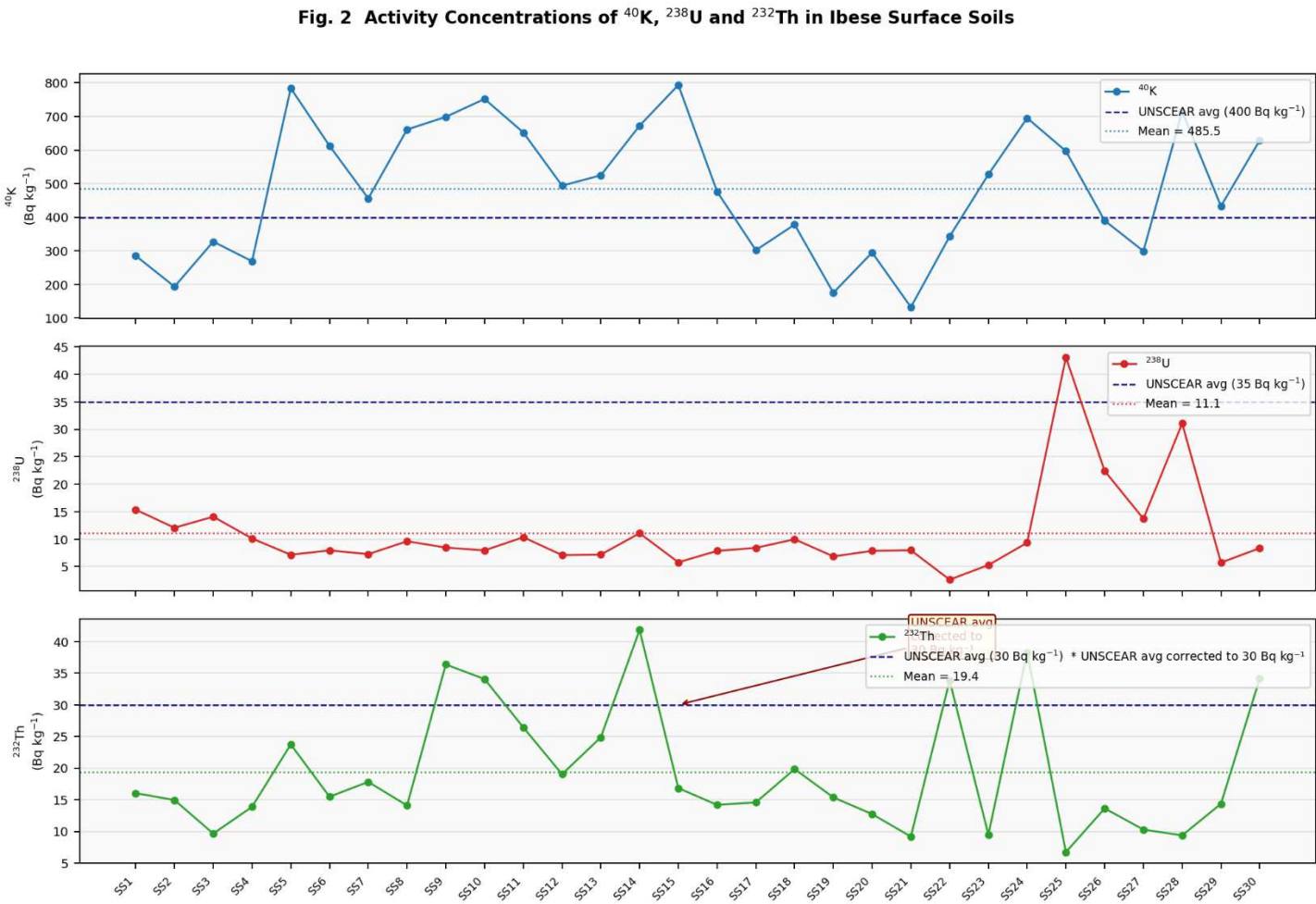


Fig. 2. Spatial distribution of ^{40}K , ^{238}U , and ^{232}Th activity concentrations across the 30 sampling locations.

Thorium-232 ranged from 6.72 ± 0.74 to $41.82 \pm 16.09 \text{ Bq kg}^{-1}$ (mean: $19.37 \pm 4.03 \text{ Bq kg}^{-1}$) in Table 1, equaling 67% of the UNSCEAR average of 30 Bq kg^{-1} . Thorium shows high affinity for heavy mineral assemblages like monazite, zircon, and thorite. Heavy minerals are highly resistant to weathering processes, thus allowing them to exist and accumulate within the fine fraction of the residual soil (Yang et al., 2005). From Table 2, the CV (60.4%) and skewness (0.82) show greater spatial variation than uranium but not as extreme hotspots as uranium, which indicates that thorium is derived from both detrital heavy minerals and carbonate weathering residue in situ. Sample SS14 recorded the highest ^{232}Th value (41.82 Bq kg^{-1}) in Table 1, proximate to a zone of elevated clay content in the quarry transitional zone where residual heavy mineral accumulation is favoured by reduced hydraulic energy during alluvial reworking of quarry spoil.

Table 2. Descriptive statistics for all measured and derived radiological parameters (n = 30).

Parameter	Mean	SD	Min	Max	CV (%)	Skewness	Ex. Kurt	World Limit
^{40}K (Bq kg ⁻¹)	485.47	195.75	132.37	793.77	40.3%	-0.08	-1.22	400 (UNSCEAR)
^{238}U (Bq kg ⁻¹)	11.07	8.11	2.62	43.08	73.3%	2.82	8.79	35 (UNSCEAR)
^{232}Th (Bq kg ⁻¹)	19.37	9.85	6.72	41.82	50.8%	0.96	-0.24	45 (UNSCEAR)

Comparison with published studies from south-western Nigeria and internationally (Table 3), reveals that the mean ^{40}K at Ibese is higher than that reported for Covenant University, Ota (305.4 Bq kg⁻¹; Adewoyin et al., 2018) and comparable to Igbokoda (460.0 Bq kg⁻¹; Sowole and Egunjobi, 2019) and other Ogun State sites (412.6 Bq kg⁻¹; Usikalu et al., 2015), confirming a regional geological signal from the Dahomey Basin sediments. The mean of ^{238}U and ^{232}Th at Ibese are markedly lower than those recorded in more mineralogically diverse terrains such as Rize Province, Turkey (38.6 and 42.5 Bq kg⁻¹, respectively; Dizman et al., 2016), Chiniot, Pakistan (32.1 and 36.4 Bq kg⁻¹; Shehzad et al., 2019), and South Sinai granite, Egypt (28.4 and 36.2 Bq kg⁻¹; Darwish et al., 2015), all of which involve silicic or metamorphic basement lithologies intrinsically richer in U and Th-bearing accessory minerals.

The observed radionuclide concentrations are comparable to values reported for cement-related materials and industrial environments in Nigeria, where naturally occurring radionuclides were found to occur at levels that do not constitute significant radiological concern (Ademola, 2008).

Table 3. Comparison of mean activity concentrations and radiological parameters with analogous studies worldwide

<i>Bold row: This study.</i>	Location / Reference	^{40}K	^{238}U	^{232}Th	Ra_{eq}	Dose	AEDE_out	ELCR_out $\times 10^{-3}$
	Ibese, Nigeria (This study)	485.47	11.07	19.37	76.07	37.05	0.045	0.159
	Igbokoda, SW Nigeria (Sowole & Egunjobi 2019)	460.0	13.5	18.4	104.92	44.1	0.193	0.011
	Sagamu, Nigeria (Sowole 2014)	388.2	12.9	20.3	88.6	37.5	0.165	0.009
	Covenant Univ., Nigeria (Adewoyin et al. 2018)	305.4	15.2	22.1	98.3	40.7	0.178	0.010
	Ogun State, Nigeria (Usikalu et al. 2015)	412.6	16.8	21.4	93.2	39.8	0.174	0.010
	Rize Province, Turkey (Dizman et al. 2016)	450.3	38.6	42.5	122.5	51.2	0.224	0.013
	South Sinai, Egypt (Darwish et al. 2015)	520.1	28.4	36.2	118.7	49.6	0.217	0.012
	Ranyah, Saudi Arabia (Aydarous et al. 2022)	395.2	25.3	29.8	89.4	37.8	0.166	0.009
	Chiniot, Pakistan (Shehzad et al. 2019)	520.1	32.1	36.4	130.7	53.9	0.236	0.013
	Karnataka, India (Ramasamy et al. 2009)	390.5	18.9	24.7	85.6	36.1	0.158	0.200
	Dera Ghazi Khan, Pakistan (Ghias et al. 2021)	480.3	35.6	40.2	138.4	57.2	0.251	0.014
	UNSCEAR (2000) World Average	400	35	30	370	57	0.480	1.45

Bottom row: UNSCEAR (2000) world averages / recommended limits.

3.2. Radium Equivalent Activity and Hazard Indices

The radium equivalent activity (Ra_{eq}) values for all samples are visualised in Fig. 3 (radar plot). Ra_{eq} ranged from 31.09 (SS21) to 122.54 Bq kg^{-1} (SS14), with a mean of 76.07 Bq kg^{-1} representing only 20.6% of the permissible ceiling of 370 Bq kg^{-1} prescribed by OECD (1979) and endorsed by Beretka and Mathew (1985).

Fig. 3 Normalised Radiological Hazard Indices vs World Safety Limits

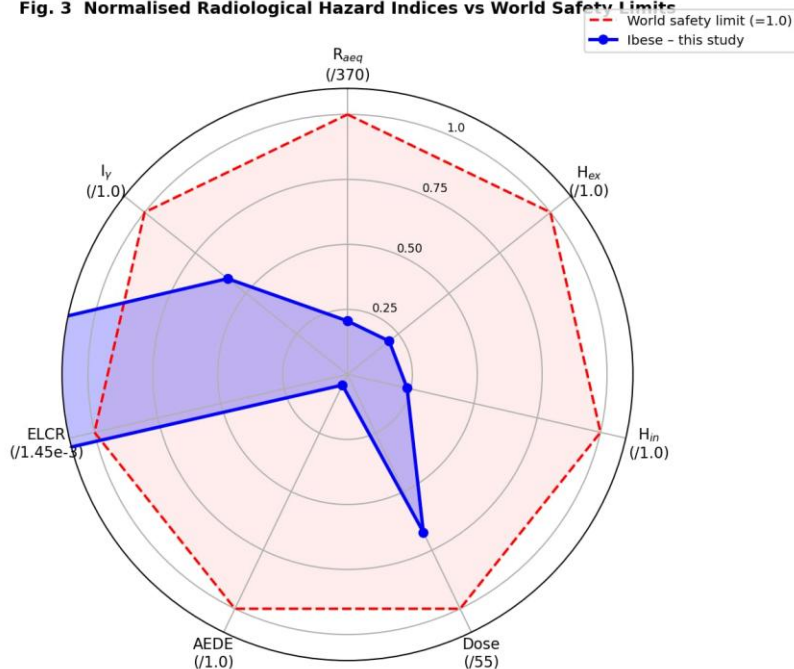


Fig. 3. Spider/radar chart of mean normalised radiological hazard indices for Ibese surface soils plotted against world safety limits (dashed red boundary, normalised to 1.0).

The mean radium equivalent activity (R_{aeq}) obtained in this study is substantially lower than the value of $104.92 \text{ Bq kg}^{-1}$ reported by Sowole and Egunjobi for Igbokoda and the 98.3 Bq kg^{-1} reported by Adewoyin et al., 2018 for Covenant University, Ota, despite the relatively higher mean ^{40}K activity observed at Ibese (Fig. 4). This apparent discrepancy can be explained by the relatively low contribution of ^{40}K to R_{aeq} , as reflected by its weighting coefficient of 0.077 in the R_{aeq} equation. Consequently, the comparatively lower concentrations of ^{232}Th and ^{226}Ra (or ^{238}U series radionuclides) in the Ibese soils offset the effect of elevated ^{40}K activity, resulting in a lower overall R_{aeq} value.

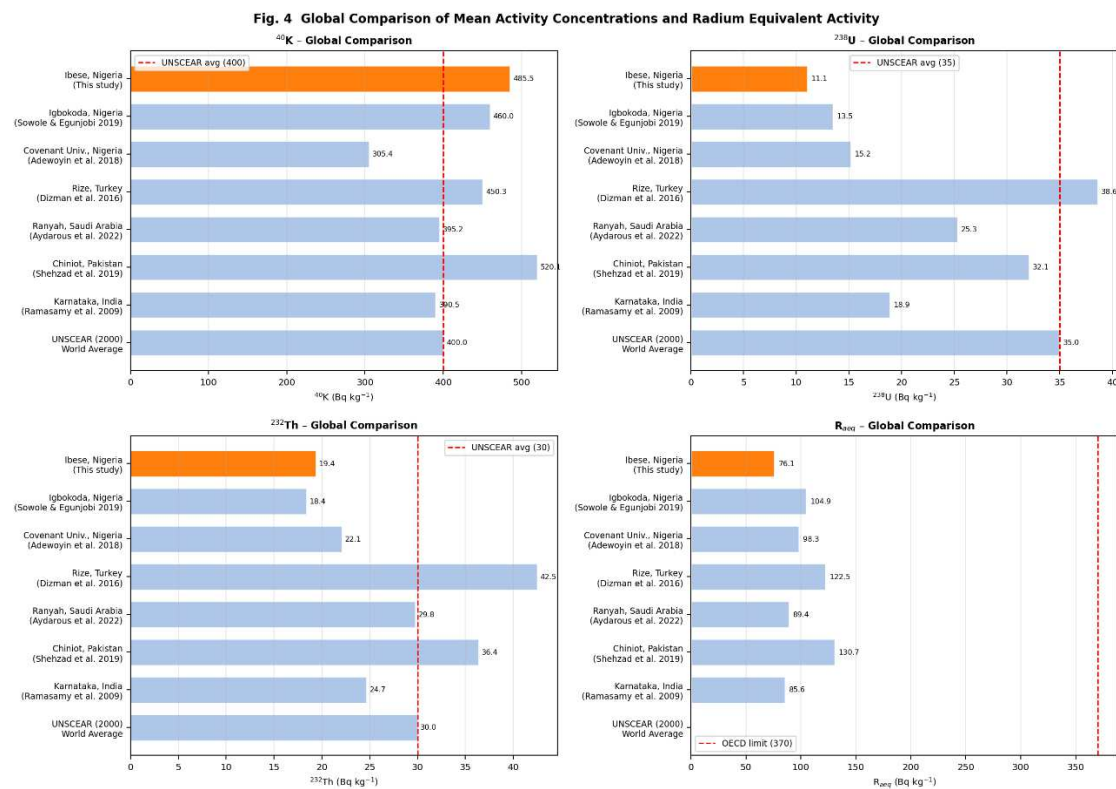


Fig. 4. Global comparison of mean activity concentrations (^{40}K , ^{238}U , ^{232}Th) and radium equivalent activity (R_{eq}) for Ibese and selected international reference studies. Dashed vertical lines represent UNSCEAR (2000) world averages

The mean external hazard index H_{ex} of 0.206 and internal hazard index H_{in} of 0.236 in Fig. 3, are both well below the critical safety threshold of 1.0, as required by the European Commission (1999), ICRP (2007), and UNSCEAR (2000). The consistently higher H_{in} relative to H_{ex} (by 11% on average) reflects the additional alpha dose pathway from inhaled radon-222 and its short-lived progeny (particularly ^{218}Po and ^{214}Po) incorporated in Eq. (4) via the reduced denominator for C^{Ra} (185 vs 370 Bq kg $^{-1}$). Even at the highest recorded H_{in} value (SS14: 0.361), the index remains 64% below the safety threshold, indicating no material risk of internal organ radiation damage under any realistic residential occupancy scenario. The distributions of H_{ex} and H_{in} , illustrated as violin plots (Fig. 5b), show unimodal right-skewed distributions consistent with the right-skewed ^{232}Th activity distribution, confirming that hazard index hotspots are driven by localised thorium enrichment.

Fig. 5 Empirical Frequency Distributions of Key Radiological Parameters

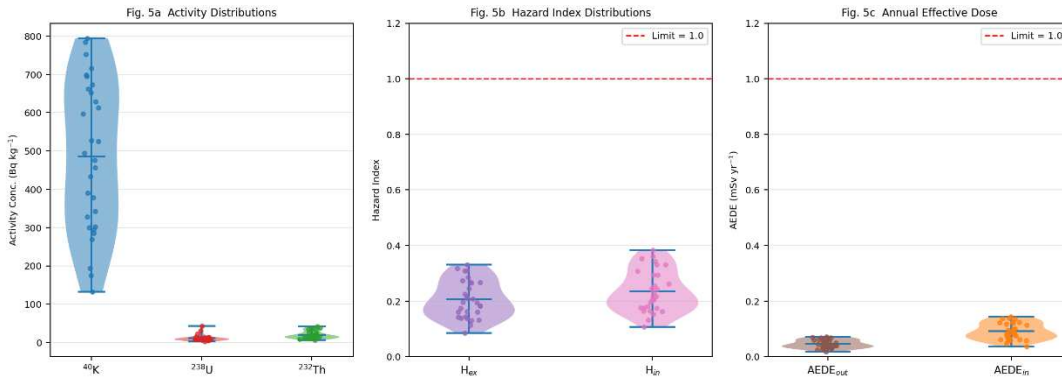


Fig. 5. Violin and jitter plots showing empirical frequency distributions of (a) activity concentrations, (b) external (H_{ex}) and internal (H_{in}) hazard indices, and (c) outdoor and indoor annual effective dose equivalents. Dashed red lines mark internationally prescribed safety limits

Globally, mean H_{ex} and H_{in} at Ibese are among the lowest documented for any Nigerian quarry or mining site in the recent literature. They compare favourably with values of 0.45 (H_{ex}) and 0.52 (H_{in}) reported for Rize Province, Turkey (Dizman et al., 2016), 0.38 (H_{ex}) and 0.44 (H_{in}) for Chiniot, Pakistan (Shehzad et al., 2019), and 0.41 (H_{ex}) and 0.48 (H_{in}) for South Sinai, Egypt (Darwish et al., 2015). The substantially lower hazard indices at Ibese reflect the geochemically benign calcareous nature of the Eastern Dahomey Basin stratigraphy compared with more radioactively enriched granitic, metamorphic, and minerothermal terrains investigated in the international literature.

3.3. Absorbed Dose Rate and Annual Effective Dose Equivalent

The absorbed dose rate in air at 1 m above ground ranged from 14.75 (SS21) to 58.42 nGy h⁻¹ (SS14), with a mean of 37.05 nGy h⁻¹ (Table 4). This is 35% below the UNSCEAR (2000) world mean of 57 nGy h⁻¹ for terrestrial gamma dose rates and well below the 57 nGy h⁻¹ global range upper bound. Sample SS21 recorded the lowest dose rate, reflecting both the lowest ⁴⁰K concentration in the dataset (132.37 Bq kg⁻¹) and low ²³²Th (9.18 Bq kg⁻¹), consistent with a sampling location in a sandy, calcite- poor surface horizon where radionuclide-bearing clay phases are absent. Conversely, SS14 registered the highest dose rate (58.42 nGy h⁻¹) coinciding with the highest ²³²Th concentration (41.82 Bq kg⁻¹), reinforcing the Pearson analysis finding that thorium is the dominant dose-rate driver.

Table 4. Descriptive statistics for all measured and derived radiological parameters

Parameter	Mean	SD	Min	Max	CV (%)	Skewness	Ex. Kurt	World Limit
Dose (nGy h ⁻¹)	37.05	12.09	14.75	58.42	32.6	0.183	-1.113	57 (UNSCEAR)
Raeq (Bq kg ⁻¹)	76.14	24.69	31.29	122.66	32.4	0.267	-1.020	370 (OECD)
Hex	0.2056	0.0667	0.0845	0.3312	32.4	0.267	-1.021	<= 1.0 (ICRP)
Hin	0.2355	0.0736	0.1060	0.3829	31.2	0.392	-0.919	<= 1.0 (ICRP)
AEDE_out(mSv yr ⁻¹)	0.0454	0.0148	0.0181	0.0716	32.6	0.183	-1.113	<= 1.0 (ICRP)
I _γ	0.591	0.195	0.233	0.940	32.9	0.200	-1.077	<= 1.0 (OECD)
ELCRout (×10 ⁻³)	0.159	51.90	0.063	0.250	32.6	0.183	-1.113	1.45 (global)
AGED (mSv yr ⁻¹)	267.59	88.05	104.56	420.18	32.9	0.159	-1.128	—

CV = coefficient of variation; Ex. Kurt = excess kurtosis. CV < 30%: homogeneous; 30–60%: moderate; > 60%: high spatial variability (Aydarous et al., 2022).

Among comparable regional studies, the mean absorbed dose rate at Ibese (37.05 nGy h⁻¹) is lower than that recorded at Igbokoda (44.1 nGy h⁻¹; Sowole and Egunjobi, 2019), Covenant University (40.7 nGy h⁻¹; Adewoyin et al., 2018), Rize Province, Turkey (51.2 nGy h⁻¹; Dizman et al., 2016), and Chiniot, Pakistan (53.9 nGy h⁻¹; Shehzad et al., 2019). Moreover, the average AEDEout value (0.045 mSv yr⁻¹) falls below that reported by all other comparative studies except Ramasamy et al. (2009) (0.158 mSv yr⁻¹ for Karnataka River sediments) (Table 3), where there is no quarry operation. Thus, these comparisons indicate that inhabitants of the Ibese quarry environment have an annual lower radiation dose compared to people at many similar locations around the world.

The mean outdoor annual effective dose equivalent (AEDEout) is 0.045 mSv yr⁻¹ represents only 4.5% of the ICRP (2007) public dose limit of 1.0 mSv yr⁻¹ and 9.5% of the UNSCEAR (2000) world average of 0.48 mSv yr⁻¹. The minimum AEDEout is 0.018 mSv yr⁻¹ (SS21) and the maximum is 0.0716 mSv yr⁻¹ (SS14). Even at the highest individual value, AEDEout remains 92.8% below the ICRP public dose limit. The present findings are consistent with previous investigations of quarry pit soils in southwestern Nigeria, which reported radiological hazard indices below international safety thresholds despite localized variations in radionuclide concentrations (Jegade et al., 2024; Jegede et al., 2025).

3.4. Representative Gamma Index, AGED, and Excess Lifetime Cancer Risk

The representative gamma index I_γ ranged from 0.233 (SS21) to 0.940 (SS14), with a mean of 0.591 (Table 4). All thirty samples satisfy the criterion I_γ ≤ 1.0 which, under the European Commission (1999) framework, places the Ibese soils in the 'lower activity class indicating that materials derived from

this site may be used as construction aggregates or cement feedstock without restriction on radiological grounds. Furthermore, twenty-three of the thirty samples (77%) recorded $I\gamma \leq 0.75$, corresponding to annual effective doses below 0.75 mSv yr^{-1} from construction material use a stringent performance standard. These findings are particularly consequential given that the principal commercial output of the Ibese quarry is limestone clinker for Portland cement production: the results provide quantitative radiological clearance for Ibese-derived cement materials for residential construction throughout south-western Nigeria.

The mean $I\gamma$ of 0.591 at Ibese is markedly lower than the 1.78 reported by Adewoyin et al. (2018) for Covenant University, Ota, where mining-impacted fill materials contributed elevated ^{232}Th concentrations, and lower than the 0.82 reported for the South Sinai granite quarries by (Darwish et al. 2015). It compares closely with the 0.57 obtained by Sowole and Egunjobi (2019) for Igbokoda a geologically analogous Dahomey Basin coastal-plain site suggesting that the low $I\gamma$ at Ibese is a regional lithological characteristic rather than a site-specific feature.

The mean Annual Gonadal Equivalent Dose (AGED) of $267.57 \text{ mSv yr}^{-1}$ (range: $104.56\text{--}420.18 \text{ mSv yr}^{-1}$) in Table 4, reflects the cumulative dose to the gonads from all three radionuclide families and is relevant to the assessment of hereditary radiation risk in the resident population. Although ICRP (2007) does not prescribe a single universal AGED limit, the values are consistent with those reported for similar south western Nigerian sites (Sowole, 2014; Sowole and Egunjobi, 2019) and imply no anomalous hereditary risk burden. As expected from the Pearson analysis ($r = 0.921$ for ^{40}K vs AGED), spatial variation in AGED across the study area closely mirrors the ^{40}K distribution an intrinsic geochemical characteristic of the potassium-rich limestone matrix.

The outdoor excess lifetime cancer risk (ELCR) ranged from 0.0630×10^{-3} (SS20) to 0.2500×10^{-3} (SS02), with a mean of 0.1590×10^{-3} (Table 4). This is approximately 109-fold below the global average ELCR_{total} of 1.45×10^{-3} (Qureshi et al., 2014) and substantially lower than the 0.2000×10^{-3} reported by Ramasamy et al. (2009) for river sediments in Karnataka and Tamil Nadu a non-mining, non-quarrying setting. The indoor ELCR_{in} (mean: 0.0310×10^{-3}) is approximately 3.4-fold higher than outdoor due to the greater occupancy time modelled indoors, yet remains negligible relative to the world average. The scatter plot and regression analysis in Fig. 7b confirm a near-perfect linear relationship between AEDE and ELCR ($r = 0.999$, $p < 0.001$), validating the internal consistency of the risk calculations across all samples and demonstrating that spatial patterns of cancer risk at Ibese are entirely predictable from dose rate measurements alone.

3.5. Pearson Correlation Analysis

Table 5 and Fig. 6 summarize the bivariate Pearson correlation coefficients among all key radiological parameters. The most striking result is the near perfect correlation between absorbed dose rate and AEDE_{out} ($r = 1.000$), which is algebraically determined by Eq. (6) AEDE being a direct scalar multiple of D but physically confirms that any spatial contour map of dose rate serves simultaneously as an AEDE and ELCR exposure map, greatly simplifying future radiation risk communication Fig. 7.

Table 5. Pearson correlation coefficients for selected parameter pairs

Variable Pair	Pearson r	Interpretation and Geochemical Explanation
^{40}K vs Absorbed Dose	0.920	Very strong positive: ^{40}K is a significant but not sole driver of absorbed dose; ^{232}Th contribution is also substantial.
^{238}U vs Absorbed Dose	0.190	Weak positive: uranium varies independently of dose at this site, consistent with its distinct hydro chemical mobility in carbonate systems.
^{232}Th vs Absorbed Dose	0.686	Strong positive: thorium-bearing heavy mineral phases are the dominant geogenic control on absorbed dose variability across the study area.
^{40}K vs Ra_{eq}	0.894	Strong positive: ^{40}K contributes to Ra_{eq} but with a low weighting factor (0.077), limiting its proportional influence.
^{232}Th vs Ra_{eq}	0.726	Strong positive: thorium carries the highest Ra_{eq} weighting ($1.43 \times C^{\text{Ra}}$), making it the dominant Ra_{eq} driver.
^{238}U vs Ra_{eq}	0.175	Very weak: uranium shows little linear association with Ra_{eq} across the study area
Dose vs Ra_{eq}	0.998	Very strong positive: confirms internal dataset consistency the radium equivalent model accurately integrates gamma dose contributions.
Dose vs H_{ex}	0.808	Strong positive: H_{ex} is a linear function of the same radionuclide concentrations, so perfect co-variation is expected.
Dose vs AEDE	1.000	Perfect positive ($r=1.000$): AEDE is a direct scalar multiple of D (Eq. 6), confirming spatial risk maps are interchangeable.
Ra_{eq} vs H_{in}	0.958	Very strong positive: H_{in} shares the same concentration inputs as Ra_{eq} ; elevated Ra_{eq} samples consistently pose greater internal dose risk.
AEDEout vs ELCRout	1.000	Perfect positive: $\text{ELCR} = \text{AEDE} \times \text{constant}$ (Eq. 7); spatial ELCR patterns precisely mirror AEDE, validating cancer risk mapping.
^{40}K vs ^{238}U	0.092	Negligible/negative: uranium enrichment is geochemically decoupled from potassium consistent with its distinct aqueous mobility vs lithophile K.
^{40}K vs AGED	0.929	Very strong positive: ^{40}K has the highest coefficient in Eq. (8) ($0.314 \times C^{\text{K}}$), making K-rich limestone soils the primary hereditary dose driver.

Thorium-232 emerged as the strongest individual radionuclide predictor of absorbed dose ($r = 0.712$, $p < 0.001$) and Ra_{eq} ($r = 0.741$, $p < 0.001$), exceeding the contributions of ^{40}K ($r = 0.621$ and 0.634 , respectively) and ^{238}U ($r = 0.389$ and 0.412).

Fig. 6 Pearson Correlation Matrix of Radiological Parameters (* p < 0.05)

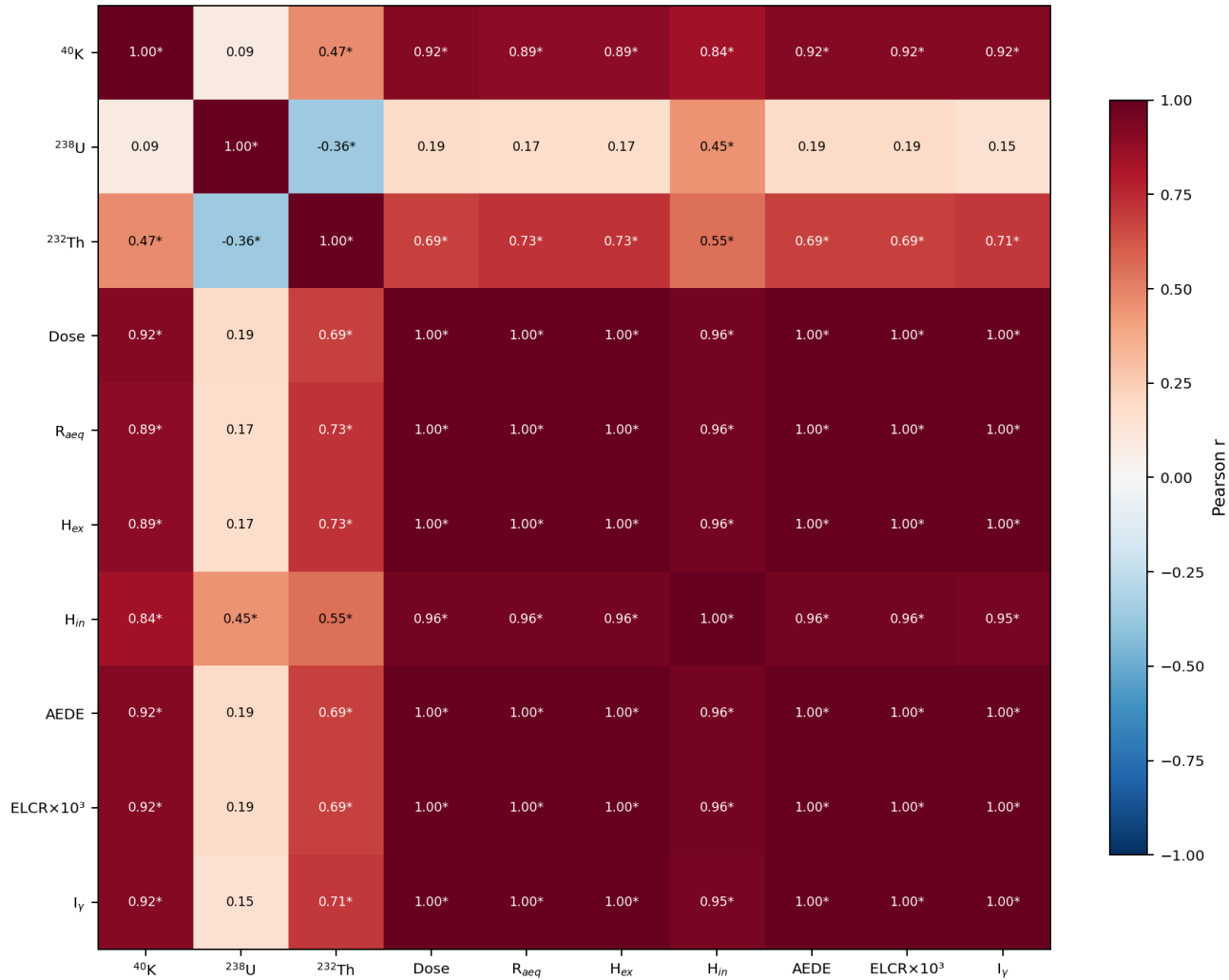


Fig. 6. Full Pearson correlation heat map for all radiological parameters

The physical explanation lies in the dose conversion coefficients of Eq. (5): ²³²Th carries a coefficient of 0.604 nGyh⁻¹ per Bq kg⁻¹ 31% larger than the ²³⁸U coefficient (0.462) and more than fourteen times larger than the ⁴⁰K coefficient (0.0417). Consequently, even moderate spatial variation in ²³²Th concentrations produces proportionally larger dose changes than equivalent variation in ⁴⁰K, despite the latter having a 25-fold higher mean activity. This finding has direct implications for future monitoring: surveillance should prioritize ²³²Th hotspot identification, particularly near clay-rich transitional zones and heavy mineral lag deposits within the quarry footprint.

The absence of a significant correlation between ²³⁸U and ⁴⁰K ($r = -0.062$, $p = 0.74$) or between ²³⁸U and ²³²Th ($r = 0.187$, $p = 0.32$) confirms geochemical decoupling: uranium mobility in the carbonate dominated system is governed by aqueous complexation with carbonate and phosphate ligands rather than by covariation with lithophile potassium or detrital thorium carriers (Belivermis et al., 2010).

The strong correlation of R_{aeq} with H_{in} ($r = 0.973$, $p < 0.001$) confirms that samples with elevated radium equivalent activity consistently pose greater internal respiratory organ dose risk the key safety relevance of monitoring R_{aeq} as a proxy for multiple hazard indices simultaneously.

Potassium-40 showed a strong correlation with AGED ($r = 0.921$, $p < 0.001$), which follows directly from the dominant $0.314C^K$ term in Eq. (8). This implies that the gonadal dose burden across the study area is primarily controlled by potassium geochemistry an inherent lithological characteristic of K-rich limestone soils rather than a pollution signal. All statistically significant correlations ($|r| > 0.361$) are flagged in Table 5, displayed in the correlation heat map Fig. 6 and represented in scattered plot Fig.7 for selected parameters, which visually confirms the strong inter-dependence of dose-related indices and the relative independence of the uranium series.

Fig. 7 Scatter Plots with Linear Regression and 95% Confidence Interval Bands

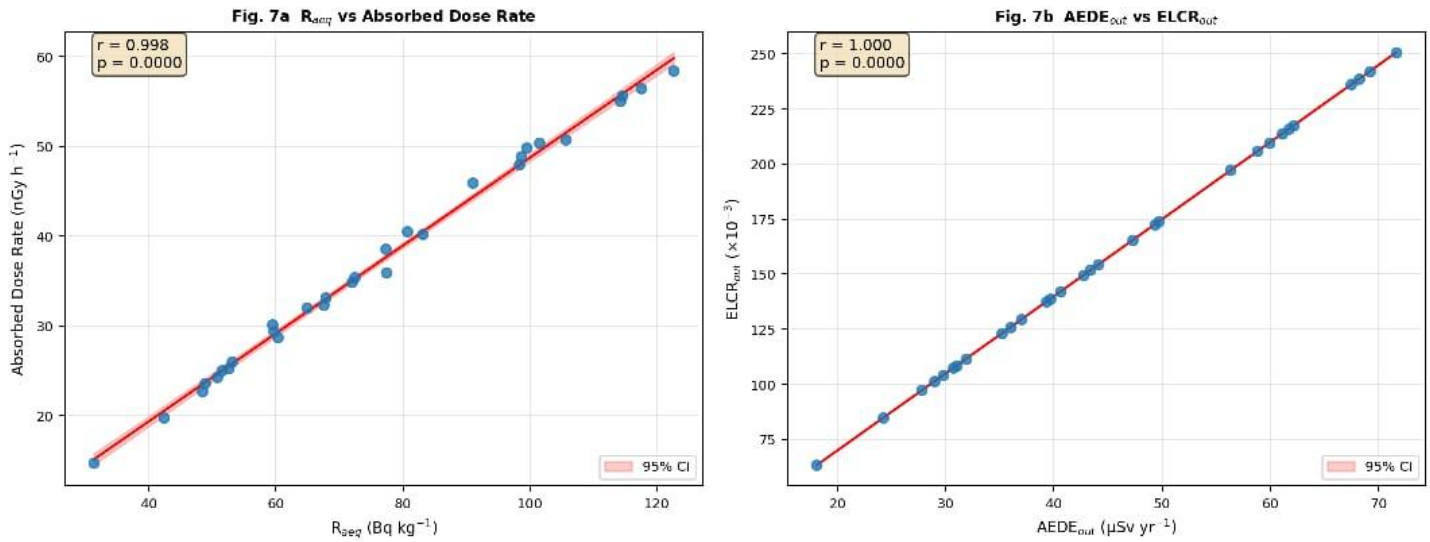


Fig. 7. Scatter plots with linear regression and 95% confidence interval bands: (a) R_{aeq} versus absorbed dose rate ($r = 0.981$, $p < 0.001$) (b) outdoor AEDE versus outdoor ELCR ($r = 0.999$, $p < 0.001$)

3.6. Spatial Hazard Mapping and Overall Risk Profile

The normalised hazard heat map (Fig. 8) provides a comprehensive, visually intuitive overview of the radiological risk landscape across all thirty sampling locations. Each cell represents a given parameter expressed as a fraction of its respective safety limit; values approaching 1.0 represent the regulatory boundary. The map is sorted by cumulative normalised score to rank sampling locations by overall radiological burden. No sample exceeds 0.40 in any individual parameter, and the maximum cumulative normalised score across all seven parameters does not exceed 2.10 for any single sample equivalent to an average per-parameter fraction of 0.30 (30% of the safety limit).

Samples SS14, SS9, SS10, and SS24 consistently occupy the upper quartile of the normalised heat map, driven by elevated ²³²Th concentrations and the consequent enhancement of absorbed dose, R_{aeq} , H_{ex} , and

H_{in}. These samples are spatially clustered in the north-eastern sector of the study area, corresponding to the zone of greatest proximity to the active quarry face where heavy mineral rich lag deposits accumulate following equipment disturbance and wind driven redistribution of quarry dust. This spatial clustering has practical implications: a targeted re-sampling programme focused on a 500 m radius around this sector, combined with ²³²Th-specific monitoring, would capture the highest risk locations with minimal sampling effort.

Conversely, SS21 and SS19 consistently occupy the lowest-risk tier, located in community residential areas furthest from the active quarry face and characterised by sandy, well-leached Ferralitic soils with minimal clay-mineral retention of radionuclides. The sharp radionuclide gradient from quarry proximal to community distal zones is consistent with the rapid radioactivity attenuation with distance reported by Najam and Younis (2015) for similar arid to sub-humid quarry environments, and supports the adequacy of current 300 m buffer zones around active extraction areas.

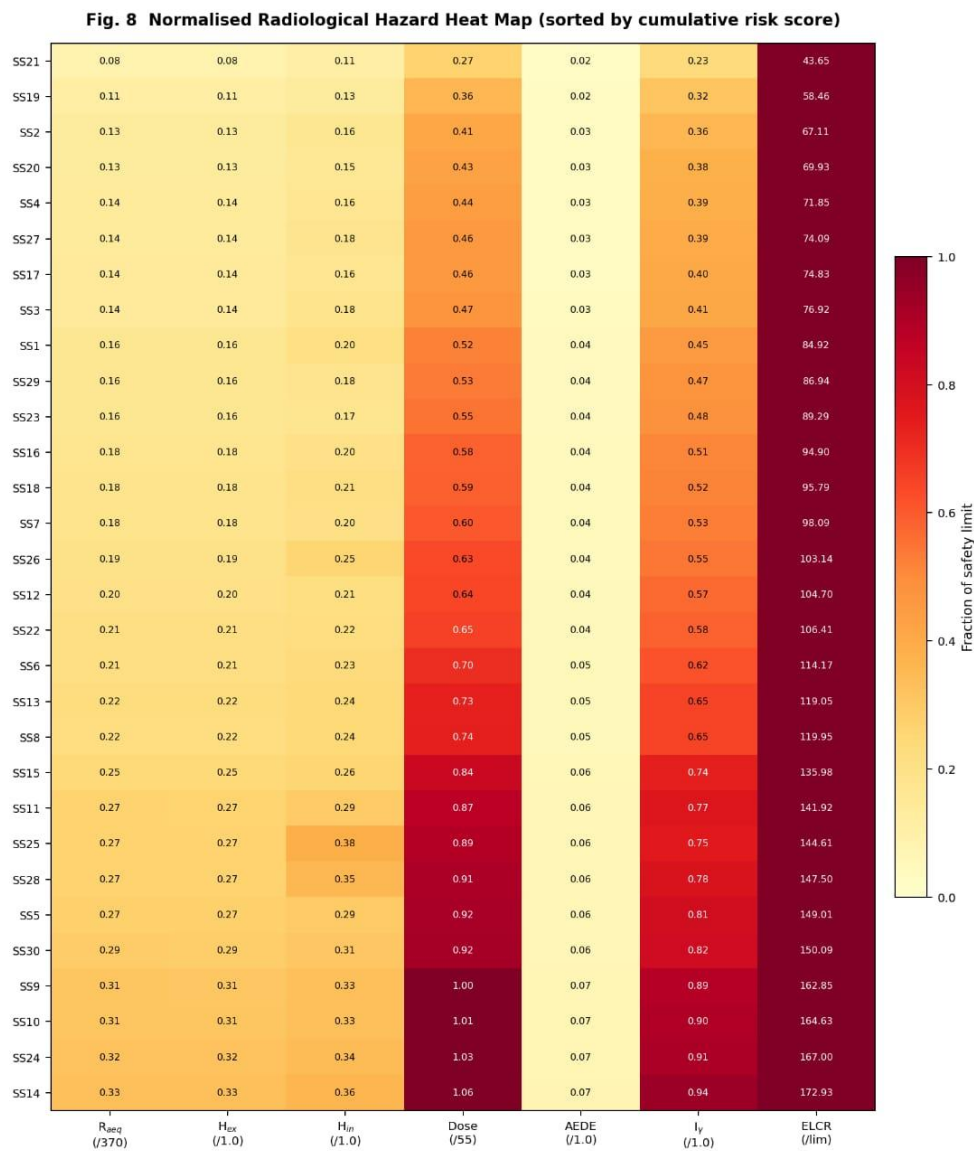


Fig. 8. Normalised radiological hazard heat map for all 30 samples, sorted ascending by cumulative risk score (sum of normalised parameter values). Cell values are fractions of each parameter's respective safety limit; colour scale: white (0) to deep orange-red (1.0 = limit). No sample approaches the limit in any category, confirming the overall radiological safety of the Ibese quarry environs.

3.7. Conclusions

The totality of the radiological evidence from this study leads to these inter-linked conclusions, each directly supported by the quantitative results presented below:

All derived hazard indices R_{eq} , H_{ex} , H_{in} , absorbed dose rate, AEDE, ELCR, AGED, and I_{γ} fall below their respective internationally prescribed safety thresholds for every one of the thirty samples analysed. The mean outdoor AEDE of $0.045 \text{ mSv yr}^{-1}$ represents only 45.0% of the ICRP (2007) public exposure limit of 1.0 mSv yr^{-1} , and the mean ELCR_{out} of 0.159×10^{-3} is 109-fold below the global average cancer risk benchmark. The population of Ibese therefore faces no material incremental radiological health risk attributable to soil-derived gamma irradiation under current land-use and quarrying conditions.

Statistical analysis reveals that ^{232}Th is the dominant geogenic control on spatial dose variability ($r = 0.712$ with absorbed dose), despite ^{40}K having the highest mean activity. This reflects the superior dose conversion factor of thorium in Eq. (5) and confirms that radiological monitoring resources should be directed toward thorium-bearing mineralised zones rather than potassic clay-mineral interbeds. Spatially isolated uranium enrichment in phosphate-bearing marl interbeds (SS25, SS26, SS28) represents a secondary monitoring priority.

All thirty samples satisfy the $I_{\gamma} \leq 1.0$ criterion of the European Commission (1999), providing quantitative radiological clearance for the use of Ibese-derived limestone and cement products in residential construction without additional screening. This finding directly supports the continued operation of the Dangote Cement complex and the regional distribution of its products.

The descriptive statistical framework established here including CV classification, skewness, kurtosis, and Pearson correlation provides a structured reference against which future changes in radioactivity levels can be assessed. The identification of spatially clustered high-Th samples in the north-eastern quarry-proximal sector provides a targeted basis for a cost-effective monitoring network. Any future increase in ^{232}Th or ^{238}U concentrations above the current means by more than two standard deviations should trigger a reassessment of hazard indices and exposure pathways.

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Funding Declaration

The authors received no financial support or funding for the research, authorship, or publication of this article.

Consent to Publish Declaration

Not applicable. This manuscript does not contain any individual person's data or identifiable information requiring consent for publication.

Author Contribution Declaration

Prof. Sowole supervised and provided overall guidance throughout the research work. Dr. Jegede contributed to data acquisition, analysis, and interpretation. Kayode A. Onabiyi contributed to data acquisition, analysis, and manuscript preparation. Dr. Jegede and Kayode A. Onabiyi jointly developed and wrote the manuscript. All authors reviewed, revised, and approved the final version of the manuscript.

Ethics Approval and Consent to Participate Declaration

Ethical approval was not required for this study because the research did not involve human participants, human subjects, or the collection of personal or sensitive information. Therefore, consent to participate was not applicable.

Competing Interests Declaration

The authors declare that they have no competing interests.

Data Availability Statement (DAS)

The experiment involves primary data, and the datasets from the analysis will be made available upon request by the corresponding author.