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Radiometric Characterization of Selected Solid Minerals in Nigeria for Radiological Health Hazard Profiling

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Abstract: The occurrence of naturally occurring radioactive materials (NORMs) in solid minerals has become an important environmental and public health concern due to the increasing utilization of mineral resources in industrial, construction, metallurgical, and energy-related applications. This study presents a comprehensive radiometric characterization and radiological assessment of selected solid mineral samples collected from different geological provinces across Nigeria. Fifty representative mineral samples comprising metallic minerals, industrial minerals, rock-forming minerals, and clay minerals were analyzed using Nal (Tl) gamma-ray spectrometry for the determination of activity concentrations of naturally occurring radionuclides, namely (potassium-40 (^{40}K), uranium-238 (^{238}U), and thorium-232 (^{232}Th)). The measured activity concentration values ranged from 108.36–223.37 Bq kg⁻¹ for ^40K, 9.07–16.72 Bq kg⁻¹ for ^238U, and 2.00–7.33 Bq kg⁻¹ for ^232Th, with mean activity concentrations of 148.12 ± 1.46 Bq kg⁻¹, 11.64 ± 1.12 Bq kg⁻¹, and 3.84 ± 0.07 Bq kg⁻¹, respectively. The distribution pattern revealed that potassium-40 (^{40}K) contributed the highest radiological activity among all investigated radionuclides due to the abundance of potassium-bearing silicate minerals within the geological formations. Granitic and pegmatitic mineral samples exhibited relatively elevated uranium and thorium concentrations compared with sedimentary and clay-rich materials. Radiological hazard indices including absorbed dose rate, radium equivalent activity, annual effective dose equivalent, external hazard index, internal hazard index, and excess lifetime cancer risk were evaluated using standard UNSCEAR and ICRP models. The computed radiological parameters were below internationally recommended safety limits, indicating low radiological risks associated with the investigated minerals. Statistical analysis revealed strong positive correlations among radionuclides and hazard parameters, suggesting common geological and mineralogical controls. The findings establish an important baseline radiological database for solid minerals in Nigeria and confirm that the investigated materials are radiologically safe for industrial, domestic, and construction applications under current exposure conditions.

Keywords: *NORMs Profiling, Solid Minerals, Gamma Spectrometry; Radiological Hazard, Nigeria.*

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I. INTRODUCTION

Naturally occurring radioactive materials (NORMs) are ubiquitous constituents of the Earth's crust and occur naturally within rocks, soils, sediments, groundwater systems, and mineral deposits (UNSCEAR, 2016; Avwiri *et al.*, 2017; Agbalagba *et al.*, 2021). The primordial radionuclides (potassium-40 (^{40}K), uranium-238 (^{238}U), and thorium-232 (^{232}Th)), together with their progenies, are incorporated into geological materials through magmatic, metamorphic, hydrothermal, and sedimentary processes (Agbalagba *et al.*, 2021). These radionuclides contribute significantly to terrestrial background radiation and constitute major pathways of environmental radiation exposure to humans and ecosystems. Their concentrations in geological materials vary considerably depending on lithology, mineralogical composition, tectonic setting, weathering intensity, and geochemical evolution (Suleiman *et al.*, 2022). The increasing global demand for solid minerals for industrial, infrastructural, metallurgical, ceramic, and energy applications has intensified mining and mineral beneficiation activities in many developing economies, including Nigeria (Ugbede *et al.*, 2021). Nigeria possesses extensive solid mineral resources distributed across its six geopolitical zones,

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which include; limestone, baryte, kaolin, feldspar, marble, lead-zinc ores, gold, tantalite, columbite, gypsum, lithium, iron ore, clay minerals etc. These minerals are exploited for construction, ceramics, cement manufacturing, drilling operations, metallurgy, electronics, and energy-related industries. However, several mineral deposits are associated with enhanced concentrations of radionuclides due to the presence of uranium and thorium bearing accessory minerals such as monazite, zircon, xenotime, pyrochlore, and allanite (UNSCEAR, 2020).

Mining, crushing, milling, beneficiation, and transportation (local or trans-border) of mineral ores can redistribute radionuclides into surrounding environmental compartments, resulting in elevated radiation exposure through external irradiation, inhalation of dust particles, ingestion pathways, and radon emanation (Hassan *et al.*, 2020; Faanu *et al.*, 2016). Prolonged and chronic exposure to ionizing radiation may induce stochastic and deterministic biological effects, including carcinogenesis, genetic mutations, tissue damage, pulmonary complications, hematological abnormalities, and kidney dysfunction (Ekeocha, 2016). Consequently, radiometric characterization and radiological health hazard assessment of solid minerals have become essential components of environmental radiation protection, occupational health safety procedures (monitoring), and sustainable mineral resource management. Several studies have investigated natural radioactivity in soils, sediments, beach sands, rocks, and selected mineral deposits in different parts of the world in recent time (Omotehinse & Ako, 2019; Ajeh *et al.*, 2022; Okoye *et al.*, 2022; Alausa *et al.*, 2025; Iwa *et al.*, 2026). In Nigeria, radiological investigations have mainly focused on localized assessments involving quarry sites, tin mining regions, granitic terrains, and industrial areas. However, most previous studies remain geographically fragmented and often limited to basic activity concentration measurements without comprehensive integration of radiological hazard profiling, statistical modelling, uncertainty assessment, and long-term dose simulation. Furthermore, there is limited nationally representative data evaluating radiological implications of diverse solid mineral categories across Nigeria's major geological provinces.

In response to the increasing strategic importance of Nigeria's solid mineral sector under the national economic diversification policy, there is a pressing need for systematic radiometric evaluation of mineral resources and associated health risks these lay credence to this research work (Silver *et al.*, 2022). The present study, therefore, aims to provide a comprehensive radiometric characterization of selected solid minerals across Nigeria using gamma-ray spectrometric analysis, evaluating their respective radiological hazard indices, and using multivariate statistical analysis for result interpretation.

- *Geological Framework of Nigeria*

Nigeria lies within the Pan-African mobile belt between the West African and Congo cratons and possesses highly diverse geological terrains comprising Precambrian basement complexes and extensive sedimentary basins. The major geological units include crystalline basement rocks, sedimentary sequences, Younger Granite complexes, volcanic terrains, and alluvial deposits (Samuel *et al.*, 2022). The Basement Complex consists predominantly of migmatite-gneiss complexes, schist belts, granitic intrusions, quartzites, marbles, pegmatites, and meta-sedimentary units. These rocks host economically important minerals, including gold, feldspar, tantalite, marble, mica, lithium-bearing pegmatites, and gemstones. The Younger Granite province of the Jos Plateau contains tin-bearing and uranium-associated mineralization with significant concentrations of accessory radioactive minerals (Olade *et al.*, 2019). The sedimentary basins of Nigeria include the Niger Delta Basin, Benue Trough, Chad Basin, Dahomey Basin, Sokoto Basin, Bida Basin, and Anambra Basin. These basins contain extensive deposits of limestone, gypsum, coal, bitumen, clay minerals, and hydrocarbon-bearing formations. Several sedimentary units also contain naturally occurring radionuclides associated with shale, phosphate-rich layers, and heavy mineral accumulations (Echeweozo *et al.*, 2024). Geological processes such as magmatism, hydrothermal alteration, metamorphism, sedimentation, and weathering significantly influence radionuclide enrichment and distribution within mineralized zones. Granitic and pegmatitic rocks are generally enriched in uranium and thorium due to incompatible element concentration during magmatic differentiation, whereas sedimentary formations may accumulate radionuclides through adsorption, precipitation, and diagenetic processes. (Ugbede & Osahon, 2021)

- *Sources of Natural Radioactivity in Minerals*

Natural radioactivity in geological materials originates primarily from primordial radionuclides that have existed since the formation of the Earth Echeweozo *et al.*, 2024. The major contributors are (potassium-40 (^{40}K), uranium-238 (^{238}U), and thorium-232 (^{232}Th)). Uranium occurs in minerals such as uraninite, pitchblende, monazite, zircon, xenotime etc. while thorium is commonly associated with monazite, allanite, thorite etc. (^{40}K) is present in potassium-bearing minerals such as feldspars, micas, clays etc. Weathering, hydrothermal alteration, and geochemical mobilization may redistribute radionuclides into surrounding soils, groundwater systems, and sedimentary environments. The radiological significance of these radionuclides arises from their decay products and emitted alpha, beta, and gamma radiations. Gamma radiation contributes predominantly to external exposure, whereas radon inhalation and ingestion pathways contribute to internal exposure. Consequently, the radiological characterization of minerals is essential for evaluating environmental and occupational exposure risks.

II. MATERIALS AND METHOD

- *Study Location:*

Nigeria is located in West Africa between approximately latitudes 4°N–15°N and longitudes 3°E–14°E within the Pan-African mobile belt, situated between the West African and Congo Cratons. The country is divided into six geo-political zones: North West, North East, North Central, South West, South South, and South East. Its geology comprises three major rock units: Precambrian

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Basement Complex rocks, sedimentary formations, and minor volcanic rocks. The Basement Complex, consisting mainly of granite, gneiss, and schist, hosts significant mineral resources such as gold, tin, and gemstones, particularly within the Jos Plateau. Sedimentary basins, including the Niger Delta and Benue Trough, contain petroleum, coal, limestone, barite, and other industrial minerals. The geological diversity of Nigeria reflects complex tectonic and depositional processes, which have influenced the distribution of mineral resources and shaped major landforms. These geological characteristics make Nigeria a suitable region for mineralogical, environmental, and radiological studies (Michael and Peter, 2016).

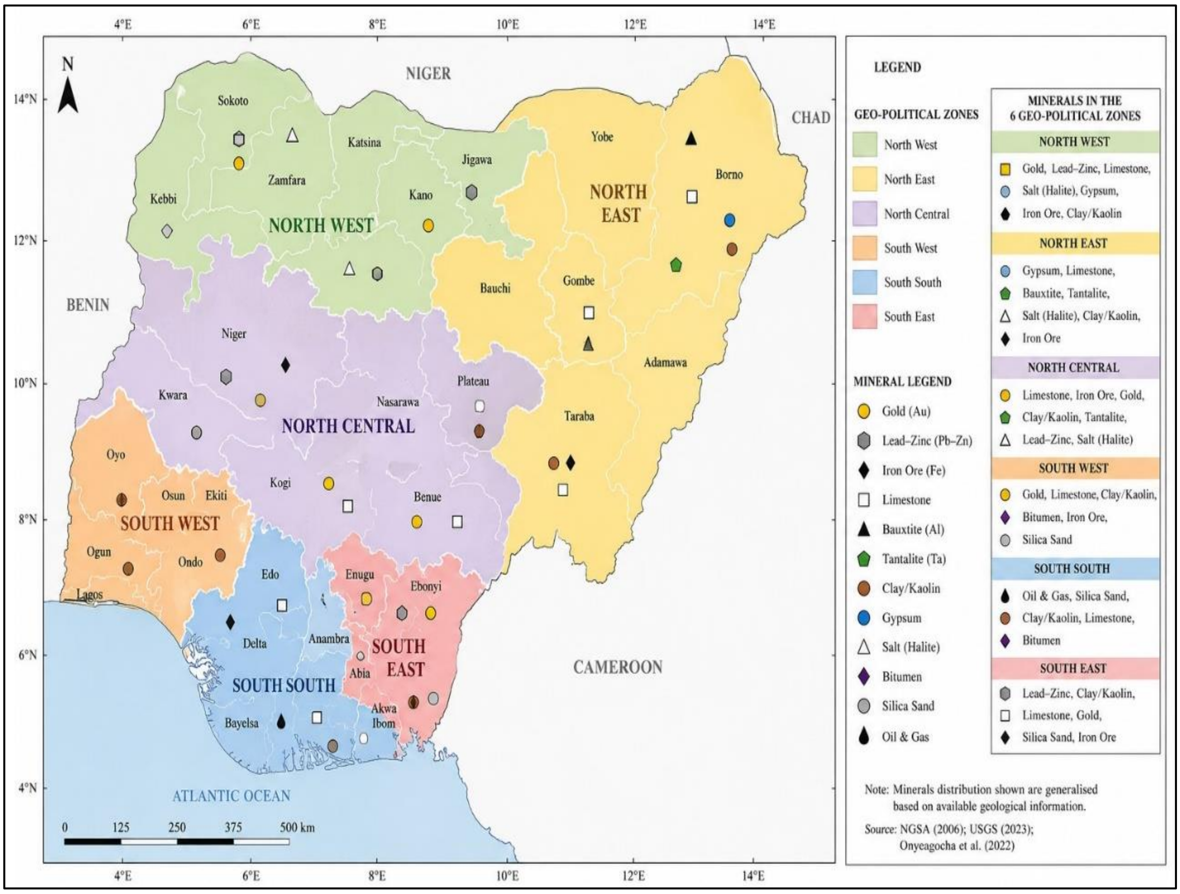

Fig 1 Map of Nigeria showing the geopolitical zones of the Mineral Samples

➢ *Mineral Sampling Collection*

In this study, Forty-nine (49) mineral samples were collected from different locations within the six geopolitical zones in Nigeria, capturing spatial variability in radionuclide distribution for the study with the help of the National Metallurgical Development Center. Jos, Plateau State, Nigeria. The collected mineral samples were sealed in a black polythene bag and carefully labeled with masking tape and pen/marker to avoid sample mix-up. The labelled mineral bags were then taken to the Lab for preparation before being transported to the National Institute of Radiation Protection and Research (NIRPR), Ibadan, Nigeria, for processing using NaI-TI gamma spectrometry measurements and analysis.

➢ *Mineral Sample Preparation*

The mineral samples were sun-dried to constant weight to remove moisture content and prevent photon attenuation (Yusuf *et al.*, 2020). Dried samples were crushed using a mechanical crusher and agate mortar. The pulverized samples were sieved to obtain homogeneous grain size distributions using a 500 µm mesh sieved. Prepared samples were sealed in airtight Marinelli beakers and stored for approximately 28 days to attain secular equilibrium between ^{226}Ra and its progeny (Girigisu *et al.*, 2014; Okeoghene *et al.*, 2024) before being transported for analysis using the gamma ray spectrometry analyzer.

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Fig 2 Preparation of Mineral Sample for Analysis

➢ *Evaluation of Radioactivity Concentration in Samples*

Activity concentrations of (^{40}K), (^{238}U), and (^{232}Th) were determined using a NaI (Tl) gamma-ray spectrometry system coupled with a multichannel analyzer. Gamma-ray spectrometry using sodium iodide NaI (Tl) or high-purity germanium detectors has been widely applied for quantifying these radionuclides in environmental water samples (Eke *et al.*, 2024; Naeem *et al.*, 2025). The detector system was calibrated for energy and efficiency using standard reference materials. Each sample was counted for sufficient acquisition time to obtain statistically reliable spectra and minimize counting uncertainty.

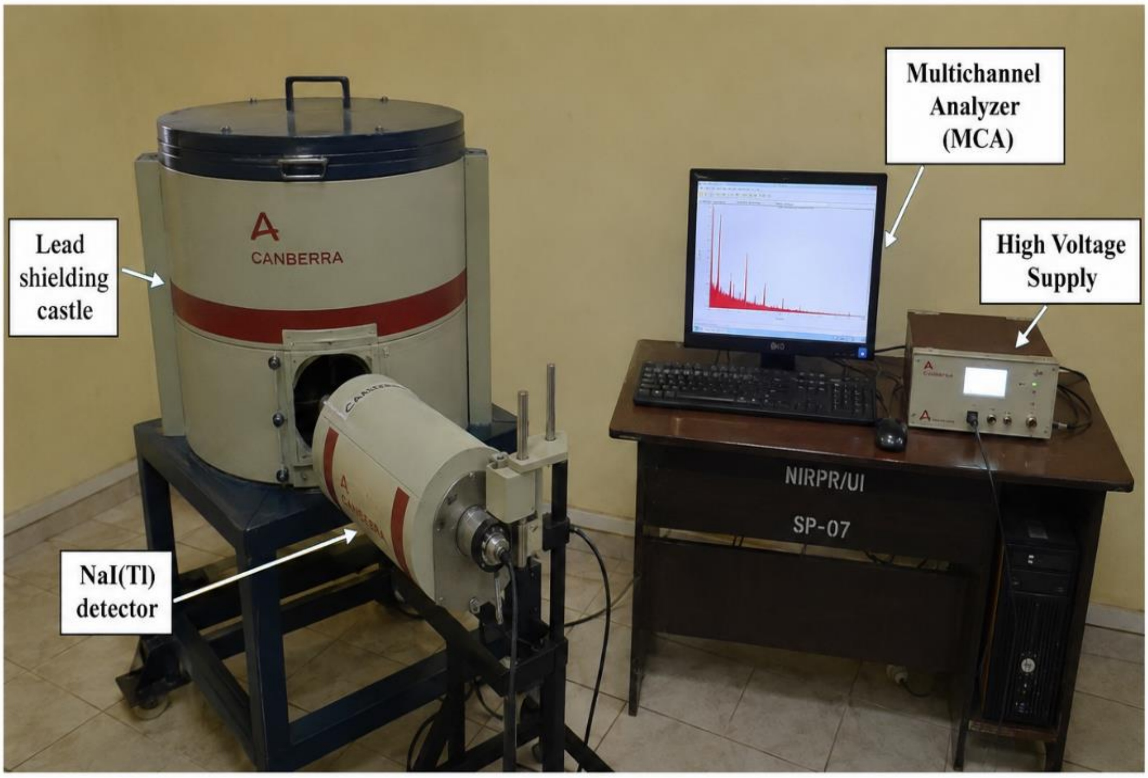

Fig 3 NaI (TI) Scintillation Detector System Used for Gamma-Ray Spectrometric Analysis at the National Institute of Radiation Protection and Research (NIRPR)

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The activity concentration of each radionuclide was calculated using (Adedokun *et al.*, 2022):

$$C = B / (\varepsilon \times P\gamma \times M \times T) \quad (1)$$

Where:

C = activity concentration (Bq kg⁻¹) of a particular radionuclide in the sample, B = net count rate per second, ε = is the absolute efficiency of the detecting system, Pγ = gamma emission probability of a specific energy photo peak, M = Mass of the sample in Kg, T = is the sample counting time.

➢ *Statistical Analysis*

Pearson correlation analysis was used to evaluate relationships among radionuclides radiological parameters. Principal component analysis (PCA) was applied to identify dominant controlling factors influencing radionuclide distributions and radiological variability. Monte-Carlo uncertainty analysis was carried out to evaluate uncertainty in the highest-ranked minerals.

➢ *Radiological Hazard Assessment Parameters*

Radiological risk associated with naturally occurring radionuclides is commonly assessed using standardized hazard indices.

- *Absorbed Dose Rate (D)*

The absorbed dose rate represents the gamma radiation dose delivered in air at 1 m above ground level and is expressed in nGy h⁻¹ (Agbalagba *et al.*, 2012; Ajeh *et al.*, 2022).

$$D_R = 0.462C_U + 0.6211.43C_{Th} + 0.0417C_K \quad (2)$$

- *Radium Equivalent Activity (Raeq)*

Raeq provides a unified radiological index representing combined activities of (^{40}K), (^{238}U), and (^{232}Th) (Avwiri *et al.*, 2017; Alausa *et al.*, 2025).

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (3)$$

- *Annual Effective Dose Equivalent (AEDE)*

AEDE estimates annual human exposure considering occupancy factors and dose conversion coefficients (Ononugbo *et al.*, 2017; Nduka *et al.*, 2022).

$$\text{AEDE (outdoor)} = (D_R) \times 8760 \times (0.7 \times 10^{-3}) \quad (4)$$

- *External Hazard Index (Hex)*

Hex evaluates external gamma exposure hazards from radionuclide-containing materials (Agbalagba *et al.*, 2021; UNSCEAR 2020)

$$(H_{ex}) = C_U/370 + C_{Th}/259 + C_K/4810 \quad (5)$$

- *Internal Hazard Index (Hin)*

Hin accounts for internal exposure risks, especially from radon inhalation (Agbalagba *et al.*, 2021; UNSCEAR, 2020).

$$(H_{in}) = C_U/185 + C_{Th}/259 + C_K/4810 \quad (6)$$

- *Excess Lifetime Cancer Risk (ELCR)*

ELCR estimates the probability of developing cancer over a lifetime due to prolonged radiation exposure (Dembo *et al.*, 2023; Echeweozo *et al.*, 2024).

$$\text{ELCR} = (AEDE) \times \text{DL} \times \text{RF} \quad (7)$$

These indices provide important quantitative tools for comparing measured radiological conditions with internationally recommended safety limits.

III. PRESENTATION OF RESULTS

➢ *Activity Concentration of Natural Radionuclides*

The measured activity concentrations of naturally occurring radionuclides in the investigated mineral samples showed considerable lithological and mineralogical variations across the different geological environments. The summarized activity concentration of the mineral samples based on their classifications is presented in Table 1-5.

Table 1 Specific Activity Concentration of (^{40}K, ^{238}U, and ^{232}Th (Bq kg-1) Results of Metallic Minerals

S/N	Minerals	K-40 (Bq/kg)	U-238 (Bq/kg)	Th-232 (Bq/kg)
1.	Magnetite	164.34±1.55	12.79±0.12	4.43±0.08
2.	Iron Ore	167.62±1.57	13.01±0.12	4.57±0.08
3.	Tin Concentrate	214.86±1.81	16.15±0.14	7.08±0.10
4.	Columbite	220.19±1.83	16.51±0.14	7.23±0.10
5.	Bismuth	127.29±1.33	10.33±0.11	3.08±0.06
6.	Manganese	157.84±1.51	12.36±0.12	4.07±0.07
7.	Lithium	128.97±1.34	10.44±0.11	2.95±0.06
8.	Molybdenite	133.48±1.37	10.74±0.11	3.16±0.07
9.	Tantalite	209.41±1.78	15.79±0.13	6.62±0.10
10.	Zinc	175.71±1.61	13.55±0.12	5.30±0.09
11.	Lead	168.14±1.57	13.05±0.12	4.68±0.08
12.	Wolframite	203.71±1.75	15.41±0.13	6.28±0.09
13.	Iron	131.33±1.36	10.60±0.11	2.96±0.06
MEAN VALUE		**169.45±1.56**	**13.13±0.12**	**4.80±0.07**

The investigated metallic minerals showed consistent occurrence of the primordial radionuclides (^{40}K, ^{238}U, and ^{232}Th), with mean activity concentrations of 169.45 ± 1.56, 13.13 ± 0.12, and 4.80 ± 0.07 Bq/kg, respectively, all below internationally recommended background limits. Elevated radionuclide concentrations observed in tin concentrate, columbite, tantalite, and wolframite were attributed to granitic and pegmatitic mineralization processes associated with magmatic differentiation (Ramli *et al.,* 2005). The distribution pattern further indicates that uranium and thorium are preferentially concentrated within accessory mineral phases, while ^{40}K is mainly associated with gangue and silicate inclusions, consistent with established geochemical models reported by (Orusun *et al.*, 2018; Arogunjo *et al.,* 2009). The relatively higher values recorded in columbite, tin concentrate, tantalite, and wolframite suggest the need for routine monitoring during mining and mineral processing activities (Olarinoye, 2019). Although the estimated ELCR values remained within acceptable limits, potential exposure through dust inhalation and environmental contamination highlights the importance of occupational safety measures and continuous environmental monitoring in accordance with International Atomic Energy Agency guidelines for NORM management.

Table 2 Specific Activity Concentration of (^{40}K, ^{238}U and ^{232}Th ($Bqkg^{-1}$) Results of Industrial Solid Minerals.

S/N	Minerals	K-40 (Bq/kg)	U-238 (Bq/kg)	Th-232 (Bq/kg)
1.	Gypsum	129.75±1.35	10.49±0.11	3.09±0.06
2.	Magnesite	110.00±1.22	9.18±0.100	2.0±0.050
3.	Glass Sand	134.06±1.37	10.78±0.11	3.0±0.060
4.	Rutile	177.90±1.62	13.07±0.12	5.32±0.09
5.	Silica Sand	113.60±1.24	9.42±0.020	2.08±0.05
6.	Sepiolite	139.30±1.40	11.13±0.11	3.31±0.07
7.	Bentonite	163.27±1.54	12.72±0.12	4.57±0.08
8.	Zircon Sand	223.37±1.85	16.72±0.14	7.33±0.10
9.	Limestone	124.58±1.31	10.15±0.11	2.67±0.06
10.	Phosphate	214.24±1.80	16.11±0.14	6.95±0.11
11.	Mica	155.30±1.50	12.19±0.12	4.1±0.080
12.	Phosphate Clay	189.23±1.68	14.45±0.13	5.85±0.09
13.	Monazite	213.75±1.80	16.08±0.14	6.92±0.10
14.	Feldspar	157.08±1.51	12.31±0.12	4.15±0.08
15.	Kyanite	143.50±1.43	11.41±0.11	3.83±0.07
16.	Ilmenite	199.50±1.73	15.13±0.13	6.34±0.09
17.	Baryte	175.92±1.61	13.56±0.12	5.01±0.08
18.	Zircon	206.49±1.77	15.6±0.13	6.37±0.09
19.	Fluorite	165.89±1.56	12.9±0.12	4.50±0.08
20.	Diatomite	108.36±1.21	9.07±0.11	2.02±0.05
21.	Graphite	156.61±1.51	12.28±0.12	4.07±0.07
22.	Ilmenite (alt)	191.32±1.69	14.59±0.13	5.83±0.09
MEAN VALUE		**163.32±1.65**	**12.70±0.13**	**4.51±0.08**

The investigated industrial minerals exhibited mean activity concentrations of 163.32 ± 1.65 Bq/kg for ^{40}K, 12.70 ± 0.13 Bq/kg for ^{238}U, and 4.51 ± 0.08 Bq/kg for ^{232}Th, all within internationally accepted background limits. However, relatively elevated radionuclide concentrations were observed in zircon sand, phosphate, monazite, and zircon due to the preferential incorporation of uranium and thorium into accessory mineral phases during geological and sedimentary processes (Echeweozo *et al.*, 2024), while diatomite, magnesite, and silica sand recorded comparatively lower values. Nevertheless, higher radionuclide enrichment and ELCR values in zircon sand and phosphate suggest the need for routine occupational and environmental monitoring, particularly during mining and processing activities. The observed geochemical association among ^{40}K, ^{238}U, and ^{232}Th further indicates common geological origins and enrichment mechanisms, consistent with previous findings by (Ademola and Bello 2011; Suleiman *et al.*, 2022), and international reports by the UNSCEAR, (2020).

Table 3 Specific Activity Concentration of (^{40}K, ^{238}U, and ^{232}Th ($Bqkg^{-1}$) Results of Clay Minerals.

S/N	Minerals	K-40 (Bq/kg)	U-238 (Bq/kg)	Th-232 (Bq/kg)
1.	Fire Clay	112.14±1.23	9.32±0.10	2.16±0.05
2.	Smectite	132.33±1.36	10.66±0.11	2.99±0.06
3.	Ball Clay	119.67±1.28	9.82±0.11	2.62±0.06
4.	Kaolin	159.96±1.52	12.50±0.12	4.53±0.08

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5.	Halloysite	135.97±1.38	10.91±0.11	3.25±0.07
6.	Laterite	170.03±1.58	13.17±0.12	5.04±0.08
7.	Silty Clay	121.71±1.30	9.96±0.11	2.54±0.06
8.	Clay	120.57±1.29	9.88±0.11	2.49±0.06
9.	Sandy Clay	114.82±1.25	9.50±0.10	2.12±0.05
10.	Loamy Clay	136.96±1.39	10.97±0.11	3.54±0.07
MEAN VALUE		**132.01±1.35**	**10.64±0.11**	**3.11±0.07**

The radiological and geochemical assessment of clay minerals in Nigeria revealed the ubiquitous presence of primordial radionuclides (^{40}K, ^{238}U, and ^{232}Th) with mean activity concentrations of 132.82 ± 1.39 Bq/kg, 10.20 ± 0.11 Bq/kg, and 3.15 ± 0.07 Bq/kg, respectively. These values are within internationally accepted background limits reported by UNSCEAR, (2020), indicating low radiological risk. Lateritic soils recorded the highest radionuclide concentrations due to residual enrichment during tropical weathering (Okoye *et al.*, 2022), whereas sandy clay exhibited the lowest concentrations because of its quartz-rich composition and reduced radionuclide retention capacity. The calculated radiological hazard indices, including Ra_eq, H_ex, H_in, AEDE, and ELCR, were all below recommended safety limits, confirming the radiological safety of the investigated materials for agricultural and construction purposes. However, elevated hazard values observed in laterite suggest the need for periodic environmental monitoring, especially in areas where lateritic soils are extensively utilized (Ugbede & Osahon, 2021). The observed radionuclide distribution patterns and statistical relationships further indicate strong geological and geochemical controls associated with mineral composition, weathering processes, and adsorption mechanisms (Ramli *et al.*, 2005). These findings are consistent with studies on tropical soils and naturally occurring radioactive materials reported by Alloway (2013), Zhang et al. (2022), and International Atomic Energy Agency guidelines. From other studies, the activity concentrations reported in this work are consistent with values observed in soils from similar geological and climatic settings (Godwin et al., 2019). Studies conducted in tropical regions have reported comparable ranges of radionuclide concentrations, with lateritic soils often exhibiting higher values due to residual enrichment processes.

Table 4 Specific Activity Concentration of (^{40}K, ^{238}U, and ^{232}Th (Bqkg^{-1}) Results of Energy Minerals.

S/N	Minerals	K-40 (Bq/kg)	U-238 (Bq/kg)	Th-232 (Bq/kg)
1.	Bituminous Sand	132.72±1.36	10.69±0.11	3.12±0.07
2.	Coal	159.82±1.52	12.49±0.12	4.44±0.08
MEAN VALUE		**146.27±1.44**	**11.59±0.12**	**3.78±0.07**

The radiological evaluation of selected Nigerian energy minerals, namely coal and bituminous sand, confirmed the presence of naturally occurring radionuclides (^{40}K, ^{238}U, and ^{232}Th) with mean activity concentrations of 146.27 ± 1.44 Bq/kg, 11.59 ± 0.12 Bq/kg, and 3.78 ± 0.07 Bq/kg, respectively. Coal consistently exhibited higher radionuclide concentrations than bituminous sand, reflecting the influence of organic matter, mineral impurities, and sedimentary depositional processes on radionuclide enrichment (Michael and Peter, 2016). The measured values remain within global background ranges and internationally recommended safety limits reported by the UNSCEAR and the IAEA, indicating minimal radiological risk under normal conditions. Although coal recorded relatively higher values, suggesting a greater contribution to radiation exposure. The radionuclide distribution patterns further reflect established geochemical behavior, where uranium exhibits affinity for organic matter while thorium and potassium are mainly associated with detrital and silicate mineral fractions (Orusun *et al.*, 2018). These findings are consistent with published studies on naturally occurring radioactive materials in fossil fuel systems reported by Qureshi *et al.*, 2014; Aliyu *et al.*, (2015), confirming that the studied energy minerals pose low radiological hazards but require continuous environmental monitoring and proper management during mining, storage, and combustion activities. Comparing with global literature, the activity concentrations reported in this study are consistent with values observed in coal and bituminous sands from other regions. Studies conducted in Asia, Europe, and North America report similar ranges of radionuclide concentrations in coal, with variations attributed to geological setting and mineral composition (Favas et al., 2016; Godwin et al., 2019; UNSCEAR, 2020).

Table 5 Specific Activity Concentration of (^{40}K, ^{238}U and ^{232}Th (Bqkg^{-1}) Results of Rock Minerals.

S/N	Minerals	K-40 (Bq/kg)	U-238 (Bq/kg)	Th-232 (Bq/kg)
1.	Granite	205.29±1.76	15.52±0.13	6.37±0.09
2.	Marble	128.46±1.34	10.41±0.11	2.82±0.06
MEAN VALUE		**166.86±1.55**	**12.97±0.12**	**4.60±0.07**

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The radiological assessment of granite and marble in Nigeria shows that primordial radionuclides (^{40}K, ^{238}U, and ^{232}Th) are present in both rock types, with mean activity concentrations of 166.86 ± 1.55, 12.97 ± 0.12, and 4.60 ± 0.07 Bq/kg, respectively, and consistently higher values in granite than marble. Granite recorded elevated activities (^{40}K: 205.29 Bq/kg; ^{238}U: 15.52 Bq/kg; ^{232}Th: 6.37 Bq/kg) due to enrichment of incompatible elements during magmatic differentiation, while marble showed lower concentrations consistent with its carbonate composition and limited radionuclide incorporation (Ramli *et al.*, 2005). All measured values fall within global background ranges, with low uncertainties confirming high analytical reliability of gamma spectrometry (IAEA, 2020). However, granite consistently exhibits higher values, indicating relatively greater radiation contribution compared to marble. These trends align with established geochemical behavior of uranium, thorium, and potassium in igneous versus metamorphic systems and are consistent with global findings identifying granitic rocks as more radioactively enriched than carbonate rocks (UNSCEAR, 2020). Overall, both materials are radiologically safe for use, but granite requires more cautious application in prolonged indoor exposure scenarios. Comparing with existing literature, the activity concentrations reported in this study are consistent with values observed in similar rock types (Alexander et al., 2015; Ademila 2018). Granitic rocks are widely recognized as having higher concentrations of uranium, thorium, and potassium compared to sedimentary and metamorphic rocks (Michael and Peter 2016), a trend that is clearly reflected in the present data.

Table 6 Mean Values of Activity Concentration of Minerals Compared with World Acceptable Limits (UNSCEAR, IAEA, and E.U Guidelines)

S/N	Minerals	K-40 (Bq/kg)	U-238 (Bq/kg)	Th-232 (Bq/kg)
1.	METALLIC	169.45±1.56	13.13±0.12	4.80±0.07
2.	INDUSTRIAL	163.32±1.65	12.70±0.13	4.51±0.08
3.	ROCK	166.86±1.55	12.97±0.12	4.60±0.07
4.	ENERGY	146.27±1.44	11.59±0.12	3.78±0.07
5.	CLAY	132.01±1.35	10.64±0.11	3.11±0.07
MEAN VALUE		**157.47±1.46**	**12.35±1.12**	**4.28±0.07**
WORLD AVERAGE		**400 Bq/kg**	**35 Bq/kg**	**30 Bq/kg**

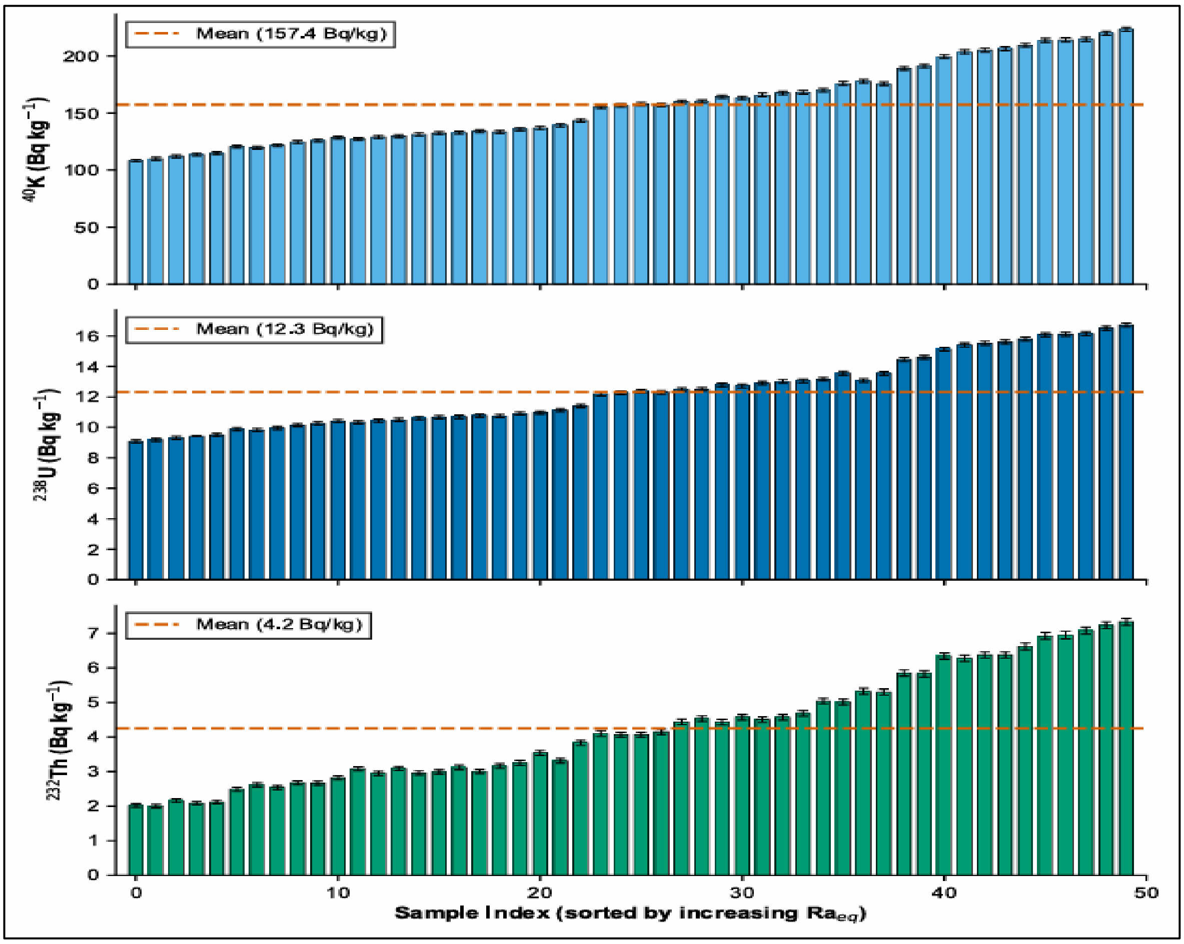

Fig 4 Activity Concentrations of Naturally Occurring Radionuclides in Solid Minerals Under Study: (a) Potassium-40, (b) Uranium-238, and (c) Thorium-232. Dashed Lines Indicate Mean Values

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Table 7 Mean Values of the Radiological Hazard Indices for all Solid Minerals Compared with World Permissible Limits. (UNSCEAR, IAEA, and E.U Guidelines)

S/N	Mineral Samples	D (nGyh^{-1})	AEDE Outdoor (mSvy^{-1})	AEDE Indoor (mSvy^{-1})	H_{ex} (mSvy^{-1})	H_{in} (mSvy^{-1})	Iγ	Iα	ELCR Outdoor (×10^{-3})	ELCR Indoor (×10^{-3})
1	Metallic	16.033	0.020	0.079	0.089	0.125	0.248	0.066	0.069	0.275
2	Industrial	15.403	0.019	0.076	0.086	0.120	0.239	0.064	0.066	0.264
3	Rock	15.724	0.020	0.077	0.088	0.123	0.244	0.065	0.068	0.270
4	Energy	13.738	0.017	0.068	0.077	0.108	0.213	0.058	0.059	0.236
5	Clay	12.300	0.015	0.060	0.068	0.097	0.190	0.053	0.053	0.211
MEAN TOTAL	**13.883**	**0.017**	**0.068**	**0.077**	**0.109**	**0.215**	**0.059**	**0.060**	**0.238**	
WORLD PERMISSIBLE LIMITS	**59**	**0.070**	**0.410**	**1.0**	**1.0**	**1.0**	**1.0**	**0.29**	**1.16**	

➢ *Radiological Hazard Indices*

Table 7 presents the evaluated radiological hazard parameters. The mineral samples demonstrated relatively low radiological burden across all investigated mineral categories. The mean absorbed dose rate was 13.883 nGy h^{-1}, which is substantially lower than the worldwide average outdoor terrestrial gamma dose rate recommended by UNSCEAR, 2020. Similarly, the computed annual effective dose equivalent values were below internationally permissible exposure limits for members of the public. The radium equivalent activity values for all samples remained below the recommended safety threshold of 370 Bq kg^{-1}, indicating that the minerals do not pose significant gamma radiation hazards when used for industrial or construction purposes. External and internal hazard indices were less than unity for all investigated samples, confirming acceptable radiological safety conditions. The excess lifetime cancer risk values were also within internationally acceptable limits, suggesting negligible long-term carcinogenic risks associated with the investigated minerals.

➢ *Correlation Analysis*

Pearson correlation analysis from Figure 5 revealed strong positive relationships among radionuclides and radiological hazard parameters. From Figure 6, the high correlation coefficients between ^{238}U, ^{232}Th, and ^{40}K suggest common geological controls and co-enrichment mechanisms within the mineral matrices. Strong positive correlations were also observed between radionuclide concentrations and hazard indices such as Raeq, absorbed dose rate, indicating that radiological risks are directly influenced by radionuclide abundance (Samuel et al., 2022). These relationships further confirm the reliability and internal consistency of the radiological dataset.

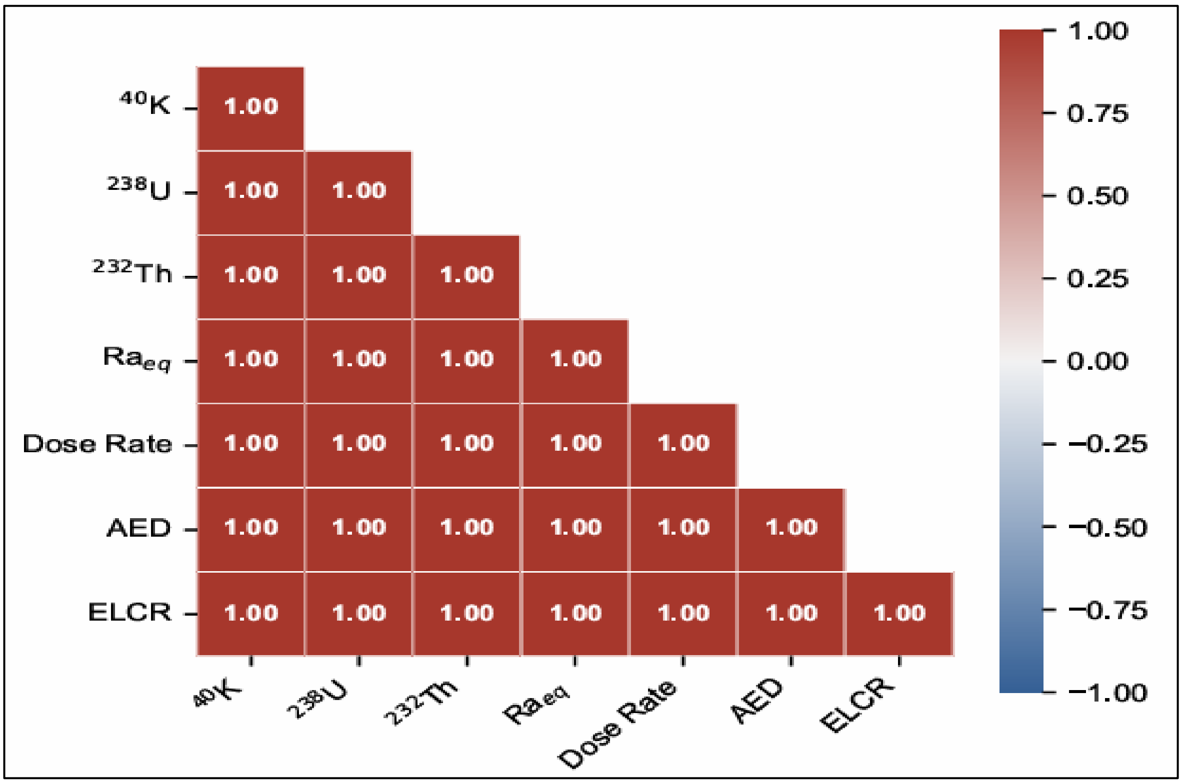

Fig 5 Pearson Correlation Coefficients Between Radionuclide Concentrations and Radiological Hazard Indices

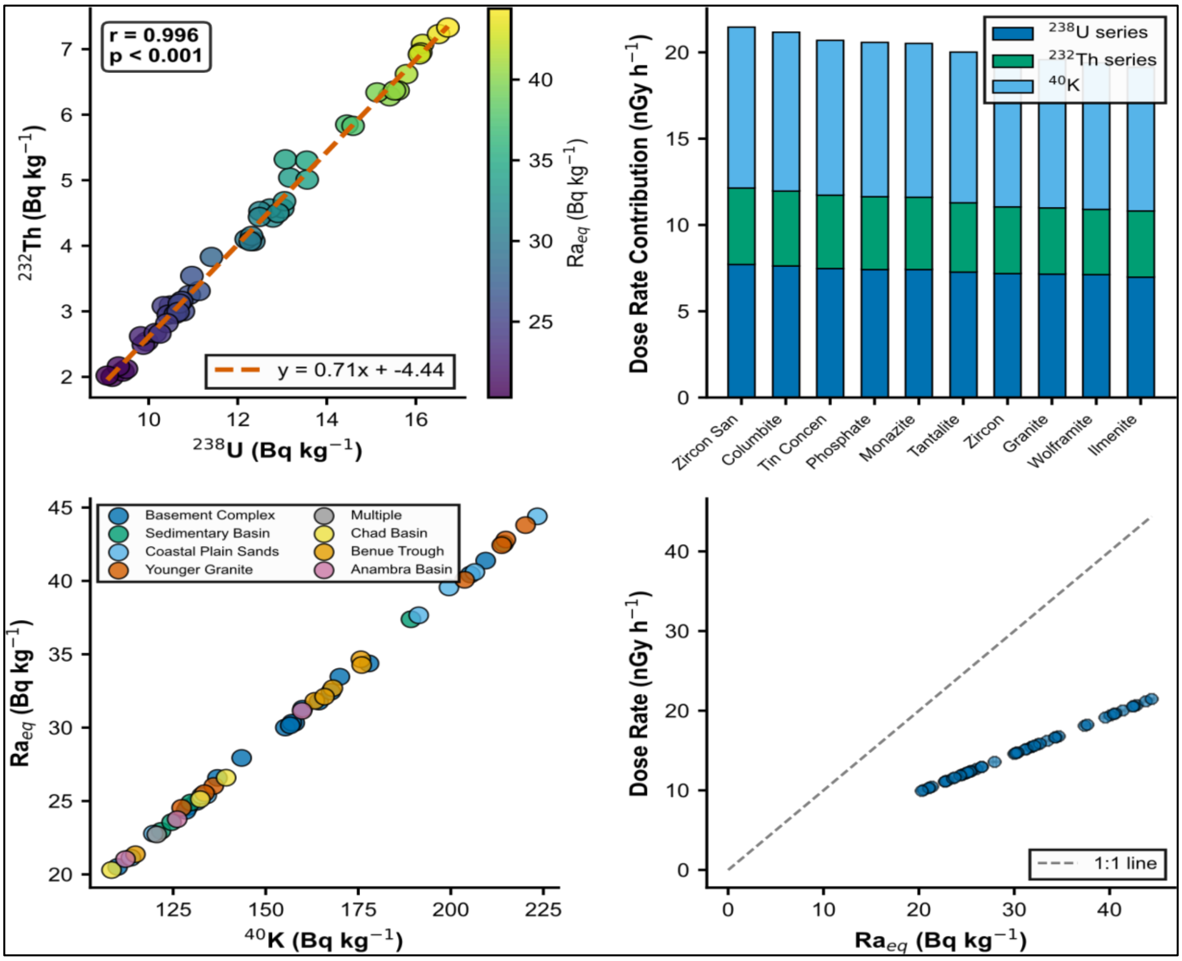

Fig 6 Pearson Correlation Coefficients Between Radionuclide Concentrations and Radiological Hazard Indices.

IV. DISCUSSION

The present study provides a comprehensive radiometric assessment of some solid minerals across Nigeria and establishes a national baseline dataset for radiological characterization of geological materials. The relatively low activity concentrations of ^{238}U, ^{232}Th, and ^{40}K observed in this study indicate that the investigated minerals are generally radiologically safe for industrial and domestic utilization.

The measured values are lower than or comparable to global averages reported by UNSCEAR and similar studies conducted in other regions (Ofumola *et al.*, 2024; Eghaghe *et al.*, 2024). The dominance of ^{40}K activity concentrations is consistent with the abundance of potassium-bearing silicate minerals such as feldspars, micas, and clay minerals within Nigeria's geological formations. Granitic and pegmatitic terrains exhibited relatively elevated uranium and thorium concentrations due to magmatic differentiation and incompatible element enrichment processes (Samuel et al, 2022; Ramli *et al.*, 2005). The low radiological hazard indices observed across all samples suggest minimal external and internal radiation exposure risks to workers and the general public. The computed absorbed dose rates and annual effective dose equivalents were substantially below internationally recommended exposure limits, indicating that prolonged utilization of these materials is unlikely to produce significant radiological health effects.

The strong positive correlations among radionuclides reflect common geochemical controls and mineralogical associations within the investigated materials Hassan *et al.*, 2020. Such correlations have been widely reported in granitic terrains and mineralized geological environments where uranium, thorium, and potassium coexist within accessory minerals (Samuel *et al.*, 2022; Girigisu *et al.*, 2014). The principal component analysis further confirmed that geological origin constitutes the primary determinant of radiological variability. The absence of strong anthropogenic signatures indicates that radionuclide occurrence within the studied minerals is predominantly natural.

The present findings have important implications for environmental radiation protection, occupational health monitoring, and regulatory policy development within Nigeria's mining sector. The establishment of baseline radiological datasets is essential for future monitoring programmes, risk communication, and environmental impact assessments. Furthermore, the study supports the integration of radiological safety considerations into mineral exploration, mining operations, construction material utilization, and industrial processing activities. Continuous monitoring remains necessary, especially in areas associated with uranium-bearing pegmatites, granitic intrusions, and hydrothermal mineralization.

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➤ *Environmental and Public Health Implications*

The exploitation of solid minerals contributes significantly to socioeconomic development, industrialization, and infrastructure expansion. However, mining activities may also introduce radiological concerns through enhanced exposure to naturally occurring radioactive materials. The findings of this study demonstrate that the investigated minerals currently pose low radiological risks. Nevertheless, improper mining practices, dust generation, poor waste management, and inadequate occupational safety measures may increase exposure pathways.

Workers involved in drilling, blasting, crushing, grinding, transportation, and beneficiation operations may experience increased inhalation exposure to radioactive dust particles and radon progeny. Similarly, communities residing near mining environments may be exposed through contaminated soils, airborne particulates, and groundwater systems.

V. CONCLUSION

This study presents a comprehensive radiometric characterization and radiological health hazard assessment of selected solid minerals across Nigeria using gamma-ray spectrometric analysis, radiological hazard indices assessment, and multivariate statistical evaluation. The measured activity concentrations of ^{238}U, ^{232}Th, and ^{40}K were generally lower than international reference values, indicating relatively low levels of natural radioactivity within the investigated mineral samples. All computed radiological hazard indices, including absorbed dose rate, annual effective dose equivalent, radium equivalent activity, external hazard index, internal hazard index, and excess lifetime cancer risk, were below internationally recommended safety thresholds. Statistical analysis revealed strong positive relationships among radionuclides and radiological parameters, while principal component analysis identified geological origin as the dominant controlling factor governing radionuclide distribution. The investigated minerals are considered radiologically safe for industrial, domestic, and construction applications under current exposure conditions. However, continuous radiological monitoring, occupational safety enforcement, and regulatory oversight remain essential for sustainable mineral resource development and environmental protection. The present study establishes an important national baseline radiological dataset and contributes significantly to environmental radiation research, public health protection, and sustainable mining policies.

The measured natural radioactivity levels in mineral samples from all locations in this study pose no immediate radiological threat, but cumulative exposure risk cannot be ignored, since they could lead to some radiological problems to people living or working within mining sites and it environ. Based on these, continuous radiological monitoring and radon assessment is recommended to ensure environmental safety and public health protection.

➤ *Supplementary Material*

The full fifty-sample names, class, activity concentration, radiological hazard indices evaluation are supplied in separate word document attached to this manuscript. It was not reproduced in full in the main manuscript to preserve readability and comply with normal article-length expectations.

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