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Evaluation of Radioactivity and Potential Radiological Health Risks of Mined Soils Used as Building Materials in Ijero-Ekiti, Nigeria

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ABSTRACT
The utilization of mined soils in building construction has raised serious concerns about radiological hazards to the public due to elevated concentrations of naturally occurring radioactive materials (NORMs). This study assesses the natural radioactivity levels and potential radiological health risks associated with mined soils commonly used as building materials in Ijero-Ekiti, a major mining community in Southwestern Nigeria. Gamma spectrometry analysis was performed on thirty (30) randomly sampled mined soil samples using a high-purity Germanium (HPGe) detector to determine activity concentrations of the radium-226 (^{226}Ra), uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K). Radiological models based on these measured activity concentrations were used to evaluate potential health risk indicators, including hazard indices (H_{ex} and H_{in}), Annual Gonadal Dose Equivalent (AGDE), annual effective dose (AED_{out} and AED_{in}), radium equivalent activity (Ra_{eq}), and excess lifetime cancer risk (ELCR). The average activity concentrations of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K in the samples were 512.28 ± 26.76, 241.26 ± 12.55, 31.07 ± 3.56, and 2808.01 ± 148.52 Bq/kg, respectively. Radionuclide concentrations and calculated health risk indicators exceeded global average values reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and recommended safe limits set by the International Atomic Energy Agency (IAEA). These findings indicate elevated ionizing radiation levels in the samples, posing potential radiological health risks to exposed residents. To address these concerns, stringent policies, public awareness, further research, and safer building materials are recommended.

Keywords:
Radioactivity,
Health Risk,
Mined Soil,
Building Material,
Nigeria.

INTRODUCTION

Mined soils are soil materials left over from mining activities after valuable minerals or ore are extracted from the earth. These mined soils are often used as building materials, and this practice has become common in many developing countries, including Nigeria. In many mining communities in Nigeria, such as Ijero-Ekiti community, local builders frequently use mined soil for landfilling, wall construction, and decking of buildings without considering the potential effects on public health, particularly for residents of buildings constructed with such materials. Unfortunately, this practice is often carried out without adequate public awareness of the radiological risks associated with these materials as mined soil typically contains naturally occurring radioactive materials (NORMs), including ^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K, which can cause the walls, floors, and roofs of the buildings to emit ionizing radiation continuously. Previous studies have shown that prolonged exposure to ionizing radiation emitted by these radionuclides poses serious health risks to the residents, including increased chances of cancer, reproductive health issues, genetic damage, and other harmful effects on human organs (UNSCEAR 2000; IAEA, 2018). An assessment of epidemiological studies of low-dose ionizing radiation carried out by Hauptmann et al. (2020)

further supports excess cancer risk from low-dose ionizing radiation. As a result, when these materials are used in building construction, they can become a source of indoor radiation exposure, endangering the health of the occupants over time.

To evaluate this exposure, several radiological health risk indicators derived from measured radionuclide activity concentrations are commonly used. The radium equivalent activity (Raeq) is a weighted index that combines the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K into a single value, based on the assumption that 370 Bq/kg of ^{226}Ra, 259 Bq/kg of ^{232}Th, and 4810 Bq/kg of ^{40}K produce equivalent gamma dose rates; it accounts for the non-uniform distribution of these radionuclides in building materials. The external (H_{ex}) and internal (H_{in}) hazard indices place an upper limit on the permissible radionuclide concentration to keep the external and internal (radon-related) radiation exposure within safe limits, with values required to remain below unity. The absorbed dose rate (D) measures the rate at which radiation energy is deposited per unit mass of material at a reference height of 1 m above the ground, and is calculated from the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K using established dose-conversion coefficients. The annual effective dose (AED_{out} and AED_{in}) converts the absorbed dose rate into the effective dose received by an individual over one year, accounting for occupancy factors for outdoor and indoor exposure, respectively, and is compared against the ICRP/UNSCEAR public exposure limit of 1 mSv/year. The excess lifetime cancer risk (ELCR) estimates the probability that an individual will develop cancer over an assumed lifetime as a result of continuous exposure to the annual effective dose, using a fatal cancer risk factor of 0.057 Sv^{-1} recommended by the ICRP. Together, these indicators provide a comprehensive framework for assessing the radiological safety of building materials.

Although numerous studies have investigated the concentrations of radionuclides and radiological risks in soil, sediments, and mine waste from mining sites across the world and within Nigeria, the radiological hazards for people living in houses built with mined soils remain comparatively underexplored. Globally, elevated radiological hazards exceeding recommended limits were reported in uranium-impacted soils in Chad (Penabei et al., 2020), whereas building material studies in India (Lyngkhoi and Nongkynrih, 2020), Spain (Mas et al., 2021), and Iraq (Othman et al., 2022) generally reported radiological parameters within acceptable international limits, except for specific materials such as granite and certain fly-ash-based concrete samples. These studies highlight that radiological safety depends strongly on the geological origin and composition of construction materials. In Nigeria, similar investigations have been conducted in several mining regions. Studies in Nasarawa State (Aliyu et al., 2015), Itagunmodi (Ademola et al., 2014), Kogi State (Olabamiji et al., 2025), and Jos Plateau (Odusote et al., 2014) largely reported radiological indices below recommended safety limits, although localized elevations in radiation dose and potential long-term health concerns were observed in some mining environments. Conversely, Laniyan and Adewumi (2021) reported elevated dose levels and excess lifetime cancer risks around selected Nigerian mining sites, suggesting possible long-term radiological health implications for nearby residents.

Despite these growing studies, radiological risk assessments specifically focused on mined soils reused as building materials remain limited, particularly in mining-intensive communities such as Ijero-Ekiti. The area is well known for extensive deposits of feldspar, cassiterite, columbite–tantalite, quartz, kaolin, mica, gemstones, and other economically valuable minerals. However, there remains insufficient information regarding the radioactivity levels of mined soils incorporated into residential structures and the associated health risks to occupants. This study, therefore, seeks to fill the gap by assessing the radioactivity levels and potential radiological health risks associated with mined soils used as building materials in Ijero-Ekiti, Southwestern Nigeria.

MATERIALS AND METHODS

Study Area

This study was conducted in Ijero-Ekiti within the Ijero Local Government Area of Ekiti State. Ijero-Ekiti is situated within the Precambrian basement complex of Southern Nigeria and covers a landmass area of 5.3 km² (Afeni and Ibitolu, 2018). The town occupies a significant geological position within the Ilesha-Ekiti Schist belt (Olusesan-Remi, 2018). Its geographical coordinates place it on a latitude of 7.82534ºN and longitude of 5.06905ºE. The region experiences a rainy season from April to October with an annual rainfall ranging from 1200-1400 mm and a dry season from November to April with a mean temperature of 27°C (Adebayo and Arohunsoro, 2014). Ijero-Ekiti is in a region characterized by metamorphic rock formations, including schists, gneisses, and quartzites. The town is famous for its pegmatites, rock formations distinguished by substantial crystals of minerals such as quartz, feldspar, mica, and other rare elements. These pegmatites are hosted within older rock formations, specifically gneisses, amphibolites, and granites. One of the outstanding features of Ijero-Ekiti is the presence of gemstones, particularly tourmaline, in various colours and varieties. The mining in the area is mostly artisanal and small-scale. The area is moderately populated, and residents frequently sourced mined soil for housing and public buildings without considering the potential health implications. Figure 1 shows the geographical map of Ijero-Ekiti, indicating the sampling points.

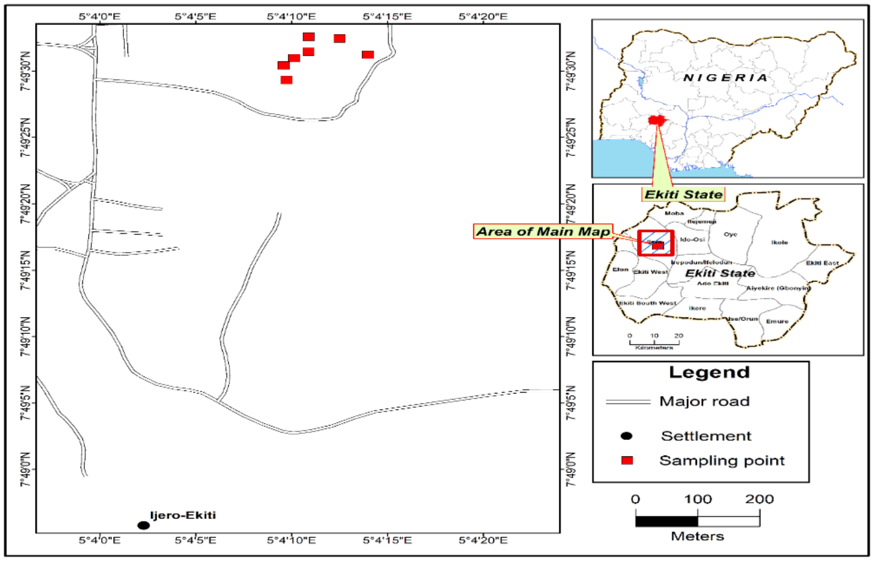

Figure 1: Map showing sampling points in Ijero-Ekiti, Southwestern Nigeria

Sample Collection and Preparation

A total of 30 mined soil samples were randomly collected from pegmatite mining site in Ijero-Ekiti where these materials are commonly collected and used as building materials by builders and people from far and near. Samples were taken from the topsoil (0 – 15 cm deep) and stored in labelled and airtight containers. The samples were subsequently taken to the laboratory for preparation and analysis. In the laboratory, samples were oven-dried at 110 °C to remove moisture, crushed into fine powder, and passed through a 1 mm geological sieve to separate target particles from unwanted materials and ensure homogeneity. 650 g of each sample was sealed in clean containers and stored for 30 days to allow for secular equilibrium between radon and its short-lived progenies.

Radiological Analysis

To determine the activity concentrations of radionuclides (^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K) in the samples, gamma-ray spectrometry was carried out using a Canberra coaxial high-purity Germanium (HPGe) detector with a 50% relative efficiency and a resolution of 2.4keV at 1.33 MeV (Co-60). The model is 8023GC (serial no. 9744), paired with a 2002CSL pre-amplifier. It is enclosed in a lead shield to reduce background radiation interference during counting. The energy and efficiency of the detector were calibrated using IAEA Multi-Gamma Ray Standard (MCS6M315) source, under strict procedures, to ensure the results were reliable and accurate. After applying corrections for the detector's efficiency and background radiation, gamma-ray peaks corresponding to the decay of ^{238}U and ^{232}Th, as well as the direct emission from ^{40}K were used to quantify the activity concentrations. The activity of ^{238}U was determined from 351.9 keV peak of ^{214}Pb and 609.3 keV peak of ^{214}Bi, assuming secular equilibrium with the decay chain. ^{232}Th activity was determined from 583.1 keV peak of ^{208}Tl and 911.2 keV peak of ^{228}Ac. The activity of ^{40}K was directly measured from its characteristic 1460.8 keV gamma-ray peak. The activity concentrations of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K radionuclides in the samples were calculated according to Model (Alausa, 2020):

$$A_i(\mathrm{Bq.kg^{-1}}) = \frac{N}{\varepsilon_i \times P_\gamma \times m_s \times T} \quad (1)$$

where A_i is the activity concentration of the i^{th} energy of the radionuclide of interest in the sample, N is the net counts of the i^{th} energy (background subtracted) in the resulting photopeak, ε_i is the efficiency of the detector at the i^{th} gamma-ray energy, P_γ is the emission probability of the i^{th} gamma-ray energy, m_s is the mass of the sample in kg, and T is the counting time.

Radiological Health Risk Assessment

Potential radiological health risk indicators associated with the mined soil samples were computed using models that depend on the measured activity concentrations of radionuclides in the samples.

Radium Equivalent Activity

Radium equivalent activity (Ra_{eq}), which represents the combined radiological effect of ^{40}K, ^{226}Ra, and ^{232}Th in the mined soil samples, considering their different gamma radiation contributions, was calculated using Model (UNSCEAR, 2000):

$$Ra_{eq} = 0.077\, A_K + A_{Ra} + 1.43\, A_{Th} \quad (2)$$

Where A_{Ra}, A_{Th}, and $A_K$are the activity concentrations (in Bq/kg) of ^{226}Ra, ^{232}Th, and ^{40}K, respectively. The Ra_{eq} value of 370 Bq/Kg translates to approximately an annual effective dose of 1 mSv/yr. Hence, if $Ra_{eq} > 370$ Bq/kg, it implies that the radiation could be harmful to the residents over time.

External Hazard Index

The external hazard index (H_{ex}) was used to determine whether the radiation emitted from buildings constructed with mined soil is safe for residents. H_{ex} should be ≤ 1 to ensure safety; values above this threshold may pose a risk to external radiation exposure. H_{ex} of each sample is calculated using Model (Beretka and Mathew, 1985; Isinkaye and Ajiboye, 2022):

$$H_{ex} = \frac{A_K}{4810} + \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} \leq 1 \quad (3)$$

Internal Hazard Index

In enclosed indoor environments, radon can accumulate and be inhaled, increasing the risk of lung cancer (Sethi et al., 2012). H_{in} was used to evaluate the internal exposure risk due to the inhalation of dust or radon gas and its short-lived progeny, primarily from ^{226}Ra. It becomes a concern when $H_{in} > 1$, which is determined by the Model (UNSCEAR, 2000; Beretka and Mathew, 1985):

$$H_{in} = \frac{A_K}{4810} + \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} \leq 1 \quad (4)$$

Alpha Representative Index

The alpha representative index (I_α) was used to estimate the potential internal exposure resulting from radon and its progeny due to the presence of ^{226}Ra (alpha-emitting radionuclide). This index is crucial for indoor air safety assessments, as it helps determine whether the material could lead to unsafe radon levels indoors if mined soil is used as building material. It is calculated using the Model (EC, 1999):

$$I_\propto = \frac{A_{Ra}}{200} \quad (5)$$

If $I_\alpha > 1$, the materials may be unsuitable for indoor use or require radon mitigation measures.

Gamma Index

The gamma index (I_γ) was used to evaluate external gamma-radiation doses from mined soil samples. It was used to determine whether the material might expose occupants to harmful gamma radiation above the recommended limit of unity. It is calculated using the Model (EC, 1999):

$$I_\gamma = \frac{A_K}{3000} + \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} \quad (6)$$

Absorbed Dose Rate in Air

The absorbed dose rate in air (*D*) measures the amount of radiation present in air resulting from the decay of ^{226}Ra, ^{232}Th, and ^{40}K in the mined soil samples when used as building material. According to UNSCEAR (2000), the global average absorbed dose rate from natural sources is about 59 $nGyh^{-1}$. A high value of *D* indicates increased background radiation exposure and greater potential for biological damage. *D* is calculated using the Model (UNSCER, 2000):

$$D = \sum A_R DC_{ext,R} = 0.462 A_{Ra} + 0.604 A_{Th} + 0.0417 A_K \quad (7)$$

Where *D* (nGy/h) is the absorbed dose rate in air, A_R is the concentration of specific radionuclide in the sample (Bq/kg), $DC_{ext,R}$ is the coefficient of dose rate per unit activity concentration of radionuclide. The coefficients 0.462, 0.604, and 0.0417 (measured in nGy/h per Bq/kg) in the model correspond to the specific dose conversion factors for the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

Annual Gonadal Dose Equivalent

Due to the radio-sensitivity of the gonads and the radiation-induced genetic effects of gamma radiation, the Annual Gonadal Dose Equivalent (AGDE) is an important radiation metric. The AGDE estimates the amount of ionizing radiation absorbed by the gonads (testes or ovaries) over a year. Increased radiation exposure to the gonads can increase the risk of hereditary genetic damage, reproductive issues, and potentially cause anaemia and other blood-related problems. According to UNSCEAR reports, the benchmark for AGDE is 0.3 mSv per year. The AGDE was calculated using the Model (Sivakumar et al., 2017; Gaafar et al., 2022):

$$AGDE\left(\frac{mSv}{y}\right) = \frac{3.09 A_{Ra} + 4.18 A_{Th} + 0.314 A_K}{1000} \quad (8)$$

Annual Effective Dose

The Annual Effective Dose *(AED)* estimates the amount of ionising radiation an individual may receive for a year, adjusted for the biological impact of different radiation types and exposure settings. It serves as a critical indicator of long-term radiological risk to human health.

In this study, the *AED* was derived from the measured absorbed dose rate *(D)*, using the standard model recommended by UNSCEAR (2000):

$$AED\ (mSv/y) = D \times 10^{-6} \times 8760 \times 0.7 \times OF \qquad (9)$$

Where *D* is Absorbed dose rate converted from nGy/h to mGy/h (by multiplying by10^{-6}), 8760 h/y is the total hours in a year, 0.7 Sv/Gy is the dose conversion coefficient accounting for biological effectiveness, and *OF* is occupancy factor (0.8 for indoor exposure), reflecting the proportion of time individuals spend in a given environment. For this research, the *AED* was calculated specifically for indoor exposure, considering the living conditions of individuals residing in houses constructed with mined soil. According to threshold set by the ICRP (1991) and supported by UNSCEAR (2000), the *AED* should be $\leq$ 1 mSv/y, for the exposure to be considered within safe limits for the public.

Excess lifetime cancer risk

The Excess Lifetime Cancer Risk (ELCR) estimates the likelihood of an individual developing cancer over their lifetime due to prolonged exposure to ionising radiation. The ELCR was calculated using the Model (ICRP, 1991; Taskin et al., 2009):

$$ELCR = AED \times DL \times RF \times 10^{-3} \qquad (10)$$

Where *DL* is the average duration of a life, taken as 62 years based on Nigeria's life expectancy in 2023 (Doris, 2023), *RF* is the risk factor for stochastic effects, adopted as 0.05 Sv^{-1} (ICRP, 1991), and 10^{-3} is a conversion factor.

RESULTS AND DISCUSSION

The results of the activity concentrations of the radionuclide of interest in the samples are presented in Table 1.

Table 1: Activity Concentrations of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K (Bq/kg) in the Samples

SAMPLE	^{226}Ra	^{238}U	^{232}Th	^{40}K
1	617.19 ± 33.92	289.59 ± 16.88	30.88 ± 4.65	3625.05 ± 193.67
2	613.09 ± 29.82	285.49 ± 12.78	26.78 ± 0.55	3620.95 ± 189.57
3	612.38 ± 29.11	284.78 ± 12.07	26.07 ± 0.16	3620.24 ± 188.86
4	614.40 ± 31.13	286.80 ± 14.09	28.09 ± 1.86	3622.26 ± 190.88
5	617.90 ± 34.63	290.30 ± 17.59	31.59 ± 5.36	3625.76 ± 194.38
6	614.99 ± 31.72	287.39 ± 14.68	28.68 ± 2.45	3622.85 ± 191.47
7	614.26 ± 30.99	286.66 ± 13.95	27.95 ± 1.72	3622.12 ± 190.74
8	620.82 ± 37.55	293.22 ± 20.51	34.51 ± 8.28	3628.68 ± 197.30
9	619.16 ± 35.89	291.56 ± 18.85	32.85 ± 6.62	3627.02 ± 195.64
10	607.21 ± 23.94	279.61 ± 6.90	20.90 ± 5.33	3615.07 ± 183.69
11	236.49 ± 14.87	128.81 ± 8.58	26.97 ± 3.92	1236.39 ± 67.34
12	232.39 ± 10.77	124.71 ± 4.48	22.87 ± 0.18	1232.29 ± 63.24
13	231.68 ± 10.06	124.00 ± 3.77	22.16 ± 0.89	1231.58 ± 62.53
14	233.70 ± 12.08	126.02 ± 5.79	24.18 ± 1.13	1233.60 ± 64.55
15	237.20 ± 15.58	129.52 ± 9.29	27.68 ± 4.63	1237.10 ± 68.05
16	234.29 ± 12.67	126.61 ± 6.38	24.77 ± 1.72	1234.19 ± 65.14
17	233.56 ± 11.94	125.88 ± 5.65	24.04 ± 0.99	1233.46 ± 64.41
18	240.12 ± 18.50	132.44 ± 12.21	30.60 ± 7.55	1240.02 ± 70.97
19	238.46 ± 16.84	130.78 ± 10.55	28.94 ± 5.89	1238.36 ± 69.31
20	226.51 ± 4.89	118.83 ± 1.40	16.99 ± 6.06	1226.41 ± 57.36
21	689.30 ± 37.63	311.53 ± 18.06	41.51 ± 4.61	3568.75 ± 190.70
22	685.20 ± 33.53	307.43 ± 13.96	37.41 ± 0.51	3564.65 ± 186.60
23	684.49 ± 32.82	306.72 ± 13.25	36.70 ± 0.20	3563.94 ± 185.89
24	686.51 ± 34.84	308.74 ± 15.27	38.72 ± 1.82	3565.96 ± 187.91
25	690.01 ± 38.34	312.24 ± 18.77	42.22 ± 5.32	3569.46 ± 191.41
26	687.10 ± 35.43	309.33 ± 15.86	39.31 ± 2.41	3566.55 ± 188.50
27	686.37 ± 34.70	308.60 ± 15.13	38.58 ± 1.68	3565.82 ± 187.77
28	692.93 ± 41.26	315.16 ± 21.69	45.14 ± 8.24	3572.38 ± 194.33
29	691.27 ± 39.60	313.50 ± 20.03	43.48 ± 6.58	3570.72 ± 192.67
30	679.32 ± 27.65	301.55 ± 8.08	31.53 ± 5.37	3558.77 ± 180.72

Mean ± σ	512.28 ± 26.76	241.26 ± 12.55	31.07 ± 3.56	2808.01 ± 148.52
Minimum	226.51 ± 4.89	118.83 ± 1.40	16.99 ± 6.06	1226.41 ± 57.36
Maximum	692.93 ± 41.26	315.16 ± 21.69	45.14 ± 8.24	3628.68 ± 197.30
Skewness	-0.672	-0.702	0.259	-0.743
Kurtosis	-1.552	-1.546	-0.740	-1.554

Table 1 presents the descriptive statistics of the radionuclide activities of the soil samples. The statistics include the mean, standard deviation, minimum, maximum, skewness, and kurtosis. The mean activity concentrations of ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K in the samples are 512.28 ± 26.76 Bq/kg, 241.26 ± 12.55 Bq/kg, 31.07 ± 3.56 Bq/kg, and 2808.01 ± 148.52 Bq/kg, respectively. The statistical distribution of the activity concentrations for ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K was calculated using skewness and kurtosis to determine data normality and dispersion characteristics. The skewness value for ^{226}Ra (-0.672), ^{238}U (-0.702), and ^{40}K (-0.743) indicate moderate negative skewness. This suggests that the data distribution is slightly asymmetric with the tails extending towards the lower concentration values, while the bulk of the data is concentrated at relatively higher values. However, ^{232}Th data exhibits slightly positive skewness (0.259). This implies that the distribution has a marginal elongation towards the higher activity concentration values. Conventionally, skewness values between +1 and -1 indicate approximately symmetric distribution.

For the kurtosis, all radionuclides exhibit negative kurtosis ranging from -1.554 to -0.740. This indicates that the distribution is platykurtic, suggesting that the datasets are flatter than a normal distribution with a lower likelihood of extreme outlier data and a more uniform spread of activity concentrations. This suggests that the soil samples exhibit homogeneity, that is, the samples are likely to have emanated from the same source. The distribution of the activity concentrations of the radionuclides indicate that the soil samples exhibit consistent lithological characteristics.

When compared with other mining sites across Nigeria, the Ijero-Ekiti site recorded among the highest reported activity concentrations of radionuclides, particularly ^{226}Ra and ^{40}K, significantly exceeding values documented in previous studies. Specifically, among mining sites in Southwestern Nigeria, the mean activity concentration of ^{226}Ra in Ijero-Ekiti mined soil samples was over 13 times higher than the value reported for tantalite mining areas in Oke-Ogun (39.8 Bq/kg) by Ademola and Obed (2012). Similarly, the mean activity concentration of ^{40}K at Ijero-Ekiti (2808.01 Bq/kg) was substantially higher than those reported for kaolin deposits in Ifonyintedo (93.9 Bq/kg) by Adagunodo et al. (2018) and the gold mining area in Itagunmodi (505.1 Bq/kg) reported by Ademola et al. (2014). Although the mean activity concentration of ^{232}Th at Ijero-Ekiti (31.07 Bq/kg) was not the highest among the compared sites, it exceeded values reported for Paago (0.623 Bq/kg) by Babatunde et al. (2023) and Oke-Ogun (17.7 Bq/kg), but remained lower than the thorium-rich kaolin deposits in Ifonyintedo (65.1 Bq/kg) reported by Adagunodo et al. (2018). Overall, these comparisons indicate that mined soils from Ijero-Ekiti possess relatively elevated radionuclide burdens, particularly for ^{226}Ra, ^{232}Th, and ^{40}K, which may pose greater radiological health risks to residents exposed to these materials over prolonged periods.

As shown in Figure 1, the average activity concentrations of naturally occurring radionuclides (^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K) measured at the Ijero-Ekiti mining site far exceed global safety benchmarks established by UNSCEAR (2000) and IAEA guidelines.

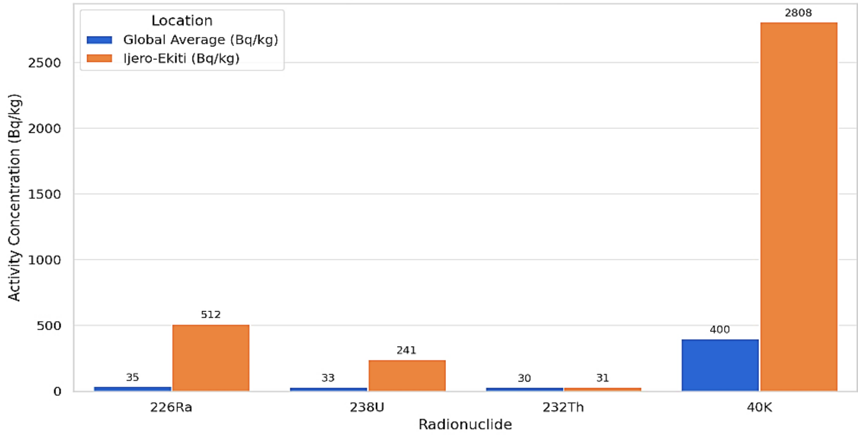

Figure 1: Comparison of Radionuclide Activity Concentrations (Ijero-Ekiti versus Global Averages)

Table 2 shows the comparison of activity concentrations of radionuclides in the present study to those reported around the world. The average activity concentrations of ^{226}Ra, ^{238}U, and ^{40}K at the Ijero-Ekiti site far exceed both the world average values and most values reported from other mining environments globally. The extreme ^{40}K average activity concentration indicates a substantial source of external gamma radiation, likely associated with potassium-rich minerals typical of pegmatite formations or geological factors. These findings confirm that the radiological conditions in Ijero-Ekiti are not only elevated locally but are among the highest when viewed in a global context.

Table 2: Comparison of Activity Concentrations of Radionuclides (Bq/kg) in the Present Study to those Reported Around the World

Country	^{226}Ra	^{238}U	^{232}Th	^{40}K	Mining Site(s)	References
Brazil	104.8	64.9	1813.9	1184.2	Niobium mining site in Brazil	El Hajj et al. (2021)
China	75.4		48.6	533.9	Petroleum refinery area in South China	Ma et al. (2022)
Indonesia	72.47		86.905	1802.05	Tanjung Enim's Coal Mine, South Sumatra Indonesia	Muhammad et al. (2022)
Philippines	-	64.2	14.2	939.0	Philippine Iron Mine in Jose Panganiban, Camarines Norte	Gibaga et al. (2022)
South Africa	-	785.3	43.9	427.0	Gold mining site in the province of Gauteng in South Africa	Kamunda et al. (2016)
Tanzania	42.59	-	35.48	652.36	Gold mining sites in Tanzania	Focus et al. (2021)
Turkey	1749		3467	309	Beylikova-Sivrihisar Complex (Chromite) Ore Site in Turkey	Yücel et al. (2020)
Nigeria	512.28	241.26	31.07	2808.01	Pegmatite mining site in Ijero-Ekiti	Present Study
World average	35	35	30	400		UNSCEAR (2000)

Table 3: Radium Equivalent, External Hazard Index, Internal Hazard Index, Gamma Index, and Alpha Index Due to Samples from Ijero-Ekiti

	Ra_{eq} (Bq/kg)	H_{ex}	H_{in}	I_{γ}	I_{α}
Mean ± σ	772.92±295.46	2.18±0.83	3.56±1.38	5.60±2.14	2.56±1.01
Minimum	345.23	0.97	1.58	2.50	1.13
Maximum	1032.56	2.90	4.77	7.45	3.46

From Table 3, the average value of Ra_{eq} (772.92 Bq/kg) exceeds the safe limit (370 Bq/kg), which implies that the radiation could be harmful to the residents over time. The results also reveal significantly elevated levels of radiation, as indicated by the mean external hazard index (H_{ex}) of 2.18, internal hazard index (H_{in}) of 3.56, gamma index (Iγ) of 5.60, and alpha index (Iα) of 2.56. These indices substantially exceed the recommended safety threshold of 1, which indicates considerable radiological concerns. The elevated indices reflect heightened risks of both external and internal exposure to ionizing radiation, particularly from gamma rays and alpha-emitting radionuclides. Given these findings, the use of mine residues from the pegmatite site in Ijero-Ekiti for construction purposes, particularly in building materials, is deemed radiologically unsafe.

Table 4: Absorbed Dose Rate in Air (D), Annual Gonadal Dose Equivalent (AGDE), Outdoor and Indoor Annual Effective Dose Equivalent (AED), Excess Lifetime Cancer Risk (ELCR) Due to the Samples

	D (nGy/h)	AGDE (mSv/y)	AED (mSv/y)	ELCR (x 10^{-3})
Mean	372.53	2.59	1.83	5.67
Minimum	166.05	1.16	0.81	2.53
Maximum	496.37	3.45	2.43	7.55

The results from Table 4 reveal significantly elevated radiation exposure levels across all measured indices. The mean absorbed dose rate (D) in air was 372.53 nGy/h, which is considerably higher than the global average of 59 nGy/h as reported by UNSCEAR (2000). This indicates a pronounced presence of gamma-emitting radionuclides in the environment. The mean Annual Gonadal Dose Equivalent (AGDE) was found to be 2.59 mSv/year, with values ranging from 1.16 to 3.45 mSv/year. These figures exceed the typical safety reference level of 0.3 – 1.0 mSv/year, suggesting a heightened radiological impact on sensitive human tissues. The Annual Effective Dose Equivalent (AED), averaged 1.83 mSv/year, surpasses the recommended public exposure limit of 1.0 mSv/year by the ICRP, indicating a potential long-term health concern. The evaluated average Excess Lifetime Cancer Risk (ELCR) yields a value of 5.67×10^{-3}. This value indicates the probability of approximately 6 persons developing cancer in a thousand population over a lifetime period. The value is significantly higher than the global average risk benchmark of 0.29×10^{-3}, suggesting that individuals in this environment may face a substantially increased lifetime risk of developing cancer due to radiological exposure.

CONCLUSION

The data from this study firmly established Ijero-Ekiti as one of the most radiologically active mining environments in Nigeria based on naturally occurring radionuclide concentrations. The findings of this study reveal a consistently elevated exposure profile across all key doses and risk indicators. The mean absorbed dose rate in air (372.53 nGy/h) far exceeds the global average of 59 nGy/h (UNSCEAR, 2000), while both the Annual Effective Dose (1.83 mSv/year) and the Annual Gonadal Dose Equivalent (2.59 mSv/year) surpass globally recommended exposure limits. Most notably, the calculated Excess Lifetime Cancer Risk (5.67×10^{-3}) is nearly 20 times greater than the accepted global reference value, indicating a considerable long-term health risk to exposed populations. These findings not only emphasize a significant radiological issue in the study area but also raise serious concerns regarding the use of mined soil for building construction. Given the elevated external and internal dose rates associated with the materials, using them for building homes and public structures would inadvertently introduce chronic exposure pathways, particularly for vulnerable groups such as children, pregnant women, and the elderly.

To effectively address these concerns, it is vital to establish well-defined policies and regulations on the handling and reuse of radiologically contaminated soil or waste materials, raise public awareness, conduct further research and monitoring of the area, discourage the use of mined soils for building construction, and promote the use of safer and more sustainable building materials. These actions will help reduce long-term risks and support healthier living environments.

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