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In Situ Gamma Dose Rates and Radiological Risk Indices at Artisanal Mining Sites in Kauru, Kaduna State, Nigeria

[1,2]Hayatu Umar, [1]Mohammad. Y. Onimisi, [3]Yakub I. Viva, [1]Olumide O. Ige, [1]Hauwa K. Shuaibu, [1]Abubakar Yahaya, [1]Mansur A. Hussain and [2]Beatrice B. Humphrey

[1]Department of Physics, Nigerian Defence Academy, Kaduna, Nigeria.
[2]Department of Physics, Federal University of Agriculture Mubi, Adamawa State, Nigeria.
[3]Centre for Energy Research and Training, Ahmadu Bello University, Zaria, Kaduna State, Nigeria.

*Corresponding Author's Email: hayatuumar1016@gmail.com Phone: +234 810 343 7393

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ABSTRACT
Artisanal and small-scale mining is widespread across the Precambrian Basement Complex of Northern Nigeria, a geological setting known to host elevated concentrations of naturally occurring radioactive materials (NORM). This cross-sectional study measured ambient gamma radiation dose rates once, during the dry season, at thirty (30) locations (coded K1–K30) selected by combined systematic and purposive sampling within mining areas of Kauru Local Government Area (LGA), Kaduna State, Nigeria, using a portable scintillation survey meter (Thermo Fisher Scientific RadEye PRD) held 1 m above ground level, following UNSCEAR protocol. The absorbed dose rates in air were used to derive indoor and outdoor annual effective dose (AED) and excess lifetime cancer risk (ELCR) with standard UNSCEAR/ICRP conventions; indoor AED and ELCR were modelled from the outdoor readings using occupancy factors and were not measured indoors, and ELCR is a model-derived screening index, not an observed cancer outcome. Dose rates ranged from 20 to 400 nGy h^{-1}, with a mean of 139.2 ± 105.4 nGy h^{-1} (median 117.5 nGy h^{-1}), about 2.4 times the UNSCEAR world average of 59 nGy h^{-1}; 19 of the 30 locations exceeded this value, one (K30) equalled it and ten fell below it. The mean indoor and outdoor AED were 0.683 mSv y^{-1} (0.098–1.962) and 0.171 mSv y^{-1} (0.025–0.491), respectively; eight locations (26.7%) exceeded 1 mSv y^{-1} indoors, and the mean total AED of 0.854 mSv y^{-1} was about 1.8 times the UNSCEAR world average of 0.48 mSv y^{-1} for terrestrial gamma exposure. The mean indoor and outdoor ELCR were 2.39×10^{-3} and 0.60×10^{-3}, about 8.2 and 2.1 times the reference value of 0.29×10^{-3}; every location exceeded this reference indoors and 18 of the 30 exceeded it outdoors. Spatial variability was high (coefficient of variation 75.7%), with the highest readings at K9 and K18 (400 nGy h^{-1} each), K19 (300 nGy h^{-1}) and K20 (260 nGy h^{-1}). The findings show that terrestrial gamma radiation at the sampled locations in the mining areas of Kauru LGA is moderately elevated on average but strongly localized. Because sampling was purposive and confined to one season, the results are screening-level estimates for the sampled points and are not representative of the whole LGA; they provide a baseline for radionuclide-specific investigation, targeted radiological protection, regulatory monitoring and community risk communication.

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INTRODUCTION

Natural radiation is a permanent part of the human environment. Its main components are cosmic and cosmogenic radiation, gamma radiation from radionuclides in rocks and soil, and radiation from radioelements in air and water (Saied et al., 2016). People are exposed to these radioelements through water and food intake and to background gamma radiation of terrestrial and cosmic origin (Abba et al., 2017). The Earth's crust has been radioactive since the planet's

formation, with naturally occurring radioactive materials (NORM), principally uranium-238 (^{238}U), thorium-232 (^{232}Th) and potassium-40 (^{40}K), distributed throughout rocks, soils and mineral deposits. Terrestrial gamma radiation from these primordial radionuclides and their decay products is the main external source of natural exposure outdoors, with a population-weighted world average absorbed dose rate in air of 59 nGy h^{-1} outdoors and 84 nGy h^{-1} indoors (United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR], 2000). Dose rates are generally higher over soils and rocks of granitic igneous origin (Abba et al., 2017; UNSCEAR, 2000). Gamma radiation is highly penetrating and can deposit energy deep within biological tissue (Hall & Giaccia, 2012).

Mining pathways add to this natural background. Mining and mineral processing can redistribute and concentrate NORM-bearing material in pits, waste heaps and tailings, thereby raising exposure for workers and nearby communities (International Atomic Energy Agency [IAEA], 2003, 2006). Mining has been carried out in the Basement Complex of northern Nigeria for a long time (Olasehinde et al., 2012), and some workings lie close to settlements and farmland where agricultural and other human activities continue (Umar et al., 2023).

At low chronic doses, the principal health concern is the stochastic induction of cancer through DNA damage. The linear no-threshold (LNT) model adopted by the International Commission on Radiological Protection [ICRP] holds that any dose of ionizing radiation carries a finite probability of causing cancer (ICRP, 2007), a view consistent with the BEIR VII assessment of low-dose risks (National Research Council, 2006). Risk indices derived in this way, such as the excess lifetime cancer risk (ELCR), are model-based screening quantities and not observed cancer outcomes. This underpins the value of systematic dose-rate monitoring wherever natural exposure may be enhanced.

Mining in Nigeria is largely artisanal and small-scale, and its radiological consequences have been documented most extensively on the Jos Plateau, where tin and columbite mining has been associated with elevated radiation levels and environmental concern (Ibeanu, 2003; Ademola, 2008; Jibiri et al., 2009). These studies differ in ways that limit direct comparison. Nationwide and urban baselines come from outdoor dose-rate surveys that were not targeted at mining sites (Jibiri & Farai, 1998; Farai & Jibiri, 2000); the Jos Plateau and Abeokuta farm-soil values of Jibiri et al. (2009) were calculated from gamma-spectrometric soil data rather than measured in the field; and studies of mining sites elsewhere in Nigeria used soil spectrometry at an artisanal gold site (Kolo et al., 2020) or soil-to-plant transfer and risk assessment (Orosun et al., 2022). Measurement method, geology (tin and columbite on the Jos Plateau, gold in north-central Nigeria), sample coverage and exposure assumptions therefore all vary between studies.

Kauru LGA lies in southern Kaduna State within the Precambrian Basement Complex and adjoins Plateau State, yet, to the best of the authors' knowledge, no systematic in situ gamma dose rate survey of its mining areas has been published. This paper addresses that gap. The aim of this study is to evaluate the radiological exposure from terrestrial gamma radiation at sampled locations in the mining areas of Kauru LGA. The specific objectives are to: (i) measure in situ ambient gamma dose rates at thirty georeferenced locations; (ii) derive the indoor and outdoor annual effective dose and the excess lifetime cancer risk from the measured dose rates; and (iii) compare the results with international reference values and identify locations that warrant priority follow-up. The study is confined to in situ ambient gamma dose-rate measurement with a portable survey meter; it does not extend to laboratory radionuclide-specific spectrometry, alpha or beta measurement, indoor radon assessment, or analysis of non-radioactive contaminants, which are addressed in companion investigations.

MATERIALS AND METHODS

Study Area

Kauru LGA is in southern Kaduna State, in the North West geopolitical zone of Nigeria, with its headquarters at Kauru town (approximately 10°39′N, 8°09′E) and a land area of about 2,810 km². It shares boundaries with Bassa and Riyom LGAs of Plateau State to the south-east, among other neighbouring LGAs. The area has a tropical wet and dry (Sudan Guinea savanna) climate, with a rainy season that runs from about April to October. Kaduna State is underlain by the Precambrian Basement Complex, consisting essentially of granites, gneisses, migmatites, schists and quartzites, and its known mineral occurrences include cassiterite, columbite, tantalite, gold and wolframite among others (Obaje, 2009). Granitic and pegmatitic bodies are generally richer in uranium and thorium than most other crustal rock types (UNSCEAR, 2000), and the neighbouring Jos Plateau is a documented area of elevated radiation levels (Ademola, 2008; Jibiri et al., 2009). Artisanal miners in Kauru LGA extract solid minerals, reportedly including feldspar, mica, quartz, gold and columbite.



Figure 1: Map of the Kauru LGA and its Wards

Study Design and Site Selection

A cross-sectional environmental radiological survey was adopted, with each location measured once during the dry season (November–March) [survey dates to be supplied by the author]. Thirty (30) sampling points (K1–K30) were selected within the mining areas using a combination of systematic and purposive sampling. The purposive component placed points where radiological significance was expected (mining faces, waste heaps, processing sites, rocky and granitic outcrops, and densely populated settlements); the systematic component was intended to spread points across the north, south, east and west sectors of the study area. The categories sampled were mining faces, waste heaps, processing sites, residential compounds, farmland, schools, health centres, markets, stream banks, rocky and granitic outcrops, forest fringes and urban centres. Because the selection was not random, the results describe the sampled points only and should not be read as representing the whole LGA; with 30 points over about 2,810 km², the sampling density is roughly one point per 94 km². Each point was georeferenced with a handheld GPS receiver (Garmin eTrex 10/30) to an accuracy of ±5 m; latitude, longitude, land-use type, proximity to settlement and visible geological features were recorded in field notebooks, and locality names and coordinates are listed in Appendix A. The wider study design also defined three zone types (active mining; peripheral, within 1–2 km of mining; and control, at least 5 km from mining), but zone assignments are not part of the dose-rate dataset reported here, so no zone-wise or control-site comparison is made.

Instrumentation

Ambient gamma dose rates were measured with a portable scintillation survey meter (Thermo Fisher Scientific RadEye PRD) with a NaI(Tl) detector , which responds to gamma and X-rays. The instrument displays dose rate in μSv h^{-1} (also in mR h^{-1}, counts per second and counts per minute) with a stated accuracy of ±10%. The instrument was calibrated against a certified ^{137}Cs reference source traceable to national standards before fieldwork, and the calibration certificate was verified to be within its validity period. A ^{137}Cs calibration establishes the response at a single photon energy (662 keV) and does not by itself demonstrate an energy-independent response to the natural gamma field of the ^{238}U, ^{232}Th and ^{40}K series; the energy response is therefore treated as a source of systematic uncertainty (Section 4.6). The principle and limitations of scintillation detectors are described by Knoll (2010).

Field Measurement Protocol, Quality Control and Uncertainty

The survey meter was allowed a 5-minute warm-up and stabilization period before use, and background readings were taken in an open field at the start of each field day to establish a daily baseline. At each point the detector was held vertically at 1.0 m above the ground surface, the UNSCEAR reference height for terrestrial gamma measurements, and clear of the surveyor's body. At least five consecutive readings were recorded at approximately one-minute intervals, and their arithmetic mean was taken as the representative dose rate. Measurements were confined to the dry season and to 08:00–16:00 h, and were suspended during or immediately after rainfall. Quality control comprised ^{137}Cs check-source readings at the start and end of each field day, duplicate measurements at 10% of the sites on separate days (coefficient of variation < 5% between repeats) and blinded field recording.

Two uncertainty components are distinguished. The instrument's stated accuracy (±10%) is a systematic term, whereas field repeatability (coefficient of variation < 5% between duplicate measurements) describes the reproducibility of the measurement procedure. Treated as independent relative uncertainties, they combine to about 11% (quadrature sum) for an individual site reading; this figure excludes energy-response effects, the dose-

quantity conversion described below and counting statistics, which were not quantified.

The meter displays μSv h^{-1}. Readings were converted to absorbed dose rate in air in nGy h^{-1} by taking 1 μSv h^{-1} as 1,000 nGy h^{-1}, that is, by assuming a Sv/Gy ratio of unity for the photon energies concerned. For convenience, values are also expressed in μrem h^{-1} using 1 nGy h^{-1} = 0.1 μrem h^{-1}, which follows from the same assumption (1 Sv = 100 rem). This is a simplified conversion between dose-equivalent and absorbed-dose numerics, not an identity between absorbed dose and dose equivalent.

Derived Parameters

The indoor and outdoor annual effective doses were computed following UNSCEAR (2000, 2008):

$$AED_{indoor}\ (mSv\ y^{-1}) = D\ (nGy\ h^{-1}) \times 8{,}760\ h\ y^{-1} \times 0.8 \times 0.7\ Sv\ Gy^{-1} \times 10^{-6} \quad (1)$$

$$AED_{outdoor}\ (mSv\ y^{-1}) = D\ (nGy\ h^{-1}) \times 8{,}760\ h\ y^{-1} \times 0.2 \times 0.7\ Sv\ Gy^{-1} \times 10^{-6} \quad (2)$$

where D is the absorbed dose rate in air derived from the measured readings, 0.8 and 0.2 are the indoor and outdoor occupancy factors, and 0.7 Sv/Gy is the conversion coefficient from absorbed dose in air to effective dose for adults (UNSCEAR, 2000, 2008). The indoor AED is modelled, not measured: the same outdoor reading is used in both equations, no indoor measurements were made, and no allowance is made for building materials or shielding. The total AED is the sum of the indoor and outdoor values. The excess lifetime cancer risk was calculated as:

$$ELCR = AED\ (Sv\ y^{-1}) \times DL \times RF \quad (3)$$

where DL is the assumed duration of life (70 y), a conventional approximation to average life expectancy in ELCR studies, and RF is the fatal-cancer risk coefficient for the general public, taken as 0.05 Sv^{-1} (ICRP, 1991), the nominal low-dose, low-dose-rate value for the public. ELCR values are reported in units of 10^{-3}. ELCR is a model-derived screening index obtained under the LNT assumption; it is not an observed cancer outcome. As a worked example, K9 (D = 400 nGy h^{-1}) gives AED_{indoor} = 400 × 8,760 × 0.8 × 0.7 × 10^{-6} = 1.962 mSv y^{-1} and $ELCR_{indoor}$ = 1.962 × 10^{-3} × 70 × 0.05 = 6.87 × 10^{-3}.

Results were compared with the following benchmarks: the UNSCEAR (2000) world average outdoor dose rate of 59 nGy h^{-1}; the UNSCEAR world average outdoor AED of 0.07 mSv y^{-1} and total terrestrial-gamma AED of 0.48 mSv y^{-1}; the ICRP public dose limit of 1 mSv y^{-1}, used here as an indicative benchmark for modelled indoor AED only (the limit applies to planned exposure and is not a regulatory limit on natural background); and a world-average ELCR reference value of 0.29 × 10^{-3} that is widely used in the literature (Taskin et al., 2009), which is a literature reference value and not a regulatory limit.

Statistical Analysis

Descriptive statistics (minimum, maximum, arithmetic mean, median, sample standard deviation and coefficient of variation) were computed for D, AED and ELCR. Because AED and ELCR are linear functions of D, their coefficients of variation are identical to that of D. Locations with dose rates at or above the mean plus one standard deviation were classed as hotspots. The number of locations exceeding each reference value was also tallied. The 95% confidence interval of the mean was computed from the t-distribution (29 degrees of freedom). Because the points were not selected at random, it describes the uncertainty in the mean of the 30 sampled points and is not a confidence interval for the LGA as a whole.

RESULTS AND DISCUSSION

Results

Table 1 presents the measured dose rate and the derived AED and ELCR at all thirty sampling points. Table 2 summarizes the descriptive statistics, and Table 3 compares the study means with the reference values. Figures 2–4 show the distribution of dose rate, AED and ELCR across the sampling points. The exceedance counts below refer to the 30 sampled points and do not estimate the proportion of the LGA's area or population above any reference value. Every site value in Table 1 was independently recomputed from Equations (1)–(3) and agreed with the tabulated value to the precision shown, and all exceedance counts were re-tallied from the dose rates.

Table 1: Sampling Locations and Coordinates

Code	Locality	Latitude (°N)	Longitude (°E)
K1	Dan Mai kogi	9.11	7.11
K2	Ruwan mancha	9.36	7.12
K3	Doka	9.37	7.13
K4	Kadagen kauru	9.26	7.32
K5	Libere	9.25	7.43
K6	Likarbu	9.21	7.33
K7	Hayin bagobiri	9.32	7.23
K8	Gidan kuku	9.34	7.45
K9	Kishesha	9.76	7.35

Code	Locality	Latitude (°N)	Longitude (°E)
K10	Gwarzo	9.38	7.54
K11	Makole	9.37	7.43
K12	Bakin Dutse	9.29	7.56
K13	Kiporo	9.27	7.47
K14	Makera	9.28	7.87
K15	Unguwan isah	9.35	7.98
K16	Randa	9.31	7.65
K17	Kure	9.12	7.55
K18	Nandu mine	9.31	7.67
K19	Kuru Zircon	9.71	7.57
K20	Gindin Akwati	9.46	7.98
K21	Kauru town	10.22	8.21
K22	Kauru West	10.57	8.12
K23	Unguwan Shinkafa	10.81	8.13
K24	Yadin Kauru	10.59	8.32
K25	Barwa	10.66	8.43
K26	Unguwan Haske	9.76	7.39
K27	Sara Hills	9.65	7.81
K28	Buji Complex	10.66	8.45
K29	Kwanan Kaza	9.33	7.56
K30	Wutana settlement	9.23	7.54

Table 2: Measured Dose Rate (D), Annual Effective Dose (AED) and Excess Lifetime Cancer Risk (ELCR) at Sampling Points K1–K30

Code	D (nGy h^{-1})	D (μrem h^{-1})	AED indoor (mSv y^{-1})	AED outdoor (mSv y^{-1})	ELCR indoor (× 10^{-3})	ELCR outdoor (× 10^{-3})
K1	200	20.00	0.9811	0.2453	3.4339	0.8585
K2	100	10.00	0.4906	0.1226	1.7170	0.4292
K3	150	15.00	0.7358	0.1840	2.5754	0.6439
K4	210	21.00	1.0302	0.2575	3.6056	0.9014
K5	160	16.00	0.7849	0.1962	2.7471	0.6868
K6	240	24.00	1.1773	0.2943	4.1207	1.0302
K7	140	14.00	0.6868	0.1717	2.4037	0.6009
K8	220	22.00	1.0792	0.2698	3.7773	0.9443
K9	400	40.00	1.9622	0.4906	6.8678	1.7170
K10	55	5.50	0.2698	0.0675	0.9443	0.2361
K11	30	3.00	0.1472	0.0368	0.5151	0.1288
K12	20	2.00	0.0981	0.0245	0.3434	0.0858
K13	40	4.00	0.1962	0.0491	0.6868	0.1717
K14	54	5.40	0.2649	0.0662	0.9272	0.2318
K15	60	6.00	0.2943	0.0736	1.0302	0.2575
K16	170	17.00	0.8340	0.2085	2.9188	0.7297
K17	147	14.70	0.7211	0.1803	2.5239	0.6310
K18	400	40.00	1.9622	0.4906	6.8678	1.7170
K19	300	30.00	1.4717	0.3679	5.1509	1.2877
K20	260	26.00	1.2755	0.3189	4.4641	1.1160
K21	45	4.50	0.2208	0.0552	0.7726	0.1932
K22	25	2.50	0.1226	0.0307	0.4292	0.1073
K23	55	5.50	0.2698	0.0675	0.9443	0.2361
K24	211	21.10	1.0351	0.2588	3.6228	0.9057
K25	125	12.50	0.6132	0.1533	2.1462	0.5365
K26	110	11.00	0.5396	0.1349	1.8887	0.4722
K27	43	4.30	0.2109	0.0527	0.7383	0.1846
K28	50	5.00	0.2453	0.0613	0.8585	0.2146

Code	D (nGy h^{-1})	D (μrem h^{-1})	AED indoor (mSv y^{-1})	AED outdoor (mSv y^{-1})	ELCR indoor (× 10^{-3})	ELCR outdoor (× 10^{-3})
K29	98	9.80	0.4807	0.1202	1.6826	0.4207
K30	59	5.90	0.2894	0.0724	1.0130	0.2533
Min	20.000	2.000	0.098	0.025	0.343	0.086
Max	400.000	40.000	1.962	0.491	6.868	1.717
Mean	139.233	13.923	0.683	0.171	2.391	0.598

Note: Indoor AED and ELCR are Modelled from the Outdoor Reading (Equations 1–3), not Measured Indoors

Table 3: Descriptive statistics for D, AED and ELCR (n = 30)

Parameter	Min	Max	Mean	Median	SD	CV (%)	95% CI of mean
D (nGy h^{-1})	20.0	400.0	139.2	117.5	105.4	75.7	99.9–178.6
D (μrem h^{-1})	2.00	40.00	13.92	11.75	10.54	75.7	9.99–17.86
AED indoor (mSv y^{-1})	0.098	1.962	0.683	0.576	0.517	75.7	0.490–0.876
AED outdoor (mSv y^{-1})	0.025	0.491	0.171	0.144	0.129	75.7	0.122–0.219
AED total, indoor + outdoor (mSv y^{-1})	0.123	2.453	0.854	0.721	0.646	75.7	0.612–1.095
ELCR indoor (× 10^{-3})	0.343	6.868	2.391	2.017	1.810	75.7	1.715–3.066
ELCR outdoor (× 10^{-3})	0.086	1.717	0.598	0.504	0.452	75.7	0.429–0.767
ELCR total (× 10^{-3})	0.429	8.585	2.988	2.522	2.262	75.7	2.144–3.833

Note: The Confidence Interval Describes the Mean of the 30 Sampled Points (t-distribution, 29 Degrees of Freedom) and is not an Estimate for the Whole LGA.

Table 4: Comparison of Study Means with International Reference Values

Parameter	Study mean	Reference value	Mean relative to reference	Locations exceeding reference
D (nGy h^{-1})	139.2	59 (UNSCEAR world average, outdoor)	≈2.4×	19 of 30 (K30 equals 59; 10 below)
AED indoor (mSv y^{-1})	0.683	1.0 (ICRP public dose limit; indicative benchmark only)	≈0.68× (below)	8 of 30 (26.7%)
AED outdoor (mSv y^{-1})	0.171	0.07 (UNSCEAR world average)	≈2.4×	20 of 30
AED total (mSv y^{-1})	0.854	0.48 (UNSCEAR world average, terrestrial gamma, indoor + outdoor)	≈1.8×	18 of 30
ELCR indoor (× 10^{-3})	2.391	0.29 (world-average reference)	≈8.2×	30 of 30
ELCR outdoor (× 10^{-3})	0.598	0.29 (world-average reference)	≈2.1×	18 of 30

Absorbed Dose Rate

Dose rates ranged from 20 nGy h^{-1} (K12) to 400 nGy h^{-1} (K9 and K18), with a mean of 139.2 nGy h^{-1} (95% confidence interval of the mean 99.9–178.6 nGy h^{-1}), a median of 117.5 nGy h^{-1} and a standard deviation of 105.4 nGy h^{-1} (Table 2). The mean is about 2.4 times the UNSCEAR world average of 59 nGy h^{-1}. Nineteen of the 30 locations exceeded the world average, K30 equalled it, and ten locations (K10–K14, K21–K23, K27 and K28) fell below it. Thirteen locations recorded below 100 nGy h^{-1}, eight between 100 and 199 nGy h^{-1}, six between 200 and 299 nGy h^{-1}, and three at or above 300 nGy h^{-1}. The highest readings were at K9 and K18 (400 nGy h^{-1} each), K19 (300 nGy h^{-1}) and K20 (260 nGy h^{-1}), which are the four locations at or above the hotspot threshold of 245 nGy h^{-1} (mean + 1 SD). The lowest readings were at K12 (20 nGy h^{-1}), K22 (25 nGy h^{-1}) and K11 (30 nGy h^{-1}) (Figure 2).

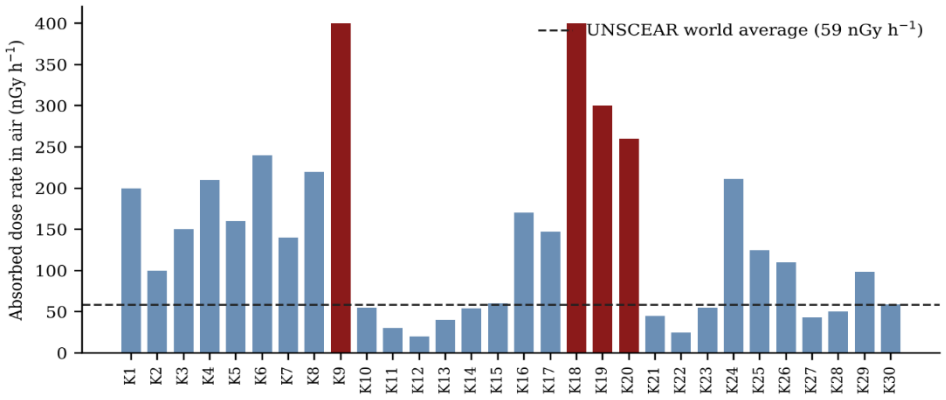


Figure 2: Absorbed Dose Rate in Air at Sampling Locations K1–K30. Hotspots (≥ Mean + 1 SD) are Shown in Dark Red; the Dashed Line is the UNSCEAR World Average (59 nGy h^{-1})

Annual Effective Dose

The indoor AED (modelled) ranged from 0.098 to 1.962 mSv y^{-1} with a mean of 0.683 mSv y^{-1}, and the outdoor AED ranged from 0.025 to 0.491 mSv y^{-1} with a mean of 0.171 mSv y^{-1}. The total AED (indoor plus outdoor) averaged 0.854 mSv y^{-1}, with a range of 0.123 to 2.453 mSv y^{-1}, which is about 1.8 times the UNSCEAR world average of 0.48 mSv y^{-1}. The mean indoor AED was below 1 mSv y^{-1}, but eight of the 30 locations (26.7%; K4, K6, K8, K9, K18, K19, K20 and K24) exceeded it. Twenty locations exceeded the world average outdoor AED of 0.07 mSv y^{-1}, giving a mean about 2.4 times that value (Figure 3).

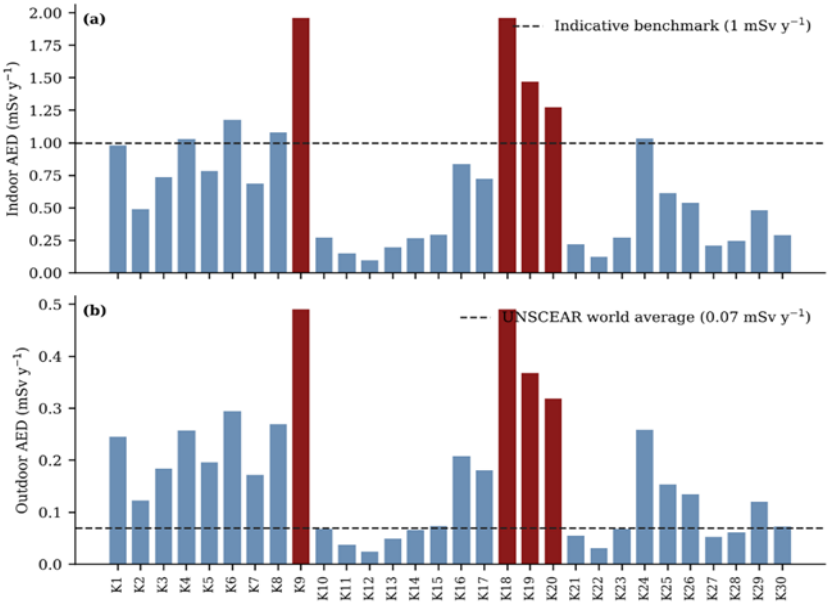


Figure 3: (a) Indoor (Modelled) and (b) Outdoor Annual Effective Dose at K1–K30 Compared with Reference Values

Excess Lifetime Cancer Risk

The indoor ELCR (modelled) ranged from 0.343 × 10^{-3} to 6.868 × 10^{-3} with a mean of 2.391 × 10^{-3}, about 8.2 times the reference value of 0.29 × 10^{-3}, and all 30 locations exceeded the reference. The outdoor ELCR ranged from 0.086 × 10^{-3} to 1.717 × 10^{-3} with a mean of 0.598 × 10^{-3}, about 2.1 times the reference value, and 18 of the 30 locations exceeded it (Figure 4). The combined indoor and outdoor ELCR averaged 2.988 × 10^{-3}, with a maximum of 8.585 × 10^{-3} at K9 and K18.

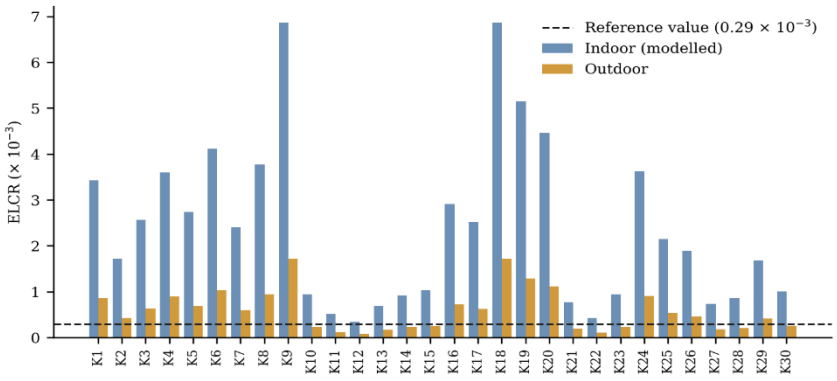


Figure 4: Indoor (Modelled) and Outdoor Excess Lifetime Cancer Risk at K1–K30 Compared with the Reference Value of 0.29×10^{-3}

Spatial Variability

The coefficient of variation was 75.7% for dose rate (and therefore for AED and ELCR), indicating substantial spatial heterogeneity among the sampled points. The mean exceeds the median and the distribution is right-skewed (skewness 0.99), reflecting a small group of high-reading locations superimposed on a large number of locations close to or below the global average.

Discussion

Dose-Rate Levels

The mean dose rate of 139.2 nGy h^{-1} is about 2.4 times the UNSCEAR outdoor world average and about 1.7 times the world indoor average of 84 nGy h^{-1} (UNSCEAR, 2000). The elevation is therefore moderate rather than extreme, and it is carried by a minority of locations: the median (117.5 nGy h^{-1}) is only about twice the world average, and ten locations lie below it. The elevated readings are consistent with the Basement Complex geology of the area, including its granitic and pegmatitic bodies. Mining may add locally by exposing mineralized rock and generating waste material (IAEA, 2003; Ibeanu, 2003), but the present data cannot show this: there are no matched control locations, no lithological information and no radionuclide analyses, so the hotspots cannot be attributed specifically to mining. Likewise, the ten low-reading locations may lie on less mineralized ground or away from workings, although lithology and distance to workings were not recorded and this cannot be confirmed from the present data. Because the survey relied on gross scintillation-meter dose-rate readings and included no radionuclide-specific measurements, geogenic and mining-related contributions cannot be separated here; gamma spectrometry of the ^{238}U, ^{232}Th and ^{40}K content of soils and waste material is needed for that purpose.

Spatial Variability and Hotspots

The high coefficient of variation (75.7%) and the right skew show that a few locations drive the mean. K9 and K18 (400 nGy h^{-1}), K19 (300 nGy h^{-1}) and K20 (260 nGy h^{-1}) stand out as hotspots, and K6 (240 nGy h^{-1}), K8 (220 nGy h^{-1}), K24 (211 nGy h^{-1}) and K4 (210 nGy h^{-1}) lie just below the hotspot threshold of 245 nGy h^{-1}. Area-wide averages therefore understate conditions at the highest-reading locations and overstate them at the lowest. This heterogeneity may reflect variation in geology and, at mining sites, non-uniform waste handling and exposure of mineralized material, but the present data cannot distinguish these causes. These locations should receive priority in any follow-up work.

Annual Effective Dose

The indoor AED is four times the outdoor AED at every location. This ratio reflects the 0.8 versus 0.2 occupancy assumption of UNSCEAR rather than any difference in the underlying radiation field, and the indoor values are modelled from outdoor readings, not measured indoors. It shows why indoor exposure should be evaluated separately for residents. The mean total AED of 0.854 mSv y^{-1} from external gamma radiation is about 1.8 times the UNSCEAR (2000) world average of 0.48 mSv y^{-1}, and ten locations have a total AED above 1 mSv y^{-1}. The ICRP public limit of 1 mSv y^{-1} applies to exposures from planned sources and excludes natural background, so the eight locations whose modelled indoor AED exceeds it do not represent a regulatory breach as such; they do indicate naturally elevated exposure that merits evaluation. Under the ICRP (2007) system such situations are managed as existing exposure situations, for which reference levels are typically selected within the 1–20 mSv y^{-1} band, and the highest total AED observed here (2.45 mSv y^{-1} at K9 and K18) lies in the lower part of that band. The AED values do not include exposure from radon or from ingestion and inhalation pathways, so total exposure is likely to be higher.

Excess Lifetime Cancer Risk

Every location exceeded the 0.29×10^{-3} reference value for modelled indoor ELCR, and 18 of 30 did so outdoors.

The mean combined ELCR of 3.0×10^{-3} corresponds to roughly three modelled excess fatal cancers per thousand people under the assumption of continuous residence at the measured levels for 70 years, rising to about 8.6 per thousand at K9 and K18. These figures are screening-level indicators derived from the LNT model and conservative occupancy assumptions; they are not predictions of observed cancer incidence, do not demonstrate an increase in cancer cases, and they overstate risk for people who live or work at a location for shorter periods. They do show that, at the hotspots in particular, the modelled exposure is large enough to justify protective follow-up.

Comparison with Other Studies

Table 4 places the Kauru results alongside values reported in other studies. The Kauru mean dose rate (139.2 nGy h^{-1}) is lower than the values reported for farm soils on the Jos Plateau and in Abeokuta, two Nigerian areas of known elevated radiation (Jibiri et al., 2009), and is about 1.2 times the in situ mean reported for Kırklareli, Turkey (Taskin et al., 2009). The outdoor ELCR of 0.60×10^{-3} is about 1.5 times that reported for an artisanal gold mining site in Minna, Nigeria (Kolo et al., 2020) and about 1.2 times that for Kırklareli. The maximum readings at K9 and K18 (400 nGy h^{-1}) nevertheless exceed the mean values reported in all of these studies. These comparisons should be read with caution, because the studies differ in method (in situ survey versus soil spectrometry), sampling design and season. The levels recorded in Kauru are well below the extremes documented in the world's best-known high background areas (Sohrabi, 1998), and risks within acceptable limits have been reported at some other Nigerian mining sites (Orosun et al., 2022), which underlines that conditions differ markedly between mining districts. The Kauru data place the area among moderately elevated environments in which local hotspots, rather than the area mean, are the main concern.

Table 5: Comparison of Dose Rate and ELCR with Other Studies

Location / Setting	Method	Mean dose rate (nGy h^{-1})	ELCR ($\times 10^{-3}$)	Reference
Kauru LGA, Kaduna State (this study)	In situ scintillation survey meter, 1 m	139.2 (20–400)	0.60 (outdoor)	This study
Jos Plateau farm soils, Nigeria	Calculated from gamma-spectrometric soil data	194 ± 59 to 350 ± 270	–	Jibiri et al. (2009)
Abeokuta farm soils, Nigeria	Calculated from gamma-spectrometric soil data	167 ± 140	–	Jibiri et al. (2009)
Gababiyu artisanal gold site, Minna, Nigeria	NaI(Tl) spectrometry of soil	–	0.40	Kolo et al. (2020)
Kırklareli, Turkey	In situ portable survey meter, 1 m	118 ± 34	0.50	Taskin et al. (2009)
World average		59	0.29 (reference)	UNSCEAR (2000)

Table 4 necessarily sets an in situ survey against dose rates calculated from soil activity concentrations and against soil spectrometry, because the comparison studies used different methods; these approaches capture different quantities and carry different assumptions, so the comparison is indicative only. The ELCR comparison is restricted to outdoor values because the Kauru indoor values are modelled. For Kırklareli, the reported ELCR of 0.50×10^{-3} is consistent with the same definition used here (an annual effective dose of 144 µSv multiplied by 70 y and 0.05 Sv^{-1}), so the two outdoor values are comparable; the occupancy factor and risk coefficient behind the Minna value could not be checked, and that comparison should be treated with more caution.

LIMITATIONS

This study has several limitations. Measurements were taken once, in the dry season, with a scintillation survey meter that does not resolve gamma energies; the instrument is calibrated against ^{137}Cs, so its response to the natural-series photon spectrum is not established by that calibration and approximate. The conversion of the displayed µSv h^{-1} to absorbed dose rate in air assumes a Sv/Gy ratio of unity; ambient dose equivalent per unit air kerma is typically somewhat above unity at these photon energies (about 1.1–1.2 Sv/Gy), so the absorbed dose rates may be overestimated by up to roughly 20%. The indoor AED assumes that the indoor dose rate equals the outdoor reading, with no allowance for building-material contribution or shielding, so indoor values are indicative and modelled. The risk coefficient of 0.05 Sv^{-1} follows ICRP (1991); the later ICRP (2007) nominal risk coefficient for cancer in the whole population is somewhat higher (about 0.055 Sv^{-1}, detriment-adjusted), which would raise all ELCR values by roughly 10%. Finally, thirty points selected purposively in one season cannot fully characterize a local government area of this size, and the results should not be extrapolated to

unsampled parts of the LGA. No control or background locations are reported separately, so the effect of mining cannot be isolated.

RECOMMENDATIONS

Follow-up should begin with radionuclide-specific investigation: gamma spectrometry of soil, rock and waste material should be carried out at the hotspots K9, K18, K19 and K20 and extended to K6, K8, K24 and K4, to identify the contributing radionuclides and to separate geogenic from mining-related enhancement. The georeferenced dose-rate data should be extended to a denser survey that includes matched control locations and used to produce isodose maps of the LGA, delineating hotspots and informing land-use and mining-licensing decisions. Dwellings, schools and health centres near the eight locations whose modelled indoor AED exceeds 1 mSv y^{-1} (K4, K6, K8, K9, K18, K19, K20 and K24) should be assessed for measured indoor gamma dose and indoor radon, and the use of locally sourced mineralized material as building stone or aggregate should be discouraged.

Miners working at the highest-dose-rate locations should be supported with limits on time spent at working faces and waste heaps, basic protective practices, and personal dosimetry where feasible. Public health and environmental authorities should run awareness programmes that explain the findings, including the localized nature of the elevated readings, to residents and miners and describe practical precautionary measures. The relevant regulatory and environmental agencies, including the Nigerian Nuclear Regulatory Authority, should establish periodic (for example annual) radiological monitoring of the area so that temporal changes can be tracked and risk assessments updated. If spectrometric follow-up confirms enhanced exposure at the hotspots, health surveillance of long-term residents and miners there should be considered.

CONCLUSION

This study provides a baseline of in situ gamma radiation dose rates at thirty locations in the mining areas of Kauru LGA, Kaduna State. Dose rates ranged from 20 to 400 nGy h^{-1} with a mean of 139.2 nGy h^{-1}, about 2.4 times the world average, although ten locations fell below the world average. The mean modelled indoor and outdoor AED were 0.683 and 0.171 mSv y^{-1}, respectively, with eight locations exceeding 1 mSv y^{-1} indoors, and the ELCR exceeded the 0.29×10^{-3} reference value at every location indoors (mean about 8.2 times the reference) and at 18 of 30 locations outdoors (mean about 2.1 times). Strong spatial variability and four clear hotspots (K9, K18, K19 and K20) were identified. These results show that the surveyed mining areas are moderately elevated on average but strongly heterogeneous. They are screening-level estimates from 30 sites sampled in one season and not a complete radiological assessment of the LGA; they do not establish mining as the cause of the elevated readings or a demonstrated increase in cancer cases. They provide the quantitative basis for spectrometric and indoor/radon follow-up, targeted radiation-protection measures at the hotspots, regulatory monitoring and community risk communication in the study area.

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