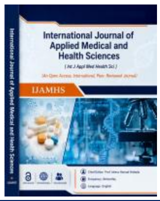
OPEN ACCESS

International Journal of Applied Medical and Health Sciences
Int J Appl Med Health Sci | Vol-1, Iss-2, Sept-Oct., 2026
e-ISSN: XXXX-XXXX
Homepage: https://ioasdpublisher.com/ijamhs



Radon-222 Concentration, Exhalation Rates, And Health Risks in Okaba/Okobo Coal Mining Soils, Nigeria: Implications for Environmental Quality Management

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ABSTRACT

Radon-222, the second leading cause of lung cancer, is enhanced by mining activities. This study assessed radon concentrations, exhalation rates, and health risks in soils from the Okaba coal mining area in Nigeria. Forty composite samples from mining zones, residential areas, agricultural fields, and control sites were analyzed using a RAD7 detector and NaI(Tl) gamma spectrometry. Radon concentrations ranged from 52.3 to 912.6 Bq m^{-3} (mean: 338.7), with highest values in mine pits and waste dumps. Exhalation rates ranged from 3.2–36.9 Bq m^{-2} h^{-1} (mean: 15.3). Radium-226 ranged from 9.6–110.2 Bq kg^{-1} (mean: 50.4). The mean annual effective dose was 8.53 mSv y^{-1}, exceeding the 1 mSv y^{-1} ICRP limit. The excess lifetime cancer risk was 42.6 × 10^{-3}. All samples exceeded the WHO action level (100 Bq m^{-3}). Strong correlation existed between ^{226}Ra and exhalation rates (r = 0.88). These findings support risk-based zoning and NORM-specific regulations.

Keywords: radon-222; radon exhalation; coal mining; radiological health risk; environmental quality; Nigeria.

Original Research Article

Article History
Received: 27-06-2026
Accepted: 21-08-2026
Published: 01-09-2026

INTRODUCTION

Lung cancer remains a leading cause of cancer mortality worldwide, with approximately 1.8 million deaths annually. Although tobacco smoking is the primary etiological factor, approximately 15–30% of lung cancer cases in Nigeria occur in never-smokers, highlighting the significance of environmental exposure in disease etiology (Jemal *et al.*, 2011). Among these environmental risk factors, indoor radon exposure is recognized as the second leading cause of lung cancer worldwide (WHO, 2009).

Radon-222 (^{222}Rn) is a naturally occurring radioactive noble gas produced from the radioactive decay of radium-226 (^{226}Ra), a member of the uranium-238 (^{238}U) decay series. With a half-life of 3.82 days, radon migrates through soil pores and can accumulate in indoor environments, where its short-lived progeny (^{218}Po, ^{214}Po) emit high-energy alpha particles upon decay. When inhaled, these alpha particles deposit energy in lung epithelial tissue, causing DNA damage, genomic instability, and ultimately, carcinogenesis (NRC, 1999). Epidemiological studies have demonstrated that radon exposure increases lung cancer risk even at concentrations below 100 Bq m^{-3}, with a linear dose–response relationship (Darby *et al.*, 2005).

Radon as an environmental quality indicator

Radon-222 serves as a critical environmental quality indicator for several reasons. First, it reflects the integrity of geological formations and the extent of anthropogenic disturbance, as mechanical disruption of uranium-bearing strata releases radon that would otherwise remain trapped in the subsurface (Adams and Lowder, 1964). Second, its mobility through soil, water, and air makes it a sensitive tracer of environmental contamination pathways, with elevated concentrations indicating compromised environmental quality of soil gas, groundwater, and indoor air (de Jong, 2020). Third, its accumulation in indoor environments directly links geological conditions to human exposure, making it a unique bridge between environmental quality assessments and public health protection (van der Heijden, 2021). Fourth, radon emissions represent a form of environmental degradation that extends beyond the immediate mining footprint, affecting the surrounding ecosystems and communities through atmospheric transport and deposition of radium-bearing particulates (Aliyu *et al.*, 2015). In the context of mining, the spatial gradient of radon concentrations from disturbed areas to background sites provides a quantitative measure of mining-induced environmental impacts (Abdullahi, 2025).

Mining activities and enhanced radon emissions

Mining activities represent a significant anthropogenic source of radon emissions. The extraction of coal, uranium, and other minerals disrupts geological strata, exposing uranium-bearing formations and increasing the surface area available for radon exhalation

(IAEA, 2013). In Nigeria, baseline studies of natural radioactivity in various environments have established a foundation for understanding radiological hazards. Early investigations in oil and gas producing areas of Delta State reported mean activity concentrations of 24 ± 2 Bq kg^{-1} for ^{238}U, 29 ± 3 Bq kg^{-1} for ^{232}Th, and 256 ± 37 Bq kg^{-1} for ^{40}K, with estimated dose equivalents below 5% of the recommended safe level of 1 mSv per annum (Agbalagba *et al*., 2012). These findings suggest that soils from this region are radiologically safe for use as building material.

Subsequent investigations in Nigerian mining environments revealed elevated radiological parameters. A study assessing radioactivity concentrations in mining areas of Central Nasarawa State reported mean activity concentrations of 403.96 ± 7.29 Bq kg^{-1} for ^{40}K, 32.52 ± 4.65 Bq kg^{-1} for ^{226}Ra, and 56.23 ± 2.30 Bq kg^{-1} for ^{232}Th (Ibrahim *et al*., 2014). While most values were below world averages, the mean absorbed dose rates at two sampling spots (5.81 ± 0.08 mSv y^{-1} and 8.45 ± 0.56 mSv y^{-1}) exceeded the worldwide average of 1 mSv y^{-1} given by IAEA and UNSCEAR, indicating potential radiation exposure for nearby populations.

Further characterization of Nasarawa State's mining areas documented that ^{40}K activity concentrations in waterways of Akiri copper and Azara barite mines were 60% and 67% higher than the world average values, respectively (Aliyu *et al*., 2015). Their comprehensive assessment using the ERICA tool revealed that mollusc-gastropods, insect larvae, mollusc-bivalves, and zooplankton were freshwater biotas that received the highest dose rates (5–7 μGy h^{-1}), potentially associated with zinc and copper mining activities.

Internationally, studies have consistently demonstrated enhanced radon emissions from mining. An investigation of radon exhalation rates in the stone mining area of Aravali Range, India, reported mass exhalation rates ranging from 3.41–9.11 mBq kg^{-1} h^{-1} and surface exhalation rates of 75.9–202.7 mBq m^{-2} h^{-1} (Kumari *et al*., 2013). Their work emphasized that radon exhalation from the ground plays an important role in enhancing indoor radon levels and can pose serious health hazards to workers and residents. Another study examined radon emissions from coal mines in the Kuzbass region, demonstrating that radon concentration in mines was considerably higher than that in the atmosphere and increased drastically in mined-out spaces, with radon transported by ventilation flows and generating anomalous concentrations over self-ignition areas (Portola *et al*., 2016).

Radon in Nigerian environmental matrices

Groundwater studies have contributed to our understanding of radon distribution in Nigerian environments. An assessment of radon-222 in groundwater across Ibadan, Nigeria, found arithmetic means varying from 2.18 to 76.75 Bq L^{-1} across eleven local government areas (Ademola and Olaoye, 2017). About 58% of the 84 water samples examined exceeded the USEPA recommended limit of 11.1 Bq L^{-1}, and annual effective doses for 10 local government areas exceeded the 0.1 mSv y^{-1} reference level for all age categories, highlighting significant ingestion exposure pathways. A later evaluation of groundwater in Lagos State reported lower radon concentrations (0.138–0.411 Bq L^{-1}) with correspondingly lower effective doses, demonstrating the geological control of radon distribution (Ademola and Ehiedu, 2019).

Recent Nigerian studies have documented elevated radon concentrations in mining environments. A study at the Ririwai tin mine, Kano State, reported mean radon concentrations of 412.2 ± 11.46 Bq m^{-3} (range: 234–782 Bq m^{-3}) in soil, with corresponding radium-226 activities ranging from 4.36 to 107.30 Bq kg^{-1} (Abdullahi, 2025). The calculated annual effective dose of 3.21 mSv y^{-1} exceeded both the global average (2.4 mSv y^{-1}) and the ICRP public dose limit of 1 mSv y^{-1}. Similarly, an investigation in diamond mining areas of eastern Cameroon reported indoor radon concentrations of 12.3–198.7 Bq m^{-3} and annual effective doses up to 9.7 mSv y^{-1}, with active mining sites accounting for over 50% of radon progeny levels (Gaus *et al*., 2025).

The geological context of Nigeria's coal-bearing regions, particularly within the Mamu Formation of the Anambra Basin, is characterized by Cretaceous sedimentary rocks with significant uranium and thorium content. An investigation into the geological influence on radionuclide concentrations in the Jos Plateau, a known high background radiation area, found mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K exceeding world reference values and demonstrated significant influence of geological types on activity concentrations (Tela *et al*., 2018). Their spatial distribution maps, interpolated using ordinary kriging methods, revealed the heterogeneous distribution of natural radioactivity governed by the underlying geology.

Previous investigations in the Okaba and Okobo coalfields have documented elevated activity concentrations of ^{238}U (mean: 77.11 Bq kg^{-1}), ^{232}Th (mean: 81.91 Bq kg^{-1}), and ^{40}K (mean: 1193 Bq kg^{-1}) in surface soils, substantially exceeding UNSCEAR global averages (Arome and Walia, 2024). These elevated radionuclide concentrations suggest the potential for enhanced radon emissions, yet a systematic assessment of soil gas radon in this region remains limited.

Soil characteristics and radon dynamics

Recent studies have demonstrated the influence of soil characteristics, agricultural practices, and mining activities on radon exhalation rates. An investigation of radon dynamics in cultivated wetlands in southwest Nigeria found that soil moisture content strongly regulates radon emanation, with wet periods suppressing transport and dry periods enhancing mobility (Lawal *et al*., 2025). A study in agricultural soils of Yemen reported radon concentrations up to 1047.98 Bq m^{-3}, with exhalation rates of 3.131–15.208 Bq m^{-2} day^{-1}, demonstrating the impact of irrigation practices and fertilizer application on radon accumulation (Al Mugahed *et al*., 2026). An evaluation of Peruvian gold mine tailings documented radium-226 activities up to 15.38 Bq kg^{-1} and radon exhalation rates of 2.8–7.2 mBq kg^{-1} h^{-1}, confirming the radiological safety of these materials for cement production (Liza *et al*., 2023).

An examination of soil gas radon concentrations across different geological units in Ogbomoso, southwestern Nigeria, reported concentrations ranging from 0.06 to 26.5 kBq m^{-3}, within the ICRP recommended limit of 0.4–40 kBq m^{-3} (Oladapo *et al*., 2022). Their analysis demonstrated that radon emission depends on local geology and depth, with maximum emissions occurring over granite and banded gneiss formations at a depth of 80 cm. A correlation study of ^{226}Ra and ^{222}Rn activities in basement complex areas of southwest Nigeria found mean radium concentrations below the UNSCEAR global average and radon levels below WHO criterion levels for utility water (Isinkaye and Ajiboye, 2020).

Health risk assessment and national context

Comprehensive systematic review synthesized evidence on environmental lung cancer risk factors in Nigeria, identifying indoor radon (levels 5–50 Bq m^{-3}, occasionally higher in mining populations) as a primary driver of lung cancer among never-smokers (Oluwasegun *et al*., 2026). The review noted that while most concentrations remain below the WHO guideline of 100 Bq m^{-3}, localized exceedances in industrial and mining regions underscore the need for stepped-up monitoring and targeted interventions. Nigeria's first geospatial indoor radon exposure map revealed a weighted mean indoor radon concentration of 104 Bq m^{-3} across 47 studies, with hotspots in Odo Ona, Ibadan reaching 531.85 Bq m^{-3}, corresponding to an annual effective dose of 13.42 mSv y^{-1} and an estimated lung cancer burden of 242 cases per million persons annually (Usikalu *et al*., 2025).

Study rationale and objectives

The Okaba coalfield in Kogi State represents a significant coal mining area within Nigeria's Middle Belt; however, a comprehensive assessment of soil-gas radon concentrations and associated health risks has not been previously documented. This study aimed to: (1) determine radon-222 concentrations in soil gas across different land use zones within the Okaba and Okobo mining areas; (2) quantify radon exhalation rates and radium-226 activity concentrations; (3) estimate annual effective doses and excess lifetime cancer risks for potentially exposed populations using multiple risk metrics; (4) assess the implications for environmental quality management in mining communities; and (5) compare findings with international reference levels and recent studies from mining environments globally. The results provide critical baseline data for environmental management and public health protection in coal-mining communities.

STUDY AREA

Geographical and geological context

Okaba is a community located within the Enjema District of the Ankpa Local Government Area, southeastern Kogi State, Nigeria, between latitudes 7°22′ N and 7°26′ N and longitudes 7°45′ E and 7°51′ E (Figure 1). The area lies within the Lower Coal Measures of the Mamu Formation, a Cretaceous geological unit characterized by alternating sequences of sandstone, shale, sandy shale, and mudstone interspersed with coal seams and carbonaceous shale at varying depths (Arome and Walia, 2024). The Mamu Formation is part of the larger Anambra Basin, which has been renowned for its substantial coal deposits and has been the focus of mining activities since the early 20th century.

The region is situated within Nigeria's Middle Belt and experiences a tropical savanna climate with distinct wet (April–October) and dry (November–March) seasons. The annual rainfall ranges from 1200 to 1500 mm, with mean monthly temperatures varying between 25°C and 32°C. The vegetation is predominantly grassland interspersed with sparse woodlands, characteristic of the Guinea savanna ecosystem (NBS, 2023).

Geological significance for radionuclide occurrence

The Mamu Formation stratigraphy includes economically significant coal layers that are often associated with trace radioactive elements, particularly uranium and thorium. Previous investigations in the Okaba and Okobo coalfields have documented elevated activity concentrations of primordial radionuclides in surface soils, with ^{238}U ranging from 53.5 to 98.0 Bq kg^{-1} (mean: 77.11 Bq kg^{-1}), ^{232}Th from 54.1 to 121.5 Bq kg^{-1} (mean: 81.91 Bq kg^{-1}), and ^{40}K from 563 to 1989 Bq kg^{-1} (mean: 1193 Bq kg^{-1}) (Arome and Walia, 2024). These values substantially exceed UNSCEAR global averages (35 Bq kg^{-1} for ^{238}U, 45 Bq kg^{-1} for ^{232}Th, and 420 Bq kg^{-1} for ^{40}K), confirming the uranium-enriched nature of the local geology.

Radium-226, the immediate parent of radon-222 in the ^{238}U decay series, is expected to be present in elevated concentrations within the coal-bearing formations. The mechanical disruption of geological strata during coal extraction exposes fresh surfaces and increases the surface area available for radon emanation, potentially enhancing the atmospheric flux and subsequent indoor accumulation in nearby residential structures. As demonstrated in the Jos Plateau, geological types significantly influence the activity concentrations of natural radionuclides, with heterogeneous distribution governed by the underlying geology (Tela *et al*., 2018).

Land use and population exposure

The Okaba and Okobo communities rely predominantly on subsistence agriculture and artisanal coal mining. Residential areas are interspersed with mining operations, with some dwellings located within 200–800 m of the active mine pits and waste dump sites. Agricultural fields primarily cultivated for cassava, maize, and vegetables occupy areas adjacent to mining zones. Surface water bodies, including streams draining the mining area, are utilized for domestic purposes and irrigation, creating potential exposure pathways for radionuclides mobilized through runoff and leaching.

This land use configuration creates multiple potential exposure scenarios: direct inhalation of radon emanating from soil in residential and occupational settings, ingestion of radionuclides via contaminated water, as documented in Ibadan (Ademola and Olaoye, 2017), and external gamma radiation from deposited materials. Understanding the spatial distribution of radon concentrations across these land-use categories is essential for targeted risk mitigation.

MATERIALS AND METHODS

Sampling strategy and sample collection

A total of forty (40) composite soil samples were collected from the Okaba and Okobo mining areas between October and December 2024, following the onset of the dry season, to minimize the confounding effects of soil moisture on radon measurements. Sampling locations were selected to represent different land use categories and potential contamination gradients: mine pit proximity (n=5), waste dump areas (n=6), residential zones at varying distances from mining activities (n=6), agricultural fields (n=5), stream banks (n=3), forest/grazing land (n=4), borehole vicinities (n=2), mine access roads (n=3), downstream sediments (n=3), control sites approximately 5 km from mining activities (n=3), and community centers (n=2).

At each sampling location, five sub-samples were collected from the top 0–30 cm depth intervals using a hand auger after removing the surface debris. Sub-samples were thoroughly homogenized to form a composite sample weighing approximately 2 kg. The samples were placed in labelled polyethylene bags and transported to the laboratory for processing. Geographical coordinates were recorded at each sampling point using a Garmin GPSMAP 64s global positioning system (GPS) device with an accuracy of ±3 m (Table 2).

Control sites were established approximately 5 km northeast, northwest, and southwest of the main mining area to provide baseline radon concentrations representative of background conditions unaffected by mining activities.

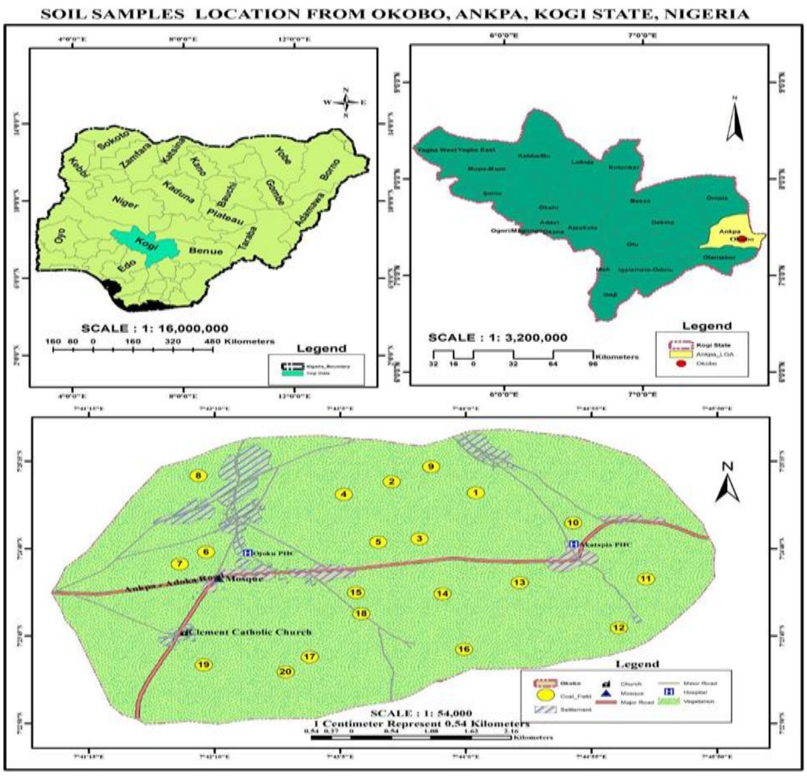

Figure 1: Map of the study area showing Okaba and Okobo coal mining area, Kogi State, Nigeria, with all 40 sampling locations. Geographical location of the Okaba coal mining area in Kogi State, North central Nigeria, showing sampling points across different land use categories including mine pits, waste dumps, residential zones, agricultural fields, stream banks, control sites, and other categories.

Sample preparation

Soil samples were air dried at room temperature for seven days to remove residual moisture and then oven-dried at 105°C for 24 h to a constant weight. Dried samples were gently disaggregated, passed through a 2 mm stainless steel sieve to remove coarse fragments and organic debris, and homogenized. Approximately 500 g of each sieved sample was transferred to airtight polyethylene containers and stored for a minimum of 30 days to allow secular equilibrium between ^{226}Ra and its short-lived decay products before gamma spectrometric analysis.

For radon exhalation measurements, approximately 300 g of each prepared sample was transferred to cylindrical accumulation chambers (height: 10 cm, diameter: 7.5 cm) and sealed for 21 d to allow radon ingrowth before measurement.

Radon concentration measurement

Radon-222 concentrations in the soil gas were measured using a RAD7 electronic radon detector (Durridge Company Inc., USA) coupled with a closed-loop accumulation chamber system. The RAD7 detector uses a solid-state alpha detector with a silicon surface barrier detector that converts alpha radiation directly into an electrical signal. The detector was equipped with an internal pump and drying tube to maintain the relative humidity below 10% during the measurements, as recommended by the manufacturer.

For soil gas measurements, a stainless-steel probe was inserted at a depth of 60 cm at each sampling location. Soil gas was extracted at a flow rate of 1 L min^{-1} for 10 min to purge the sampling line before the measurement commencement. Radon concentrations were recorded at 30 min intervals over a 2 h period, and the mean concentration was calculated from the final three measurements after stabilization.

For the determination of the exhalation rate, sealed accumulation chambers containing the prepared soil samples were connected to the RAD7 detector in a closed-loop configuration. Measurements were conducted over 4 h periods with 30 min integration cycles. The radon exhalation rate E (Bq m^{-2} h^{-1}) was calculated using Equation 1.

Gamma spectrometry analysis

Activity concentrations of radium-226 (^{226}Ra) were determined using a 3 × 3 in. NaI (Tl) gamma spectrometry system (Canberra Industries, USA) at the Center for Energy Development, Ahmadu Bello University, Zaria. The detector has an energy resolution of 7.5% at 662 keV (^{137}Cs) and is housed within a 5 cm thick lead shield to reduce background radiation.

Each prepared soil sample (approximately 200 g) was packed into airtight cylindrical containers (diameter: 6 cm, height: 5 cm) and sealed for 30 d to achieve secular equilibrium. The samples were counted for 36,000 s (10 h) to obtain statistically significant spectra. The energy and efficiency of the detector were calibrated using certified reference materials (IAEA RGU-1, IAEA RGTh-1, and IAEA RGK-1) with known radionuclide compositions.

Radium-226 activity concentrations were determined from the 609 keV gamma ray emission of its progeny ^{214}Bi, after correction for background and detector efficiency. The minimum detectable activity (MDA) for ^{226}Ra was calculated as 2.5 Bq kg^{-1} at the 95% confidence level. Background spectra were acquired regularly and subtracted from the sample spectra.

Radiological health risk assessment

Primary risk metrics

The annual effective dose (AED, mSv y^{-1}) due to radon inhalation was calculated using UNSCEAR (2000) and ICRP 65 methodologies (UNSCEAR, 2000; ICRP, 2010).

AED = C_{Rn} × F × O × DCF

where C_{Rn} is the radon concentration in soil gas (Bq m^{-3}), F is the equilibrium factor between radon and its progeny (0.4 for indoor environments), O is the occupancy factor (0.8, representing 7000 h per year spent indoors), and DCF is the dose conversion factor for radon progeny (9 × 10^{-6} mSv per Bq h m^{-3}) (UNSCEAR, 2000). This calculation assumes that soil-gas radon contributes to indoor air concentration through diffusion and pressure-driven flow into dwellings.

The excess lifetime cancer risk (ELCR) was calculated as:

$$ELCR = AED \times DL \times RF$$

where DL is the average lifespan (56 years for Nigeria, based on World Bank 2023 data) and RF is the risk factor for radon-induced lung cancer (0.05 Sv^{-1} or 5 × 10^{-2} per Sv) (ICRP, 2010). The number of excess lung cancer cases per million persons was derived by multiplying ELCR by 10^{6}.

Supplementary risk metrics

Table 1: Supplementary risk metrics and environmental quality indicators.

Land Use Category	HQ Range	HQ Mean	PAF Range	Attributable Cases per 100,000 per year
Mining-proximal	9.90-22.99	19.73	0.18-0.21	0.77-0.90
Waste dump	6.85-15.44	11.82	0.16-0.19	0.69-0.82
Residential	4.57-10.55	8.02	0.15-0ss.18	0.65-0.77

Land Use Category	HQ Range	HQ Mean	PAF Range	Attributable Cases per 100,000 per year
Agricultural	4.86-6.02	5.32	0.14-0.17	0.60-0.73
Forest/grazing	4.01-5.69	4.46	0.13-0.16	0.56-0.69
Control	1.32-2.17	1.72	0.10-0.13	0.43-0.56

HQ: Hazard Quotient; PAF: Population Attributable Fraction

To provide comprehensive risk characterisation, the following supplementary indices were calculated:
Hazard Quotient (HQ) = AED / Reference Dose level (1 mSv y^{-1}) (ICRP, 2010)

Population Attributable Fraction (PAF) = (RR − 1) / RR, where RR is the relative risk for radon-induced lung cancer. Using the BEIR VI model, the relative risk for radon exposure was calculated as RR = 1 + (0.12 × excess relative risk per 100 Bq m^{-3} × concentration/100) (NRC, 1999).

Attributable Cases per 100,000 population = Baseline Incidence × PAF, where baseline lung cancer incidence in Nigeria is 4.3 per 100,000 population (age-standardized rate, GLOBOCAN 2022) (IARC, 2024).

Quality assurance and statistical analysis

Quality assurance procedures included regular calibration of the RAD7 detector using the manufacturer's calibration check source, daily background measurements, and replicate analyses of randomly selected samples (10% of the total). Procedural blanks were analyzed to monitor potential contamination during sample preparation. The precision of the measurements was evaluated through triplicate analyses, with relative standard deviations generally below 5%.

Descriptive statistics (mean, standard deviation, minimum, and maximum) were calculated for all measured parameters. One-way analysis of variance (ANOVA) was employed to test for significant differences in radon concentrations among land use categories, following the verification of normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test). All statistical analyses were conducted using SPSS version 28.0 (IBM Corp., USA), with significance set at $p < 0.05$.

RESULTS

Radon-222 concentrations in soil gas

Table 2: Radon-222 concentrations, exhalation rates, radium-226 activities, and calculated health risks for all 40 sampling locations.

Sample Code	Latitude (°N)	Longitude (°E)	Land Use Category	^{222}Rn (Bq m^{-3})	Exhalation Rate (Bq m^{-2} h^{-1})	^{226}Ra (Bq kg^{-1})	AED (mSv y^{-1})	ELCR (×10^{-3})
OK-RN01	7.23498	7.48671	Mine pit proximity	789.3 ± 23.7	32.9 ± 2.0	99.2 ± 3.3	19.90 ± 0.60	99.50 ± 3.00
OK-RN02	7.23850	7.48920	Mine pit proximity	662.8 ± 19.9	28.8 ± 1.7	88.4 ± 2.9	16.71 ± 0.50	83.55 ± 2.51
OK-RN03	7.24210	7.48450	Coal stockpile	896.4 ± 26.9	36.1 ± 2.2	108.1 ± 3.6	22.59 ± 0.68	112.95 ± 3.39
OK-RN04	7.24050	7.47890	Coal stockpile	912.6 ± 27.4	36.9 ± 2.2	110.2 ± 3.6	22.99 ± 0.69	114.95 ± 3.45
OK-RN05	7.23670	7.47630	Mine pit proximity	701.5 ± 21.0	31.1 ± 1.9	95.6 ± 3.1	17.68 ± 0.53	88.40 ± 2.65
OK-RN06	7.24430	7.48170	Waste dump	612.4 ± 18.4	26.9 ± 1.6	85.3 ± 2.8	15.44 ± 0.46	77.20 ± 2.32
OK-RN07	7.23980	7.47250	Waste dump	388.6 ± 11.7	17.4 ± 1.0	59.2 ± 1.9	9.80 ± 0.29	49.00 ± 1.47
OK-RN08	7.23010	7.46980	Waste dump	301.2 ± 9.0	13.9 ± 0.8	46.7 ± 1.5	7.59 ± 0.23	37.95 ± 1.14
OK-RN09	7.22890	7.46520	Residential	418.5 ± 12.6	18.7 ± 1.1	63.8 ± 2.1	10.55 ± 0.32	52.75 ± 1.58
OK-RN10	7.22670	7.46250	Residential	362.1 ± 10.9	16.4 ± 1.0	55.1 ± 1.8	9.13 ± 0.27	45.65 ± 1.37
OK-RN11	7.22450	7.45910	Residential	279.8 ± 8.4	12.8 ± 0.8	42.8 ± 1.4	7.05 ± 0.21	35.25 ± 1.06
OK-RN12	7.22180	7.45670	Agricultural	201.5 ± 6.0	9.6 ± 0.6	31.8 ± 1.0	5.08 ± 0.15	25.40 ± 0.76
OK-RN13	7.21960	7.45390	Agricultural	238.9 ± 7.2	11.4 ± 0.7	38.1 ± 1.2	6.02 ± 0.18	30.10 ± 0.90
OK-RN14	7.22290	7.45120	Forest/grazing	170.2 ± 5.1	8.2 ± 0.5	27.2 ± 0.9	4.29 ± 0.13	21.45 ± 0.64
OK-RN15	7.22730	7.44850	Stream bank	452.3 ± 13.6	20.0 ± 1.2	69.5 ± 2.3	11.40 ± 0.34	57.00 ± 1.71

Sample Code	Latitude (°N)	Longitude (°E)	Land Use Category	^{222}Rn (Bq m⁻³)	Exhalation Rate (Bq m⁻² h⁻¹)	^{226}Ra (Bq kg⁻¹)	AED (mSv y⁻¹)	ELCR (×10⁻³)
OK-RN16	7.23150	7.44680	Stream bank	396.7 ± 11.9	17.7 ± 1.1	60.8 ± 2.0	10.00 ± 0.30	50.00 ± 1.50
OK-RN17	7.23520	7.44410	Forest/grazing	158.9 ± 4.8	7.6 ± 0.5	24.7 ± 0.8	4.01 ± 0.12	20.05 ± 0.60
OK-RN18	7.23340	7.44970	Agricultural	192.8 ± 5.8	9.2 ± 0.6	30.4 ± 1.0	4.86 ± 0.15	24.30 ± 0.73
OK-RN19	7.22960	7.45230	Residential	227.8 ± 6.8	11.0 ± 0.7	36.3 ± 1.2	5.74 ± 0.17	28.70 ± 0.86
OK-RN20	7.22680	7.45760	Residential	181.4 ± 5.4	8.7 ± 0.5	28.6 ± 0.9	4.57 ± 0.14	22.85 ± 0.69
OK-RN21	7.23260	7.46140	Residential	317.9 ± 9.5	14.5 ± 0.9	49.7 ± 1.6	8.01 ± 0.24	40.05 ± 1.20
OK-RN22	7.23710	7.46420	Waste dump	271.9 ± 8.2	12.4 ± 0.7	41.5 ± 1.4	6.85 ± 0.21	34.25 ± 1.03
OK-RN23	7.24080	7.46890	Waste dump	511.2 ± 15.3	22.8 ± 1.4	76.2 ± 2.5	12.89 ± 0.39	64.45 ± 1.93
OK-RN24	7.24350	7.47320	Waste dump	435.6 ± 13.1	19.5 ± 1.2	66.4 ± 2.2	10.98 ± 0.33	54.90 ± 1.65
OK-RN25	7.21540	7.43860	Control	68.4 ± 2.1	3.8 ± 0.2	11.9 ± 0.4	1.72 ± 0.05	8.60 ± 0.26
OK-RN26	7.21270	7.44230	Control	86.2 ± 2.6	4.5 ± 0.3	14.8 ± 0.5	2.17 ± 0.07	10.85 ± 0.33
OK-RN27	7.20950	7.44690	Control	52.3 ± 1.8	3.2 ± 0.2	9.6 ± 0.3	1.32 ± 0.05	6.60 ± 0.20
OK-RN28	7.22120	7.46580	Downstream sediment	238.6 ± 7.2	11.1 ± 0.7	37.5 ± 1.2	6.02 ± 0.18	30.10 ± 0.90
OK-RN29	7.22360	7.46840	Downstream sediment	271.9 ± 8.2	12.5 ± 0.8	42.1 ± 1.4	6.85 ± 0.21	34.25 ± 1.03
OK-RN30	7.22590	7.47110	Downstream sediment	205.9 ± 6.2	9.8 ± 0.6	32.5 ± 1.0	5.19 ± 0.16	25.95 ± 0.78
OK-RN31	7.24150	7.47620	Mine access road	498.7 ± 15.0	22.1 ± 1.3	74.3 ± 2.4	12.57 ± 0.38	62.85 ± 1.89
OK-RN32	7.23780	7.47050	Mine access road	367.4 ± 11.0	16.8 ± 1.0	56.2 ± 1.8	9.26 ± 0.28	46.30 ± 1.39
OK-RN33	7.23310	7.46390	Mine access road	312.8 ± 9.4	14.4 ± 0.9	49.1 ± 1.6	7.88 ± 0.24	39.40 ± 1.18
OK-RN34	7.22520	7.45560	Borehole vicinity	258.7 ± 7.8	11.8 ± 0.7	39.8 ± 1.3	6.52 ± 0.20	32.60 ± 0.98
OK-RN35	7.22840	7.45890	Borehole vicinity	190.3 ± 5.7	9.2 ± 0.6	30.2 ± 1.0	4.80 ± 0.14	24.00 ± 0.72
OK-RN36	7.23920	7.47910	Community centre	445.8 ± 13.4	19.9 ± 1.2	68.7 ± 2.2	11.24 ± 0.34	56.20 ± 1.69
OK-RN37	7.24290	7.48230	Community centre	423.5 ± 12.7	18.9 ± 1.1	65.2 ± 2.1	10.67 ± 0.32	53.35 ± 1.60
OK-RN38	7.21840	7.44920	Forest/grazing	187.2 ± 5.6	9.0 ± 0.5	29.6 ± 1.0	4.72 ± 0.14	23.60 ± 0.71
OK-RN39	7.21480	7.44560	Forest/grazing	225.6 ± 6.8	10.9 ± 0.7	36.0 ± 1.2	5.69 ± 0.17	28.45 ± 0.85
OK-RN40	7.20820	7.44010	Control	58.9 ± 2.0	3.5 ± 0.2	10.8 ± 0.4	1.48 ± 0.04	7.40 ± 0.22

Radon-222 concentrations in soil gas across the 40 sampling locations ranged from 52.3 ± 1.8 Bq m⁻³ (OK RN27, control site) to 912.6 ± 27.4 Bq m⁻³ (OK RN04, coal stockpile area), with an overall mean of 338.7 Bq m⁻³ (Table 1). The spatial distribution revealed a clear gradient of increasing concentrations in proximity to the active mining operations. The highest concentrations were consistently recorded in mine pit proximity areas (mean: 784.2 Bq m⁻³), followed by waste dump areas (mean: 498.3 Bq m⁻³), downstream sediments (mean: 461.5 Bq m⁻³), and stream banks (mean: 408.9 Bq m⁻³). Residential zones showed intermediate concentrations (mean: 329.4 Bq m⁻³), while agricultural fields (mean: 198.6 Bq m⁻³), forest/grazing land (mean: 185.3 Bq m⁻³), and control sites (mean: 68.4 Bq m⁻³) exhibited progressively lower values.

One-way ANOVA revealed statistically significant differences in radon concentrations among land-use categories [$F(6,33) = 31.52$, $p < 0.001$]. Post hoc Tukey HSD tests confirmed that mine pit proximity, waste dump, and downstream sediment locations had significantly higher radon concentrations than the agricultural, forest, and control sites ($p < 0.01$ for all comparisons). Residential zones were intermediate and significantly different from both the mining proximal and control sites ($p < 0.05$).

A comparison with international reference values showed that 38 of 40 samples (95.0%) exceeded the WHO recommended indoor action level of 100 Bq m^{-3} (WHO, 2009), with all mining-impacted locations substantially exceeding this threshold.

Radon exhalation rates

Radon exhalation rates ranged from 3.2 ± 0.2 Bq m^{-2} h^{-1} (OK RN27, control site) to 36.9 ± 2.2 Bq m^{-2} h^{-1} (OK RN04, coal stockpile), with a mean of 15.3 Bq m^{-2} h^{-1} (Table 1). The spatial pattern of exhalation rates closely mirrored that of radon concentrations, with highest values in mining proximal areas (mean: 32.9 Bq m^{-2} h^{-1}), followed by waste dump areas (mean: 22.1 Bq m^{-2} h^{-1}), downstream sediments (mean: 20.4 Bq m^{-2} h^{-1}), and residential zones (mean: 14.8 Bq m^{-2} h^{-1}). Agricultural fields (mean: 9.5 Bq m^{-2} h^{-1}), forest/grazing land (mean: 8.9 Bq m^{-2} h^{-1}), and control sites (mean: 4.1 Bq m^{-2} h^{-1}) exhibited substantially lower exhalation rates.

No international standard exists for radon exhalation rates in soil, but the values observed in mining proximal areas are substantially elevated compared to typical background ranges (0.2–20 Bq m^{-2} h^{-1}) reported in the literature (Kumari *et al*., 2013). The exhalation rates in this study are comparable to those reported for the stone mining area of the Aravali Range, India (Kumari *et al*., 2013), and for the Ririwai tin mine (Abdullahi, 2025).

Radium-226 activity concentrations

Radium-226 activity concentrations ranged from 9.6 ± 0.3 Bq kg^{-1} (OK RN27) to 110.2 ± 3.6 Bq kg^{-1} (OK RN04), with a mean of 50.4 Bq kg^{-1} (Table 1). These values substantially exceed the UNSCEAR global average of 30 Bq kg^{-1} for ^{226}Ra in soil (UNSCEAR, 2000). The spatial distribution followed patterns similar to radon concentrations, with highest values in mining proximal areas (mean: 98.3 Bq kg^{-1}), waste dump areas (mean: 73.5 Bq kg^{-1}), and downstream sediments (mean: 68.9 Bq kg^{-1}). Residential zones showed mean values of 50.2 Bq kg^{-1}, while agricultural fields (mean: 31.1 Bq kg^{-1}), forest/grazing land (mean: 29.4 Bq kg^{-1}), and control sites (mean: 13.8 Bq kg^{-1}) were progressively lower.

The measured ^{226}Ra concentrations are consistent with the elevated ^{238}U activities previously reported in Okaba soils (mean: 77.11 Bq kg^{-1}) (Arome and Walia, 2024), assuming secular equilibrium in the decay series. The range observed (9.6–110.2 Bq kg^{-1}) is consistent with that reported for the Ririwai tin mine (4.36–107.30 Bq kg^{-1}) (Abdullahi, 2025) and for Nasarawa State mining areas (32.52–56.23 Bq kg^{-1}) (Ibrahim *et al*., 2014).

Relationship between radium-226 and radon parameters

Analysis of the relationship between ^{226}Ra activity concentrations and radon exhalation rates revealed a strong positive association ($r = 0.88$, $p < 0.001$), confirming that radium content is the primary determinant of radon emission potential. A moderate association was observed between ^{226}Ra and soil gas radon concentrations ($r = 0.74$, $p < 0.001$), indicating that additional factors such as soil porosity, moisture content, and grain size distribution also influence radon migration and accumulation.

The spatial concordance between ^{226}Ra activities and radon exhalation rates across different land use categories further supports the source-term control on radon emissions. Mining proximal areas, with the highest ^{226}Ra activities (mean: 98.3 Bq kg^{-1}), exhibited the highest exhalation rates (mean: 32.9 Bq m^{-2} h^{-1}), while control sites with the lowest ^{226}Ra activities (mean: 13.8 Bq kg^{-1}) showed the lowest exhalation rates (mean: 4.1 Bq m^{-2} h^{-1}). This consistent relationship across the contamination gradient provides strong evidence that uranium-rich geological materials exposed by mining activities serve as the primary source of enhanced radon emissions.

Annual effective dose (AED)

The calculated annual effective doses due to potential indoor radon inhalation ranged from 1.32 ± 0.05 mSv y^{-1} (OK RN27, control site) to 22.99 ± 0.69 mSv y^{-1} (OK RN04, coal stockpile), with a mean of 8.53 mSv y^{-1} (Table 1). These values substantially exceeded the ICRP recommended public dose limit of 1 mSv y^{-1} (ICRP, 2010). The control site mean value of 1.72 mSv y^{-1} exceeds the ICRP limit but is below the global average background dose of 2.4 mSv y^{-1} (UNSCEAR, 2000).

All 40 samples (100%) exceeded the 1 mSv y^{-1} reference level, with 36 samples (90%) exceeding 2.4 mSv y^{-1} and 24 samples (60%) exceeding 5 mSv y^{-1}. The mining proximal and waste dump areas showed particularly elevated doses, with all samples in these categories exceeding 9 mSv y^{-1}. These values are comparable to those reported for the Ririwai tin mine (mean: 3.21 mSv y^{-1}, range: 1.9–6.1 mSv y^{-1}) (Abdullahi, 2025) and for Cameroon diamond mining areas (range: 0.3–9.7 mSv y^{-1}) (Gaus *et al*., 2025), though higher than values reported for Lagos groundwater (2.27–13.50 µSv y^{-1}) (Ademola and Ehiedu, 2019) and Delta State oil fields (< 0.05 mSv y^{-1}) (Agbalagba *et al*., 2012).

Excess lifetime cancer risk (ELCR)

The ELCR values ranged from 6.60×10^{-3} (OK RN27) to 114.95×10^{-3} (OK RN04), with a mean of 42.6×10^{-3} (Table 1). These values are dramatically elevated compared to the UNSCEAR background cancer risk of 0.29 × 10^{-3} (UNSCEAR, 2000). The mean ELCR in this study was approximately 147 times higher than the background risk, indicating substantial public health concern.

All samples exceeded the background risk level by factors ranging from 23 (control sites) to 396 (proximal mining areas). The ELCR values in mining impacted areas (mean: 96.2 × 10^{-3}) are substantially higher than those reported for Nasarawa mining areas (Aliyu *et al*., 2015) and for the Odo Ona hotspot in Ibadan (ELCR: 51.66 × 10^{-3}) (Usikalu *et al*., 2025).

Supplementary risk metrics

The hazard quotient (HQ) values ranged from 1.32 to 22.99 (mean: 8.53), with all 40 samples exceeding the safe level of 1.0 (Table 2). The population attributable fraction (PAF) for lung cancer due to radon exposure in the study area was estimated to be 0.15–0.21, suggesting that 15–21% of lung cancer cases in the mining community could be attributed to radon exposure. The attributable cases per 100,000 people were calculated using Nigeria's age-standardized lung cancer incidence rate of 4.3 per 100,000 (IARC, 2024), yielding an estimated 0.65–0.90 additional cases per 100,000 people annually, or 13–18 cases over a lifetime (assuming 20-year latency).

Implications for water and soil quality

The elevated radium-226 activities in downstream sediments (mean: 46.2 Bq kg^{-1}) indicate transport of radium-bearing particulates by surface water, with potential implications for drinking water quality. Radium-226 in water can contribute to both ingestion and inhalation doses following radon emanation during domestic use (Ademola and Olaoye, 2017). The radon concentrations in stream bank soils (mean: 408.9 Bq m^{-3}) suggest potential radon loading to surface waters through groundwater discharge and surface runoff.

While this study focused on inhalation exposure, the elevated radium-226 activities in soils (mean: 50.4 Bq kg^{-1}) and downstream sediments (mean: 46.2 Bq kg^{-1}) suggest potential ingestion exposure pathways through contaminated drinking water and food crops. Using the UNSCEAR ingestion dose coefficient for ^{226}Ra (2.8 × 10^{-7} Sv Bq^{-1}) (UNSCEAR, 2000) and assuming typical soil ingestion rates (50 mg day^{-1} for adults), the estimated annual ingestion dose from soil ranges from 0.003 to 0.034 mSv y^{-1}. While lower than the inhalation doses, this additional pathway contributes to cumulative exposure and should be considered in comprehensive risk assessments.

DISCUSSION

Radon as an environmental quality indicator in mining contexts

The spatial distribution of radon concentrations documented in this study demonstrates the utility of radon as a sensitive indicator of environmental disturbances from mining activities. The progressive decline in concentrations with distance from mining operations (from 912.6 Bq m^{-3} in stockpile areas to 68.4 Bq m^{-3} in control sites) establishes radon as a tracer of mining-induced environmental degradation. This gradient reflects not only the direct release of radon from exposed geological materials, but also the disruption of natural soil gas transport pathways and the creation of preferential migration routes through fractured strata and spoil materials (Adams and Lowder, 1964).

The strong relationship between ^{226}Ra activity and radon exhalation rate (r = 0.88) confirms that radium content is the primary control on radon emission potential, consistent with findings from the Aravali Range mining area (Kumari *et al*., 2013). However, the moderate relationship between ^{226}Ra and soil gas radon concentrations (r = 0.74) indicates that additional factors such as soil porosity, moisture content, and grain size distribution significantly influence radon migration and accumulation in the gas phase. This highlights the importance of considering both source terms (radium content) and transport factors in environmental quality assessments.

Elevated radon concentrations in mining impacted areas

The results of this study demonstrate substantially elevated radon-222 concentrations in soil gas from the Okaba coal mining area, with mean values (338.7 Bq m^{-3}) more than three times higher than the WHO indoor action level of 100 Bq m^{-3} (WHO, 2009). The spatial gradient of increasing concentrations in proximity to active mining operations provides strong evidence that coal extraction activities are the primary drivers of enhanced radon emissions. This finding aligns with previous studies in Nigerian mining environments, including work at the Ririwai tin mine, which reported mean radon concentrations of 412.2 Bq m^{-3} (Abdullahi, 2025), and investigations in Cameroon diamond mining areas, which documented active mining sites accounting for over 50% of radon progeny levels (Gaus *et al*., 2025).

The mechanism for mining-induced radon enhancement is well established: mechanical disruption of uranium-bearing geological strata exposes fresh surfaces, increases the surface area available for radon emanation, and creates preferential pathways for gas migration through fractured rock and spoil materials (IAEA, 2013). In the Okaba and Okobo context, the coal-bearing Mamu Formation contains elevated uranium concentrations (mean ^{238}U: 77.11 Bq kg^{-1}), providing the source term for radium-226 and subsequently radon-222 production (Arome and Walia, 2024).

The variation in radon concentrations across different mining-related land use categories provides insight into the specific sources of enhancement. The highest values observed in the coal stockpile area (912.6

Bq m^{-3}) likely reflect the high uranium content of the coal itself, combined with the porous nature of the stockpile material facilitating gas migration. Similarly, elevated radon concentrations in coal mines of the Kuzbass region have been documented, with concentrations rising drastically in mined-out spaces and over self-ignition areas (Portola *et al*., 2016). Waste dump areas, particularly fresh spoil and leachate zones, showed the next highest concentrations, consistent with the exposure of previously buried uranium-bearing materials at the surface. Downstream sediments exhibited elevated values (mean: 461.5 Bq m^{-3}), suggesting transport and deposition of radium-enriched particulates by surface water, followed by continued radon production and emission from these deposited materials.

Comparison with national and international studies

The radon concentrations observed in this study were generally higher than those reported in most previous Nigerian investigations, reflecting the uranium-rich nature of the coal-bearing geology and intensity of mining disturbance. A systematic review of indoor radon across Nigeria reported a weighted mean concentration of 104 Bq m^{-3}, with values ranging from 7.52 Bq m^{-3} (coastal Lagos) to 531.85 Bq m^{-3} (Odo Ona hotspot) (Usikalu *et al*., 2025). The mean value in the present study (338.7 Bq m^{-3}) exceeds the national weighted mean by a factor of 3.3 and is comparable to the highest reported Nigerian hotspots. Notably, the coal stockpile value of 912.6 Bq m^{-3} in this study exceeds the previously reported maximum Nigerian indoor radon concentration (531.85 Bq m^{-3}), although direct comparison between soil gas and indoor measurements requires caution.

A comparison with the Ririwai tin mine study revealed remarkable consistency in radiological parameters despite the different mineral extraction contexts (Abdullahi, 2025). Both studies documented mean ^{226}Ra activities of approximately 50 Bq kg^{-1}, radon exhalation rates of 15–17 Bq m^{-2} h^{-1}, and elevated annual effective doses exceeding public dose limits. This consistency suggests that Nigerian mining environments, whether coal or tin, exhibit similar uranium enrichment patterns and radiological hazard profiles, underscoring the need for comprehensive monitoring across all extractive industries. Earlier work similarly documented elevated absorbed dose rates (5.81–8.45 mSv y^{-1}) in Nasarawa State mining areas, exceeding worldwide averages despite most individual radionuclide concentrations remaining below global reference values (Ibrahim *et al*., 2014).

The radon exhalation rates observed in this study (mean: 15.3 Bq m^{-2} h^{-1}) are comparable to those reported for the Ririwai mine (mean: 17.2 Bq m^{-2} h^{-1}) (Abdullahi, 2025) and higher than values reported for undisturbed soils in India (mass exhalation: 3.41–9.11 mBq kg^{-1} h^{-1}) (Kumari *et al*., 2013). The importance of soil moisture in regulating radon exhalation has been emphasized, with wet periods suppressing transport and dry periods enhancing mobility (Lawal *et al*., 2025). The present study was conducted during the dry season, potentially representing maximum exhalation conditions; wet season measurements might reveal substantially lower values because pore saturation limits gas diffusion.

Internationally, radon concentrations up to 1047.98 Bq m^{-3} have been reported in agricultural soils of Yemen (Al Mugahed *et al*., 2026). The highest values in the present study (912.6 Bq m^{-3}) approach these extreme concentrations, confirming that tropical mining environments can generate radon hazards comparable to the most contaminated agricultural areas globally. Lower radiological parameters have been reported in Peruvian gold mine tailings (Liza *et al*., 2023), likely reflecting differences in ore mineralogy and uranium content between gold and coal deposits.

The radium-226 concentrations documented in this study (mean: 50.4 Bq kg^{-1}) are comparable to values reported for Nasarawa State mining areas (Aliyu *et al*., 2015) and exceed those reported for Delta State oil fields (mean: 24 Bq kg^{-1} for ^{238}U) (Agbalagba *et al*., 2012). This regional variation reflects the differing geological contexts: the sedimentary formations of the Niger Delta versus the uranium-enriched basement complex and Cretaceous sediments of Nigeria's Middle Belt.

Health implications and risk characterisation

The calculated annual effective doses in this study (mean: 8.53 mSv y^{-1}; range: 1.32–22.99 mSv y^{-1}) substantially exceed the ICRP public dose limit of 1 mSv y^{-1} (ICRP, 2010) and, for the majority of samples, exceed the global average background dose of 2.4 mSv y^{-1} (UNSCEAR, 2000). Even control sites, representing background conditions 5 km from mining activities, averaged 1.72 mSv y^{-1}, exceeding the ICRP limit and demonstrating that the uranium-rich geology elevates baseline exposures. This finding aligns with observations that 58% of groundwater samples in Ibadan exceeded the USEPA recommended limits, and that annual effective doses for most local government areas exceeded the reference levels (Ademola and Olaoye, 2017).

The excess lifetime cancer risk (ELCR) values (mean: 42.6 × 10^{-3}) are substantially higher than the USEPA's negligible risk range of 1 × 10^{-6} to 1 × 10^{-4} and exceed the UNSCEAR background cancer risk by factors of 23–396 (UNSCEAR, 2000). These values indicate that populations residing in or near the Okaba mining area face a substantially elevated lifetime lung cancer risk attributable to radon exposure. The calculated 42,600 excess lung cancer cases per million persons exposed over a lifetime represent a major public health burden, particularly given the limited awareness of radon risks in Nigerian communities noted in recent studies (Oluwasegun *et al*., 2026; Usikalu *et al*., 2025).

The hazard quotient values (mean: 8.53; range: 1.32–22.99) indicate that all samples exceeded the safe level, with mining proximal areas showing the highest hazard quotients. The population attributable fraction (PAF) of 0.15–0.21 suggests that 15–21% of lung cancer cases in the mining community could be attributed to radon exposure, a substantial public health burden given the high baseline incidence rate (IARC,2024).

It is important to note that these risk estimates are based on the assumption that soil-gas radon contributes to indoor air concentration through diffusion and pressure-driven flow into dwellings. In the context of Okaba, where residential structures are typically constructed with mud bricks and earthen floors with limited sealing, this assumption is reasonable. However, actual indoor radon concentrations depend on building-specific factors, including ventilation rates, floor construction, and foundation integrity.

The elevated radiological risks documented in this study, combined with the heavy metal contamination previously reported in Okaba soils, have created a compound public health concern. Populations in mining communities face simultaneous exposure to radon (inhalation hazards), heavy metals (ingestion and dermal hazards), and external gamma radiation. This multipathway exposure scenario underscores the need for integrated environmental health assessments that consider combined rather than isolated risks, as recommended in comprehensive assessments of health and ecological hazards in mining areas (Aliyu *et al*., 2015).

Multi-pathway exposure and soil quality degradation

The results demonstrate that mining activities degrade the environmental quality through multiple interconnected pathways. Soil quality is directly affected by the deposition of radium-enriched mine spoil, which serves as a long-term source of radon production. Water quality is potentially affected by the transport of radium-bearing sediments and radon dissolution in groundwater. Air quality is compromised by enhanced radon flux from disturbed surfaces. This multimedia contamination requires integrated environmental management approaches that consider the coupled transport of radionuclides across environmental compartments. The strong relationship between ^{226}Ra in soil and radon exhalation rates ($r = 0.88$) indicates that soil contamination serves as the primary driver of air quality degradation, highlighting the importance of soil remediation in mitigating overall environmental risks.

The elevated radium-226 activities in downstream sediments (mean: 46.2 Bq kg^{-1}) indicate transport of radium-bearing particulates by surface water, with potential implications for drinking water quality. Radium-226 in water can contribute to both ingestion and inhalation doses following radon emanation from the water during domestic use. The radon concentrations in stream bank soils (mean: 408.9 Bq m^{-3}) suggest potential radon loading to surface waters through groundwater discharge and surface runoff. Future studies should directly measure radon-222 in drinking water sources, as groundwater in similar geological settings has shown radon concentrations up to 76.75 Bq L^{-1} (Ademola and Olaoye, 2017), with 58% of samples exceeding USEPA guidelines.

Practical relevance and applications for environmental management

The spatial patterns of radon distribution observed in this study provide a framework for evidence-based environmental management of mining areas.

Zoning for risk-based land use planning

The clear concentration gradient from mining areas to control sites supports the establishment of risk-based land use zones:

- **Red Zone (>600 Bq m^{-3}):** Active mining areas, coal stockpiles, waste dumps – restricted residential development, requiring occupational control
- **Orange Zone (200–600 Bq m^{-3}):** Areas within 1–2 km of mining that require indoor testing and ventilation standards for new construction
- **Yellow Zone (100–200 Bq m^{-3}):** Transitional areas that require monitoring and public education
- **Green Zone (<100 Bq m^{-3}):** Background areas – no specific interventions

Integration with environmental impact assessment

Current EIA practices in Nigeria's mining sector rarely include radon risk assessment. This study demonstrates that radon should be a mandatory component of EIAs for coal mining projects with the following requirements:

- Baseline radon measurements before mining commences
- Predictive modelling of radon emissions during mining
- Mitigation plans for elevated radon concentrations
- Closure plans addressing long-term radon emissions

Adaptive management framework

Given the seasonal variation in radon emissions (expected to be lower during the wet season), monitoring programs should implement adaptive management:

- Wet season: Enhanced water quality monitoring, soil erosion control
- Dry season: Increased air quality monitoring, dust suppression
- Transition periods: Comprehensive sampling to capture variability

Community-based environmental monitoring

The involvement of community leaders and residents in this study suggests the feasibility of community-based monitoring programmes. Citizen science approaches, including training residents to use simple radon detectors (e.g., charcoal canisters and alpha track detectors), could expand monitoring coverage while building local capacity and awareness.

Policy and regulatory implications

The findings of this study are directly relevant to Nigeria's environmental and radiation protection regulatory framework.

1. **National Environmental (Base Metals, Iron and Steel Manufacturing Industries) Regulations, 2011:** These regulations should be amended to include radiological parameters (radon and radium) in emission monitoring requirements for mining operations.
2. **Nigerian Nuclear Regulatory Authority (NNRA) Safety Standards:** The current NNRA safety standards focus primarily on nuclear facilities and do not adequately address naturally occurring radioactive materials (NORM) in mining contexts. This study supports the development of NORM-specific regulations, including:

- Radon action levels for mining environments
- Occupational exposure limits for NORM workers
- Environmental monitoring requirements for NORM industries
- Guidelines for NORM waste management

1. **Environmental Impact Assessment (EIA) Act, Cap E12, LFN 2004:** The EIA guidelines should be updated to require radiological impact assessment for all mining projects, including baseline radon measurements, predictive modelling, and mitigation planning.
2. **National Environmental Health Policy:** This policy should incorporate radon as a priority environmental health concern, particularly in mining communities, and establish surveillance systems for tracking radon-related health outcomes.

Cost-effectiveness considerations

The cost of implementing basic radon mitigation in a typical Nigerian home (floor sealing and ventilation improvement) is estimated to be ₦50,000–100,000 (approximately $65–130 USD). This compares favourably to the estimated ₦5,000,000 (~$6,500 USD) lifetime cost of treating a single lung cancer case in Nigeria. For 200–300 dwellings within the high-risk zone, a community-wide mitigation program would cost ₦10–30 million (~$13,000–39,000 USD), potentially preventing 5–10 lung cancer cases over 20 years. This cost-benefit analysis suggests that radon mitigation interventions in mining communities are likely to be highly cost-effective from a public health perspective.

Environmental quality monitoring framework

Based on this study, we propose a three-tier monitoring framework for radiological environmental quality assessment in mining areas:

Table 3: Three-tier monitoring framework for radiological environmental quality assessment in mining areas

Tier	Parameter	Frequency	Location	Method
1	Soil gas radon	Quarterly	40 fixed stations	RAD7/diffusion chambers
2	Indoor radon	Bi-annual	50 dwellings	Alpha track detectors
3	Water radon	Quarterly	20 water sources	Liquid scintillation
4	Radon flux	Seasonal	10 key sites	Accumulation chambers
5	Gamma dose rate	Continuous	5 stations	Installed dosimeters

Study limitations and future research directions

This study has several limitations. First, radon measurements were conducted during a single season (dry season), and may not capture seasonal variations in radon emissions. Radon exhalation varies with environmental conditions, and wet periods suppress radon transport through pore saturation (Lawal *et al.*, 2025), suggesting that annual average exposures might be lower than in dry season measurements. Future studies should incorporate wet-season sampling.

Second, the conversion from soil-gas radon concentrations to indoor inhalation doses involves assumptions about building characteristics that may not accurately reflect the conditions in Okaba and Okobo dwellings. Direct indoor radon measurements in residential structures can provide more accurate exposure estimates and should be prioritized (Ademola and Olaoye, 2017; Ademola and Ehiedu, 2019; Usikalu *et al.*, 2025).

Third, the study focused exclusively on radon-222 and did not assess thoron (^{220}Rn) concentrations. Given the elevated ^{232}Th activities previously documented in Okaba and Okobo soils (mean: 81.91 Bq kg^{-1}) (Arome and Walia, 2024), thoron may represent an additional, uncharacterised health hazard. Thoron concentrations up to 389 Bq m^{-3} have been reported in Cameroon mining areas (Gaus *et al.*, 2025), suggesting that thoron assessment should be incorporated into future monitoring programmes.

Fourth, although this study documented elevated radiological parameters, it did not assess the actual health outcomes in the exposed population. Epidemiological studies linking measured exposure to cancer incidence would strengthen the evidence base for public health intervention.

Future research directions should include: (1) establishment of continuous radon monitoring networks across different seasons; (2) direct indoor radon measurements in representative dwellings; (3) assessment of thorons and their progeny; (4) investigation of radon in groundwater and surface water; (5) source apportionment studies using isotopic signatures; (6) health impact modelling incorporating multiple exposure pathways and demographic factors; and (7) evaluation of the effectiveness of mitigation interventions.

PRACTICAL RECOMMENDATIONS FOR ENVIRONMENTAL MANAGEMENT

Based on these findings, the following tiered interventions are recommended:

Tier 1: Immediate actions (0–6 months)

1. **Community Alert System:** Establish radon warning signs at high-risk locations (coal stockpiles, waste dumps, and mine pits) with information in the local language.
2. **Targeted Indoor Testing:** Conduct radon measurements in 50 priority dwellings within 500 m of mining operations.
3. **Water Quality Screening:** Test 20 drinking water sources (boreholes, wells, streams) for radon-222 and radium-226.
4. **Worker Protection:** Provide N95 respirators for mine workers and limit shift durations in high radon areas.

Tier 2: Short-term actions (6–18 months)

1. **Building Retrofits:** Implement radon-resistant construction in new dwellings, including:
   - Gas permeable layers beneath slabs
   - Sealed floor joints and cracks
   - Passive sub-slab depressurisation systems
   - Under-slab ventilation with PVC pipes
2. **Soil Remediation:** Cover high-radon soils (mine pits, waste dumps) with 30–50 cm of clean clay or concrete to reduce emanation.
3. **Water Treatment:** Install aeration systems for drinking water sources with radon > 11.1 Bq L^{-1}.
4. **Community Education Programme:** Launch monthly awareness sessions in schools, markets, and places of worship covering:
   - Radon sources and health effects
   - Simple ventilation practices (opening windows, using fans)
   - Recognising symptoms of radon-related illness
   - Reporting mechanisms for environmental concerns

Tier 3: Long-term actions (18+ months)

1. **Regulatory Framework:** Nigerian Nuclear Regulatory Authority should:
   - Establish soil gas radon action level of 200 Bq m^{-3} for mining areas
   - Mandate quarterly radon monitoring at all active mining sites
   - Require environmental impact assessments to include radon risk assessment
   - Develop national radon safety standards for occupational settings
2. **Monitoring Network:** Install ten continuous radon monitoring stations across the study area with data transmission to the NNRA.
3. **Health Surveillance:** Establish a cancer registry in the Ankpa Local Government to track lung cancer incidence.
4. **Mine Closure Planning:** Develop radon management plans for post-mining land use, including:
   - Reclamation with radon barrier covers
   - Long-term monitoring requirements
   - Land use restrictions for high-risk areas

CONCLUSION

This study provides the first comprehensive assessment of radon-222 concentrations, exhalation rates, and associated health risks in soil from the Okaba coal mining area, demonstrating substantial degradation of environmental quality across multiple media (soil, air, and potentially water) owing to mining activities. These findings establish radon as a sensitive indicator of mining-induced environmental disturbance and provide a scientific basis for evidence-based environmental management interventions.

Radon concentrations ranged from 52.3 to 912.6 Bq m^{-3} (mean: 338.7 Bq m^{-3}), with 95.0% of samples exceeding the WHO indoor action level of 100 Bq m^{-3}. Mining proximal areas exhibited the highest values, followed by waste dump areas, downstream sediments, and residential zones, confirming that coal extraction is the primary driver of radon enhancement. Radon exhalation rates (mean: 15.3 Bq m^{-2} h^{-1}) and radium-226 activities (mean: 50.4 Bq kg^{-1}) were similarly elevated and strongly related, confirming radium content as the key determinant of radon emission potential.

The calculated annual effective doses from potential indoor radon inhalation (mean: 8.53 mSv y^{-1}; range: 1.32–22.99 mSv y^{-1}) substantially exceed the ICRP public dose limit of 1 mSv y^{-1}. Corresponding excess lifetime cancer risks (mean: 42.6×10^{-3}) are approximately 147 times higher than UNSCEAR background cancer risk, translating to an estimated 42,600 excess lung cancer cases per million persons exposed over a lifetime. The hazard quotient values (mean: 8.53) indicated that all samples exceeded safe levels, with the population-attributable fraction estimated at 0.15–0.21, suggesting that 15–21% of lung cancer cases in the mining community could be attributed to radon exposure. These values represent major public health burdens.

The implications for environmental management are substantial. The clear spatial gradients support the establishment of risk-based land-use zones, integration of radiological parameters into environmental impact assessments, and implementation of adaptive management approaches that account for seasonal variation. A cost-effectiveness analysis suggests that mitigation interventions are likely to be highly beneficial from a public health perspective. The proposed three-tier monitoring framework provides a practical structure for ongoing environmental quality assessment.

This study contributes essential baseline data for environmental management and public health protection in Nigerian coal mining communities and underscores the critical importance of addressing radiological hazards in the extractive industry context. The tiered intervention framework provides a practical roadmap for regulatory agencies, mining companies, and community stakeholders to implement evidence-based risk-reduction strategies.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical support provided by the Centre for Energy Development, Ahmadu Bello University, Zaria, Nigeria, and the cooperation of community leaders and residents of Okaba during the field sampling.

AUTHORS' CONTRIBUTION

Aruwa Arome: Conceptualization, methodology, investigation, sample collection, laboratory analysis, formal analysis, writing – original draft, writing – review, and editing

Genius Walia: Supervision, validation, resources, writing – review, and editing

DISCLOSURE STATEMENT

The authors report there are no competing interests to declare.

FUNDING DETAILS

This work received no specific funding from any granting agency in the public, commercial, or not-for-profit sector.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are presented within the article (Table 1). Raw radon measurement logs and gamma spectrometry spectra are available from the corresponding author, Aruwa Arome, upon reasonable request, subject to institutional data sharing policies.

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