



Evaluation of Radon Concentration and Age-dependent Health Risks from Water Samples within Selected University Environments of Katsina State, Nigeria



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ABSTRACT

Groundwater is the principal drinking-water source on Nigerian university campuses, yet its radiological quality, and the age-differentiated radon doses delivered to the students, staff and resident children who depend on it, remains largely uncharacterised, and no comparative campus-scale assessment exists for the semi-arid basement terrain of Katsina State. This study assessed radon gas concentration and associated radiological health risks in drinking water samples collected from three universities in Katsina State, Nigeria: Federal University Dutsin-Ma (FUDMA), Umaru Musa Yar'adua University, Katsina (UMYU), and Federal University of Transportation Daura (FUTD). A total of 30 water samples were analyzed for radon activity concentration, and the annual effective doses (AED) due to inhalation and ingestion were calculated for adults, children, and infants. Total annual effective doses (TAED) and excess lifetime cancer risks (ELCR) were also determined. Radon concentrations ranged from 10^{-4} to 1.14×10^{-1} Bq L⁻¹ at FUDMA, 8×10^{-3} to 1.875 Bq L⁻¹ at UMYU, and 6.1×10^{-2} to 12.964 Bq L⁻¹ at FUTD, with mean values of 1.58×10^{-2} , 6.81×10^{-1} , and 4.501 Bq L⁻¹, respectively. All mean concentrations were below the WHO/UNSCEAR safe limit of 11 Bq L⁻¹. However, the Admin Block at FUTD recorded 12.964 Bq L⁻¹, slightly exceeding this threshold. The mean TAED values remained well below the ICRP reference level of 0.1 mSv yr⁻¹ across all institutions, though FUTD's Admin Block slightly exceeded this limit (0.198 mSv yr⁻¹ for infants). ELCR values were generally within acceptable EPA ranges (10^{-6} – 10^{-4}), except at FUTD's Admin Block where infant ingestion risk reached 6.61×10^{-4} , nearing the upper bound of acceptability. Infants consistently exhibited the highest doses and cancer risks across all sites, followed by children and adults. The findings indicate that while most water sources are radiologically safe, localized hotspots, particularly at FUTD require continuous monitoring.

Keywords:

Radon concentration,
Annual effective dose,
Excess lifetime cancer
Risk,
Drinking water,
Radiological health
Assessment

INTRODUCTION

Radon-222, a naturally occurring radioactive gas from the uranium-238 decay chain with a half-life of ~3.82 days, is odorless, colorless, and tasteless. As a noble gas, it migrates from soil and rock into groundwater, creating significant human exposure through ingestion and inhalation pathways. During domestic use such as showering, cooking, and drinking, dissolved radon releases into indoor air while direct consumption delivers stomach-lining doses. International bodies have established regulatory frameworks: the World Health Organization (WHO) sets a 100 Bq L⁻¹ reference level, the United States Environmental Protection Agency (USEPA) mandates an 11 Bq L⁻¹ maximum contaminant level,

and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommends 4 – 40 Bq L⁻¹ for drinking water (Zeeb & Shannoun, 2009; UNSCEAR, 2000; WHO, 2011).

In Nigeria, groundwater dominates drinking water supply, especially in semi-arid Katsina State where surface water is scarce. The region's crystalline basement rocks and sedimentary formations favor uranium mineralization and radon emanation into aquifers, rendering boreholes and hand-dug wells vulnerable (Lawal et al., 2026). Recent Nigerian studies document widespread contamination: Kolo et al. (2023) reported 1.5 – 42.5 Bq L⁻¹ in Bosso Community; Farai et al. (2023) found 1.41 – 29.50 Bq L⁻¹ in Abeokuta; and Shuaibu et al.

(2023) recorded a mean of 38.32 Bq L^{-1} in Gadau, Bauchi State, a mean value of 36.1 Bq L^{-1} was reported in the Shanono and Bagwai gold-mining belt (Bello et al., 2020), and 39.55 Bq L^{-1} in Katagum (Abdulrasheed et al., 2024). Therefore, highlighting urgent needs for systematic institutional assessment.

Radon health risks are well-established. Its short-lived progeny emits alpha particles damaging cellular DNA. Inhalation is the second leading lung cancer cause after smoking, while ingestion links to stomach malignancies. The excess lifetime cancer risk (ELCR) quantifies 70-year cancer probability, with USEPA acceptable ranges of 1.0×10^{-6} to 1.0×10^{-4} . The International Commission on Radiological Protection (ICRP) recommends 0.1 mSv yr^{-1} total annual effective dose from natural radiation sources (ICRP, 2017).

Age-dependent vulnerability remains underexplored. ICRP Publication 137 (2017) provides age-specific dose coefficients accounting for breathing rates, water intake, body mass, and tissue radiosensitivity. Infants and children face disproportionate risks due to higher metabolic rates, greater water consumption per body weight, smaller concentrating organs, and longer lifespans for stochastic effects. The University of Kentucky BREATHE program (2024) confirms children's smaller lungs and faster breathing yield higher per-unit doses, while immature organs show heightened mutation sensitivity. Childhood acute lymphoblastic leukemia studies demonstrate 63% greater risk at highest radon exposures, necessitating disaggregated assessment for adults, children, and infants.

Nigerian university campuses represent unique radiological microenvironments. Federal University Dutsin-Ma (FUDMA), Umaru Musa Yar'adua University (UMYU), and Federal University of Transportation Daura (FUTD) rely majorly on ground water supplying heterogeneous populations including students, staff, and campus childcare residents. Despite their strategic importance, these institutions lack comprehensive radon evaluation. Spatial variability driven by ground water depth, aquifer characteristics, geological heterogeneity, and uranium-proximity demands site-specific investigation rather than generalized risk assumptions. This study systematically assesses radon-222 in water samples across all three universities.

The significance is multifaceted. Public health benefits include empirical exposure data enabling evidence-based water quality management. Academically, it extends literature on Nigerian campus radioactivity, complementing Namadi et al. (2025), Isinkaye et al. (2021), Obed et al. (2010), and Afolabi et al. (2015). Age-disaggregated analysis specifically highlights differential infant, child, and adult vulnerability within identical environments, informing targeted protective measures. Comparative institutional assessment reveals how local geological and infrastructural factors shape

contamination patterns. Grounded in the precautionary principle and safe drinking water rights, this research responds to radon's established carcinogenicity, Nigerian universities' groundwater dependence, and documented regional elevations. The presence of campus childcare centers and staff residences with children amplifies ethical monitoring imperatives. Generated baseline data on concentrations, doses, and cancer risks equip administrators, health officials, and regulators for monitoring protocols, remediation strategies, and awareness campaigns. Ultimately, findings model radiological risk assessment for similar institutional settings across Nigeria and developing nations where groundwater dependence and geological radon potential create latent health risks.

Although there is a substantial body of literature on groundwater radon in Nigeria, existing studies are spatially fragmented and infrequently compared. Most investigations have focused on single-source surveys at the community level (Abdulrasheed et al., 2024; Shuaibu et al., 2023; Farai et al., 2023; Bello et al., 2020;). These studies employed varied instrumentation, occupancy assumptions, and dose coefficients, which hinder direct cross-site comparisons. Notably, no study has assessed multiple tertiary institutions within a shared geological province using a unified protocol, leaving the impact of campus-specific hydrogeology on the radon dose received by resident populations unquantified to date. This study specifically addresses this university-scale gap.

The present study aims to achieve three primary objectives: (i) to quantify radon-222 activity concentrations in drinking water across FUDMA, UMYU, and FUTD using a consistent sampling and liquid-scintillation protocol; (ii) to calculate inhalation and ingestion annual effective doses, total annual effective doses, and excess lifetime cancer risks for adults, children, and infants, employing age-specific coefficients (UNSCEAR, 2000; ICRP, 2017); and (iii) to compare the three campuses to determine the influence of local geology and groundwater dependence on radiological burden. The novelty of this research lies in its harmonized, multi-institutional, and age-disaggregated design within a single semi-arid basement-complex province. This approach explicitly connects the uranium-bearing crystalline and sedimentary formations of the region (Abdulkadir et al., 2023; Lawal et al., 2026), and the near-total reliance on untreated groundwater to the differential vulnerability of its youngest consumers.

MATERIALS AND METHODS

Study Area

Federal University Dutsin-Ma is located in Dutsin-Ma Local Government Area of Katsina State, northwestern Nigeria. The university operates within Sudan savannah vegetation characterized by tropical climatic conditions,

moderate rainfall, and crystalline basement geology (Abdulkadir et al., 2023). These environmental and geological features may influence natural radionuclide distribution and radon dissolution in groundwater sources (National Population Commission [NPC], 2010; UNSCEAR, 2008).

Umaru Musa Yar'adua University is situated in Katsina metropolis, northwestern Nigeria, within a semi-arid Sudan savannah zone. The area experiences high temperatures, seasonal rainfall, and extensive groundwater utilization for domestic activities. The geological formations surrounding the university consist mainly of sedimentary and basement complex rocks, which may contribute to varying levels of radon concentration in water sources (NPC, 2010; Abdulkadir et al., 2023).

Federal University of Transportation Daura is located in Daura, Katsina State, Nigeria, close to the Niger Republic border. The region lies within the Sudan savannah belt and is characterized by dry climatic conditions and sandy soil formations (Abdulkadir et al., 2023). Groundwater serves as a major water supply source in the area, making radiological assessment important for evaluating possible radon-related health risks among the population (IAEA, 2014; UNSCEAR, 2008).

Disposable hypodermic syringe (20 mL, 10 mL capacities), surgical gloves, scintillation vials (20 mL capacity) with polyethylene inner seal cap liners, scintillation cocktail, distilled water, indelible ink and masking tape, liquid scintillation counter (Packard Tri-Card LSA 1000TR), global positioning system (GPS), a piece of clean cloth and ethanol.

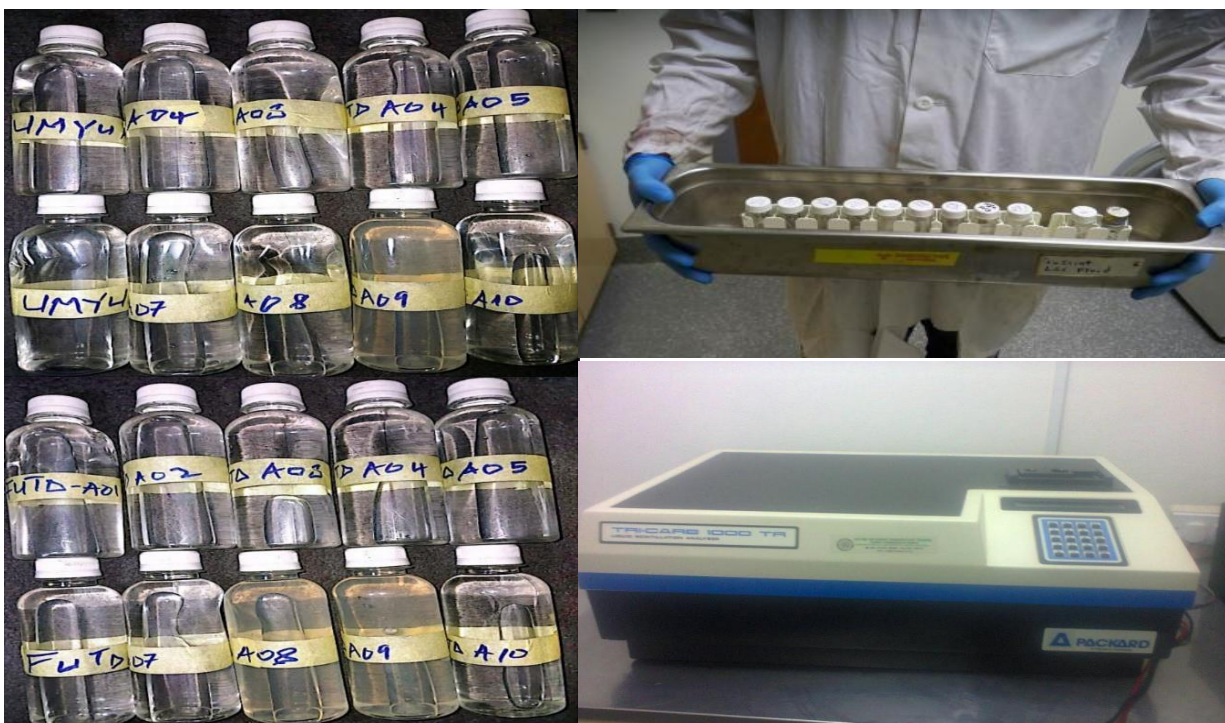


Figure 1. Collected water samples, Prepared samples in Secondary Containment and Liquid Scintillation Analyzer (Tri-carb- LSA 1000), CERT, ABU, Zaria

Sample Collection

From each of the three institutions, ten (10) water samples were collected for analysis from different locations. During sampling, a global positioning system (GPS) was used to mark the geographical locations (latitude and longitude) on the earth surface of the sample collection points. Boreholes were pumped and taps were on and allowed to flow for at least three (3) minutes before samples were collected in order to ensure that fresh samples were obtained. Each collected sample was properly labelled and recorded as shown in Figure 1.

Sample Preparation

10 mL of each sample were added into a vial containing 10 mL of toluene-based cocktail (scintillator) using a hypodermic syringe. The vials were tightly capped and shaken vigorously for three (3) minutes to extract ^{222}Rn in water phase into the organic scintillator. In a similar manner a blank sample for the background were prepared using distilled water that were kept in a glass bottle for at least 21 days. The prepared samples were allowed to stand undisturbed for at least three (3) hours each in order

for ^{222}Rn and its alpha decay products to attain equilibrium before counting.

Sample Analysis

The prepared samples and the blank were analysed using a liquid scintillation counter (TriCarb-LSA1000) at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, Nigeria. Radiation emitted from the samples transferred energy to the organic scintillator which in turn emits light photons. This way each emission result is a pulse of light in form of digit. The ^{222}Rn activity concentration was calculated.

Determination of radon concentrations in water

The counting vials were placed in the liquid scintillation counter. According to the manufacturer, Tri-Carb-LSA1000 is equipped with alpha/beta discrimination features and can achieve a detection limit of 0.407 BqL^{-1} in 60 min. Each vial was counted for a preset period of time using a calibrated IAEA ^{226}Ra standard solutions (IAEA-423, IAEA-431 and IAEA-427). It was ensured that, when transferring vials from storage to the counter after the 3 hours in growth, they were not shaken as this will greatly disturb the state of equilibrium between ^{222}Rn and its short-lived daughters in the organic scintillate (Bunger and Ruhle, 1994). Background of the counting system was determined by counting a vial with 10 mL of the organic scintillant solution and 10 mL of deionized or distilled water. The time and date at which counting commenced were noted. The background, calibration and sample solutions were measured over the same spectral range and for the same counting period of 60 min. The background and sample count rate ($\text{counts}\cdot\text{min}^{-1}$) were recorded. ^{222}Rn and its short-lived daughters emit a total of 5 radioactive particles (3 α and 2 β) per every disintegration of ^{222}Rn . Since, secular equilibrium was established between ^{222}Rn and these daughters, all the 5 emissions were used to detect and quantify ^{222}Rn in water. ^{222}Rn activity concentrations were evaluated by considering sample volume, total and background count rates, decay time (time between sample collection and counting), and efficiency of detection. The ^{222}Rn concentration in a sample of water was determined using equation 1 (Abba *et al.*, 2022).

$$C_{Rn} = \frac{100(Sc - Bc) e^{\lambda \Delta t}}{60 \times 5 \times 0.964} \quad 1$$

where C_{Rn} is ^{222}Rn concentration at the time of sample collection (Bq L^{-1}); Sc is the sample total count rate ($\text{counts}\cdot\text{min}^{-1}$); Bc is the background count rate ($\text{counts}\cdot\text{min}^{-1}$); t is the elapsed time between sample collection and counting (4320 min. (3 days)); λ is ^{222}Rn decay factor ($1.26 \times 10^{-4} \text{ min}^{-1}$); 100 is a conversion factor from per 10 mL to per liter (L^{-1}); 5 is the number of emissions per count; 60 is conversion factor from minute to second ($\text{s}\cdot\text{min}^{-1}$) and 0.964 is the fraction of ^{222}Rn in the cocktail in a vial of 22 mL total capacity,

assuming it contains 10 mL cocktail, 10 mL water and 2 mL air.

Annual affective doses and excess life cancer risk due to radon concentration

The annual effective dose due to inhalation and ingestion of ^{222}Rn through drinking water, was calculated using the equations below (Abba *et al.*, 2022).

$$AED_{inh} = \frac{C_{Rn} \times RW \times F \times T \times DF}{1000} \quad 2$$

AED_{inh} is the annual effective dose due to inhalation, C_{Rn} is the radon concentration, RW is the transfer coefficient ($=10^{-4}$), F is the equilibrium factor between radon and its progeny (0.4), T is the indoor occupancy time per year (7000 hr yr^{-1}), DF is the dose conversion factor, and 1000 is the conversion coefficient from Sv to mSv

$$AED_{ing} = K \times G \times C_{Rn} \times 1000 \quad 3$$

where AED_{ing} is the annual effective dose due to ingestion (mSv yr^{-1}), C_{Rn} is the ^{222}Rn concentration in water (Bq L^{-1}), G is the water ingestion rate (182.5 L yr^{-1} , 547.5 L yr^{-1} and 730 L yr^{-1}) for infants, children and adults respectively (UNSCEAR, 2008). K is the dose coefficient (7×10^{-8} , 2×10^{-8} , and 10^{-8}) for infants, children and adult, respectively (UNSCEAR, 2000), and 1000 is the conversion coefficient from Sv to mSv.

Total Annual Effective Dose due to inhalation and ingestion was calculated by summing up equation 2 and 3 above.

$$TAED = AED_{inh} + AED_{ing} \quad 4$$

Excess life cancer risk (ELCR) due to inhalation and ingestion for different age categories was calculated from annual effective dose using equation 5 and 6 respectively

$$ELCR_{inh} = AED \times LE \times RF \quad 5$$

$$ELCR_{ing} = AED \times LE \times RF \quad 6$$

Where AED = annual effective dose in mSvyr^{-1} , LE = life expectancy (70 years) and RF = fatal risk factor per Sievert (Sv^{-1}). In case of stochastic effects, ICRP-60 uses RF of 0.057 for the public.

Quality assurance and uncertainty treatment

Quality assurance and quality control followed standard radioanalytical practice. The liquid-scintillation counter was energy- and efficiency-calibrated prior to each batch against certified IAEA radium-226 standard solutions (IAEA-423, IAEA-431 and IAEA-427), and a quench-correction curve was established and applied across the count window. Instrument background and a method blank (10 mL distilled water plus 10 mL cocktail, aged at least 21 days) were counted under spectral and 60 min conditions identical to those of the samples, and vials were transferred from storage to the counter without shaking to preserve secular equilibrium between radon-222 and its short-lived progeny (Bunger and Ruhle, 1993). Radon loss during collection and transport was limited by filling the vials without headspace, capping with polyethylene-lined liners, keeping samples cool, and

minimising the interval between collection and counting. It should be acknowledged, however, that field blanks, field duplicates, matrix spikes and formal control charts were not implemented in this experimental design; their inclusion, together with an inter-comparison exercise, is recommended for future surveys to fully document analytical accuracy and reproducibility.

Two distinct time intervals govern the measurement and are clarified here to avoid ambiguity. After preparation, each vial was held undisturbed for at least three hours to establish secular equilibrium between radon-222 and its short-lived progeny before counting; this in-growth

period is separate from the elapsed time, Δt , between field collection and counting that enters the decay correction $e^{(\lambda\Delta t)}$ in Equation 1. Where a single nominal Δt of three days (4320 min) was applied, the sample-specific Δt should instead be used for each vial, and its uncertainty propagated together with counting statistics (proportional to the square root of the net counts), background subtraction and detector-efficiency uncertainty to yield a combined standard uncertainty and coverage interval for every reported concentration and dose.

RESULTS AND DISCUSSION

Table 1a. FUDMA sampling points and geographical coordinates

	Sample Code	Sample Location	Latitude	Longitude
1.	FUDMA WS-1	School Mosque	12.473297°	7.487789°
2.	FUDMA WS-2	New labs complex	12.473615°	7.486594°
3.	FUDMA WS-3	New auditorium	12.471540°	7.486436°
4.	FUDMA WS-4	Sport complex	12.472866°	7.484490°
5.	FUDMA WS-5	Student centre	12.471667°	7.484730°
6.	FUDMA WS-6	Library	12.472055°	7.485571°
7.	FUDMA WS-7	ICT centre	12.472226°	7.485169°
8.	FUDMA WS-8	Senate building	12.472519°	7.486189°
9.	FUDMA WS-9	Exit gate	12.471163°	7.487209°
10.	FUDMA WS-10	Girls hostel	12.470995°	7.485845°

Table 1b. UMYU sampling points and geographical coordinates

	Sample Code	Sample Location	Latitude	Longitude
1.	UMYU WS-1	Senate	12.892323°	7.585470°
2.	UMYU WS-2	Faculty of science	12.894409°	7.585572°
3.	UMYU WS-3	Auditorium	12.895150°	7.587562°
4.	UMYU WS-4	ICT Complex	12.895335°	7.583091°
5.	UMYU WS-5	Faculty of Law	12.892161°	7.580493°
6.	UMYU WS-6	Library Unit	12.893202°	7.582913°
7.	UMYU WS-7	Clinic	12.889403°	7.585283°
8.	UMYU WS-8	Staff School	12.889447°	7.588572°
9.	UMYU WS-9	DPP Department	12.888905°	7.585967°
10.	UMYU WS-10	Central Mosque	12.890514°	7.586801°

Table 1c. FUTD sampling points and geographical coordinates

	Sample Code	Sample Location	Latitude	Longitude
1.	FUTD WS-1	University Gate	12.971636°	8.343477°
2.	FUTD WS-2	Admin Block	12.972457°	8.346989°
3.	FUTD WS-3	Library	12.972447°	8.348353°
4.	FUTD WS-4	Clinic	12.973898°	8.346511°
5.	FUTD WS-5	Block A	12.972658°	8.348824°
6.	FUTD WS-6	Block B	12.974529°	8.347781°
7.	FUTD WS-7	Transport Management	12.974166°	8.346955°

8.	FUTD WS-8	Water Works	12.976866°	8.350022°
9.	FUTD WS-9	Cafeteria	12.975936°	8.344935°
10.	FUTD WS-10	Female Hall	12.976866°	8.346147°

Tables 1a–1c present the sampling locations and corresponding geographical coordinates of the water sampling points selected across the campuses of Federal University Dutsin-Ma (FUDMA), Umaru Musa Yar'adua University (UMYU), and Federal University of Transportation, Daura (FUTD). The sampling points were strategically distributed to encompass major academic, administrative, residential, and public service areas, thereby providing comprehensive spatial

representation of each campus water distribution network. The recorded geographic coordinates facilitate precise site identification, reproducibility of future investigations, and geospatial analysis. This systematic sampling design enhances the reliability and representativeness of the dataset, providing a robust basis for subsequent assessment of radon concentration, associated radiological risks, and water quality characteristics across the three institutions.

Table 2a. Radon concentration, Annual Effective Dose due to Inhalation and Ingestion for Adult, Children and Infants (FUDMA)

Sample ID	Sample Location	Rn (Bq/L)	AED _{inh} (mSv/yr)	AED _{ing-A} (mSv/yr)	AED _{ing-C} (mSv/yr)	AED _{ing-I} (mSv/yr)
FUDMA WS-1	School Mosque	4.65×10^{-3}	1.17×10^{-5}	3.39×10^{-5}	5.09×10^{-5}	5.94×10^{-5}
FUDMA WS-2	New Labs Complex	1.14×10^{-1}	2.85×10^{-4}	8.32×10^{-4}	1.24×10^{-3}	1.46×10^{-3}
FUDMA WS-3	New Auditorium	1.00×10^{-4}	2.52×10^{-7}	7.30×10^{-7}	1.10×10^{-6}	1.28×10^{-6}
FUDMA WS-4	Sport Complex	7.78×10^{-3}	1.96×10^{-5}	5.68×10^{-5}	8.52×10^{-5}	9.94×10^{-5}
FUDMA WS-5	student Centre	1.04×10^{-2}	2.61×10^{-5}	7.56×10^{-5}	1.13×10^{-4}	1.32×10^{-4}
FUDMA WS-6	Library	1.02×10^{-2}	2.57×10^{-5}	7.43×10^{-5}	1.11×10^{-4}	1.30×10^{-4}
FUDMA WS-7	ICT centre	7.00×10^{-4}	1.76×10^{-6}	5.11×10^{-6}	7.67×10^{-6}	8.94×10^{-6}
FUDMA WS-8	Senate Building	7.84×10^{-3}	1.98×10^{-5}	5.72×10^{-5}	8.58×10^{-5}	1.00×10^{-4}
FUDMA WS-9	Exit Gate	1.84×10^{-3}	4.64×10^{-6}	1.34×10^{-5}	2.01×10^{-5}	2.35×10^{-5}
FUDMA WS-10	Girls Hostel	2.10×10^{-4}	5.29×10^{-7}	1.53×10^{-6}	2.30×10^{-6}	2.68×10^{-6}
	Mean	1.58×10^{-2}	3.97×10^{-5}	1.15×10^{-4}	1.73×10^{-4}	2.01×10^{-4}

Table 2a above presents results of Radon concentration (Rn) and annual effective dose (AED) due to inhalation and ingestion across sampling locations in FUDMA. Radon concentration ranges from 1.00×10^{-4} Bq L⁻¹ at the New Auditorium (WS-3) to 1.14×10^{-1} Bq L⁻¹ at the New Labs Complex (WS-2), indicating spatial heterogeneity. AED via ingestion is consistently higher than inhalation,

with infants recording the highest values (up to 1.46×10^{-3} mSv yr⁻¹), followed by children and adults. Lower values occur at WS-3 and WS-10. The mean radon concentration is 1.58×10^{-2} Bq L⁻¹, while mean AED values are 3.97×10^{-5} (inhalation), 1.15×10^{-4} (adult ingestion), 1.73×10^{-4} (child), and 2.01×10^{-4} mSv/yr (infant), indicating age-dependent exposure.

Table 2b: Total Annual Effective Dose due to inhalation and ingestion for Adult (A), Children (C), and Infant (I) (FUDMA)

Sample ID	Sample Location	TAED-A (mSv yr ⁻¹)	TAED-C (mSv yr ⁻¹)	TAED-I (mSv yr ⁻¹)
FUDMA WS-1	School Mosque	4.57×10^{-5}	6.26×10^{-5}	7.11×10^{-5}
FUDMA WS-2	New Labs Complex	1.12×10^{-3}	1.54×10^{-3}	1.74×10^{-3}
FUDMA WS-3	New Auditorium	9.82×10^{-7}	1.35×10^{-6}	1.53×10^{-6}
FUDMA WS-4	Sport Complex	7.64×10^{-5}	1.05×10^{-4}	1.19×10^{-4}
FUDMA WS-5	student Centre	1.02×10^{-4}	1.39×10^{-4}	1.58×10^{-4}
FUDMA WS-6	Library	1.00×10^{-4}	1.37×10^{-4}	1.56×10^{-4}

FUDMA WS-7	ICT centre	6.87×10^{-6}	9.43×10^{-6}	1.07×10^{-5}
FUDMA WS-8	Senate Building	7.70×10^{-5}	1.06×10^{-4}	1.20×10^{-4}
FUDMA WS-9	Exit Gate	1.81×10^{-5}	2.48×10^{-5}	2.81×10^{-5}
FUDMA WS-10	Girls Hostel	2.06×10^{-6}	2.83×10^{-6}	3.21×10^{-6}
	Mean	1.55×10^{-4}	2.21×10^{-4}	2.41×10^{-4}

Table 2b above presents results of Total Annual Effective Dose (TAED) due to combined inhalation and ingestion pathways, the results show clear spatial and age-dependent variation across FUDMA water samples. Adults record values ranging from 9.82×10^{-7} to 1.12×10^{-3} mSv yr⁻¹, with the highest dose observed at the New Labs Complex (WS-2). Children and infants exhibit higher exposure, reaching 1.54×10^{-3} and 1.74×10^{-3} mSv

yr⁻¹ respectively. The lowest values are observed at the New Auditorium (WS-3) and Girls Hostel (WS-10). Mean TAED values follow the pattern: adult (1.55×10^{-4}), children (2.21×10^{-4}), and infants (2.41×10^{-4} mSv yr⁻¹). This confirms ingestion as the dominant exposure pathway and highlights increased vulnerability in younger age groups.

Table 2c. Excess Life Cancer Risk due to inhalation and ingestion (FUDMA)

Sample ID	Sample Location	ELCR _{inh}	ELCR _{ing-A}	ELCR _{ing-C}	ELCR _{ing-I}
FUDMA WS-1	School Mosque	4.68×10^{-8}	1.35×10^{-7}	2.03×10^{-7}	2.37×10^{-7}
FUDMA WS-2	New Labs Complex	1.15×10^{-6}	3.32×10^{-6}	4.98×10^{-6}	5.81×10^{-6}
FUDMA WS-3	New Auditorium	1.01×10^{-9}	2.91×10^{-9}	4.37×10^{-9}	5.10×10^{-9}
FUDMA WS-4	Sport Complex	7.82×10^{-8}	2.27×10^{-7}	3.40×10^{-7}	3.97×10^{-7}
FUDMA WS-5	student Centre	1.04×10^{-7}	3.01×10^{-7}	4.52×10^{-7}	5.28×10^{-7}
FUDMA WS-6	Library	1.02×10^{-7}	2.97×10^{-7}	4.45×10^{-7}	5.19×10^{-7}
FUDMA WS-7	ICT centre	7.04×10^{-9}	2.04×10^{-8}	3.06×10^{-8}	3.57×10^{-8}
FUDMA WS-8	Senate Building	7.88×10^{-8}	2.28×10^{-7}	3.43×10^{-7}	4.00×10^{-7}
FUDMA WS-9	Exit Gate	1.85×10^{-8}	5.36×10^{-8}	8.04×10^{-8}	9.38×10^{-8}
FUDMA WS-10	Girls Hostel	2.11×10^{-9}	6.12×10^{-9}	9.18×10^{-9}	1.07×10^{-8}
	Mean	1.59×10^{-7}	4.59×10^{-7}	6.89×10^{-7}	8.04×10^{-7}

Table 2c above presents results of Excess Lifetime Cancer Risk (ELCR) due to radon exposure in FUDMA water samples. It demonstrates significant age dependency and spatial variation. Inhalation ELCR ranges from 1.01×10^{-9} at New Auditorium (WS-3) to 1.15×10^{-6} at New Labs Complex (WS-2). Ingestion-related risks are higher, with infants recording up to

5.81×10^{-6} , followed by children (4.98×10^{-6}) and adults (3.32×10^{-6}). Lower risks are observed at WS-3 and WS-10. Mean ELCR values are 1.59×10^{-7} (inhalation), 4.59×10^{-7} (adult ingestion), 6.89×10^{-7} (children), and 8.04×10^{-7} (infants). These findings indicate that although risks are generally low, younger populations are more susceptible to long-term radiological effects.

Table 3a. Radon concentration, Annual Effective Dose due to Inhalation and Ingestion for Adult, Children and Infants (UMYU)

SAMPLE ID	LOCATION	Rn (Bq L ⁻¹)	AED _{inh} (mSV yr ⁻¹)	AED _{ing-A} (mSV yr ⁻¹)	AED _{ing-C} (mSV yr ⁻¹)	AED _{ing-I} (mSV yr ⁻¹)
UMYU WS-1	Senate	0.512	1.29×10^{-3}	3.74×10^{-3}	5.61×10^{-3}	6.54×10^{-3}
UMYU WS-2	Fac of science	1.875	4.73×10^{-3}	1.37×10^{-3}	2.05×10^{-3}	2.40×10^{-3}
UMYU WS-3	Auditorium	0.013	3.28×10^{-3}	9.49×10^{-3}	1.42×10^{-3}	1.66×10^{-3}

UMYU WS-4	ICT Complex	0.689	1.74×10^{-3}	5.03×10^{-3}	7.54×10^{-3}	8.80×10^{-3}
UMYU WS-5	Faculty of Law	1.422	3.58×10^{-3}	1.04×10^{-3}	1.56×10^{-3}	1.82×10^{-3}
UMYU WS-6	Library Unit	0.935	2.36×10^{-3}	6.83×10^{-3}	1.02×10^{-3}	1.19×10^{-3}
UMYU WS-7	Clinic	0.008	2.02×10^{-3}	5.84×10^{-3}	8.76×10^{-3}	1.02×10^{-3}
UMYU WS-8	Staff School	1.126	2.84×10^{-3}	8.22×10^{-3}	1.23×10^{-3}	1.44×10^{-3}
UMYU WS-9	DPP Department	0.202	5.09×10^{-3}	1.47×10^{-3}	2.21×10^{-3}	2.58×10^{-3}
UMYU WS-10	Central Mosque	0.031	7.81×10^{-3}	2.26×10^{-3}	3.39×10^{-3}	3.96×10^{-3}
	Mean	0.6813	1.72×10^{-3}	4.97×10^{-3}	7.46×10^{-3}	8.70×10^{-3}

Table 3a above presents results of Radon concentrations at UMYU range from 0.008 Bq L⁻¹ (Clinic) to 1.875 Bq L⁻¹ (Faculty of Science), with a mean of 0.681 Bq L⁻¹. All AED values (inhalation and ingestion via adult, child, infant pathways) scale directly with radon levels. The Faculty of Science shows the highest doses across all categories, while the Clinic and Auditorium record

negligible values. Infant ingestion doses consistently exceed adult and child doses, reflecting higher dose conversion factors for infants. Overall, UMYU's mean AED values remain relatively low, suggesting limited radiological risk from drinking water at most sampled locations.

Table 3b. Total Annual Effective Dose due to inhalation and ingestion for Adult (A), Children (C), and Infant (I) (UMYU)

SAMPLE ID	LOCATION	TAED-A (mSV yr ⁻¹)	TAED-C (mSV yr ⁻¹)	TAED-I (mSV yr ⁻¹)
UMYU WS-1	Senate	5.03×10^{-3}	6.90×10^{-3}	7.83×10^{-3}
UMYU WS-2	Fac of science	1.84×10^{-3}	2.53×10^{-3}	2.87×10^{-3}
UMYU WS-3	Auditorium	1.28×10^{-3}	1.75×10^{-3}	1.99×10^{-3}
UMYU WS-4	ICT Complex	6.77×10^{-3}	9.28×10^{-3}	1.05×10^{-3}
UMYU WS-5	Faculty of Law	1.40×10^{-3}	1.92×10^{-3}	2.17×10^{-3}
UMYU WS-6	Library Unit	9.18×10^{-3}	1.26×10^{-3}	1.43×10^{-3}
UMYU WS-7	Clinic	7.86×10^{-3}	1.08×10^{-3}	1.22×10^{-3}
UMYU WS-8	Staff School	1.11×10^{-3}	1.52×10^{-3}	1.72×10^{-3}
UMYU WS-9	DPP Department	1.98×10^{-3}	2.72×10^{-3}	3.09×10^{-3}
UMYU WS-10	Central Mosque	3.04×10^{-3}	4.18×10^{-3}	4.74×10^{-3}
	Mean	6.69×10^{-3}	9.18×10^{-3}	1.04×10^{-3}

Table 3b above presents results of Total annual effective doses at UMYU. It combines inhalation and ingestion exposures across three age groups. Values range from 7.9×10^{-5} mSv/y (Clinic, adults) to 2.9×10^{-2} mSv/y (Faculty of Science, infants). The mean TAEDs are 6.7×10^{-3} , 9.2×10^{-3} , and 1.04×10^{-3} mSv/y for adults, children, and infants respectively. Faculty of Science,

Faculty of Law, and Staff School show the highest total doses, driven by elevated radon levels. The consistent infant > child > adult pattern reflects age-dependent dose coefficients. All TAED values fall well below international reference levels, indicating minimal health concern for the UMYU community.

Table 3c. Excess Life Cancer Risk due to inhalation and ingestion (UMYU)

SAMPLE ID	LOCATION	ELCR _{inh}	ELCR _{ing-A}	ELCR _{ing-C}	ELCR _{ing-I}
UMYU WS-1	Senate	5.15×10^{-6}	1.49×10^{-5}	2.24×10^{-5}	2.61×10^{-5}

UMYU WS-2	Fac of science	1.89×10^{-5}	5.46×10^{-5}	8.19×10^{-5}	9.56×10^{-5}
UMYU WS-3	Auditorium	1.31×10^{-7}	3.79×10^{-7}	5.68×10^{-7}	6.63×10^{-7}
UMYU WS-4	ICT Complex	6.93×10^{-6}	2.01×10^{-5}	3.01×10^{-5}	3.51×10^{-5}
UMYU WS-5	Faculty of Law	1.43×10^{-5}	4.14×10^{-5}	6.21×10^{-5}	7.25×10^{-5}
UMYU WS-6	Library Unit	9.4×10^{-6}	2.72×10^{-5}	4.09×10^{-5}	4.77×10^{-5}
UMYU WS-7	Clinic	8.04×10^{-8}	2.33×10^{-7}	3.5×10^{-7}	4.08×10^{-7}
UMYU WS-8	Staff School	1.13×10^{-5}	3.28×10^{-5}	4.92×10^{-5}	5.74×10^{-5}
UMYU WS-9	DPP Department	2.03×10^{-6}	5.88×10^{-6}	8.83×10^{-6}	1.03×10^{-5}
UMYU WS-10	Central Mosque	3.12×10^{-7}	9.03×10^{-7}	1.35×10^{-6}	1.58×10^{-6}
	MEAN	6.85×10^{-6}	1.98×10^{-5}	2.98×10^{-5}	3.47×10^{-5}

Table 3c above presents results of Excess lifetime cancer risks at UMYU. It spans several orders of magnitude, from 8.04×10^{-8} (Clinic, inhalation) to 9.56×10^{-5} (Faculty of Science, infant ingestion). Mean ELCR values are 6.85×10^{-6} (inhalation), 1.98×10^{-5} (adult ingestion), 2.98×10^{-5} (child ingestion), and 3.47×10^{-5} (infant ingestion). The Faculty of Science dominates all risk

categories, while the Clinic, Auditorium, and Central Mosque show negligible risks. The pattern confirms ingestion as the primary exposure pathway, with infants facing roughly 5× higher risks than inhalation. Despite variations, all values remain within or below typical acceptable risk thresholds (10^{-6} – 10^{-4}).

Table 4a. Radon concentration, Annual Effective Dose due to Inhalation and Ingestion for Adult, Children and Infants (FUTD)

SAMPLE ID	LOCATION	Rn (Bq L ⁻¹)	AED _{inh} (mSV yr ⁻¹)	AED _{ing-A} (mSV yr ⁻¹)	AED _{ing-c} (mSV yr ⁻¹)	AED _{ing-I} (mSV yr ⁻¹)
FUTD WS-1	University Gate	2.185	5.51×10^{-3}	1.60×10^{-3}	2.39×10^{-3}	2.79×10^{-3}
FUTD WS-2	Admin Block	12.964	3.27×10^{-3}	9.46×10^{-3}	1.42×10^{-3}	1.66×10^{-3}
FUTD WS-3	Library	0.099	2.49×10^{-3}	7.23×10^{-3}	1.08×10^{-3}	1.26×10^{-3}
FUTD WS-4	Clinic	4.913	1.24×10^{-3}	3.59×10^{-3}	5.38×10^{-3}	6.28×10^{-3}
FUTD WS-5	Block A	9.774	2.46×10^{-3}	7.14×10^{-3}	1.07×10^{-3}	1.25×10^{-3}
FUTD WS-6	Block B	5.387	1.36×10^{-3}	3.93×10^{-3}	5.90×10^{-3}	6.88×10^{-3}
FUTD WS-7	Transp Manag	0.061	1.54×10^{-3}	4.45×10^{-3}	6.68×10^{-3}	7.79×10^{-3}
FUTD WS-8	Water Works	7.845	1.98×10^{-3}	5.73×10^{-3}	8.59×10^{-3}	1.00×10^{-3}
FUTD WS-9	Cafeteria	1.494	3.76×10^{-3}	1.09×10^{-3}	1.64×10^{-3}	1.91×10^{-3}
FUTD WS-10	Female Hall	0.288	7.26×10^{-3}	2.10×10^{-3}	3.15×10^{-3}	3.68×10^{-3}
	MEAN	4.501	1.13×10^{-3}	3.29×10^{-3}	4.93×10^{-3}	5.75×10^{-3}

Table 4a above presents results of FUTD. It exhibits significantly higher radon levels than FUDMA and UMYU, ranging from 6.1×10^{-2} Bq L⁻¹ (Transport Management) to 12.964 Bq L⁻¹ (Admin Block), with a mean of 4.501 Bq L⁻¹. The Admin Block shows exceptionally high AED values across all pathways, reaching 0.166 mSv yr⁻¹ for infant ingestion. Block A and

Water Works also record elevated doses. Even the lowest FUTD location (Transport Management) approaches UMYU's mean radon concentration. The infant ingestion pathway consistently yields the highest doses. These elevated levels suggest potential radiological concerns at FUTD, particularly at the Admin Block, warranting further investigation and possible mitigation measures.

Table 4b. Total Annual Effective Dose due to inhalation and ingestion for Adult (A), Children (C), and Infant (I) (FUTD)

SAMPLE ID	LOCATION	TAED-A (mSV yr ⁻¹)	TAED-C (mSV yr ⁻¹)	TAED-I (mSV yr ⁻¹)
FUTD WS-1	University Gate	2.15×10 ⁻³	2.94×10 ⁻³	3.34×10 ⁻³
FUTD WS-2	Admin Block	1.27×10 ⁻³	1.75×10 ⁻³	1.98×10 ⁻³
FUTD WS-3	Library	9.72×10 ⁻³	1.33×10 ⁻³	1.51×10 ⁻³
FUTD WS-4	Clinic	4.82×10 ⁻³	6.62×10 ⁻³	7.51×10 ⁻³
FUTD WS-5	Block A	9.60×10 ⁻³	1.32×10 ⁻³	1.49×10 ⁻³
FUTD WS-6	Block B	5.29×10 ⁻³	7.26×10 ⁻³	8.24×10 ⁻³
FUTD WS-7	Transp Manag	5.99×10 ⁻³	8.22×10 ⁻³	9.33×10 ⁻³
FUTD WS-8	Water Works	7.70×10 ⁻³	1.06×10 ⁻³	1.20×10 ⁻³
FUTD WS-9	Cafeteria	1.47×10 ⁻³	2.01×10 ⁻³	2.29×10 ⁻³
FUTD WS-10	Female Hall	2.83×10 ⁻³	3.88×10 ⁻³	4.40×10 ⁻³
	MEAN	4.42×10 ⁻³	6.06×10 ⁻³	6.88×10 ⁻³

Table 4b above presents results of FUTD. The total annual effective doses are substantially higher than FUDMA's and UMYU's, with means of 4.4×10⁻³, 6.1×10⁻³, and 6.9×10⁻³ mSv yr⁻¹ for adults, children, and infants. The Admin Block stands out dramatically at 0.127–0.198 mSv yr⁻¹ across age groups approximately 6–7× higher than FUTD's overall mean. Block A and

Water Works also show elevated TAEDs. Even FUTD's lowest location (Transport Management) exceeds several UMYU sites. The consistent age-dependency pattern persists (infant > child > adult). While still below strict regulatory limits, the Admin Block's values approach levels where long-term monitoring and potential remediation should be considered.

Table 4c. Excess Life Cancer Risk due to inhalation and ingestion (FUTD)

SAMPLE ID	LOCATION	ELCR _{inh}	ELCR _{ing-A}	ELCR _{ing-C}	ELCR _{ing-I}
FUTD WS-1	University Gate	2.20×10 ⁻⁵	6.36×10 ⁻⁵	9.55×10 ⁻⁵	1.11×10 ⁻⁴
FUTD WS-2	Admin Block	1.30×10 ⁻⁵	3.78×10 ⁻⁴	5.66×10 ⁻⁴	6.61×10 ⁻⁴
FUTD WS-3	Library	9.95×10 ⁻⁷	2.88×10 ⁻⁶	4.33×10 ⁻⁶	5.05×10 ⁻⁶
FUTD WS-4	Clinic	4.94×10 ⁻⁵	1.43×10 ⁻⁴	2.15×10 ⁻⁴	2.50×10 ⁻⁴
FUTD WS-5	Block A	9.83×10 ⁻⁵	2.85×10 ⁻⁴	4.27×10 ⁻⁴	4.98×10 ⁻⁴
FUTD WS-6	Block B	5.42×10 ⁻⁵	1.57×10 ⁻⁶	2.35×10 ⁻⁴	2.75×10 ⁻⁴
FUTD WS-7	Transp Manag	6.13×10 ⁻⁷	1.78×10 ⁻⁶	2.67×10 ⁻⁶	3.11×10 ⁻⁶
FUTD WS-8	Water Works	7.89×10 ⁻⁵	2.29×10 ⁻⁵	3.43×10 ⁻⁴	4.00×10 ⁻⁴
FUTD WS-9	Cafeteria	1.50×10 ⁻⁵	4.35×10 ⁻⁵	6.53×10 ⁻⁵	7.62×10 ⁻⁵
FUTD WS-10	Female Hall	2.90×10 ⁻⁶	8.39×10 ⁻⁶	1.26×10 ⁻⁵	1.47×10 ⁻⁵
MEAN		4.53×10 ⁻⁵	1.31×10 ⁻⁴	1.97×10 ⁻⁴	2.29×10 ⁻⁴

Table 4c above presents results of FUTD's excess lifetime cancer risks. The results are markedly elevated compared to FUDMA and UMYU, with mean ELCR values of 4.53×10⁻⁵ (inhalation), 1.31×10⁻⁴ (adult ingestion), 1.97×10⁻⁴ (child ingestion), and 2.29×10⁻⁴ (infant ingestion). The Admin Block is exceptional, reaching 6.61×10⁻⁴ for infant ingestion, approaching the upper

bound of acceptable risk (10⁻³). Block A and Water Works also show concerning values. FUTD's mean infant ingestion risk is roughly 6.6× higher than UMYU's equivalent. These results suggest that while most FUTD locations pose moderate risk, the Admin Block requires urgent attention, potentially including water source investigation and treatment intervention.

Placed against the Nigerian and regional literature, the campus means occupy the lower-to-middle part of the reported groundwater-radon range. The FUDMA mean (1.58×10^{-2} Bq L⁻¹) is far below typical Nigerian groundwater values, whereas the UMYU mean (0.681 Bq L⁻¹) and FUTD mean (4.501 Bq L⁻¹) remain well under community-scale figures such as 39.55 Bq L⁻¹ in Katagum (Abdulrasheed et al., 2024), 36.1 Bq L⁻¹ in the Shanono–Bagwai belt (Bello et al., 2020) and 14.3–17.3 Bq L⁻¹ in Abeokuta and Bosso (Farai et al., 2023; Kolo et al., 2023). Only the FUTD Admin Block (12.964 Bq L⁻¹) approaches and marginally exceeds the 11 Bq L⁻¹ USEPA reference.

Beyond point estimates, contemporary radon assessment increasingly couples machine-learning prediction with probabilistic uncertainty propagation; quantile-regression-forest models combined with Monte Carlo sampling, for instance, have been used to generate high-resolution indoor-radon maps that carry full predictive distributions rather than single values (Petermann et al., 2024). However, the present study presents a single-period, ten-point experimental design which cannot support geostatistical interpolation.

CONCLUSION

This study evaluated radon gas concentrations and associated radiological risks in drinking water from three universities in Katsina State, Nigeria. The findings reveal significant spatial and institutional variations in radon levels across the sampled locations. Federal University Dutsin-Ma (FUDMA) demonstrated the lowest radon concentrations, with a mean of 1.58×10^{-2} Bq L⁻¹ and negligible radiological impact across all exposure pathways. Umaru Musa Yar'adua University (UMYU) showed moderate levels, with a mean radon concentration of 6.81×10^{-1} Bq L⁻¹ and total annual effective doses well below international safety thresholds. In contrast, the Federal University of Transportation Daura (FUTD) exhibited markedly elevated radon levels, with a mean of 4.501 Bq L⁻¹ and an exceptional peak of 12.964 Bq L⁻¹ at the Admin Block, exceeding the WHO/UNSCEAR recommended limit of 11 Bq L⁻¹. Across all three institutions, a consistent age-dependent risk pattern emerged, with infants receiving the highest total annual effective doses and excess lifetime cancer risks, followed by children and adults. This reflects the higher dose conversion factors and greater water intake relative to body mass in younger populations. Ingestion was identified as the dominant exposure pathway compared to inhalation, contributing substantially higher cancer risk estimates. While the majority of sampling points posed minimal health concerns, the Admin Block at FUTD recorded an excess lifetime cancer risk of 6.61×10^{-4} for infant ingestion, approaching the upper limit of EPA

acceptability (10^{-3}). This localized hotspot signals a potential long-term health concern that warrants immediate attention. Overall, the study confirms that drinking water at FUDMA and most UMYU locations is radiologically safe. However, the elevated results at FUTD particularly the Admin Block, Block A, and Water Works indicate the need for institutional-specific risk management strategies, enhanced water quality surveillance, and possible remediation interventions to safeguard the health of vulnerable campus populations. Several limitations qualify these findings and define the agenda for further work. The design rests on a single sampling campaign of ten points per campus, which captures neither seasonal variability, since groundwater radon fluctuates with recharge, temperature and water-table dynamics, nor short-term temporal change, and the modest sample size limits statistical power and generalisability. No hydrogeochemical characterisation (for example uranium and radium content, pH, conductivity or aquifer lithology) was undertaken to explain the FUTD anomaly. Future investigations should incorporate multi-season and repeated sampling, larger and randomised site networks, parallel measurement of indoor airborne radon, hydrogeochemical and lithological profiling, and uncertainty-aware spatial analysis. Such work would situate the localized FUTD hotspot within the wider question of groundwater safety and public health across the basement-complex aquifers of northern Nigeria, where heavy dependence on untreated groundwater renders even infrequent radiological exceedances consequential for vulnerable populations.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this research. The funding agencies and collaborating institutions had no influence on the study design, data collection, analysis, interpretation of results, or decision to publish the findings.

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