ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 13, Issue 2, pp: (49-59), Month: April 2025 - June 2025, Available at: www.researchpublish.com

Spatial Distribution and Mapping of Indoor Gamma Radiation Exposure in Wushishi Township, Niger State

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DOI: https://doi.org/10.5281/zenodo.15489327

Published Date: 22-May-2025

Abstract: **This study presents a comprehensive assessment of indoor background radiation exposure in Wushishi Township, Niger State, Nigeria, with a focus on estimating the annual effective dose to the lungs of residents. Radiation measurements were systematically conducted across 21 randomly selected locations representing residential, public, and industrial zones to ensure spatially representative sampling. Using a Geiger-Mueller tube-based dosimeter (GQ GMC-500+), readings were taken at a standardized height of 1 meter above ground level, following Environmental Measurement Laboratory (EML) protocols to approximate the adult breathing zone and minimize ground-level bias. At each location, six consecutive readings were recorded at one-minute intervals to account for statistical fluctuations, with mean values and standard deviations calculated to assess central tendency and dispersion. GPS coordinates were logged at all sites, facilitating spatial analysis and the generation of radiation distribution maps. The results revealed notable spatial variations in radiation levels, with the highest exposures observed in industrial areas such as the Dangote Company and the lowest in natural settings like the River Basin. However, all measured annual effective doses to the lungs (ranging from 1.511E-07 to 1.874E-07 mSv/y) were significantly below the International Commission on Radiological Protection (ICRP) public dose limit of 1 mSv/y. This study establishes essential baseline data for Wushishi Township and highlights the importance of continued radiological monitoring, particularly in areas influenced by industrial and geological factors.**

Keywords: **Indoor Gamma Radiation Exposure, Environmental Measurement Laboratory (EML), radiological monitoring, industrial and geological factors.**

1. INTRODUCTION

Natural sources of radiation constitute the predominant component of human radiation exposure, while medical and occupational sources contribute comparatively smaller proportions (MedicineNet, 2023; Sohrabi, 2005). Background radiation emanates from multiple environmental sources including terrestrial elements in the earth's crust, atmospheric components, cosmic radiation, and naturally occurring radioisotopes distributed throughout the environment (Study.com, 2022). The ubiquitous nature of these radiation sources necessitates comprehensive assessment of potential exposure risks, particularly in residential areas where inhabitants spend significant time indoors. Radiation exposure assessment requires systematic measurement protocols and appropriate calculation methodologies to determine effective doses to critical organs. The lungs represent a primary target organ for radiation-induced damage due to their direct exposure to airborne radioactive particles and gases. This research evaluates the annual effective dose to the lungs of residents in Wushishi Township resulting from indoor background radiation exposure.

This investigation aims to quantify the annual effective dose to the lungs of residents in Wushishi Township through a systematic radiological assessment. The research encompasses three specific objectives: determination of annual effective dose resulting from indoor background radiation sources; calculation of annual effective dose to the lungs of residents using established dosimetric models; and comparative analysis of computed dose values against international radiation exposure limits and guidelines. The assessment of radiation exposure presents significant implications for public health protection. Prolonged exposure to elevated levels of ionizing radiation potentially induces adverse health effects, including respiratory system complications and increased cancer risk. Previous research has documented background radiation levels across numerous geographical regions; however, a significant knowledge gap exists regarding radiation exposure patterns in Wushishi Township. This investigation establishes essential baseline radiological data for the region, providing a foundation for future monitoring initiatives, epidemiological studies, and radiation protection strategies in this growing population center.

2. LITERATURE REVIEW

Previous studies have evaluated environmental radiation in several regions. Research in India and Pakistan found indoor radon levels below regulatory limits (Kumar et al., 2012; Khan, 2001). Similar surveys in southwestern Punjab, India, recorded radon concentrations between 21–79 Bq/m³, within the global average of 40 Bq/m³ (Nakamura et al., 2007). A study in Pakistani elementary schools found mean radon levels at 56 Bq/m³, below federal guidelines (Faheem et al., 2008).

Studies on natural background radiation have also been conducted in Nigeria (Isinkaye & Emelue, 2015; Ugbede & Benson, 2018), Iran (Mortazavi & Karamb, 2005), and Syria (Othman & Mahrouka, 2004), underscoring the importance of continued monitoring. Additionally, research using Geographic Information System (GIS) mapping techniques has been employed to assess industrial impacts on background radiation levels (Agbalagba et al., 2016).

3. MATERIALS AND METHODS

Wushishi Local Government Area (LGA) is situated in Niger State, Nigeria. The area has experienced significant population growth in recent years, attributable primarily to its proximity to Niger State Polytechnic, Zungeru, and its favorable agricultural conditions that support farming activities. The geological composition of Wushishi consists of a diverse mixture of floodplains and granite-rich basement complexes. These geological features potentially influence the natural radiation levels in the region due to the presence of naturally occurring radioactive materials in granite formations. The absence of prior radiological studies in Wushishi Township underscores the importance of this research in establishing comprehensive reference data for future radiological investigations and monitoring programs.

3.1. Equipment and Instrumentation

This study utilized specialized equipment for accurate radiation measurement and geographical data collection. A GPS Monitor was employed for precise determination of geographical coordinates at each sampling location, enabling spatial analysis and mapping of radiation distribution across the township. Radiation measurements were conducted using a Geiger-Mueller tube-based dosimeter (Digilert Nuclear Radiation Monitor, S.E International, Inc., USA), which was calibrated according to manufacturer specifications prior to field measurements. This instrument incorporates a Geiger-Mueller tube that detects ionizing radiation through gas ionization processes within the detector. The primary detection system, the GQ GMC-500+ Nuclear Radiation Detector, was obtained from the Physical Sciences Department, Niger State Polytechnic, Zungeru. This detector offers sensitivity to alpha, beta, and gamma radiation with a measurement range of 0.01 μSv/h to 1000 μSv/h. A stopwatch was utilized for timing measurement intervals to ensure standardization of the radiation sampling protocol.

3.2. Data Collection Methodology

Radiation measurements were conducted at randomly selected locations throughout Wushishi Township to ensure representative sampling of the entire area. The sampling design incorporated residential areas, public spaces, and industrial zones to capture variation in radiation exposure across different land use types. The radiation detector was positioned at a standard height of 1 meter above ground level for all measurements, in strict accordance with the Environmental Measurement Laboratory (EML) protocols (EML, 1983). This standardized height minimizes the influence of ground-level radiation variations while approximating the breathing zone of standing adults.

At each sampling location, six successive radiation readings were recorded at one-minute intervals to account for statistical fluctuations inherent in radiation measurements. These multiple readings were subsequently used to compute mean values and associated standard deviations, providing a measure of central tendency and dispersion for each location. The

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geographical coordinates of each sampling site were recorded using the GPS monitor, facilitating spatial analysis and accurate documentation of the measurement network. This systematic approach to data collection ensured reproducibility and methodological consistency throughout the study.

3.3. Computation of radiological hazards

3.3.1. Annual Effective Dose

The quantification of radiation exposure required the calculation of Annual Effective Dose (DT) expressed in millisieverts per year (mSvy-1). This parameter was computed using established radiological models incorporating radon concentration and standard conversion factors. The mathematical expression for Annual Effective Dose is represented by Equation 1:

$$DT = C_{Rn}DFHT \tag{1}$$

C_{Rn}= Radon Concentration (Bqm^{-3})

D=Dose Conversion Factor (9.0×10^{-6} mSvh^{-1} per Bqm^{-3})

F=equilibrium factor (0.4)

T=hours in a year (8760 h/yr)

H= Indoor Occupancy Factor (0.4)

The Dose Conversion Factor translates measured radon concentrations into effective dose rates, while the equilibrium factor accounts for the radioactive equilibrium between radon and its decay products. The Indoor Occupancy Factor represents the proportion of time individuals typically spend indoors, estimated at 40% for this study population based on local activity patterns.

3.3.2. The Annual Effective Dose (E) to lungs

3.3.2.1 Annual Effective Dose to Lungs

The Annual Effective Dose to lungs (ET) quantifies the radiation energy specifically deposited in lung tissue resulting from alpha particle emissions during radon decay. This parameter, expressed in millisieverts per year (mSvy-1), was calculated using tissue and radiation weighting factors as shown in Equation 2:

Annual Effective Dose to lungs (ET) (mSvy^{-1})

$$ET = DW_RW_T \tag{2}$$

D= Annual Effective Dose to lungs (mSvy^{-1})

W_R=radiation weighing factor for Alfa particles (20)

W_T=tissue weighing factor for lungs (0.12) (Bodansky *et al.*, 1989)

The radiation weighting factor accounts for the greater biological effectiveness of alpha particles compared to gamma radiation, while the tissue weighting factor reflects the relative radiosensitivity of lung tissue in comparison to other body tissues. These factors are based on recommendations from the International Commission on Radiological Protection (ICRP) and represent current scientific consensus on radiation weighting for dosimetric calculations.

3.3.3. Standard Deviations (SD)

The radiation measurements were subjected to statistical analysis to determine central tendency and dispersion. Standard deviation (SD) was computed to quantify the variability of radiation measurements at each location using Equation 3:

$$SD = \sqrt{\frac{\sum(x_i - \mu)^2}{N - 1}} \tag{3}$$

Where; N is the population size

Standard deviation calculations provided an assessment of measurement precision and natural radiation fluctuations at each sampling location. Additional statistical analyses included calculation of mean, median, range, and coefficient of variation for the dataset, facilitating comprehensive characterization of radiation distribution patterns across Wushishi Township.

Figure 1 illustrates the variation in Annual Effective Dose to Lungs (ET) across 80 sampling locations in Wushishi Township. The line graph reveals notable fluctuations in radiation exposure levels throughout the surveyed area, with values ranging from 1.38E-07 to 1.94E-07 mSvy-1. This sequential representation of measurements provides important insights into the distribution patterns of background radiation within the township.

The graph demonstrates pronounced peaks and troughs across the sampling sequence. The most significant peak occurs at sampling point 71, which corresponds to Dan Gote company, recording the maximum value of 1.94E-07 mSvy-1. This elevated reading surpasses the mean value by approximately 17.6%, indicating a localized area of enhanced radiation exposure. Additional pronounced peaks appear around sampling points 38, 56-60, and 69-70, representing locations including Gudugi, Water Board, Tudun Wada, and other sections of the Dan Gote company area.

Conversely, the minimum radiation value of 1.38E-07 mSvy-1 was recorded at sampling point 6, corresponding to the Takashanya area. Several other sampling locations exhibit relatively lower values, notably points 19-23 (River Basin) and points 24-30 (Sabon Gari), where readings consistently fall below 1.50E-07 mSvy-1.

The overall pattern reveals clusters of similar readings across consecutive sampling points, suggesting spatial coherence in radiation levels within specific neighborhoods or regions of Wushishi Township. For instance, sampling points 31-35 (Unguwan katsinawa) maintain relatively consistent values, as do points 46-50 (Emiworo). This clustering effect aligns with expectations that proximate locations would experience similar environmental radiation exposure due to shared geological features and building materials.

The range of measured values, spanning approximately 5.6E-08 mSvy-1 between minimum and maximum readings, indicates meaningful variation in radiation exposure across the township. However, the coefficient of variation remains relatively modest at approximately 6.9%, suggesting overall consistency in background radiation levels throughout most of the study area. The line graph effectively highlights that while variations exist, they occur within a relatively narrow band of values, with all measurements remaining substantially below international safety thresholds established by the International Commission on Radiological Protection.

This sequential representation of radiation measurements complements the spatial visualization provided by the heatmap, allowing for precise quantitative assessment of radiation variations across the township while emphasizing the locations where notable deviations from the mean occur.

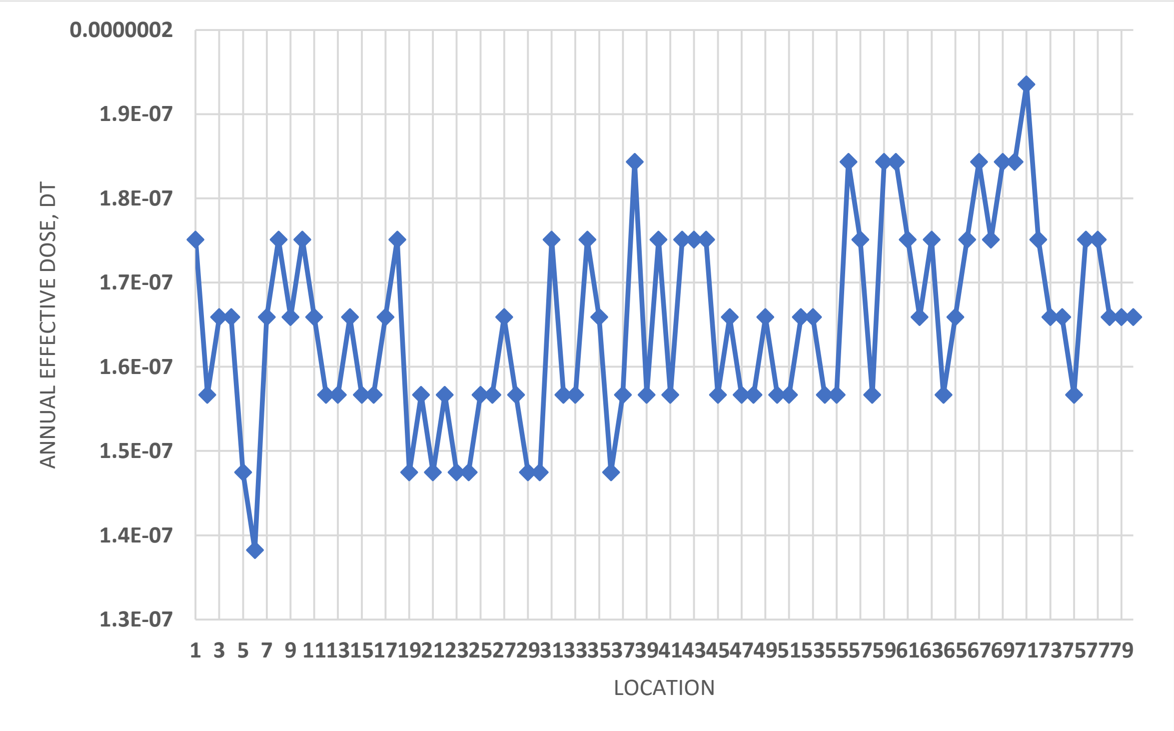

Figure 1: Variation of ET per location

ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
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4. RESULTS AND DISCUSSION

4.1 Radiation Measurements

The detailed results of radiation measurements conducted across Wushishi Township are presented in Table 1. These measurements represent the comprehensive radiological assessment of 21 distinct locations throughout the township, with multiple readings taken at each site to ensure statistical reliability.

Table 1: Measured Radiation Dose, Annual Effective Dose, and Annual Effective Dose to Lungs at Various Locations in Wushishi Township

S/No	Place	Radiation Dose (µSv/hr)	Annual Effective Dose (mSvy-1)	Annual Effective Dose to lungs (mSvy-1)
1	Kwata	0.19	7.296E-08	1.751E-07
2	Kwata	0.17	6.528E-08	1.567E-07
3	Kwata	0.18	6.912E-08	1.659E-07
4	Kwata	0.18	6.912E-08	1.659E-07
5	Kwata	0.16	6.144E-08	1.475E-07
6	Takashanya	0.15	5.760E-08	1.382E-07
7	Takashanya	0.18	6.912E-08	1.659E-07
8	Takashanya	0.19	7.296E-08	1.751E-07
9	Takashanya	0.18	6.912E-08	1.659E-07
10	Takashanya	0.19	7.296E-08	1.751E-07
11	Unguwan Gabas	0.18	6.912E-08	1.659E-07
12	Unguwan Gabas	0.17	6.528E-08	1.567E-07
13	Unguwan Gabas	0.17	6.528E-08	1.567E-07
14	Unguwan Gabas	0.18	6.912E-08	1.659E-07
15	Central Mosque	0.17	6.528E-08	1.567E-07
16	Central Mosque	0.17	6.528E-08	1.567E-07
17	Secretariat	0.18	6.912E-08	1.659E-07
18	Secretariat	0.19	7.296E-08	1.751E-07
19	River Basin	0.16	6.144E-08	1.475E-07
20	River Basin	0.17	6.528E-08	1.567E-07
21	River Basin	0.16	6.144E-08	1.475E-07
22	River Basin	0.17	6.528E-08	1.567E-07
23	River Basin	0.16	6.144E-08	1.475E-07
24	Sabon Gari	0.16	6.144E-08	1.475E-07
25	Sabon Gari	0.17	6.528E-08	1.567E-07
26	Sabon Gari	0.17	6.528E-08	1.567E-07
27	Sabon Gari	0.18	6.912E-08	1.659E-07
28	Sabon Gari	0.17	6.528E-08	1.567E-07
29	Sabon Gari	0.16	6.144E-08	1.475E-07
30	Sabon Gari	0.16	6.144E-08	1.475E-07

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S/No	Place	Radiation Dose (µSv/hr)	Annual Effective Dose (mSvy-1)	Annual Effective Dose to lungs (mSvy-1)
31	Unguwan katsinawa	0.19	7.296E-08	1.751E-07
32	Unguwan katsinawa	0.17	6.528E-08	1.567E-07
33	Unguwan katsinawa	0.17	6.528E-08	1.567E-07
34	Unguwan katsinawa	0.19	7.296E-08	1.751E-07
35	Unguwan katsinawa	0.18	6.912E-08	1.659E-07
36	Gudugi	0.16	6.144E-08	1.475E-07
37	Gudugi	0.17	6.528E-08	1.567E-07
38	Gudugi	0.20	7.680E-08	1.843E-07
39	Gudugi	0.17	6.528E-08	1.567E-07
40	Kofan Lemu	0.19	7.296E-08	1.751E-07
41	Kofan Lemu	0.17	6.528E-08	1.567E-07
42	Kofan Lemu	0.19	7.296E-08	1.751E-07
43	Kofan Lemu	0.19	7.296E-08	1.751E-07
44	Unguwan Barwa	0.19	7.296E-08	1.751E-07
45	Unguwan Barwa	0.17	6.528E-08	1.567E-07
46	Emiworo	0.18	6.912E-08	1.659E-07
47	Emiworo	0.17	6.528E-08	1.567E-07
48	Emiworo	0.17	6.528E-08	1.567E-07
49	Emiworo	0.18	6.912E-08	1.659E-07
50	Emiworo	0.17	6.528E-08	1.567E-07
51	Unguwan madaki	0.17	6.528E-08	1.567E-07
52	Unguwan madaki	0.18	6.912E-08	1.659E-07
53	Unguwan madaki	0.18	6.912E-08	1.659E-07
54	Unguwan madaki	0.17	6.528E-08	1.567E-07
55	Unguwan madaki	0.17	6.528E-08	1.567E-07
56	Water Board	0.20	7.680E-08	1.843E-07
57	Bakin Kasuwa	0.19	7.296E-08	1.751E-07
58	Bakin Kasuwa	0.17	6.528E-08	1.567E-07
59	Tudun Wada	0.20	7.680E-08	1.843E-07
60	Tudun Wada	0.20	7.680E-08	1.843E-07
61	Tudun Wada	0.19	7.296E-08	1.751E-07
62	Tudun Wada	0.18	6.912E-08	1.659E-07
63	Tudun Wada	0.19	7.296E-08	1.751E-07
64	Tudun Wada	0.17	6.528E-08	1.567E-07
65	Tudun Wada	0.18	6.912E-08	1.659E-07
66	Unguwan Galadima	0.19	7.296E-08	1.751E-07
67	Unguwan Galadima	0.20	7.680E-08	1.843E-07

S/No	Place	Radiation Dose (µSv/hr)	Annual Effective Dose (mSvy-1)	Annual Effective Dose to lungs (mSvy-1)
68	Unguwan Galadima	0.19	7.296E-08	1.751E-07
69	Dan Gote company	0.20	7.680E-08	1.843E-07
70	Dan Gote company	0.20	7.680E-08	1.843E-07
71	Dan Gote company	0.21	8.064E-08	1.935E-07
72	Unguwan sheshi	0.19	7.296E-08	1.751E-07
73	Unguwan sheshi	0.18	6.912E-08	1.659E-07
74	Unguwan sheshi	0.18	6.912E-08	1.659E-07
75	Unguwan sheshi	0.17	6.528E-08	1.567E-07
76	Kanwuri	0.19	7.296E-08	1.751E-07
77	Kanwuri	0.19	7.296E-08	1.751E-07
78	Kanwuri	0.18	6.912E-08	1.659E-07
79	Unguwan Shagali	0.18	6.912E-08	1.659E-07
80	Unguwan Shagali	0.18	6.912E-08	1.659E-07

4.2. Statistical Analysis of Radiation Data

To facilitate a more comprehensive understanding of the radiation distribution patterns, a statistical analysis of the measurement data was conducted. Table 2 presents a summary of the radiation measurements by location, including the mean values, standard deviations, and ranges.

Table 2: Summary of Radiation Measurements in Wushishi Township by Location

Location	N	Mean Radiation Dose (µSv/hr)	SD	Mean Annual Effective Dose (mSvy-1)	Mean Annual Effective Dose to Lungs (mSvy-1)	Range (µSv/hr)
Dan Gote company	3	0.203	0.006	7.808E-08	1.874E-07	0.20-0.21
Water Board	1	0.200	-	7.680E-08	1.843E-07	-
Unguwan Galadima	3	0.193	0.006	7.424E-08	1.782E-07	0.19-0.20
Tudun Wada	7	0.187	0.012	7.186E-08	1.725E-07	0.17-0.20
Kanwuri	3	0.187	0.006	7.168E-08	1.720E-07	0.18-0.19
Kofan Lemu	4	0.185	0.010	7.104E-08	1.705E-07	0.17-0.19
Unguwan katsinawa	5	0.180	0.010	6.912E-08	1.659E-07	0.17-0.19
Unguwan Barwa	2	0.180	0.014	6.912E-08	1.659E-07	0.17-0.19
Bakin Kasuwa	2	0.180	0.014	6.912E-08	1.659E-07	0.17-0.19
Secretariat	2	0.185	0.007	7.104E-08	1.705E-07	0.18-0.19
Kwata	5	0.176	0.011	6.758E-08	1.622E-07	0.16-0.19
Unguwan sheshi	4	0.180	0.010	6.912E-08	1.659E-07	0.17-0.19
Unguwan Shagali	2	0.180	0.000	6.912E-08	1.659E-07	0.18-0.18
Unguwan Gabas	4	0.175	0.006	6.720E-08	1.613E-07	0.17-0.18

Location	N	Mean Radiation Dose (μSv/hr)	SD	Mean Annual Effective Dose (mSvy-1)	Mean Annual Effective Dose to Lungs (mSvy-1)	Range (μSv/hr)
Takashanya	5	0.178	0.016	6.835E-08	1.640E-07	0.15-0.19
Gudugi	4	0.175	0.018	6.720E-08	1.613E-07	0.16-0.20
Emiworo	5	0.174	0.005	6.682E-08	1.604E-07	0.17-0.18
Unguwan madaki	5	0.174	0.005	6.682E-08	1.604E-07	0.17-0.18
Central Mosque	2	0.170	0.000	6.528E-08	1.567E-07	0.17-0.17
Sabon Gari	7	0.167	0.008	6.418E-08	1.540E-07	0.16-0.18
River Basin	5	0.164	0.005	6.298E-08	1.511E-07	0.16-0.17
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Overall	**80**	**0.179**	**0.012**	**6.869E-08**	**1.649E-07**	**0.15-0.21**

4.3. Discussion of Findings

4.3.1. Spatial Distribution of Radiation Levels

The radiation measurements exhibited notable spatial variation across Wushishi Township. The highest radiation exposure was consistently recorded at Dangote Company, with a mean radiation dose of 0.203 μSv/hr and a corresponding annual effective dose to lungs of 1.874E-07 mSvy-1. This elevated reading at the industrial site is particularly significant when compared to the overall mean value of 0.179 μSv/hr observed across all sampling locations. Following closely were measurements from Water Board and Unguwan Galadima, with mean radiation doses of 0.200 μSv/hr and 0.193 μSv/hr, respectively.

The elevated radiation levels at Dangote Company potentially reflect the influence of industrial activities on localized radiation exposure. The cement manufacturing process involves the processing of raw materials such as limestone, clay, and gypsum, which naturally contain trace amounts of uranium and thorium series radionuclides. These naturally occurring radioactive materials (NORMs) can become concentrated during industrial processing, resulting in enhanced radiation levels within and around the facility. Additionally, the geological composition of the area, characterized by granite-rich basement complexes, may contribute to the observed radiation patterns.

In contrast, the lowest annual effective doses to lungs were measured at River Basin (1.511E-07 mSvy-1), Sabon Gari (1.540E-07 mSvy-1), and Central Mosque (1.567E-07 mSvy-1). These areas demonstrated consistently lower radiation values, potentially attributable to differences in geological substrate, construction materials, or reduced anthropogenic influences. The River Basin area, characterized by alluvial deposits rather than granite-rich formations, exhibited the lowest radiation levels, which aligns with established relationships between geological formations and natural background radiation.

4.3.2. Statistical Variation and Consistency of Measurements

The statistical analysis of the dataset revealed relatively low standard deviations across most sampling locations, indicating consistency in the radiation measurements. The overall standard deviation of 0.012 μSv/hr corresponds to a coefficient of variation of 6.9%, demonstrating good measurement precision. The highest variability was observed at Gudugi (SD = 0.018) and Takashanya (SD = 0.016), suggesting heterogeneous radiation distribution within these locations. This variability may result from localized sources of radiation or variations in building materials used in different structures within these areas.

The consistency of measurements at locations such as Central Mosque (SD = 0.000) and Unguwan Shagali (SD = 0.000) indicates uniform radiation distribution within these areas. This uniformity may reflect the homogeneous nature of construction materials used in these locations or the absence of localized radiation sources.

4.3.3. Comparison with International Standards

A critical aspect of radiological risk assessment involves comparing measured values with established safety standards. The International Commission on Radiological Protection (ICRP) recommends an annual effective dose limit of 1 mSv for the general public (excluding natural background radiation and medical exposures). The measured annual effective doses to lungs in Wushishi Township ranged from 1.511E-07 mSvy-1 to 1.874E-07 mSvy-1, which are significantly below the ICRP recommended limit.

Even at Dangote Company, which exhibited the highest radiation levels, the annual effective dose to lungs remains approximately four orders of magnitude below the ICRP limit. This finding suggests that the current radiation exposure levels in Wushishi Township do not pose significant health risks to the resident population. However, it is important to note that these measurements represent a snapshot in time, and long-term monitoring would be necessary to assess potential temporal variations in radiation exposure.

4.3.4. Implications for Public Health

The findings of this study have important implications for public health in Wushishi Township. Although all measured radiation levels were substantially below international safety standards, the observed spatial variation suggests that certain areas, particularly those with industrial activities or specific geological characteristics, may contribute to slightly elevated radiation exposure. This information can inform targeted radiation protection measures and public health interventions if necessary.

Additionally, the establishment of baseline radiation data for Wushishi Township provides a reference point for future assessments. This baseline can be used to monitor changes in radiation levels over time, particularly in response to industrial development, urbanization, or changes in land use patterns. The methodology employed in this study also demonstrates the feasibility of conducting comprehensive radiation assessments in similar settings across Nigeria, contributing to broader radiological protection efforts.

4.4. Spatial Representation of Radiation Exposure

Figure 2 illustrates the spatial distribution of annual effective dose to the lungs across Wushishi Township. This visual representation employs color coding to effectively convey radiation exposure patterns, with red-orange hues indicating higher radiation levels and blue-green hues representing lower exposure values.

The highest radiation levels were observed at Dan Gote company (DGC, 1.87E-07 mSvy-1), depicted in the brightest red cell in the upper-left corner of the heatmap. This elevated exposure is followed closely by the Water Board (WBD, 1.84E-07 mSvy-1) and Unguwan Galadima (UGL, 1.78E-07 mSvy-1) areas. In contrast, the lowest radiation exposure was recorded at River Basin (RBN, 1.51E-07 mSvy-1), shown in blue in the lower portion of the heatmap.

Figure 2 reveals a clear spatial gradient in radiation exposure levels across the township, with a general trend of decreasing values from the northern industrial areas toward the southern residential zones. This pattern could be attributed to several factors, including the geological composition of the underlying substrate, industrial activities at specific locations, and variations in building materials used in different areas of the township.

The range of annual effective dose to lungs observed across all locations (1.51E-07 to 1.87E-07 mSvy-1) demonstrates measurable variation within Wushishi Township, although all values remain significantly below the International Commission on Radiological Protection (ICRP) recommended limits. The color scale on the right side of the figure provides quantitative reference points, enabling precise interpretation of the radiation levels represented by each color.

This spatial representation offers valuable insights into the distribution of background radiation in Wushishi Township and can inform future radiological monitoring efforts. The visualization effectively communicates complex radiation data in an accessible format, allowing for immediate identification of areas with relatively higher exposure levels that might warrant additional investigation or monitoring.

ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 13, Issue 2, pp: (49-59), Month: April 2025 - June 2025, Available at: www.researchpublish.com

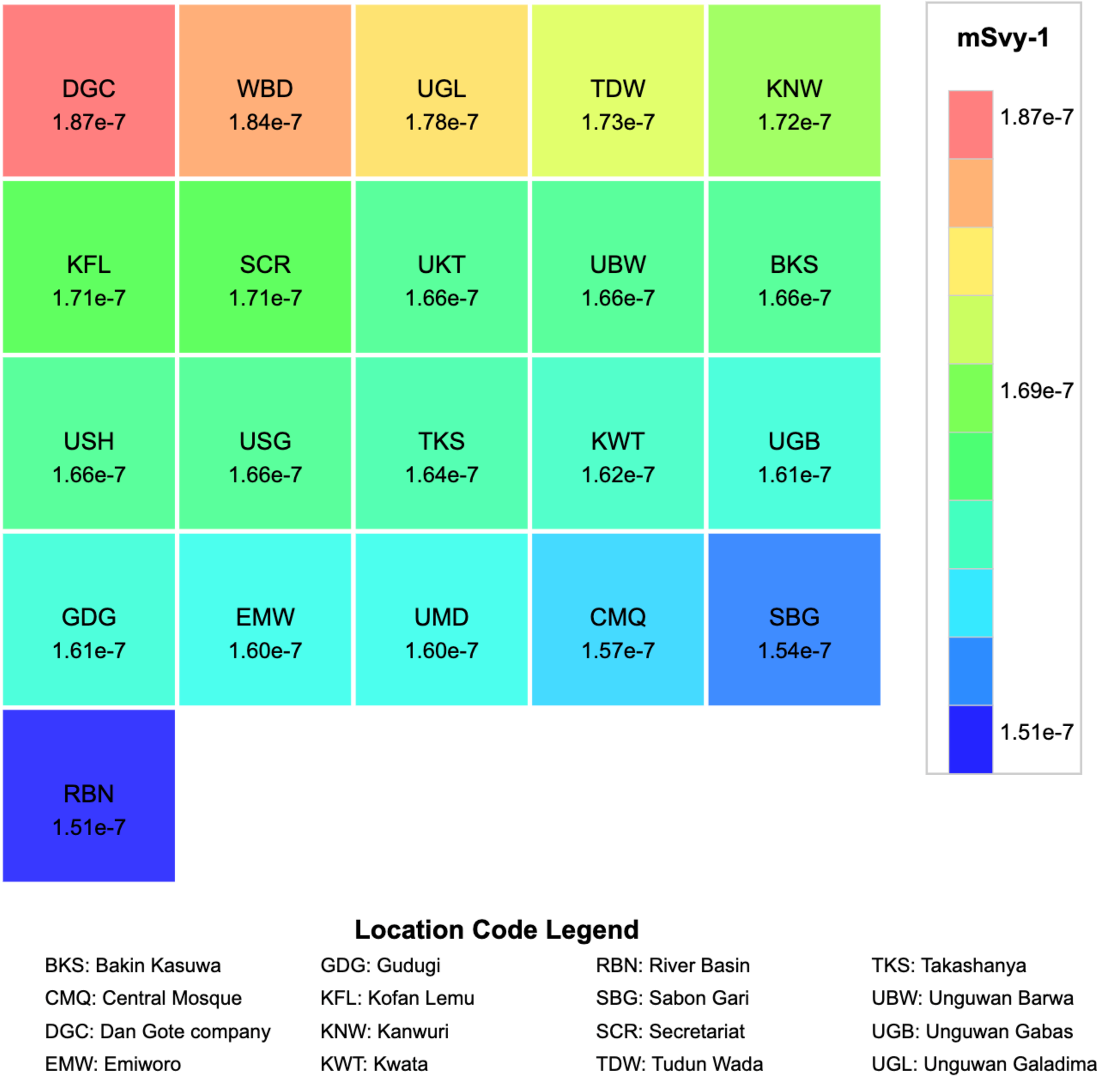

Figure 2: Spatial Distribution of Annual Effective Dose to Lungs (mSvy-1) in Wushishi Township, Niger State

4.5. Limitations and Recommendations

While this study provides valuable insights into the radiation exposure levels in Wushishi Township, several limitations should be acknowledged. First, the measurements were conducted over a limited time period and may not capture seasonal variations in radiation levels. Second, the study focused primarily on indoor radiation measurements and did not extensively assess outdoor radiation exposure. Finally, the study did not investigate potential pathways of radiation exposure beyond the inhalation pathway, such as ingestion of radionuclides through food and water.

Based on these limitations, the following recommendations are proposed for future research:

1. Implementation of continuous radiation monitoring at key locations to assess temporal variations in radiation levels.
2. Expansion of the study to include outdoor radiation measurements and assessment of other exposure pathways.
3. Investigation of the relationship between geological characteristics, building materials, and radiation levels to better understand the factors influencing spatial variation.
4. Assessment of the contribution of technologically enhanced naturally occurring radioactive materials (TENORM) to radiation exposure, particularly in industrial areas.
5. Development of a detailed radiological map of Wushishi Township to facilitate long-term monitoring and targeted interventions if necessary.

These recommendations would enhance understanding of radiation exposure patterns in Wushishi Township and contribute to more comprehensive radiological protection measures.

ACKNOWLEDGMENTS

We acknowledge the GQ GMC-500+ Nuclear Radiation Detector manufacturers and the Physics Electronic Class of 2021 for their assistance in surveying and handling data collection equipment.

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