Assessment of Radiological Safety of Migmatite Rocks around Bauchi Town, Northeastern Nigeria

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Abstract
This study evaluates the radiological safety and geochemical characteristics of migmatite rocks used as building materials in the Bauchi region of Nigeria. Twenty-four samples were collected and analyzed using gamma-ray spectrometry to determine the activity concentrations of naturally occurring radionuclides, including potassium-40 (40K), uranium-238 (238U), and thorium-232 (232Th). The results indicated elevated levels of radioactivity, with average concentrations exceeding global safety benchmarks. Radiological hazard indices such as the Annual Gonadal Dose Equivalent (AGDE) and Excess Lifetime Cancer Risk (ELCR) were notably above recommended limits, suggesting potential long-term health risks from indoor exposure, although other indices remained within acceptable international thresholds. The study therefore recommends cautious indoor use of these rocks due to elevated natural radioactivity.

INTRODUCTION

In recent decades, the potential health risks associated with prolonged exposure to ionizing radiation have become a significant global concern. Numerous studies have established that exposure to radiation levels above internationally accepted safety limits can result in a range of adverse health effects, including cancers of the lung and blood, genetic mutations, teratogenic effects leading to mental retardation in children, and, in severe cases, death Uyanik et al 2013, Rafique et al 2014. Consequently, there has been growing scientific interest in investigating natural sources of radiation and their potential impact on human health (Abdullahi S. et al 2019)

Natural radiation sources include cosmic rays, solar radiation, and terrestrial radiation from radioactive elements present in the Earth's crust. Among these, rocks and soils are significant contributors to environmental radioactivity due to their content of naturally occurring radionuclides such as potassium-40 (^{40}K), uranium-238 (^{238}U), and thorium-232 (^{232}Th) series isotopes and their decay products (Michalis et al., 2003). These radionuclides are widespread in the environment and are found in air, water, soil, rocks, plants, and, notably, building materials derived from geological formations

It has been reported that approximately 85% of the radiation dose received by the global population originates from natural radioactivity in construction materials (UNSCEAR, 2000). Therefore, the assessment of radiation levels in building materials is essential to ensure that they do not pose significant radiological hazards to occupants. The radioactivity levels in construction materials vary according to the geological origin and geochemical composition of the source materials. Additionally, factors such as the type of residence, ventilation, and building design influence the radiation dose received by individuals (Turhan et al., 2008).

Building materials commonly derived from soil and rocks can be broadly categorized into structural materials (e.g., cement, concrete, mortar, clay bricks), finishing materials (e.g., granite, marble, ceramic), and additive raw materials (e.g., fly ash, gypsum, bauxite, phosphate). The natural radioactivity associated with these materials necessitates detailed investigation to ascertain their compliance with recommended safety standards (Turhan et al., 2008).
Migmatite rocks are a type of metamorphic rock that have undergone partial melting, resulting in a heterogeneous composition comprising a neosome (newly formed melt) and a paleosome (remnant of the original rock). Depending on the extent of melting, migmatites are classified as metatexites, which retain a clear distinction between the paleosome and neosome, or diatexites, which exhibit a more homogeneous, marbled texture (Faure, 1986; Ménager et al., 1993). Rocks with granitic compositions, including migmatites, typically contain elevated concentrations of Uranium and thorium compared to basaltic or ultramafic rocks. On average, granitic rocks may contain approximately 5 ppm of uranium and 15 ppm of thorium, whereas basaltic rocks generally contain less than 1ppm of uranium.
In Nigeria, particularly in the Bauchi area, migmatite rocks are abundant and increasingly utilized as substitutes for marble and granite in the production of finishing materials, especially tiles for indoor decoration. However, despite their growing popularity, there is a paucity of specific studies examining the radiological safety of migmatite rocks from this region when used as building materials.

Given the widespread application of migmatite as a decorative material and its potential contribution to indoor radiation exposure, it is imperative to assess its radiological impact to ensure public safety. This study, therefore, focuses on systematically sampling migmatite rocks from both production sites and fresh outcrops within the Bauchi region. The samples are analyzed for their radiological properties. The results are then evaluated against internationally recognized radiation safety thresholds to determine the suitability of migmatite rocks around the study area for use as indoor tiles and other building finishing materials.

Location and Accessibility
The study area lies within latitudes N10’ 3’0” and N 10’27’00” and longitudes 9’36’00E and 10’0’0” E and forms part of sheet 149 Bauchi NE covering a total area of 2450 km2 on a scale of 1:55,000. It locations covered are all within Bauchi administrative area, except for one location at Bagel village. The area is accessible through the major road linking Bauchi to Alkaleri, Bauchi to Maiduguri, Bauchi to kano, Bauchi to Jos and Bauchi to Dass. The outcrops are accessible through minor roads and footpaths.

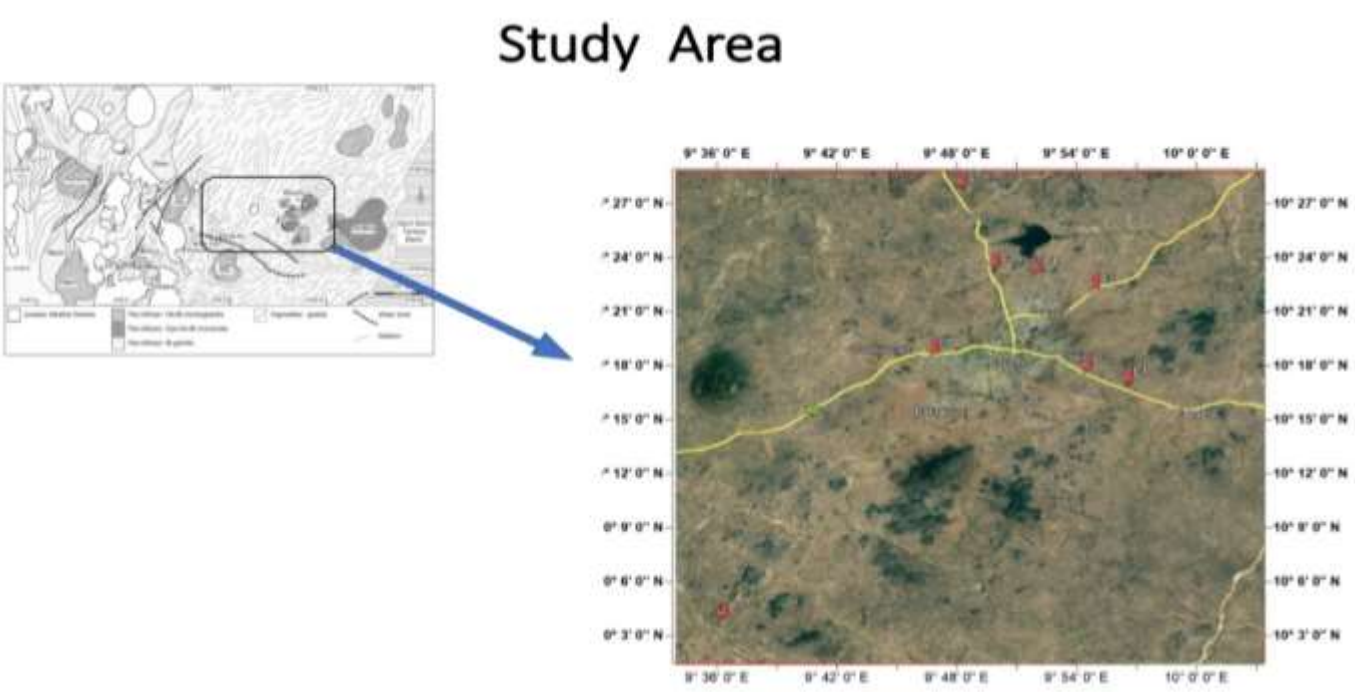

Fig 1: location of study area after geologic map of Bauchi area by Ferré et al (2002). study area displayed in the box and Expanded sampling points on the right.

METHODOLOGY

This study employed a multidisciplinary methodology to evaluate the geochemical characteristics and radiological implications of selected rock samples from the Bauchi area, northeastern Nigeria. The methodology was systematically divided into three major stages:

1. Desk Study and Reconnaissance Survey
2. Sample Collection and Analytical Procedures
3. Data Analysis and Interpretation

Desk Study and Reconnaissance Survey

The preliminary stage of this research involved a comprehensive desk study, which included a review of relevant literature on the geology, radiological background, and geochemical features of the study area. Topographic, structural, and geological maps of the region were reviewed to gain a better understanding of the field layout and lithological distribution. Special focus was placed on the geological map of the Bauchi area, as modified by Ferré et al. (2002), which served as the base map for sample location planning.

A field reconnaissance survey was subsequently conducted to validate the desk study findings and to determine optimal sampling points based on lithological exposure, accessibility, and representation of the dominant rock units, particularly migmatites, which have been previously identified as key lithological units in the region.

Sample Collection and Preparation

A total of twenty-four (24) rock samples were collected from eight distinct sampling locations (three samples per site) across the study area. Each sample was carefully labeled with the sample

ID, location coordinates, and elevation to ensure traceability and to avoid cross-contamination. Samples were stored in labeled Ziploc bags during transport and handling.

The sample locations were selected with reference to earlier works on migmatite formations (Ferré et al., 2002), and the sampling campaign was conducted in November, in accordance with the recommendations by Erbek and Dolmaz (2018), who emphasized dry season sampling to avoid radionuclide migration caused by leaching during the rainy season.

Each collected sample was subjected to gamma spectrometric analysis ensuring cross-validation for accuracy and analytical precision. An average was taken to represent each sample location from the earlier three samples taken per location.

Activity Concentration Measurement

Gamma radiation levels in the collected rock samples were measured using a RS-230 BGO Super-Spec gamma-ray spectrometer, a highly sensitive device equipped with a 1024-channel spectrometer and a large Bismuth Germanate (BGO) detector. The BGO detector offers superior resolution and sensitivity when compared to traditional Sodium Iodide (NaI) detectors.

Measurements were conducted indoors to simulate conditions relevant to the indoor use of these rocks, such as for home tiling or finishing. A 30-second integration time was applied per sample, during which the activity concentrations of Potassium-40 (K, %), Thorium (Th, ppm), and Uranium (U, ppm) were recorded. The average concentration for each radionuclide was calculated across all samples per location.

To convert elemental concentrations into specific activity concentrations (in Bq/kg), the following IAEA (2003) recommended conversion factors were used:
- 1% of K = 313 Bq/kg
- 1 ppm of U = 12.5 Bq/kg
- 1 ppm of Th = 4.06 Bq/kg

These values were subsequently used to estimate the radiological hazard indices associated with the rocks.

Calculation of Radiation Hazard Parameters

Several key radiological hazard indices were calculated using internationally recognized formulas and guidelines:
1. Absorbed Dose Rate in Air (D):
D (nGy/h) = 0.0417AK + 0.462AU + 0.621ATh
2. Annual Effective Dose Equivalent (AEDE):
AEDEout = D × 8760 × 0.2 × 0.7 × 10^-6
AEDEin = D × 8760 × 0.8 × 0.7 × 10^-6 (UNSCEAR 2000)
3. Annual Gonadal Dose Equivalent (AGDE):
AGDE (μSv/year) = 3.09AU + 4.18ATh + 0.314AK (Mamont-Ciesla et al. 1982)
4. Excess Lifetime Cancer Risk (ELCR):
ELCR = AEDEin × 70 × 0.05 (Taskin et al. (2009).
5. Gamma Activity Index (Iγ):

$I\gamma = AK/3000 + AU/300 + ATh/200$ (EU 1999)

RESULT

Radio elemental Concentrations and Spatial Distribution

The results of the measured elemental concentrations of naturally occurring radionuclides—Potassium-40 (40K), Uranium-238 (238U), and Thorium-232 (232Th)—in the analyzed rock samples from the study area are presented in Table 1. These results reflect the specific activity concentrations of the radionuclides within the sampled lithologies and provide insight into their spatial distribution across the surveyed locations.

The measured concentrations of 40K varied from Below Detection Limit (BDL) to 1.93%, while 238U ranged from BDL to 8.63 ppm, and 232Th ranged from BDL to 33.47 ppm. The calculated mean concentrations for the entire dataset were 1.68% for potassium, 7.82 ppm for uranium, and 30.47 ppm for thorium. These concentrations indicate a significant enrichment of thorium relative to uranium, which is consistent with the geochemical characteristics of high-grade metamorphic rocks such as migmatites and granitic intrusions, known for hosting elevated levels of thorium and uranium (IAEA, 2003).

The corresponding absorbed dose rates in air, calculated based on these elemental concentrations using UNSCEAR (2000) conversion coefficients, were found to range between 137.23 nGy/h and 152.93 nGy/h, with a mean dose rate of 146.24 nGy/h. These values exceed the global average outdoor dose rate of 59 nGy/h reported by UNSCEAR (2000), suggesting an elevated natural background radiation level in the study area. Such elevated dose rates may be attributed to the underlying lithology, particularly the presence of migmatites and other felsic rocks known for their high natural radionuclide content.

The spatial variation of these concentrations across different sampling sites provides an important foundation for evaluating site-specific radiological hazards, especially where these rocks may be used for domestic or construction purposes. A detailed interpretation of the radiological implications of these results is discussed in subsequent sections.

Table 1: measured activity concentration of radionuclides

SN	U (ppm)	Ka (%)	THR (ppm)	D. rate av
L1	8.63	1.60	28.87	145.97
L2	8.43	1.70	31.73	149.64
L3	7.77	1.73	31.30	149.33
L4	7.57	1.60	31.00	145.73
L5	7.13	1.83	33.47	152.93
L6	8.57	1.93	28.33	148.20
L7	7.17	1.63	29.87	140.87
L8	7.33	1.43	29.17	137.23
MAX	8.63	1.93	33.47	152.93
ADV	7.82	1.68	30.47	146.24
MIN	7.13	1.43	28.33	137.23

Conversion of Radionuclide Concentrations and Dose Rate Estimation

In order to estimate various radiological hazard parameters, it was essential to convert the measured elemental concentrations of 40K (%), 238U (ppm), and 232Th (ppm) into their corresponding specific activity concentrations in becquerels per kilogram (Bq/kg). This conversion was performed using the standard conversion factors recommended by the International Atomic Energy Agency (IAEA, 2003). The adopted conversion factors are as follows:

- 1% of 40K = 313 Bq/kg
- 1 ppm of 238U = 12.35 Bq/kg
- 1 ppm of 232Th = 4.06 Bq/kg

Based on these conversion values, Table 2 presents the calculated specific activity concentrations of the radionuclides in the analyzed samples. The converted concentrations of 40K ranged from 447.59 Bq/kg to 604.00 Bq/kg, 238U from 88.06 Bq/kg to 106.58 Bq/kg, and 232Th from 115.02 Bq/kg to 135.89 Bq/kg. The mean values for the study area were computed to be 526.13 Bq/kg for 40K, 96.65 Bq/kg for 238U, and 140.31 Bq/kg for 232Th.

Subsequently, the absorbed gamma dose rate in air at 1 meter above ground level was calculated using the equation recommended by UNSCEAR (2000):

$D\ (nGy/h) = 0.0417A_K + 0.462A_U + 0.621A_{Th}$

Where AK, AU, and ATh represent the specific activity concentrations (in Bq/kg) of 40K, 238U, and 232Th, respectively.

Application of this formula to the converted data revealed that the absorbed dose rate values for the rock samples ranged from131.14 nGy/h to 146.95 nGy/h, with a mean absorbed dose rate of 140.31 nGy/h. These results significantly exceed the global average absorbed dose rate of 59 nGy/h, as reported by UNSCEAR (2000). The elevated dose rates suggest a relatively high natural background radiation level in the studied area, most likely influenced by the lithological composition—predominantly migmatites and granitic rocks, which are known to host higher concentrations of uranium and thorium-bearing minerals.

This data forms a critical basis for further radiological risk assessment, including the calculation of annual effective dose, excess lifetime cancer risk, and other radiological indices discussed in subsequent sections.

Table 2: activity concentration for U, K, THR and D in BQKG-1

U (Bq**Kg-1)**	K (Bq**Kg-1)**	THR (Bqkg-1)	ABSORBED DOSE RATE **nGyh−1.**
106.58	500	117.21	139.47
104.11	532.1	128.82	146.95
95.96	541.49	127.08	142.76
93.49	500.8	125.86	139.24
88.06	572.79	135.89	146.14
105.84	604.09	115.02	142.13
88.55	510.19	121.27	134.66

90.53	447.59	118.43	131.14
Max. 106.58	Max. 604.09	Max. 135.89	Max 146.95
Adv. 96.65	Adv. 526.13	Adv. 123.70	Adv. 140.31
Min 88.06	Min. 447.59	Min. 115.02	Min 131.14

Radiological Dose Assessment and Hazard Evaluation

The radiological parameters assessed in this study include the Annual Effective Dose Equivalents (AEDE) for both indoor and outdoor exposure, Annual Gonadal Dose Equivalent (AGDE), Excess Lifetime Cancer Risk (ELCR), Hazard Indices (both indoor and outdoor), and the Gamma Activity Concentration Index (Iγ). These parameters were calculated using established models and Conversion factors as recommended by UNSCEAR (2000), the European Commission (EC, 1999), Mamont-Ciesla et al. (1982), and Taskin et al. (2009). The results of these calculations are presented in Table 3.

The indoor annual effective dose equivalent (AEDE_in) was found to range from 0.64 to 0.72 $mSv•y^{-1}$, with a mean value of 0.69 $mSvy^{-1}$. This estimate exceeds the global average of 0.41 $mSvy^{-1}$ for indoor exposure in dwellings as reported by UNSCEAR (2000), indicating elevated indoor radiological risk. The outdoor annual effective dose equivalent (AEDE out) varied between 0.16 and 0.18 $mSvy^{-1}$, with a mean value of 0.17 $mSvy^{-1}$, which is also slightly above the global average of 0.07 $mSvy^{-1}$

Table 3: Results of the calculated radiation hazard parameters

SN	AEDE($mSvy^{-1}$)		AGDE(	HAZARD INDEX		Iγ) (bqkg-1)	ELCR		
	IN	OUT		IN	OUT		IN	OUT	TOTAL
LI	0.98	0.24	976.70	0.86	1.15	1.11	0.34	0.086	0.43
L2	1.03	0.26	1027.66	0.91	1.19	1.17	0.36	0.090	0.45
L3	1.00	0.25	998.12	0.88	1.14	1.14	0.35	0.088	0.44
L4	0.98	0.24	972.60	0.86	1.12	1.11	0.34	0.085	0.43
L5	1.02	0.26	1020.33	0.90	1.14	1.16	0.36	0.090	0.45
L6	1.00	0.25	997.94	0.87	1.15	1.13	0.35	0.087	0.44
L7	0.94	0.24	941.08	0.83	1.07	1.07	0.33	0.083	0.41
L8	0.92	0.23	915.68	0.81	1.06	1.04	0.32	0.080	0.40
ADV	0.98	0.25	981.26	0.87	1.13	1.12	0.34	0.086	.0.43

The Annual Gonadal Dose Equivalent (AGDE), which reflects the dose received by sensitive reproductive organs and is crucial for assessing potential hereditary effects, showed values ranging

from 915.68 to 1020.33 μSv/y, with a mean value of 981.26 μSvy^{-1}. This significantly surpasses the safe threshold of 300 μSvy^{-1} recommended by Xinwei et al. (2006), suggesting a potential radiological concern in terms of genetic impacts on the population.

The hazard index (HI), which provides an assessment of potential health risks from exposure to natural radionuclides, revealed values for indoor exposure (Hin) ranging from 1.06 to 1.19, with an average of 1.13. Similarly, outdoor hazard indices (Hout) ranged from 0.81 to 0.91, with a mean value of 0.87. Notably, an HI value exceeding unity (1) indicates a possible radiological health risk, particularly in indoor environments.

The gamma activity concentration index (Iγ), used to assess the suitability of materials for construction based on gamma radiation levels, ranged between 1.04 and 1.17, with a mean value of 1.12 $Bq \bullet kg^{-1}$. This average is above the safety limit of 1.0 recommended by the European Commission (1999), which implies that some materials or environmental components in the study area may not meet international radiological safety standards.

Finally, the Excess Lifetime Cancer Risk (ELCR_in), which estimates the probability of developing cancer over a lifetime due to indoor radiation exposure, was calculated to have a mean value of 0.34×10^{-3}, with individual values ranging from 0.32×10^{-3} to 0.36×10^{-3}. These values are significantly higher than the global average of 0.29×10^{-3} (UNSCEAR, 2000), indicating a potentially elevated long-term cancer risk for residents of the area.

DISCUSSION OF RESULTS

ACTIVITY CONCENTRATIONS

- The elemental analysis results presented in Table 1 indicate that the average concentrations of uranium (U), potassium (K), and thorium (Th) in the sampled rocks are 7.80 ppm, 1.68%, and 30.47 ppm, respectively. When compared with the global average crustal values—2.35% for K, 3 ppm for U, and 12 ppm for Th. it is evident that both uranium and thorium concentrations in the study area exceed global norms, whereas potassium levels are slightly below the average (IAEA, 2003).
- Similarly, when these elemental concentrations are converted to specific activity concentrations in becquerels per kilogram ($Bq\ kg^{-1}$), as presented in Table 2, the average activity concentrations for U, K, and Th are 96.65 $Bq\ kg^{-1}$, 526.13 $Bq\ kg^{-1}$, and 123.70 $Bq\ kg^{-1}$, respectively. These values are significantly above the global average activity concentrations of 33 $Bq\ kg^{-1}$ for U, 420 $Bq\ kg^{-1}$ for K, and 45 $Bq\ kg^{-1}$ for Th, as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000). This suggests an enrichment of natural radionuclides within the lithologies of the study area.
- Figure 2 illustrates the relative distribution of the radionuclides (U, K, and Th) across the analyzed samples. The plot demonstrates a generally uniform pattern of distribution, particularly in terms of each radionuclide's percentage contribution to the total absorbed dose rate, reinforcing the observation of consistent geochemical behavior across the sampled rocks.

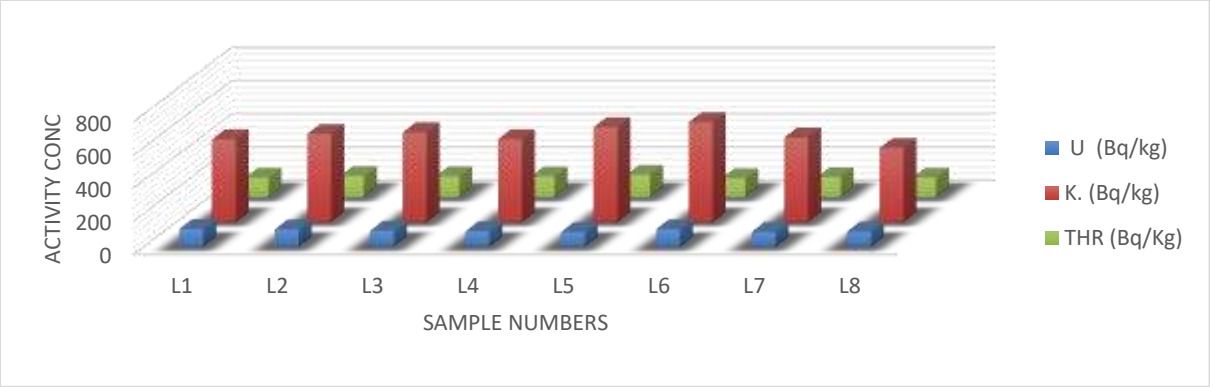

Fig 2: Activity concentrations chat of U, K, THR in each sample bqkg-1

CORRELATION ANALYSIS

Correlation analysis was conducted to assess the relationship between the absorbed dose rates (nGy h^{-1}) and the activity concentrations of naturally occurring radionuclides potassium-40 (^{40}K), uranium-238 (^{238}U), and thorium-232 (^{232}Th). The correlation analysis was also used to assess the relationship between dose rate and AEDEin. The resulting scatter plots (Figures 3, 4, 5 and 6) showed a positive correlation between the absorbed dose rate and each radionuclide as well as the dose rates against the AEDEin.

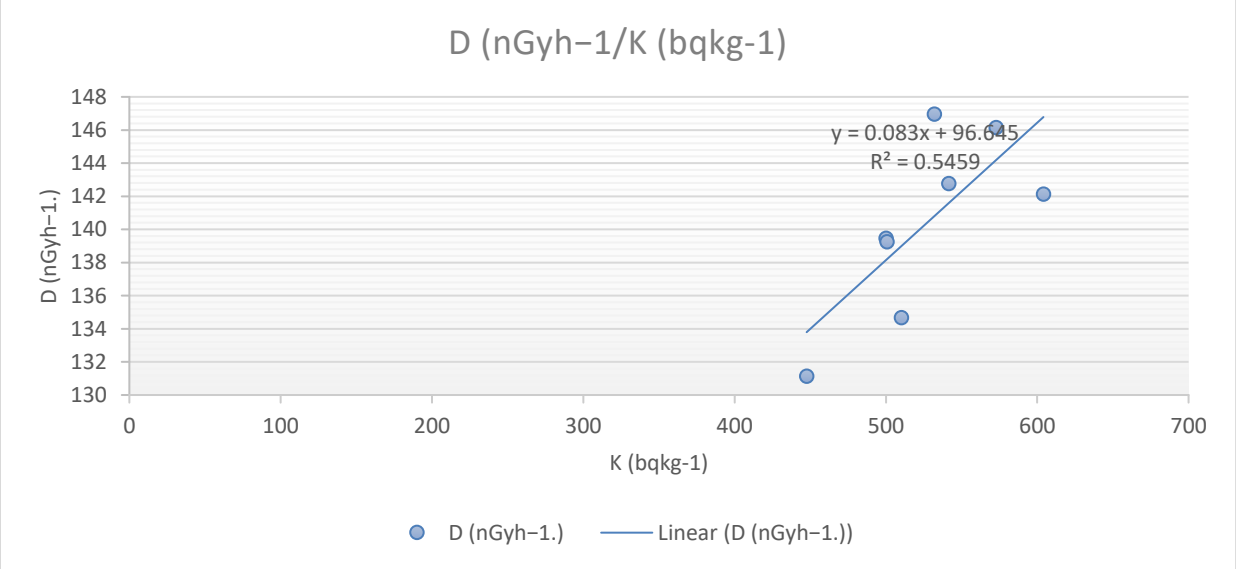

Fig 3: correlation plot of D (nGyh−1)/K (bqkg-1)

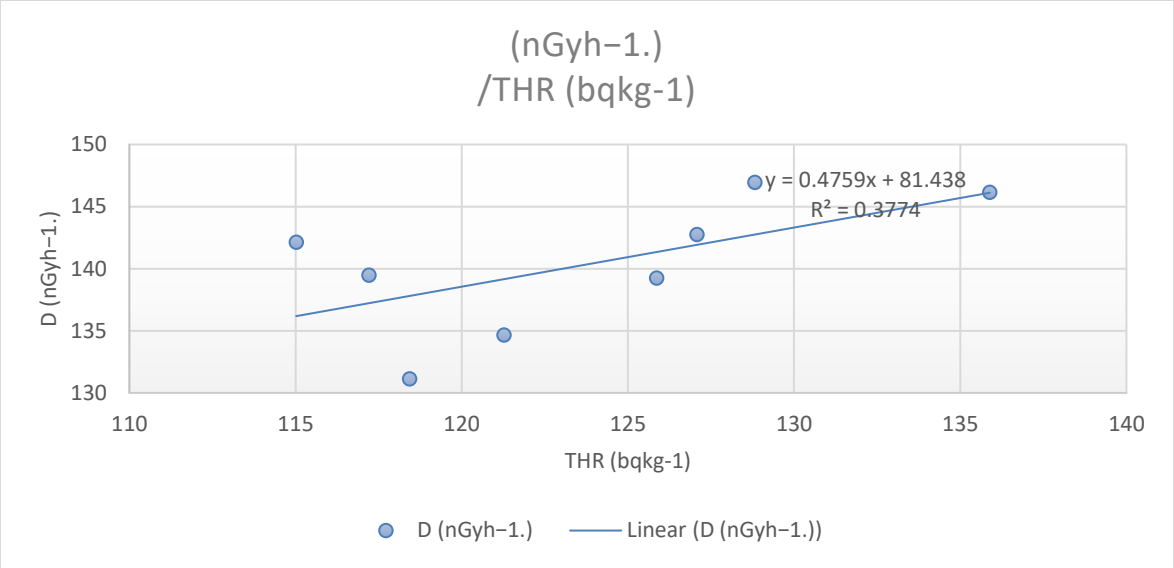

Fig 4: correlation plot of D (nGyh−1)/THR (bqkg-1)

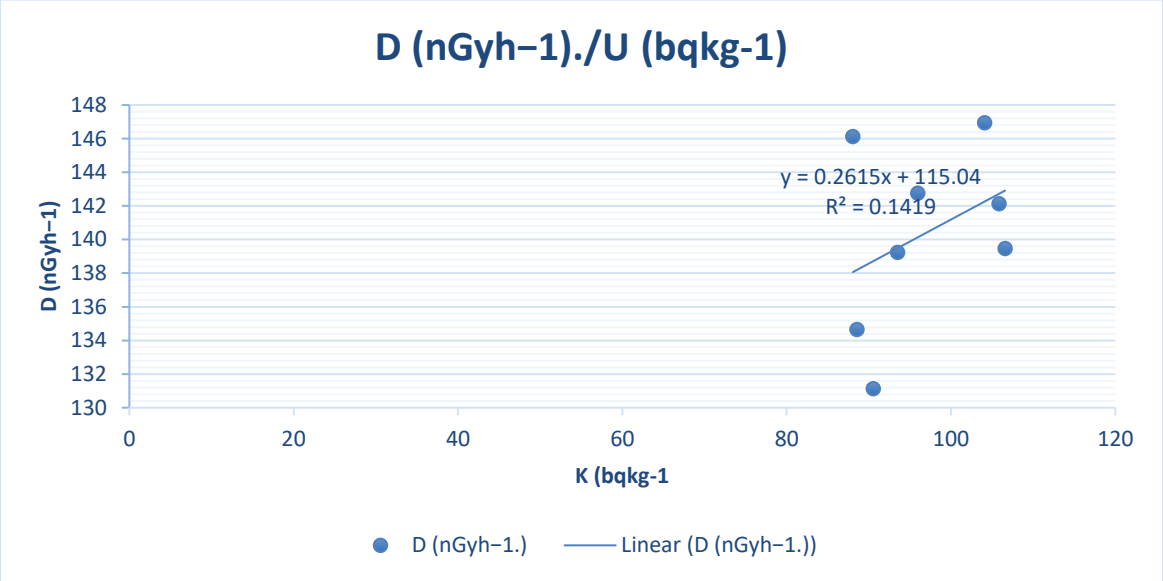

Fig 5: correlation plot of D (nGyh−1)/U (msvy-1)

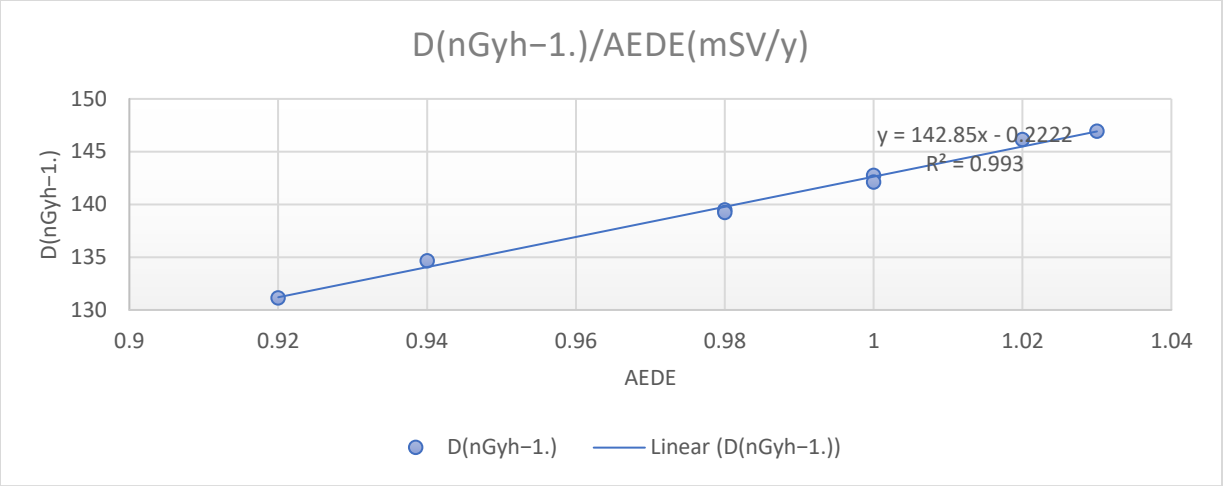

Fig 6: correlation plot of D (nGyh−1)/AEDE (msvy-1)

The highest correlation coefficient was observed for ^{40}K (r = 0.5459), followed by ^{232}Th (r = 0.3774), whereas ^{238}U exhibited a much weaker correlation (r = 0.1419). This indicates that potassium is the primary radionuclide influencing the observed dose rate in the area. Similarly, the dose rate against the AEDEin indicated a strong correlation coefficient of 0.993 suggesting that variations in gamma dose rate account for nearly all variations in AEDE, which is consistent with the direct dependence of AEDEin on gamma dose rate through established dose conversion factors. The high correlation further confirms the internal consistency and reliability of the radiological data obtained in this study.

Table 6: Range of absorbed dose rate in the air in some countries compared with values for the study area.

S/N	Country	D (nGy/h)	S/ Source
1	United States	38	Oakley 1972
2	CHINA	99	NEPA 1990
4	JAPAN	53	Abe et al 1980
5	France	75	Rannou et al 1985
6	Hong Kong	200	Wong et al 1999
7	WORLD	60	UNSCEAR (2000)
8	BAUCHI (NIGERIA)	140.1	Current work

Annual effective dose, radiological hazard indices, gamma activity index, activity utilization index, annual gonad dose equivalent and excess life cancer risk

AEDE tries to estimate the amount of dose of radiation a person is exposed to annually. It is critical for determining the possible effects of radiation over time. From the result in table 3 above, the estimated average of AEDE for both outdoor and indoor are 0.17 and 0.69 respectively which are above the average worldwide limits of 0.07 mSvy−1 and 0.41 mSvy−1 respectively (UNSCEAR 2000), but estimated average of the indoor and outdoor are both lower than the world upper limit of 1 mSvy−1 (ICRP 1977) which puts the result within safe limits. Fig:8 below shows the distribution of the dose rates across the study area showing fair distribution affirming the fact that we are dealing with same rock units.

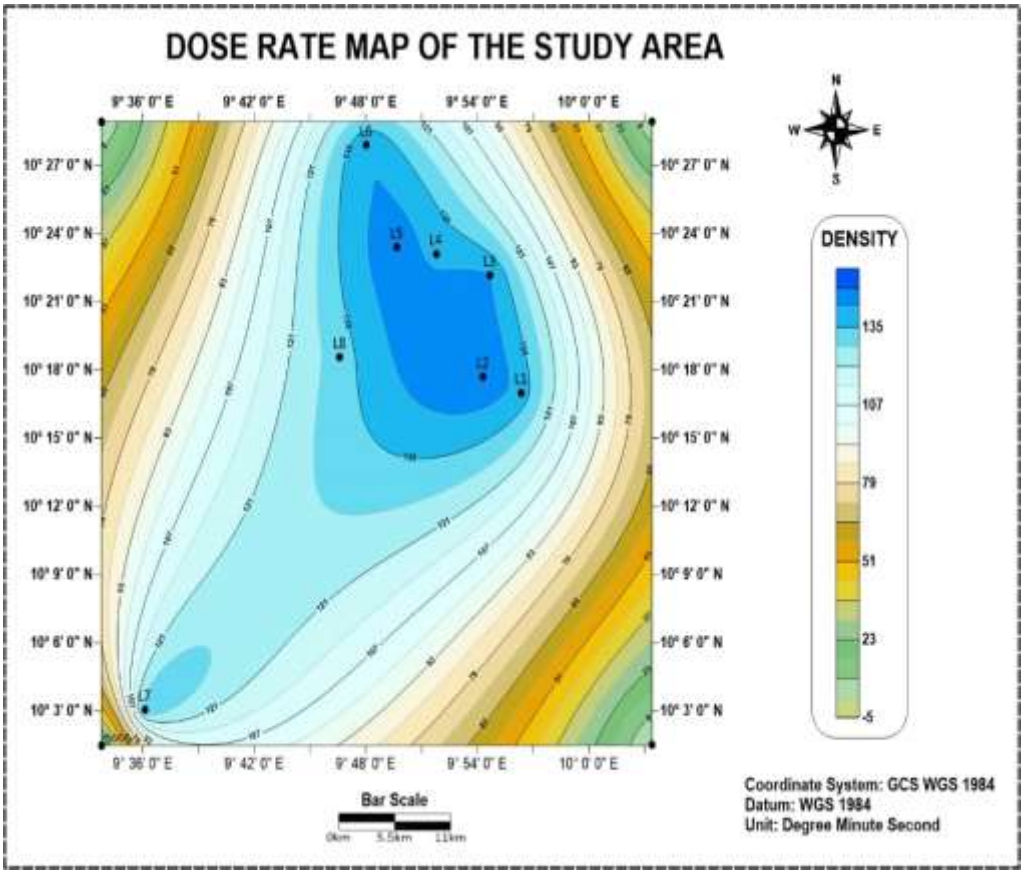

Fig:7: Dose rate density map

Radiological Hazard Assessment

The radiological parameters assessed in this study include the Annual Gonadal Dose Equivalent (AGDE), Hazard Indices (Hex and Hin), Gamma Activity Index (Iγ), and Excess Lifetime Cancer Risk (ELCR). These indices are crucial for evaluating the potential health impacts of prolonged exposure to natural background radiation from rocks, particularly when such materials are used in construction or occur near inhabited environments.

Annual Gonadal Dose Equivalent (AGDE)

The AGDE specifically estimates the radiation dose absorbed by the human reproductive organs, which are highly sensitive to ionizing radiation. This index is of particular concern as exposure to reproductive tissues can lead to heritable genetic mutations in future generations (Xinwei et al., 2006). In this study, the average AGDE value was found to be 981.26 μSv y^{-1}, which significantly exceeds the global average of 300 μSv y^{-1} as reported in natural background studies. Although the calculated value does not exceed internationally recognized intervention levels, it suggests the need for caution in the use of these rocks in environments where long-term or close human contact is expected.

Hazard Indices (Hex and Hin)

Hazard indices are used to estimate the potential radiological risk posed by internal and external exposure to naturally occurring radionuclides. The external hazard index (Hex) estimates the risk from gamma radiation emitted by materials used in buildings, while the internal hazard index (Hin)

assesses risks from inhalation or ingestion of radioactive particles particularly radon and its progeny which primarily affect the lungs and respiratory system (Hamzah et al., 2008). In this study, Hex values ranged from 0.81 to 0.91 and Hin values ranged from 1.06 to 1.19, with respective average values of 0.87 and 1.13. These results are within the globally recommended safety limits (≤2) corresponding to an annual effective dose below 0.3 mSv y^{-1}, and also remain below the upper threshold of 1 mSv y^{-1} set by the International Commission on Radiological Protection (ICRP, 1977).

Gamma Activity Index (Iγ)

The Gamma Activity Index (Iγ) is another important metric for assessing the potential radiological risk from building materials. It is used primarily for regulatory control of materials containing naturally occurring radionuclides (EC, 1999). In this study, the Iγ values ranged from 1.04 to 1.17, with a mean value of 1.12. All values are well below the recommended threshold of $I\gamma \leq 2$, which corresponds to an annual effective dose of 0.3 mSv y^{-1}, and are far lower than the upper limit of 1 mSv y^{-1}, indicating that the use of these rocks in construction does not pose a significant radiological hazard in terms of gamma exposure.

Excess Lifetime Cancer Risk (ELCR)

The ELCR estimates the probability of an individual developing cancer over a lifetime due to continuous exposure to radiation. This measure considers the cumulative dose over time and the average life expectancy of the population. In this study, the average ELCRin value was calculated to be 0.34×10^{-3}, which is higher than the global average value of 0.29×10^{-3} as reported by UNSCEAR (2000) and Tufail et al. (2007). While the ELCR value observed in this study is not immediately alarming, it does suggest the need for precautionary measures, particularly for occupational or residential scenarios involving prolonged exposure. For context, the benchmark relocation limit used during the Chernobyl nuclear disaster was 350 (J.Odoherty et al 2018), which is still significantly higher than the cumulative doses inferred from this study. Nevertheless, the elevated ELCR values highlight the importance of minimizing chronic exposure to naturally radioactive materials, especially in vulnerable populations.

CONCLUSION

Radiological analyses revealed that the concentrations of uranium (7.80 ppm), thorium (30.47 ppm), and potassium (1.68%) exceed or approach global crustal averages (IAEA, 2003). When converted to specific activities, the average values of ^{40}K (526.13 Bq kg^{-1}), ^{238}U (96.65 Bq kg^{-1}), and ^{232}Th (123.70 Bq kg^{-1}) were all higher than the global baseline values reported by UNSCEAR (2000), suggesting elevated natural radioactivity in the study area.

Correlation analysis showed a strong positive relationship between absorbed dose rate and the activity concentrations of potassium and thorium, with weaker correlation observed for uranium. This suggests that while K and Th significantly contribute to external dose rates due to their mineralogical abundance and distribution, uranium's lesser influence may reflect geochemical leaching or its depletion in metasedimentary protoliths (Braun et al., 1993, 1998).

The calculated average Annual Gonadal Dose Equivalent (AGDE) of 981.26 µSv y^{-1} exceeded the global reference level of 300 µSv y^{-1}, implying a potential radio-genetic risk, especially under conditions of chronic exposure (Xinwei et al., 2006). However, both the external (Hex) and internal hazard indices (Hin) remained below international thresholds of concern (Hamzah et al.,

2008), suggesting acceptable levels of risk for occasional or indirect human interaction. The Gamma Activity Index (Iγ) also remained within safe limits (EC, 1999).

Importantly, the Excess Lifetime Cancer Risk (ELCR) indoor was higher than global averages, with a mean value of 0.34×10^{-3}compared to the recommended global benchmark of 0.29×10^{-3} (UNSCEAR, 2000; Tufail et al., 2007). While not indicative of immediate threat, this elevated risk underscores the necessity for controlled use of these rocks, particularly in construction or areas of prolonged human occupancy.

In conclusion, the migmatites rocks around Bauchi town exhibit elevated natural radioactivity, warranting precautionary application in human environments. Although the overall radiation risk remains within acceptable global limits, the findings highlight the importance of continuous monitoring, especially when these materials are intended for use in public infrastructure or residential involving prolonged exposure.

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