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Environmental radiation levels in farmlands and associated health impacts in selected areas of Kogi State, Nigeria

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ABSTRACT

Monitoring environmental radiation in farming communities is important for safeguarding agricultural production and protecting the people whose livelihoods depend on the land. This study examined ambient gamma radiation levels at 20 farmland sites across four local government areas of Kogi State, Nigeria. Measurements were made with a portable radiation survey meter, while a Global Positioning System (GPS) device was used to record the coordinates of each sampling point. Ambient radiation levels were recorded at each site, and average dose rates were subsequently calculated. The results revealed a mean annual radiation level of $1.4833\,\mathrm{mSv\,y^{-1}}$, with values ranging from 0.8766 to $2.279\,\mathrm{mSv\,y^{-1}}$; the highest value was reported in Ajaokuta. The mean values of the absorbed dose rate (ADR), annual effective dose rate (AEDR), radium equivalent activity (Ra_{eq}), external hazard index (H_{ext}), internal hazard index (H_{int}), and excess lifetime cancer risk (ELTCR) were 79.4447 ± 12.87, 0.0975 ± 0.02, 174.7444 ± 30.89, 0.4720 ± 0.08, 0.6147 ± 0.10, and 0.3412 ± 0.06, respectively. Comparison with international radiation-protection benchmarks suggests that farmers and rural dwellers in the study areas are not currently exposed to levels that pose an immediate health threat. Nevertheless, a few isolated hotspots recorded elevated readings and should be monitored to guard against possible long-term effects. Overall, this work highlights the importance of sustained environmental monitoring and provides baseline radiometric data for agricultural zones in Kogi State.

Keywords: Ambient gamma radiation, Absorbed dose rate, Excess lifetime cancer risk, Kogi State

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1. INTRODUCTION

Naturally occurring radioactive materials (NORM) in the terrestrial environment are an important consideration in public-health protection. Ionizing radiation from the ^{238}U, ^{232}Th, and ^{40}K series contributes to the radiation dose received by the human population [1]. Although these radionuclides are widespread, their concentrations vary considerably with local geology and anthropogenic activities such as mining, mineral processing, and the use of phosphate fertilizers, which can convert NORM into technologically enhanced naturally occurring radioactive materials (TENORM) [2, 3].

This study provides a structured assessment of ambient radiation in Ajaokuta, Lokoja, Omala, and Ankpa, estimates the annual effective dose equivalent, and evaluates selected radiological hazard indices. The study area spans two geological provinces, which may influence the observed radiometric signatures.

2. MATERIALS AND METHODS

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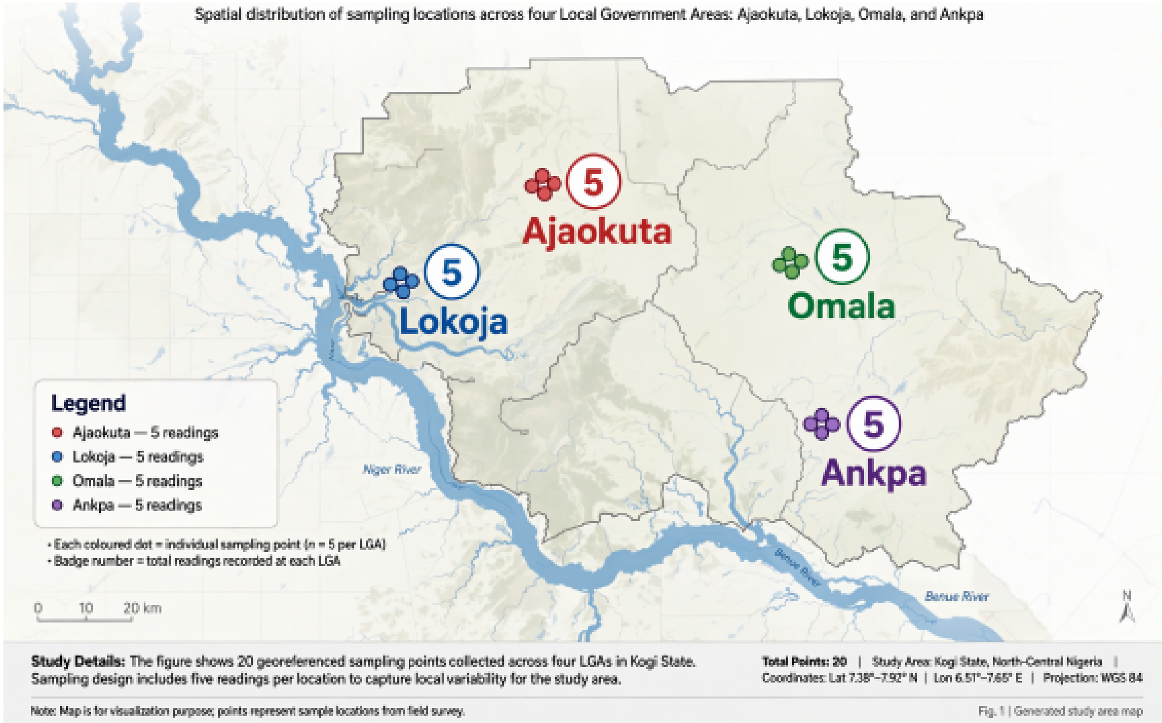

Figure 1. Map of Kogi State showing the sampling locations.

2.1. STUDY AREA

Kogi State is in north-central Nigeria and has a population of about 4,473,500 and an area of more than $29,833$ km^2. It lies around $7°45'0.00''$ N and $6°45'0.00''$ E (National Population Census, 2011). Agriculture is central to the state economy, with products including coffee, cocoa, palm oil, cashews, groundnuts, maize, cassava, yams, rice, and melon. The state is also rich in mineral resources. Ocheje and Tyovenda [4] reported coal, limestone, iron, petroleum, and tin resources in the state. Obajana Cement Factory, one of the largest cement factories in Africa, and Ajaokuta Steel Company Limited, the largest iron and steel company in Nigeria, are also located in the state.

The eastern part of the state, including Omala and Ankpa, lies within the Anambra Basin. The geology of this area is characterized by the Cretaceous Mamu Formation (Lower Coal Measures) and the overlying Ajali Sandstone. The Mamu Formation contains important coal seams and carbonaceous shales that can act as uranium geochemical traps. The Ajali Sandstone is highly porous and may allow migration of $^{222}\mathrm{Rn}$ gas from underlying sources.

2.2. METHODS

This study used *in situ* measurements to determine terrestrial outdoor radiation-exposure rates. Measurements were made using a standard field procedure to preserve the native environmental characteristics of the sampling locations. The detector tube was positioned 1.0 m above ground level. This height approximates the vital-organ level of an adult, reduces the effect of immediate soil micro-heterogeneity and alpha/beta-particle contributions, and averages the gamma field over a representative area. At each sampling coordinate, four readings were taken with the detector window facing north (F1), east (F2), south (F3), and west (F4).

The survey covered 20 farm sites in four local government areas. Five towns were randomly selected in each local government area, and the precise coordinates of the five locations were recorded using Global Positioning System (GPS) technology. GPS positions were recorded in decimal degrees for use in Geographic Information System (GIS) software.

A Radalert-100 meter was used to measure the radiation exposure rate. The instrument was a Radalert 100X nuclear radiation monitor (model R100X), a portable calibrated Geiger counter manufactured by Medcom, Inc., USA. The radiation exposure rate was recorded three times at each sampling point, and the mean of the three measurements was used as the final exposure rate. The radiation exposure rate, initially recorded in $\mu\mathrm{Sv\,h^{-1}}$, was converted to $\mathrm{mR\,h^{-1}}$ by multiplying by 0.1. Measurements were made between 10:00 AM and 4:00 PM, following the recommendation cited from the National Council on Radiation Protection and Measurements [5], because meter readings are expected to be more stable during this period, when environmental parameters such as solar intensity, atmospheric temperature, and humidity are relatively stable.

To reduce possible environmental variation, readings were made at 4-min intervals. The exposure-rate data were later analysed quantitatively with their standard deviations to assess radiation health risks to nearby populations [6]. Radiation models were used to calculate radiation health-risk indices from the measured exposure rates. The indices included absorbed dose rate (ADR), annual effective dose equivalent (AEDE), equivalent dose rate (EDR), and excess lifetime cancer risk (ELCR).

2.3. TRANSFORMATION OF EXPOSURE RATE TO DOSE RATE

The measured exposure rates in $\mathrm{mR\,h^{-1}}$ were converted to absorbed dose rate in air and ambient dose-equivalent rate as recommended in Refs. [7, 8]:

$$1\ \mathrm{mR\,h^{-1}} \approx 8.7\ \mu\mathrm{Gy\,h^{-1}} \approx 8.7\ \mu\mathrm{Sv\,h^{-1}}. \quad (1)$$

2.4. ABSORBED DOSE RATE

The background ionizing radiation (BIR) values obtained for outdoor exposure rate in $\mathrm{mR\,h^{-1}}$ were converted to absorbed dose rate in $\mathrm{nGy\,h^{-1}}$ using [9]

$$D\left(\mathrm{nGy\,h^{-1}}\right) = X\left(\mathrm{mR\,h^{-1}}\right) \times 8.7 \times 10^{3}, \quad (2)$$

where D is the absorbed dose rate and X is the measured exposure rate.

2.5. ANNUAL EFFECTIVE DOSE RATE

The conversion coefficient from absorbed dose in air to effective dose is $0.7\ \mathrm{Sv\,Gy^{-1}}$. This coefficient was used to estimate the annual effective dose rate of the population, taking into account an outdoor occupancy factor of 0.2 and an indoor occupancy factor of 0.8. The outdoor annual effective dose rate (AEDR) was obtained as [6]

$$\mathrm{AEDR}_{out}\left(\mathrm{mSv\,y^{-1}}\right) = D\left(\mathrm{nGy\,h^{-1}}\right) \times 8760\ \mathrm{h\,y^{-1}} \times 0.7\ \mathrm{Sv\,Gy^{-1}} \times 0.2 \times 10^{-6}. \quad (3)$$

Here, 8760 is the number of hours in one year and 10^{-6} is the conversion factor to millisieverts.

2.6. EXCESS LIFETIME CANCER RISK

The excess lifetime cancer risk (ELCR) was computed from the annual effective dose equivalent (AEDE) as

$$\mathrm{ELCR} = \mathrm{AEDE} \times DL \times RF, \quad (4)$$

where DL is the average duration of life (70 years) and RF is the fatal cancer risk factor in $\mathrm{Sv^{-1}}$. For probabilistic effects, ICRP Publications 60 and 106 adopted $RF = 0.05$ for the public [8].

2.7. RADIUM EQUIVALENT ACTIVITY

Radium equivalent activity is an index used to express the combined activity of $^{226}\mathrm{Ra}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ as a single quantity that reflects the radiation hazard associated with these radionuclides. It was estimated as [10]

$$\mathrm{Ra}_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_{K}, \quad (5)$$

where A_K, A_{Ra}, and A_{Th} are the mean activity concentrations of $^{40}\mathrm{K}$, $^{226}\mathrm{Ra}$ ($^{238}\mathrm{U}$), and $^{232}\mathrm{Th}$, respectively. In this expression, $4810\ \mathrm{Bq\,kg^{-1}}$ of $^{40}\mathrm{K}$, $259\ \mathrm{Bq\,kg^{-1}}$ of $^{232}\mathrm{Th}$, and $370\ \mathrm{Bq\,kg^{-1}}$ of $^{226}\mathrm{Ra}$ are assumed to produce the same gamma dose rate; therefore, the activities of $^{226}\mathrm{Ra}$ and $^{238}\mathrm{U}$ are used interchangeably.

2.8. RADIATION HAZARD INDEX

The internal and external hazard indices are defined as [11]

$$H_{int} = \frac{A_K}{4810} + \frac{A_U}{185} + \frac{A_{Th}}{259} \leq 1, \quad (6)$$

and

$$H_{ext} = \frac{A_K}{4810} + \frac{A_U}{370} + \frac{A_{Th}}{259} \leq 1. \quad (7)$$

The external hazard index is derived from radium equivalent activity on the assumption that the maximum recommended value of Ra_{eq}, $370\ \mathrm{Bq\,kg^{-1}}$, corresponds to a radiation dose limit of $1.5\ \mathrm{mSv\,y^{-1}}$. For the radiation hazard to be negligible, the index value should be lower than unity. Values above unity indicate that the area should be adequately assessed to protect people working or living in the area.

2.9. SPATIAL VARIATION

Spatial variation analysis was performed to show the geographical distribution of the measured exposure-dose indicators (F1–F4) in Lokoja, Ajaokuta, Omala, and Ankpa and to examine the relationship between the geographic data and radiological implications for farming communities in these regions.

3. RESULTS

Table 1 presents the average annual ambient radiation levels from the four directional readings at each sampling point. Table 2 gives the activity concentrations of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$, and $^{40}\mathrm{K}$ in the soil samples, while Table 3 summarizes the radiological hazard indices derived from the activity concentrations. The average absorbed dose, AEDR, Ra_{eq}, H_{ext}, H_{int}, and ELTCR values were used to assess the potential radiological implications for the sampled farmlands.

4. DISCUSSION

The global average natural background radiation level is approximately $2.4\ \mathrm{mSv\,y^{-1}}$. The International Commission on Radiological Protection (ICRP) recommends that additional exposure to artificial sources should not exceed $1.0\ \mathrm{mSv\,y^{-1}}$ for the public [8]. The Omala and Lokoja areas have average radiation levels of approximately 1.18 and $1.35\ \mathrm{mSv\,y^{-1}}$, respectively (Table 1), which are within the normal range of natural background radiation. In Ajaokuta, the radiation level is higher, with an average of about $1.49\ \mathrm{mSv\,y^{-1}}$, likely reflecting the local geology and the presence of radioactive elements. Workers in steel-processing zones around such sources should be monitored to ensure that cumulative exposure does not become excessive over time, even when the observed levels do not indicate immediate danger. A person spending only a few hours a day in some areas may exceed the $1\ \mathrm{mSv\,y^{-1}}$ threshold. This suggests that regional coal mining could discharge appreciable quantities of NORM.

The data indicate two broad radiation patterns in Kogi State. The western section, within the Basement Complex, shows higher and more stable natural background radiation, probably because of radioactive potassium ($^{40}\mathrm{K}$) in granitic rocks. Conversely, the eastern region, within the Sedimentary Basin, shows lower background radiation, although localized hotspots may occur because of uranium associated with coal seams. The ELCR

Table 1. Average ambient radiation levels $(\mathrm{mSv\,y^{-1}})$.

No.	Location	Latitude	Longitude	F1	F2	F3	F4
1	Ajaokuta	7.5235	6.5813	1.05192 ± 0.01	2.10384 ± 0.01	0.8766 ± 0.01	1.2272 ± 0.17
2	Ajaokuta	7.5623	6.6550	1.22724 ± 0.01	1.57788 ± 0.01	1.0519 ± 0.12	0.9642 ± 0.02
3	Ajaokuta	7.5640	6.6291	1.05192 ± 0.10	1.7532 ± 0.01	1.7532 ± 0.16	1.9285 ± 0.17
4	Ajaokuta	7.5100	6.6100	1.57788 ± 0.03	1.40256 ± 0.01	2.2791 ± 0.25	1.5778 ± 0.16
5	Ajaokuta	7.8023	6.7333	1.47786 ± 0.10	1.5345 ± 0.02	1.8641 ± 0.15	1.5145 ± 0.06
1	Lokoja	7.8200	6.7100	2.27916 ± 0.23	1.57788 ± 0.21	0.8766 ± 0.13	1.7532 ± 0.18
2	Lokoja	7.8000	6.7400	2.10384 ± 0.23	0.8766 ± 0.21	1.4902 ± 0.12	1.5778 ± 0.18
3	Lokoja	7.7800	6.7600	1.05192 ± 0.23	0.70128 ± 0.21	0.9642 ± 0.13	1.7532 ± 0.18
4	Lokoja	7.8100	6.7500	1.40256 ± 0.23	0.96426 ± 0.21	0.9646 ± 0.13	0.8766 ± 0.18
5	Lokoja	7.8681	7.5091	1.5778 ± 0.20	1.7532 ± 0.03	1.4025 ± 0.01	1.0519 ± 0.01
1	Omala	7.9200	7.5200	1.40256 ± 0.09	1.3149 ± 0.11	1.2272 ± 0.21	1.3149 ± 0.01
2	Omala	7.8700	7.4900	0.8766 ± 0.09	0.96426 ± 0.11	0.8766 ± 0.21	0.7889 ± 0.01
3	Omala	7.8000	7.5500	1.22724 ± 0.09	0.78894 ± 0.11	1.4025 ± 0.21	1.7532 ± 0.01
4	Omala	7.8500	7.6000	1.40256 ± 0.09	1.40256 ± 0.11	1.9285 ± 0.21	1.1395 ± 0.01
5	Omala	7.4025	7.6320	1.22724 ± 0.09	1.05192 ± 0.11	0.7012 ± 0.21	0.8766 ± 0.01
1	Ankpa	7.4100	7.6500	1.05192 ± 0.16	0.8766 ± 0.13	1.2272 ± 0.24	1.4025 ± 0.01
2	Ankpa	7.3900	7.6100	0.96426 ± 0.16	1.57788 ± 0.13	1.0519 ± 0.24	0.8760 ± 0.01
3	Ankpa	7.3800	7.6300	0.70128 ± 0.16	1.05192 ± 0.13	1.7532 ± 0.24	0.9640 ± 0.012
4	Ankpa	7.4200	7.6300	1.66554 ± 0.16	0.96426 ± 0.13	1.4025 ± 0.24	0.7012 ± 0.01
5	Ankpa	7.4300	7.6400	0.96426 ± 0.16	0.8766 ± 0.13	1.7531 ± 0.14	1.0510 ± 0.01

Table 2. Activity concentrations of radionuclides in soil samples from Kogi State.

Sample code	Latitude	Longitude	$^{238}\mathrm{U}\ (\mathrm{Bq\,kg^{-1}})$	$^{232}\mathrm{Th}\ (\mathrm{Bq\,kg^{-1}})$	$^{40}\mathrm{K}\ (\mathrm{Bq\,kg^{-1}})$
AF1	7.5235	6.5813	BDL	BDL	6.68 ± 2.02
AF2	7.5623	6.6550	45.21 ± 8.10	40.12 ± 13.14	1120.35 ± 32.26
AF3	7.5640	6.6291	BDL	33.12 ± 10.26	670.41 ± 22.56
AF4	7.5100	6.6100	37.51 ± 5.46	39.78 ± 12.24	710.25 ± 18.74
AF5	7.8023	6.7333	41.36 ± 6.78	37.67 ± 11.88	626.92 ± 18.90
LF1	7.8200	6.7100	97.80 ± 8.87	159.36 ± 12.17	251.51 ± 73.36
LF2	7.8000	6.7400	69.38 ± 11.21	133.25 ± 18.66	236.72 ± 65.24
LF3	7.7800	6.7600	BDL	64.19 ± 8.02	186.32 ± 14.04
LF4	7.8100	6.7500	16.78 ± 5.36	BDL	198.34 ± 15.48
LF5	7.8681	7.5091	61.32 ± 8.48	118.93 ± 12.95	218.22 ± 42.03
OF1	7.9200	7.5200	84.14 ± 2.16	119.34 ± 34.12	362.96 ± 84.88
OF2	7.8700	7.4900	46.72 ± 8.22	41.45 ± 22.51	80.72 ± 40.64
OF3	7.8000	7.5500	59.86 ± 22.26	48.91 ± 9.32	85.46 ± 14.70
OF4	7.8500	7.6000	78.46 ± 15.16	110.90 ± 24.66	381.25 ± 20.64
OF5	7.4025	7.6320	67.29 ± 11.95	80.15 ± 22.65	227.60 ± 40.22
ANF1	7.4100	7.6500	70.32 ± 8.22	48.64 ± 12.34	540.44 ± 35.28
ANF2	7.3900	7.6100	40.02 ± 5.11	BDL	86.74 ± 16.04
ANF3	7.3800	7.6300	20.34 ± 10.23	BDL	270.78 ± 16.28
ANF4	7.4200	7.6300	35.02 ± 6.02	16.87 ± 4.27	120.12 ± 9.03
ANF5	7.4300	7.6400	41.43 ± 7.40	32.76 ± 8.31	254.52 ± 19.16

Note: BDL, below detection limit; AF, Ajaokuta farm; LF, Lokoja farm; OF, Omala farm; ANF, Ankpa farm.

Table 3. Radiological hazard indices of soil samples from farmlands.

Location	Absorbed dose $(\mathrm{nGy\,h^{-1}})$	AEDR (mSv)	$\mathrm{Ra}_{eq}\ (\mathrm{Bq\,kg^{-1}})$	H_{ext}	H_{int}	ELTCR $(\times 10^{-3})$
Ajaokuta	68.9461	0.0846	143.5059	0.3876	0.4994	0.296113
Lokoja	109.5820	0.1345	248.1745	0.6702	0.8359	0.470638
Omala	89.3331	0.1096	199.4345	0.5387	0.7205	0.383672
Ankpa	49.9176	0.0613	107.8627	0.2913	0.4033	0.214389

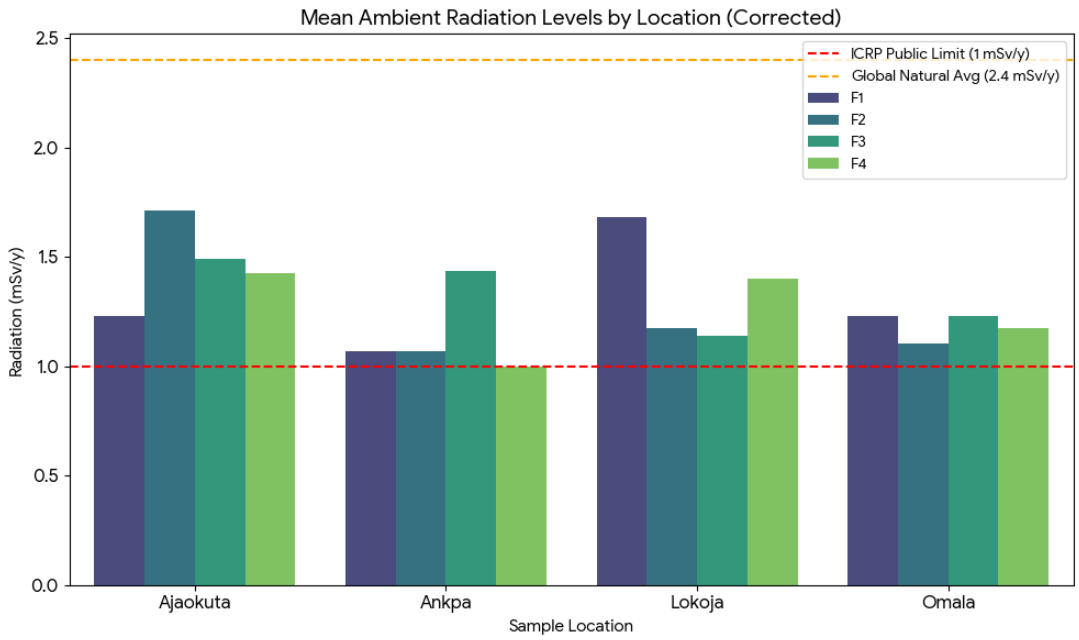

Figure 2. Mean ambient radiation levels for F1–F4 at each location. The red dashed line represents the ICRP limit for public exposure to artificial radiation, $1.0\ \mathrm{mSv\ y^{-1}}$, and the orange dashed line represents the global average natural background radiation level, $2.4\ \mathrm{mSv\ y^{-1}}$.

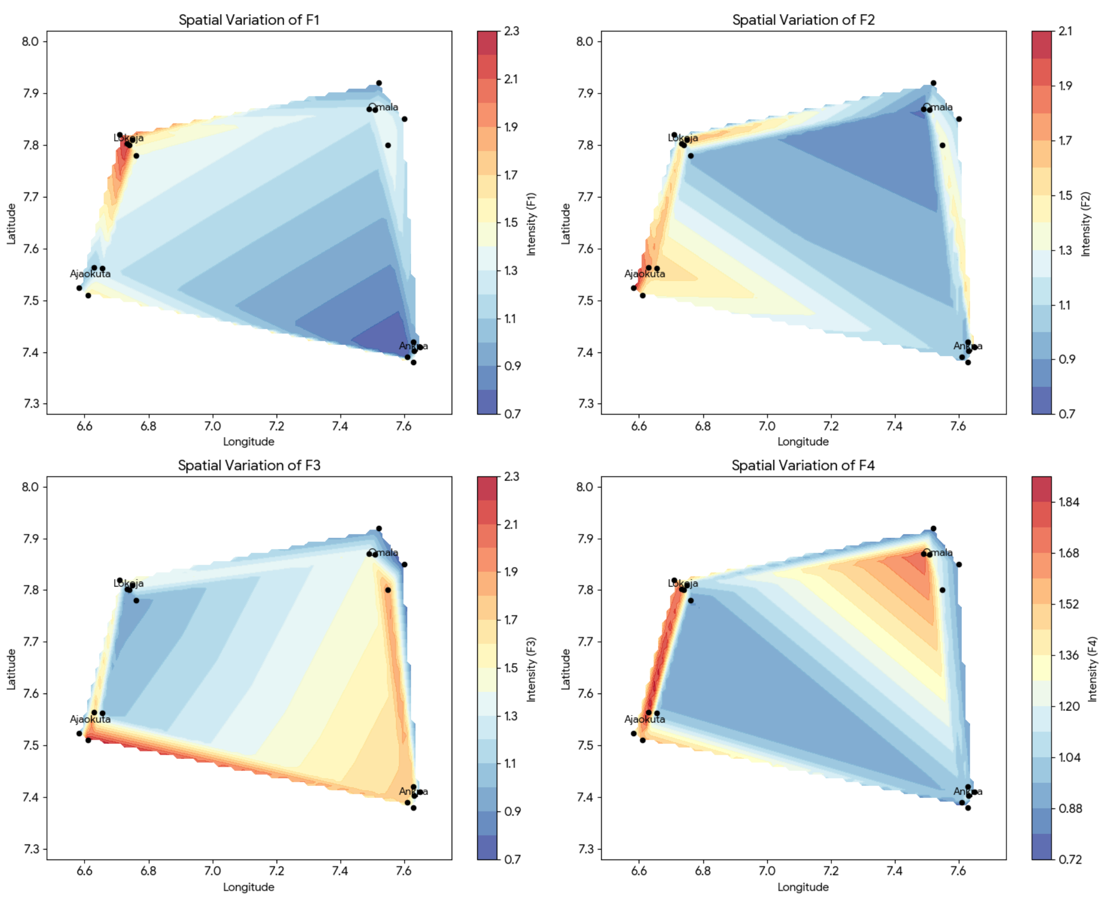

Figure 3. Spatial interpolation used to visualize and analyse the spatial variation of the measured dose-rate data across the study area.

values for Lokoja and Omala, 0.470×10^{-3} and 0.383×10^{-3}, respectively, are marginally above the stated permissible thresh-

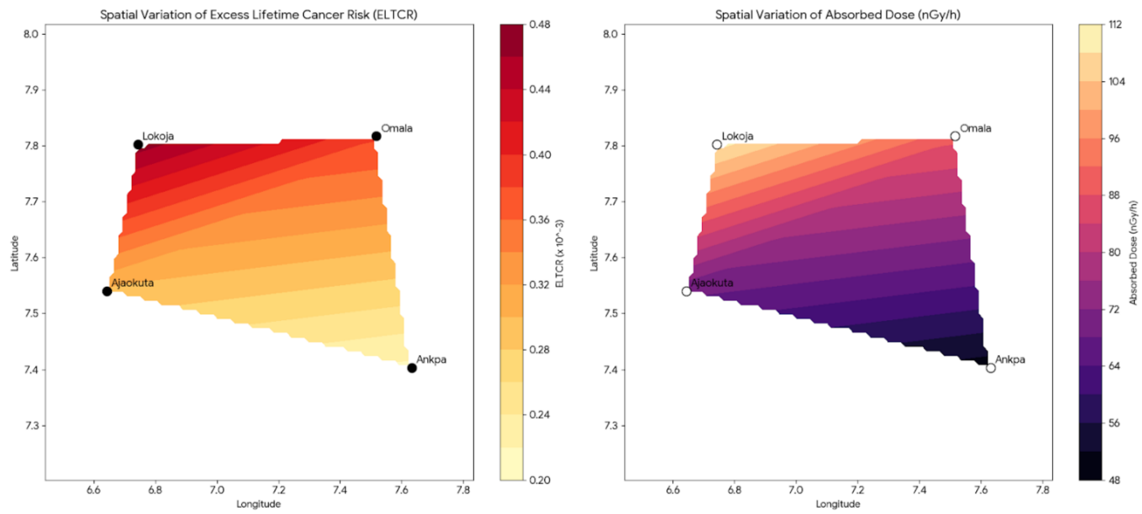

Figure 4. Spatial maps illustrating variation in ELTCR and absorbed dose across the study areas.

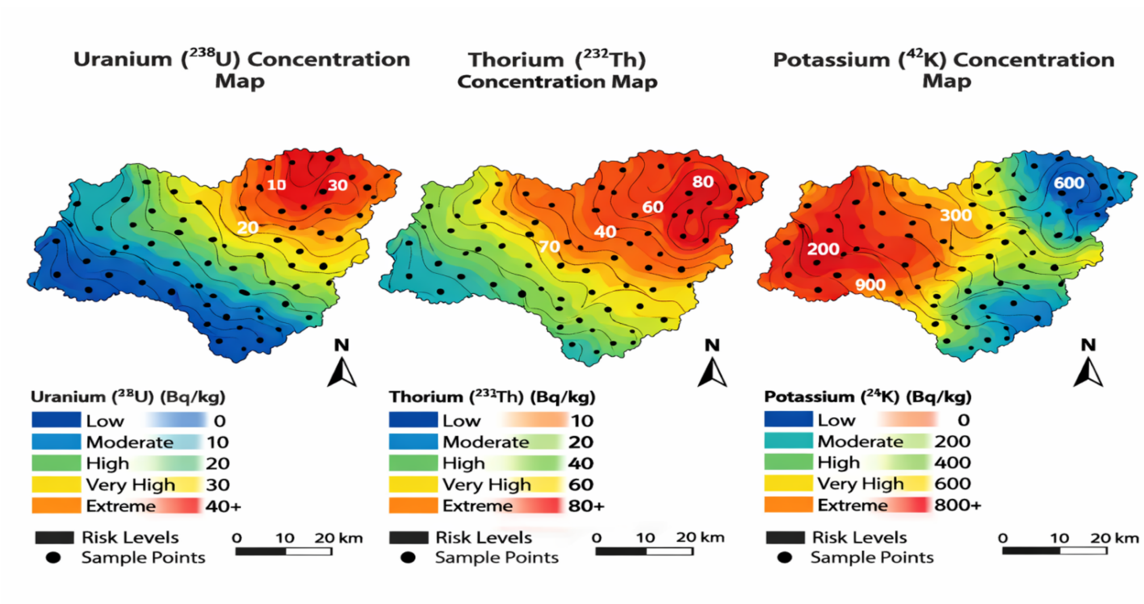

Figure 5. Interpolation of radiological risk in Kogi State, Nigeria.

old (Table 3) and require long-term observation. Nevertheless, all hazard indices are below unity, indicating no severe average health threat. These results are relevant for residents and workers in the study areas. Although the current radiation levels are not expected to pose a significant immediate health hazard, long-term monitoring is needed to ensure that they do not increase. The possibility that coal mining may release high quantities of NORM also indicates the need for further risk-reduction measures to protect the health of residents.

The spatial maps (Figure 3) show that dose-rate indicators F1–F4 vary across Lokoja, Ajaokuta, Omala, and Ankpa. The red and orange regions indicate higher intensities, while the blue and green regions indicate lower intensities. For F1, the concentrations tend to be higher in Lokoja and Ajaokuta and lower in the eastern towns. For F2, a high intensity is observed in the Ajaokuta industrial area. The F3 and F4 patterns are more distributed, with moderate or high levels at some sampling points in Omala and Ankpa.

The radiation risk is not uniform across the study area. For example, the ELTCR value of 0.47×10^{-3} in Lokoja is higher than the international average of 0.29×10^{-3}. This implies that, over a 70-year lifetime, the radiation-related cancer risk for an average farmer in Lokoja may be about 5 in 10,000. By contrast, Ankpa has a lower ELTCR value of 0.21×10^{-3}, which is below the world average and indicates a lower long-term risk for farming activities.

The H_{int} and H_{ext} hazard indices show similar spatial trends. The H_{int} value for Lokoja is 0.8359 and approaches the safety limit of 1, making it a concern for continued monitoring. These indices are important because they help identify areas where risk-reduction measures may be required for farmer and environmental safety. The results also show that geographic location is an important factor in radiation-related cancer risk, with some farmlands being more exposed than others. Lokoja has the highest farmland risk in this dataset, with an ELTCR of 0.47×10^{-3}. This is particularly relevant for agricultural communities near the Niger–Benue confluence. Conversely, the absorbed dose level in the southeast, including Ankpa, is $49.92\ \mathrm{nGy\,h^{-1}}$, which is below the stated safety level.

Variation in radiation levels among locations is largely controlled by natural geology, although farming practices, including fertilizer application, may also contribute. Although background radiation rates are above average in some farmlands in Lokoja and Ajaokuta, the overall risk to farmers is not excessive if areas with high background radiation are closely monitored. The spatial and statistical data (Figures 2 and 3) show that chronic radiation exposure is higher in the western areas, but this risk can be mitigated through targeted monitoring of the most affected locations.

The radiological-risk interpolation map for the selected farm locations in Kogi State indicates higher uranium concentration in the northeast, with contour lines of 10, 20, 30, and $40\ \mathrm{Bq\,kg^{-1}}$. The $^{232}\mathrm{Th}$ concentration map indicates high thorium concentrations in the central and northeastern areas, with contour lines of 20, 40, 60, and $80\ \mathrm{Bq\,kg^{-1}}$. The $^{40}\mathrm{K}$ concentration map indicates high potassium content in the western and central areas, with contour lines of 200, 400, 600, and $800\ \mathrm{Bq\,kg^{-1}}$. The correlation analysis suggests that the external gamma-ray field is primarily influenced by $^{232}\mathrm{Th}$, with a correlation coefficient of 0.397. $^{40}\mathrm{K}$ also contributes, although less strongly, with a correlation coefficient of 0.277. A strong correlation between $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$, with a coefficient of 0.782, suggests that these elements have a common geological origin, most likely the crystalline basement complex rocks that form the parent material of the soils. The combined radiological-risk map shows a gradient from lower levels in the southwest to higher levels in the northeast. Risk thresholds were drawn as contour lines to simplify interpretation.

5. CONCLUSION

This study establishes a radiological baseline for selected districts in Kogi State, namely Ajaokuta, Lokoja, Ankpa, and Omala. Overall, ambient radiation levels are within global safety expectations, and the average hazard indices do not indicate an immediate severe health risk. However, localized elevations and the relatively higher indices observed in parts of Lokoja and Ajaokuta justify continued environmental monitoring. The findings provide useful background radiometric information for agricultural areas of Kogi State and support periodic assessment of farmland radiation exposure.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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