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NATURAL RADIOACTIVITY CONCENTRATION AND RADIOLOGICAL ASSESSMENT OF SOIL SAMPLES FROM FERTILIZED FARMS

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ABSTRACT

Soils naturally contain radioactive elements due to the minerals in Earth's crust. However, agricultural activities, especially the use of chemical fertilisers, can also influence their radioactivity. This study aims to systematically assess both the concentrations of naturally occurring radionuclides introduced into cultivated soils by local fertilisers and the associated radiological hazards from prolonged use. We measured radionuclides using gamma ray spectrometry and analysed soil from fertilised farms to determine activity and health risk indices. All samples contained detectable radionuclides, with mean values of 40K = 590.77±5.08 Bq/kg, 238U = 4.82±0.096 Bq/kg, and 232Th = 2.72±0.05 Bq/kg. Radiological hazard indices—radium equivalent, absorbed effective dose, excess life cancer risk, and gamma representative index—were calculated and compared to international data. The results clarify how fertiliser use affects radionuclide concentrations in soil and if resulting health risks remain within internationally accepted safety limits.

INTRODUCTION

Soil is a key pathway for radioactive elements into the human body, acting as a reservoir for both natural and artificial radionuclides. Naturally occurring radionuclides such as ^{40}K, ^{238}U, and ^{232}Th originate from primordial activity in the Earth's crust, making them a major source of background gamma radiation worldwide. Their contributions to the terrestrial gamma dose rate are significant, while other factors like geology, mineral content, and climate influence regional distribution. Artificial radionuclides, such as Cs-137 from fallout or industry, also enter soils. Human activities, notably fertiliser application, may alter soil radionuclide concentrations, and these variations depend on underlying rock type and land management practices.

Chemical fertilisers are widely used to improve soil nutrient content and crop productivity, but they can also introduce radionuclides into agricultural soils.

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In particular, potassium-based fertilisers may significantly alter natural radionuclide concentrations by accumulating potassium in soil over time.

Accurately measuring soil radionuclide concentrations and assessing associated health risks are essential for environmental monitoring and radiological safety. Gamma spectrometry enables straightforward detection of multiple radionuclides. Calculated health risk parameters, such as absorbed dose rate, annual effective dose, and excess lifetime cancer risk, help compare measured exposure to established safety standards.

With most radiation exposure coming from natural sources like terrestrial radionuclides, radon, and cosmic rays, understanding soil radioactivity is crucial. Long-term exposure to elevated radionuclide levels—whether through external contact, inhalation, or ingestion—can increase health risks, including certain cancers.

Radionuclide concentrations in soil vary widely by region and can be influenced by both natural conditions and human activities. Global studies show that local geology and fertiliser use can significantly impact these concentrations. However, risk parameters often remain within international safety limits, underscoring the importance of continued monitoring in fertiliser-impacted soils.

Given the widespread use and benefits of fertilisers, it is important to identify radionuclide concentrations and related health risks in treated soils. This study focuses on quantifying ^{40}K, ^{238}U, and ^{232}Th in fertilised soils and calculating hazard indices to evaluate radiological safety under prolonged fertiliser application.

MATERIAL AND METHODS

Study Area

Agbor is a town in Ika South Local Government Area of Delta State, home to the University of Delta, Agbor. The area has high temperatures, high humidity, and much rainfall. It experiences two seasons: rainy (March to early October) and dry (October to March). The natural vegetation is rainforest. Most residents farm and use chemical fertilisers to improve crop productivity. Agbor is located between longitudes 6°25'N and 6°19' [18], as shown in Table 1, which lists the coordinates of the sample collection villages.

Table 1: Coordinates of sampling villages

Villages	Latitude (ON)	Longitude (OE)
Umunede	6.2688	6.3067
Owalero	6.2641	6.2019
Alihame	6.2456	6.1876
Agbor-nta	6.2247	6.1433
Owaoyibo	6.2538	61942
Owanta	6.2536	6.1941
Otolokpo	6.2134	6.2987
Aliokpo	6.2345	6.1897
Mbiri	6.3035	6.2774
Idumesah	6.1666	6.2402

Sample Collection and Preparation.

Ten soil samples were randomly taken from ten fertilised farms using standard methods. At each farm, five sampling points were carefully selected. The samples from each point were combined to form a single sample per farm. About 2 kg of soil was packed in a polythene bag. Samples were crushed, cleaned of particles, dried, and ground into powder. They passed through a 2 mm sieve to remove fine debris missed earlier, then dried again and sealed in a container. The container with the sample, weighing 200 g, was sealed for 30 days to let radionuclides reach secular equilibrium with their progeny [19], [20]. The samples were then analysed.>?./././././././././

Radioactivity Measurement of the Sample

Samples were measured using a high-purity 3" × 3" (NaI (TI)) detector shielded by thick lead. The (NaI (TI)) detector is a scintillator detector usually used to identify and quantify radionuclides. It is connected to a multi-channel analyser (MCA) with 4096 channels, a preamplifier base, and a photomultiplier. The setup fed data to a computer for display. The remino software handled data acquisition and gamma ray analysis. The RSS8 gamma source (traceable to Spectrum Techniques LLC, USA) was used for energy calibration by measuring known gamma sources and recording peak positions during 18,000 seconds. Efficiency calibration of the detector was done using a reference standard source consisting of radionuclides whose activities are known: ^{40}K (578.4 KeV), ^{238}U (20.9 KeV), and ^{232}Th (10.47 KeV) [25]:

Before measuring, an empty container was counted for 18,000 seconds to record background radiation. This allowed the system to calculate net count rates from total counts. After 30 days of sealing, samples were measured one by one for 18,000 seconds each, since some radionuclides may have low activity. The radionuclides were detected with the following energies: 1460.0 KeV (40K), 1764.5 keV of ^{214}Bi, (^{238}U), and 2614.7 keV of^{208}Tl (^{232}Th) [25]:

The activity concentration of the radionuclide (CS) was calculated using the relation [22]:

$$C\left(\frac{Bq}{Kg}\right) = \frac{C_n}{\varepsilon P_{YM_S}} \qquad 1$$

where C_n is the count rate under the corresponding photopeak is, P_y is the absolute transition probability of the specific gamma ray, ε is the detection efficiency at the energy line; $M_s$is the mass of the sample.

Radiological Risk Parameters

To have an in-depth knowledge of the radiological risk of the study area due the presence of ^{238}U, ^{232}Th and ^{40}K, the radiation risks were evaluated. The analysis used in radiation studies helps to obtain relevant conclusions on the associated health hazard status of individuals and environmental irradiation [23].

Radium Equivalent Activity

It is a single index used to describe the hazard associated with the presence of different mixture of radionuclides in a sample [24]. It was calculated using the relation in Equation 2 [7].

$$R = A_{\mathrm{U}} + 1.43A_{\mathrm{Th}} + 0.077A_{\mathrm{K}} \qquad 2$$

with the assumption that 370 Bqkg^{-1} of ^{234}U, 259 Bqkg^{-1} of ^{232}Th and 4810 Bqkg^{-1} of ^{40}K produce the same dose rate [25]. R is the radium equivalent activity, $A_{U,}$ A_{Th} and A_K are the activity concentration of ^{238}U, ^{232}Th and ^{40}K respectively. It is measured in Bqkg^{-1}

Absorbed Dose Rate (D_R).

The absorbed dose rate quantifies the amount of energy deposited by ionising radiation per unit mass in a medium. The D_R in nGyh^{-1} in air at 1 m above ground level was estimated by using conversion factor of 0.462, 0.604 and 0.0417 for ^{238}U, ^{232}Th and ^{40}K respectively as seen equation 3 [26].

$$D_R = O.462A_U + 0.604A_{Th} + 0.0417A_K \quad 3$$

Where A_U, A_{Th} and A_K are the activity concentration of ^{238}U, ^{232}Th and ^{40}K respectively.

Annual Outdoor Effective Dose (AED) from the soil samples.

The Annual effective dose is the measure of radiation risk relative to the air absorbed dose rate, which represents the dose quantity of the stochastic health impact of low level radiation on human tissue. AEDE was computed using the following relations [27]. in Equation 4

Outdoor AEDE (μSvy^{-1}) = D_R (nGyh^{-1}) x 8760 (hy^{-1}) x 0.7(SvGy^{-1}) x 0.2×10^{-3} 4

Equations 5 represents the outdoor AEDE respectively [22], the outdoor AEDE is the absorbed dose from ^{238}U, ^{232}Th and ^{40}K in the environment.

Where AEDE is the annual effective dose inμSvy^{-1}, D_R is the dose rate in nGyh^{-1}, the constant 0.7 (SvGy^{-1}) is the conversion coefficient from the absorbed dose in the air to the effective dose received by adult, It is the biological effectiveness of the dose to cause damage to human tissue. 0.2 is the outdoor occupancy factor (since it is assumed that people spent 20 % of their time outside the house on the average), 8760 is the number of hours per year, [28].

Lifetime Cancer Risk due to External Radiation Exposure to Farm Soil

The cancer risk due to exposure to soil radioactivity was calculated using the relation in Equation 6 [29], [23].

ELCR = AEDE ×DL ×RF 6

where DL is the duration of life (70 years), RF is the cancer risk factor (0.05 Sv^{-1}) which reflects the fatal cancer risk per sievert [30]. For stochastic effects, ICRP 60 uses values of 0.05 for the public.

Gamma Index 1_{yr}

The level of gamma radioactivity associated with different concentrations of some specific radionuclides can be estimated [8], using Equation 9

$$\mathbf{1_{yr}} = \frac{R_U}{150\ BqKg} + \frac{R_{Th}}{100\ Bq/Kg} + \frac{R_K}{1500\ Bq/Kg} \quad 9\ [19]$$

Where 1_{yr}, R_u R_{Th} and R_K are gamma index and the activity concentrations of ^{238}U, ^{232}Th and ^{40}K in Bqkg^{-1} respectively. The standard safe value of 1_{yr} is either less than 1 or equal 1. If 1_{yr} is greater than 1 in the study area, then the area is not radiologically safe.

RESULT AND DISCUSSION

The results of the activity concentration of the natural radionuclides, their uncertainties and standard deviations from the study area as presented in Table 2 shows that the activity concentration of ^{40}K varied from 565.59±5.18 to 634.23±5.52 Bqkg^{-1} with mean value of 590.77± 5.08 Bqkg^{-1}. For ^{238}U, it ranged from 3.45± 0.08 Bqkg^{-1}to 10.02 ± 0.20 Bqkg^{-}) with average value of 4.82±0.096 Bqkg^{-1}. For ^{232}Th, it varied between 1.44±0.04 and 3.98±0.07 Bqkg^{-1}with mean value of 2.72 ± 0.05Bqkg^{-1}. While the ^{40}K mean value is comparably higher than the reported value by [31], the measured mean values of ^{238}U and ^{232}Th were significantly lower than their corresponding values in the work of [32]. This is attributable to localised spartial variation of radionuclides soil in Agbor. With the exception of ^{40}K whose mean activity concentration of 590.77± 5.08 Bqkg^{-1} was higher than the world average value of 420 Bqkg^{-1}, the measured ^{238}U and ^{232}Th were much lower than the global mean values of 35 Bqkg^{-1}and 30 Bqkg^{-1} respectively. Table 3 shows the comparison between the mean values obtained from this work and other measured mean values outside study area.

Table 2: Activity concentration of radionuclide in fertilized farm soil

Farm Number	^{40}K (Bqkg^{-1})	^{238}U (Bqkg^{-1})	^{232}Th (Bqkg^{-1})
1	634.23±5.52	3.57± 0.08	2.59±0.06
2	578.25±5.25	3.54±0.08	3.98±0.07
3	565.59±5.18	8.00±0.12	1.44±0.04
4	572.34±3.21	10.02±0.20	3.50± 0.02
5	615.34±5.43	3.96±0.08	1.74±0.04
6	559.13±4.62	3.50±0.08	2.82±0.06
7	558.71±5.30	3.88±0.08	2.83±0.06
8	624.52±5.22	3.45±0.08	2.65±0.05
9	587.39±5.24	4.52±0.09	2.75±0.07
10	612.24±5.84	3.75±0.07	2.85±0.06
MEAN	**590.77± 5.08**	**4.82±0.096**	**2.72 ± 0.05**
SD	**28.41**	**2.28**	**0.73**

Table 3. Comparison of activity concentrations of the study area with values obtained in other parts of the country.

^{40}K (Bqkg^{-1})	^{238}U (Bqkg^{-1})	^{232}Th (Bqkg^{-1})	Study Area	References
590	4.82	2.72	Agbor, Delta State, Nigeria.	This study
256	24	29	Delta State (oil and gas, Nigeria	[20]
57.8	2.07	6.89	Ogwa, Edo State, Nigeria	[10]

30.19	1.14	4.85	Igueben, Edo State, Nigeria	[10]
270.14	12.14	23.23	Ile Ife, Osun State, Nigeria	[21]
455.05	128.05	24.8	Ijero, Ekiti	[19]
403.07	11.47	10.44	Agege, Lagos State, Nigeria	[21]
73.84	6.11	8.13	Ibiono 2, Akwa Ibom State, Nigeria.	[22]
106.58	3.16	5.91	Ibiono 3, Akwa Ibom State, Nigeria	[22]
420	35	30	World Average	[16]

As shown in Table 4, the radium equivalent was highest with a value of 59.09 $Bqkg^{-1}$ in Farm 4 and lowest in Farm 6 with a value of 50.58 $Bqkg^{-1}$, its mean value was 52.30 $Bqkg^{-1}$. The mean value was less than the world reported mean value of 370 $Bqkg^{-1}$ [16]. The calculated absorbed dose ranged from the value of 26.63 in Farm 6 to 30.61 $nGhy^{-1}$ in Farm 4 with mean value of 27.75 $nGhy^{-1}$. This was lower than the world safe limit of 55 $nGhy^{-1}$. The outdoor annual effective dose values varied from 32.67 to 37.54 $\mu Svy^{-1}$with average value of 34.03μSvy^{-1} and, this was significantly lower than the global permissible limit of $mSvy^{-1}$ (1000 μSvy^{-1}) [16].The excess life cancer risk was between 0.114 $\times 10^{-3}$ and 0.127 $\times 10^{-3}$ with mean value of 0.120×10^{-3},this value is lower than the world allowable value of 0.29×10^{-3}. [16]. The gamma index had the lowest value of 0.42 in Farm 6 and the highest value of o0.47 in Farm 1 and 8 with mean value of0.44., which is less than the world standard limit of 1[33].

Table 4: The radiological health risk parameters from fertilized farm soils

Farm No	Ra_{ag} ($Bqkg^{-1}$)	D ($nGhy^{-1}$)	Outdoor AED μSvy^{-1}	ELCR $\times 10^{-3}$	I_γ
I1	56.13	29.66	36.38	0.127	0.47
12	53.76	28.15	34.53	0.120	0.45
13	43.62	28.15	34.52	0.120	0.44
14	59.09	30.61	37.54	0.131	0.48
15	53.83	28.54	35.00	0.122	0.45
16	50.58	26.63	32.67	0.114	0.42
17	50.95	26.80	32.87	0.115	0.43
18	55.32	29.24	35.86	0.125	0.47
19	53.67	28.24	34.64	0.121	0.45
20	54.97	28.98	35.55	0.124	0.46
Mean	**52.30**	**27.75**	**34.03**	**0.12**	**0.44**

Table 5. Comparison of the radiological hazard parameters of the present study with values obtained in other parts of the country.

Ra_{ag} ($Bqkg^{-1}$)	D ($nGhy^{-1}$)	Outdoor AED μSvy^{-1}	ELCR $\times 10^{-3}$	I_γ	Study Area	References

52.30	27.75	34.03	0.12	0.44	Agbor and its environs, Delta State	Present Study
137.30	66.20	0.80	0.28	1.05	Ajakuta, Kogi State	[22]
19.82	9.79	0.06	0.21	0.07	Ibiono 3, Akwa Ibom State	[22]
140.77	19.65	0.17	0.60	0.30	Oshogbo, Osun State	[26]
1425.50	654.20	0.80	0.03	10.70	Odua	[8]
71.18	33.14	0.04	0.14	0.2	Ogun	[30]
6.50	3.54	0.0043	0.02	0.06	Ibadan 2, Oyo State	[31]

Table 5 shows the comparison of the values of the radiological health risk parameters from the present study and the values obtained from other studies within the country. Figures 1 and 2, show the histogram illustration comparing the various calculated health hazard parameters with their respective standard safety limits

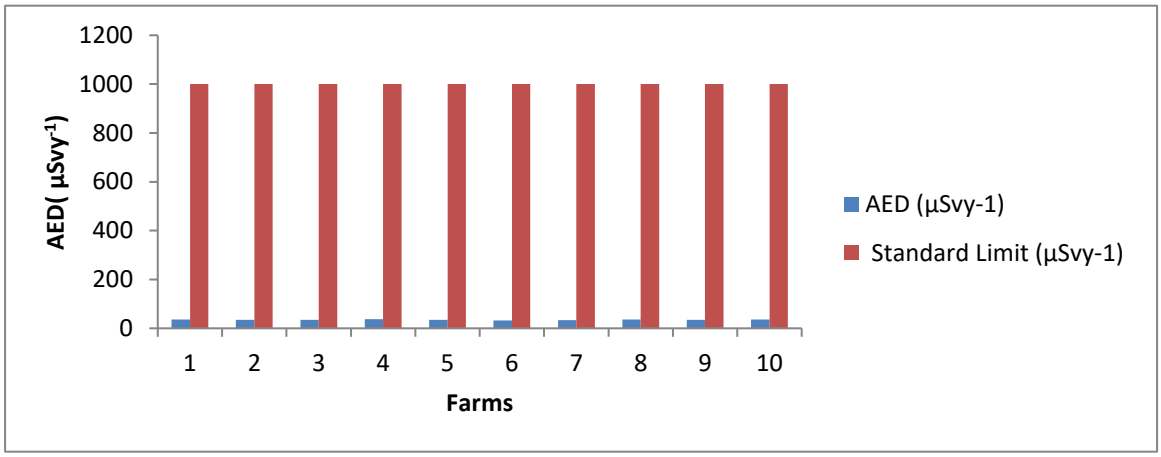

Fig. 1. Comparison of values of AED in farms with international standard limit

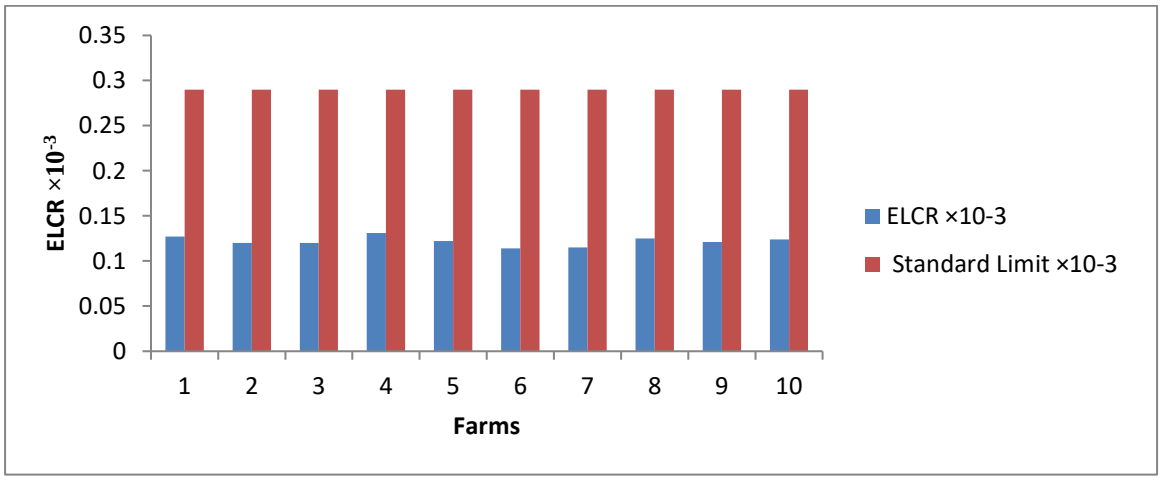

Fig. 2. Comparison of values of ELCR in farms with international standard limit

CONCLUSION

The radionuclide concentrations in ten selected farms in Agbor and its environs were investigated using gamma ray spectrometry. The measured values were 590.77 ± 5.08 $Bqkg^{-}$, 4.82 ± 0.096 $Bqkg^{-}$ and 2.72 ± 0.05$Bqkg^{-}$ for ^{40}K, ^{238}U and ^{232}Th respectively. While the calculated health risk parameters were 52.30 $Bqkg^{-}$for Ra_{aq}, 27.75 $nGhy^{-1}$ for D_R, 34.03 μSvy^{-1} for AED, 0.12×10^{-3} for ELCR and 0.44 for I_Y. These results for radionuclides activity concentrations and the computed radiological hazard parameters are within the global safe limit. These results may also serve as a baseline for future study in Ika land and beyond.

REFERENCES

[1] O. A. Abiodun, T. O. Odunayo, E. O. Tobi, and O. O. Victoria, "Evaluation of Radioactivity Level and its Radiological Impact in Soil Samples around Transmission Company of Nigeria," Radiat. Sci. Technol., vol. 5, no. 4, pp. 41–46, 2019.

[2] S. M. Adegbulugbe et al., "Assessment on Natural Radioactivity and its Radiological Risks in the Soil of Local of Government Areas (Asa, Ilorin East, South, Irepodun, Moro, and Oyun) in Kwara State, Nigeria," Chem. Environ. Eng., vol. 11, Art. no. 101040, 2025, doi: 10.1016/j.cscee.2024.101040.

[3] M. O. Adeleye, B. Musa, O. Oyebanjo, S. T. Gbenu, and S. O. Alayande, "Activity concentration of Natural Radionuclides and Assessment of the Associated Radiological Hazards in the Marine Croaker (Pseudololitus Typus) Fish from Two Coastal Areas of Nigeria," Sci. World J., vol. 15, 2020.

[4] L. E. Akpabio, P. Tchokossa, J. B. Olomo, F. A. Balogun, and C. A. Adesanmi, "Natural Radioactivity Levels and Radiological Hazards in Oil Producing Area of Delta State," Radiat. Prot. Dosimetry, vol. 152, no. 2, pp. 1–8, 2012.

[5] O. G. Avwiri and E. O. Agbalagba, "Assessment of Natural Radioactivity, Associated Radiological Health Hazards Indices and Soil to Crop Transfer Factors in Cultivated Area around a Fertilizer Factory in Onne, Nigeria," Environ. Earth Sci., vol. 71, no. 4, pp. 1541–1549, 2013.

[6] H. Bai et al., "Assessment of radioactive materials and Heavy Metals in the Surface Soil around the Bayanwula Prospective Uranium Mining Area of in China," Int. J. Environ. Res. Public Health, vol. 14, p. 300, 2017.

[7] K. Chandra, R. Proshad, H. C. Dey, and A. M. Idris, "A Review on Radionuclide Pollution in Global Soils with Environmental and Health Hazards Evaluation," Environ. Geochem. Health, vol. 45, no. 1, pp. 9245–9266, 2023, doi: 10.1007/s10653-023-01725-2.

[8] S. Dizman, F. K. Gorur, and R. Keser, "Determination of Radioactivity Level of Soil Samples and the Excess Lifetime Cancer Risk in Roze Province, Turkey," Int. J. Radiat. Res., vol. 14, no. 3, pp. 237–244, 2019.

[9] D. T. Esan et al., "Measurement of Natural Radioactivity and Assessment of Radiological Hazard Indices of Soil over the Lithologic Units in Ile-Ife Area," Environ. Health Insights, vol. 16, Art. no. 11786302221100041, 2022, doi: 10.1177/11786302221100041.

[10] K. Eseka, C. Mokobia, C. Molua, and A. Ukpene, "Characterization of Soil Radioactivity from Primordial Radionuclides in the Soil of Ika South Local Government Area of Delta State," FUDMA J. Sci., vol. 6, no. 2, pp. 180–184, 2022.

[11] I. E. Essien, A. A. Essiett, O. B. Ani, I. G. Peter, and A. E. Udofia, "Estimation of Radiological Hazard Indices due to Radioactivity in Soils in Ibiono Ibom, Akwa State, Nigeria," Int. J. Sci. Res. Publ., vol. 7, no. 4, pp. 245–250, 2016.

[12] D. Hernandez-Ramirez et al., "Spatial Distribution and Radiological Risk Assessment of Natural Radionuclides in Soil from Zacatecas, Mexico," Analytica, vol. 6, no. 2, p. 20, 2025.

[13] IAEA, "Measurement and Estimation of Radon Release from NORM Residues and Assessment of Associated Radiation Exposure," IAEA, Vienna, Safety Reports Series No. 49, 2006.

[14] R. S. Lawal, S. O. Aisida, I. Umaru, I. Mundi, and S. S. Shehu, "Evaluation of Radiological Hazard Indices and Environmental Safety in Soil Samples from different Source Term within the Tributaries of Awda Dam in the University of Ibadan," Phys. Memoir, vol. 1, pp. 152–160, 2019.

[15] C. O. Molua, "Evaluating peak flow sensitivities to spatiotemporal precipitation input resolution in a distributed hydrological model of the Ramos River system," Benin J. Phys. Sci., vol. 1, no. 1, pp. 204–221, 2024.

[16] O. C. Molua et al., "Mapping Dumpsite Plumes in Aquifers using Very Low Frequency Techniques," J. Scientometrics & Innovations, pp. 107–119, 2024.

[17] C. O. Molua, J. C. Morka, and R. O. Ijeh, "Evaluating the correlation between electromagnetic conductivity and metal detection to identify underground storage tanks: A case study of Agbor, Delta State, South-South Nigeria," J. Niger. Assoc. Math. Phys., vol. 69, no. 1, pp. 35–48, 2025.

[18] J. Musa et al., "Assessment of Natural Radioactivity and Radiological Risks in Soil of Numbupi Mining Site in Niger State, Nigeria: Public Health and Environmental Implications," FUDMA J. Sci., vol. 9, no. 5, pp. 87–96, 2025.

[19] T. D. Nafisa et al., "Natural Radioactivity and its Radiological Implications from Soil and Rocks in Jintiapur Area, North-East, Bangladesh," J. Radioanal. Nucl. Chem., vol. 331, pp. 4457–4468, 2022.

[20] K. O. Olatunji and I. Bamidele, "Natural Radioactivity Concentration and Radiological Evaluation in Soil Samples around Dangote Cement Factory, Igbese, Ogun State," Nucl. Sci., vol. 5, no. 2, pp. 22–26, 2020.

[21] S. O. Oluyide et al., "National Radioactivity and Radiological Impact Assessment of Soil, Food and Water around Iron and Steel Smealting Area in Fashina Village, Ile-Ife, Osun State, Nigeria," J. Appl. Sci. Environ. Manage., vol. 23, no. 1, pp. 135–143, 2019.

[22] C. P. Ononugbo, G. O. Avwiri, and G. Tutumeni, "Measurement of Natural Radioactivity and Evaluation of Radiation Hazards in Soil of Abua / Odua District of River State, Nigeria, Using Multivariate Statistical Approach," Br. J. Sci., vol. 4, no. 1, pp. 35–48, 2016.

[23] C. P. Ononugbo, O. Azikiwe, and G. O. Awiri, "Uptake and Distribution of Natural Radionuclides in Cassava Crops from Nigerian Government Farms," J. Sci. Res. Rep., vol. 23, no. 5, pp. 1–15, 2019.

[24] M. M. Orosun, T. O. Lawal, and F. C. Akinyose, "Natural Radionuclide Concentration and Radiological Impact Assessment of Soil and Water in Tanke-Ilorin, Nigeria," Zimbabwe J. Sci. Technol., vol. 11, pp. 158–172, 2016.

[25] F. A. Popoola, O. D. Fakeye, Q. B. Basiru, D. A. Adesina, and M. A. Sulola, "Assessment of Radionuclide Concentrations in Surface Soil and Human Health Risk Associated with Exposure in Two Higher Institutions of Esan Land, Edo State, Nigeria," J. Appl. Sci. Environ. Manage., vol. 23, no. 12, pp. 2267–2284, 2019.

[26] B. Samaila and H. M. Tampul, "Determination of Soil Radioactivity and Radiological Hazard Indices in Nigeria: A Review," Savana J. Basic Appl. Sci., vol. 3, no. 1, pp. 71–80, 2021.

[27] K. Tibor, S. Gabor, F. Ferenc, K. Richard, G. Asta, and V. Janja, "Systematic Survey of Natural Radioactivity of Soil in Slovenia," J. Environ. Radioact., vol. 12, no. 2, pp. 70–78, 2013.

[28] M. Tzortzis, H. Tsertos, S. Christofides, and G. Christodoulides, "Gamma-ray Measurement of Natural Occurring Radioactive Samples from Cyprus Characteristic Geological rocks," Radiat. Meas., vol. 37, no. 3, pp. 221–229, 2003.

[29] F. O. Ugbede and A. Akpolile, "Determination of Specific Activity of 238U, 232Th and 40K and Radiological Hazard Assessment of Tuomo River Sediment in Burutu, Delta State, Nigeria," J. Appl. Sci. Environ. Manage., vol. 23, no. 4, pp. 727–733, 2019.

[30] F. O. Ugbede and I. D. Benson, "Assessment of Outdoor Radiation Levels and Radiological Health Hazards in Emene Industrial Layout of Enugu State, Nigeria," Int. J. Phys. Sci., vol. 13, no. 2, pp. 265–272, 2018.

[31] UNSCEAR, "Sources and Effects of Ionizing Radiation," United Nations, New York, NY, 2000.

[32] M. R. Usikalu, A. B. Rabiu, K. D. Oyeyemi, J. A. Achuka, and M. Maaza, "Radiation Hazard in Soil from Ajakuta, North Central Nigeria," Int. J. Radiat. Res., vol. 15, no. 2, pp. 219–224, 2017.

[33] M. R. Usikalu et al., "Radiation Dose Assessment of Soil from Ijero, Ekiti, Nigeria," Cogent Eng., vol. 6, no. 1, Art. no. 1586271, 2019.