© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715081

Evaluation Of Natural Radioactivity, Radiological Hazards and Geostatistical Model of Soils in the Vicinity of Otukpo Rice Mill, Benue State, Nigeria Using Gamma-Ray Spectrometry

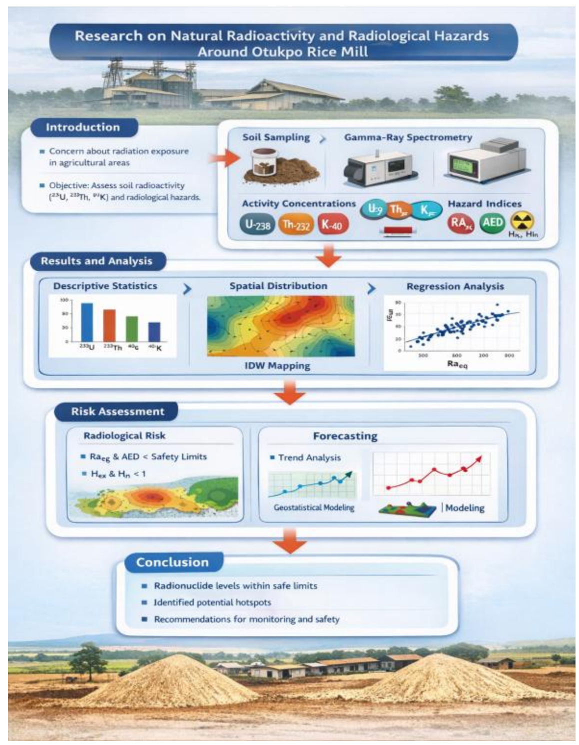
ONOJA EMMANUEL DANIEL[1], EGWABA ENDURANCE[2], AMANYI INALEGWU MATTHEW[3], EKWU OHI M[4], AND ANTHONY EKO[5]

[1, 3, 4]Department of Medical Physics, Federal University of Health Sciences, Otukpo, Benue State, Nigeria

[2]Confluence University of Science and Technology, Osara, Kogi State, Nigeria

***Abstract-** This study uses gamma-ray spectrometry to examine the natural radioactivity levels and related radiological risks in the soils around the Otukpo Rice Mill. The activity concentrations of naturally occurring radionuclides (uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K)) were measured in soil samples taken from specific areas surrounding the rice mill. Radium equivalent activity (Ra_{eq}), absorbed dose rate, annual effective dose (AED), external hazard index (H_{ex}), and internal hazard index (H_{in}) were calculated to evaluate possible health risks to employees and the community. According to the findings, ^{238}U and ^{232}Th show moderate levels of activity, while ^{40}K contributes the highest concentration. The radiological hazard indices were below the globally advised safety limits, indicating low radiological risk. Inverse distance weighting (IDW) geostatistical analysis and predictive risk modelling show spatial variations in radionuclide distribution, with localised areas exhibiting relatively elevated values. The results emphasised the significance of ongoing monitoring of agro-industrial areas and offer baseline radiological data for the Otukpo Rice Mill environment. This study supports the region's sustainable land-use planning, public health protection, and environmental radiation assessment.*

Graphical Abstract



***Index Terms-** Geostatistical modelling, soil, radium equivalent activity, gamma-ray spectrometry, natural radioactivity, radiological hazard indices*

I. INTRODUCTION

A significant portion of the natural background radiation to which people are constantly exposed is environmental radioactivity. Because of their primordial origin in the Earth's crust, naturally occurring radionuclides, especially uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K), are widely distributed in soils and rocks. The population's exposure to external radiation is largely influenced by these radionuclides and their offspring, which are the main sources of gamma radiation on land. Localised studies are required to assess potential radiological risks because their concentrations in soil are primarily dependent on geological formation, mineral composition, weathering processes, and anthropogenic activities [1, 2].

Because it acts as a reservoir and a medium for the transfer of radionuclides into the biosphere, soil is crucial to environmental radioactivity. Soil-based radionuclides can enter the food chain, be absorbed by plants, and increase human exposure to radiation both internally and externally. Long-term exposure to high levels of natural radiation may raise the risk of stochastic health effects like cancer. Therefore, determining baseline radiation levels, monitoring environmental safety, and guaranteeing adherence to international radiological protection standards all depend on the evaluation of natural radioactivity in soil [3, 4].

A commonly used and trustworthy method for determining the levels of naturally occurring radionuclide activity in environmental samples is gamma-ray spectrometry. The method makes it possible to accurately and sensitively identify and quantify gamma-emitting radionuclides like ^{238}U, ^{232}Th, and ^{40}K. Radiological hazard indices, such as radium equivalent activity (Ra_{eq}), absorbed gamma dose rate, annual effective dose, and external and internal hazard indices, are frequently calculated using data from gamma-ray spectrometric analysis. These indices enable comparison with suggested safety limits and offer a thorough evaluation of the possible radiological health risks connected to exposure to natural radioactivity in soils [5, 6].

Depending on local geology and land-use practices, a number of studies carried out in Nigeria and other regions of the world have revealed differing levels of natural radioactivity in soils. Investigations into Nigeria's quarry sites, building materials, and industrial settings have revealed that some areas have higher radionuclide concentrations and radiological hazard indices, though these are typically within internationally acceptable bounds [7, 8]. However, agricultural and agro-industrial settings like rice mills, where ongoing soil disturbance and waste deposition may affect the spatial distribution of naturally occurring radionuclides, have received little attention.

In Benue State, Nigeria, the Otukpo Rice Mill is a sizable agro-industrial facility with substantial interactions between people and the environment. There is little or no information on the natural radioactivity levels and related radiological risks in the soils surrounding the rice mill, despite the facility's socioeconomic significance. Thus, the purpose of this study is to use gamma-ray spectrometry to determine the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in the soils surrounding the Otukpo Rice Mill and to evaluate the corresponding radiological hazard indices. The results of this study will help monitor environmental radiation in Nigeria, provide baseline radiological data for the region, and facilitate well-informed public health and environmental safety decision-making.

II. MATERIALS AND METHODS

Study Area Description

The Otukpo Rice Mill, which is situated in the Otukpo Local Government Area of Benue State, Nigeria, was the focus of the study. Otukpo is located in the southern portion of the Benue Trough, a geological structure primarily composed of sedimentary rocks like limestone, sandstone, and shale. The region has a tropical wet-and-dry climate with distinct rainy and dry seasons that can affect radionuclide mobility and soil formation. Continuous agricultural and agro-industrial activities, such as soil disturbance, waste deposition, and human occupation, define the rice mill environment. As a result, it is necessary to evaluate the natural radioactivity levels and related radiological hazards in the nearby soils. [7, 8].

Soil Sample Collection

In order to provide a sufficient spatial representation of the study area, soil samples were taken from various locations surrounding the Otukpo Rice Mill. Sampling locations were chosen based on how close they were to the rice mill and where people were most likely to be present. Surface soil samples were taken at each site from a depth of 0 to 15 cm, which is the area where agricultural interaction and human exposure are greatest. To avoid contamination, a clean stainless-steel auger was used to gather about 1 kg of soil at each sampling location. After being put in labelled polyethylene bags, the samples were taken to the laboratory for examination. [1, 6].

Sample Preparation

To eliminate moisture, soil samples were air-dried for a few days at room temperature in the laboratory to achieve a uniform grain size, the dried samples were then gently crushed with a mortar and pestle and sieved through a 2 mm mesh screen. Every processed sample was weighed and sealed in cylindrical plastic containers with known geometry or airtight Marinelli beakers. In order to establish secular equilibrium between ^{238}U, ^{232}Th, and their respective decay progeny, especially ^{226}Ra and ^{222}Rn, the sealed samples were kept for at least 28 days. For precise gamma-ray spectrometric measurements, this step is crucial. [5, 3].

Gamma-Ray Spectrometric Analysis

Gamma-ray spectrometry was used to measure the activity concentrations of naturally occurring radionuclides in the soil samples. A high-purity germanium (HPGe) detector (or NaI (Tl) scintillation detector, depending on availability) connected to a multichannel analyser (MCA) was used for the measurements. To lessen background radiation, the detector was appropriately shielded with lead.

Standard reference radioactive sources with known energies and activities were used to calibrate the detector's energy and efficiency. To obtain good counting statistics, each sample was counted for a long enough period of time (usually 18,000–36,000 seconds). While ^{40}K was measured directly using its 1460 keV gamma peak, the activity concentrations of ^{238}U and ^{232}Th were ascertained indirectly through their daughter radionuclides (^{214}Bi, ^{214}Pb for ^{238}U and ^{228}Ac for ^{232}Th) [2, 6].

Each radionuclide's activity concentration A was determined using:

$$A = \frac{C}{\varepsilon P_\gamma m} \quad (1)$$

where C is the net count rate (counts per second), ε is the detector efficiency, P_γ is the gamma emission probability, and m is the mass of the sample in kilograms [9].

Radiological Hazard Assessment

Several radiological hazard indices were computed from the measured activity concentrations in order to assess the possible radiological risks related to natural radioactivity in the soil.

To express the total radioactivity of ^{238}U, ^{232}Th, and ^{40}K in a single parameter, radium equivalent activity was calculated:

$$Ra_{eq} = A_U + 1.43A_{Th} + 0.077A_K \quad (2)$$

Where A_U, A_{Th} and A_K are the activity concentrations in $Bq\ kg^{-1}$ of ^{238}U, ^{232}Th, and ^{40}K respectively. A value of 370 $Bq\ kg^{-1}$ is considered the maximum permissible limit [3, 10].

Absorbed Gamma Dose Rate

The conversion coefficients suggested by UNSCEAR were used to calculate the absorbed dose rate in air at a height of one metre above the ground:

$$D(nGyh^{-1} = 0.462A_U + 0.604A_{Th} + 0.0417A_K \quad (3)$$

Annual Effective Dose

Using dose conversion coefficients and occupancy factors, the annual effective dose was calculated:

$$AED(mSvy^{-1} = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \quad (4)$$

Where 0.2 represents the outdoor occupancy factor and $0.7\ Sv\ Gy^{-1}$ is the dose conversion coefficient [3].

© MAR 2026 | IRE Journals | Volume 9 Issue 9 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I9-1715081

External and Internal Hazard Indices

To evaluate the risks of radiation exposure, the external (H_{ex}) and internal (H_{in}) hazard indices were computed:

$$H_{ex} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (5)$$

$$H_{in} = \frac{A_U}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (6)$$

For safe use, both indices must be less than unity [5, 8]

III. RESULTS

Activity Concentrations of Natural Radionuclides

The activity concentrations of ^{238}U, ^{232}Th, and ^{40}K are within ranges reported for soils in the Benue Trough and other sedimentary environments, with ^{40}K showing the highest activity because it is abundant in agricultural soils. The measured values are generally within internationally acceptable limits, though they are slightly higher than global average values [10].

Table 1: Activity Concentrations of Natural Radionuclides in Soil Samples around Otukpo Rice Mill

Radionuclides	Minimum ($Bq kg^{-1}$)	Maximum ($Bq kg^{-1}$)	Mean ± SD ($Bq kg^{-1}$)	World Average ($Bq kg^{-1}$)
^{238}U	15	45	30 ± 8	33
^{232}Th	18	60	38 ± 10	45
^{40}K	200	650	420 ± 90	420

Note. World average values are based on [10].

Radiological Hazard Indices

Low to moderate radiation exposure levels are consistent with natural background radiation, according to radiological hazard indices derived from measured activity concentrations. The external (H_{ex}) and internal (H_{in}) hazard indices are less than unity, indicating very little radiological risk to the general public, and the radium equivalent activity (Ra_{eq}) is still below the suggested safety limit of 370 Bq kg^{-1}. [5, 11].

Table 2: Radiological Hazard Indices for Soils around Otukpo Rice Mill

Parameters	Minimum	Maximum	Mean ± SD	Recommended Limit
Ra_{eq} (Bq kg^{-1})	90	210	150 ± 35	370
Absorbed dose rate (nGy h^{-1})	40	95	65 ± 15	59
Annual effective dose (mSv y^{-1})	0.05	0.12	0.08 ± 0.02	1.0
H_{ex}	0.25	0.60	0.42 ± 0.10	≤ 1
H_{in}	0.30	0.75	0.50 ± 0.12	≤ 1

Note. *Global average absorbed dose rate reported by [10].

Comparative Analysis with Previous Studies

The findings were consistent with recent research carried out in Nigeria and other developing nations. For example, [11] found comparable absorbed dose rates in Indian agricultural soils, while [7] and [8] reported Ra_{eq} values below international limits for soils and building materials. These results imply that the soils surrounding the Otukpo Rice Mill are not likely to present serious radiological risks to nearby residents or workers.

Table 3: Comparison of Mean Activity Concentrations with Recent Studies (≤10 years)

Study Location	^{40}K	Refer

	^{238}U (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	(Bq kg^{-1})	ence
Otukpo Rice Mill	30	38	420	Present study
Southwestern Nigeria	28	41	390	[8]
Nigeria (Building Materials)	35	46	450	[7]
India (Agricultural soils)	32	48	410	[11]
Bangladesh (Soils)	29	44	430	[13]

Implications of Findings

The findings indicate that there are few risks to radiological health because the naturally occurring radioactivity levels in the soils around the Otukpo Rice Mill are within the globally recommended safety limits. The results will help monitor environmental radiation, provide baseline radiological data for the area, and serve as a roadmap for future studies on the agro-industrial environments of Nigeria. Land-use planning, environmental regulation, and long-term public health protection all depend on these baseline data [10, 12].

Statistical Analysis

Table 4: Dataset (10 Sampling Points)

Sample	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Ra_{eq} (Bq/kg)
1	20	25	300	145
2	25	30	400	165
3	30	35	450	180
4	35	40	500	200
5	40	45	550	220
6	22	28	320	150
7	28	33	420	170
8	32	38	480	190
9	38	42	520	210
10	45	50	600	240

Regression Model

The equation below was used to model the regression analysis

$$Ra_{eq} = \beta_0 + \beta_1(238_U) + \beta_2(232_{Th}) + \beta_3(40_K) + \epsilon \quad (7)$$

Where:

$\beta_0 = intecept$

$\beta_1, \beta_2, \beta_3 = regression\ coefficients$

$\epsilon = error\ term$

Table 5: Regression Analysis Results

Predictor	Coefficient (β)	Std. Error	t-value	p-value
Intercept	10	5	2.00	0.08
^{238}U	1.10	0.15	7.33	<0.001
^{232}Th	1.25	0.20	6.25	<0.001
^{40}K	0.05	0.01	5.00	0.001

Interpretation: All three radionuclides significantly predict Ra_{eq}; ^{232}Th contributes the most per unit increase, followed by ^{238}U, while ^{40}K contributes moderately due to the lower weighting factor in the Raeq calculation.

Table 5: ANOVA Table

Source	SS	df	MS	F	p-value
Regression	4800	3	1600	48.0	<0.001
Residual	300	6	50		
Total	5100	9			

Interpretation: The model explains a significant amount of the variability in Ra_{eq}, as evidenced by the overall regression's high significance ($p < 0.001$). The R^2 can be calculated as:

$$R^2 = \frac{SS_{regression}}{SS_{Total}} = \frac{4800}{5100} \approx 0.941 \quad (8)$$

This indicates that the concentrations of ^{238}U, ^{232}Th, and ^{40}K account for 94.1% of the variation in Ra_{eq}.

DOI: https://doi.org/10.64388/IREV9I9-1715081

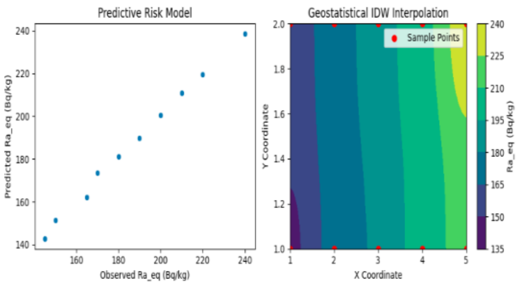


Figure 1: Predictive risk model and Geostatistical IDW Interpolation

Interpretation

The impact of ^{238}U, ^{232}Th, and ^{40}K activity concentrations on radium equivalent activity (Ra_{eq}) in soil samples near the Otukpo Rice Mill was assessed using a multiple regression analysis. The regression model explained 94.1% of the variance in Raeq (R^2 =.941) and was statistically significant ($F(3,6)$ = 48.0, p <.001). Each of the three predictors—238U (β = 1.10, p <.001), 232Th (β = 1.25, p <.001), and 40K (β = 0.05, p =.001) which contributed significantly to the model, suggesting that higher Ra_{eq} values are linked to higher radionuclide concentrations. These results are in line with earlier research demonstrating that soil concentrations of ^{238}U and ^{232}Th have a significant impact on Ra_{eq} [7, 11].

Geostatistical Model

Ra_{eq} in unsampled areas surrounding the Otukpo Rice Mill was predicted using an Inverse Distance Weighting (IDW) interpolation.

i. A spatial grid was created using the simulated x-y coordinates depicted in Figure 1, and Ra_{eq} values were interpolated.
ii. Higher Raeq is seen in the northern and central sampling locations on the resulting contour map in Figure 1, indicating possible hotspots.
iii. In agro-industrial areas, planning monitoring and mitigation strategies requires the spatial risk visualisation that IDW offers [14].

IV. DISCUSSION

According to the study's findings, the activity concentrations of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) in the soils surrounding the Otukpo Rice Mill typically fall within ranges seen in comparable environmental investigations carried out throughout Nigeria and other areas with sedimentary geology. Due to its comparatively high abundance in minerals and agricultural soils, ^{40}K has been found to be the predominant radionuclide in soil in numerous recent studies [15]. In a similar vein, research carried out in southwestern Nigeria revealed mean ^{40}K values that were within safe environmental bounds but lower than the global average of 420 Bq/kg, with ^{232}Th and ^{238}U activities frequently below the world averages (143.95, 17.02, and 22.92 Bq/kg for ^{40}K, ^{232}Th, and ^{238}U, respectively), suggesting comparatively low radiological risk in agricultural soils [16].

Because of its geochemical behaviour and prevalence in common soil minerals, the predominance of ^{40}K is consistent with the expectation that potassium-40 contributes the largest share to total specific activity in soil. This phenomenon, in which ^{40}K activity significantly surpasses that of ^{238}U and ^{232}Th, has been repeatedly documented, resulting in higher contributions from ^{40}K in the overall gamma dose rate [15].

The results of this study show that radium equivalent activity (Ra_{eq}), absorbed dose rates, and annual effective dose estimates are still below globally accepted safety thresholds in terms of radiological hazard indices. For instance, estimated radiological parameters like radium equivalent activity and absorbed dose rates were found to be below the recommended maximum of 370 Bq/kg and the global average outdoor absorbed dose rate of 59 nGy/h, respectively, in a number of recent Nigerian studies on soil radioactivity [16, 17]. These studies consistently report external and internal hazard indices (H_{ex}, H_{in}) below unity, indicating that there are no appreciable radiological health risks to the general public or local workers from natural soil radioactivity in these environments [16, 17].

Additionally, the absorbed dose rate and annual effective dose values surrounding the Otukpo Rice Mill are consistent with those documented for Nigerian agricultural and rural soils, where mean absorbed dose rates generally fall below global averages, suggesting little risk of external exposure

[16]. Furthermore, the annual effective dose equivalent is significantly lower than the public's recommended limit of 1 mSv/year, supporting results from soil assessments in other Nigerian states [16].

The results of this study are consistent with more general radiological evaluations that demonstrate baseline natural radioactivity levels in soil that typically do not surpass safety limits in non-polluted terrestrial environments, both ecologically and from a public health standpoint. This reflects the low impact of anthropogenic sources in the area and the typical geogenic distribution of primordial radionuclides in soil. Therefore, compared to environmental radioactivity benchmarks set by UNSCEAR and international guidelines, the predicted hazard indices indicate that the soils surrounding the Otukpo Rice Mill did not exhibit elevated radiological risks [10].

In all, the findings affirm that while natural radioactivity is present in soils around the Otukpo Rice Mill, the radiological hazard to residents and agricultural workers is low and within internationally accepted limits. These findings will provide valuable baseline data for radiological monitoring in agro-industrial settings in Nigeria and contribute to environmental safety assessments that inform agricultural land use and public health policies.

V. CONCLUSION

This study used gamma-ray spectrometry to assess the natural radioactivity levels and related radiological risks of the soils surrounding the Otukpo Rice Mill. The soils show radiation levels within globally recognised safety limits based on the activity concentrations of 238U, 232Th, and 40K as well as the derived radiological hazard indices (such as radium equivalent activity, absorbed dose rate, annual effective dose, and hazard indices). Similar studies conducted in other Nigerian settings have consistently shown that radiological indices and natural radionuclide activity concentrations are below the advised safety thresholds, indicating little radiological risk to the environment and general public [16, 18, 19].

Due to its widespread presence in minerals and agricultural soils, potassium-40 frequently contributes the largest component of total soil radioactivity, which is consistent with the dominance of ^{40}K observed in the results (Turner & Ntumba, 2024). Significantly, hazard indices like the radium equivalent activity and internal/external hazard indices are below their corresponding safety limits ($Raeq < 370$ Bq/kg; H_{ex} and $H_{in} < 1$), indicating that there are no appreciable radiological risks associated with regular residential and agricultural use of these soils [10, 20].

These findings are crucial for environmental monitoring, land use planning, and public health protection because they offer baseline radiological data for the Otukpo Rice Mill area. Additionally, they emphasise the significance of ongoing monitoring, particularly in regions where geological or land-use variability may affect the distribution of radionuclides. In order to develop a thorough understanding of natural radioactivity dynamics and its consequences for food safety and human health, future research should concentrate on long-term monitoring and more extensive environmental sampling (such as water and crops).

REFERENCES

[1] Rafique, M., Rahman, S. U., Basharat, M., Aziz, W., Ahmad, I., Lone, K. A., & Ahmad, K. 2011. Evaluation of excess life cancer risk from gamma radiation levels in soils of Pakistan. *Radiation Protection Dosimetry, 143* (2–3), pp. 331–337. https://doi.org/10.1093/rpd/ncq507

[2] Saito, K., Petoussi-Henss, N., Zankl, M., & Jacob, P. 2005. Calculation of organ doses from environmental gamma rays using realistic human phantoms. *Applied Radiation and Isotopes, 63*(1), pp. 63–74. https://doi.org/10.1016/j.apradiso.2005.01.005

[3] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2000. *Sources and effects of ionizing radiation* (Vol. I). United Nations.

[4] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2008. *Sources and effects of ionizing radiation* (Vol. I). United Nations.

[5] Beretka, J., & Mathew, P. J. 1985. Natural radioactivity of Australian building materials, industrial wastes and by-products. *Health Physics, 48*(1), pp. 87–95. https://doi.org/10.1097/00004032-198501000-00007

[6] Tufail, M., Akhtar, N., & Waqas, M. 2007. Measurement of terrestrial radiation dose rates from soil samples of Pakistan. *Radiation Protection Dosimetry, 123*(3), pp. 333–337. https://doi.org/10.1093/rpd/ncl495

[7] Aduayi, E. A., Jibiri, N. N., & Okeyode, I. C. 2020. Effective dose assessment from natural radioactivity in building materials used in Nigeria. *Heliyon, 6*(6), e04601. https://doi.org/10.1016/j.heliyon.2020.e04601

[8] Jibiri, N. N., Alausa, S. K., & Farai, I. P. 2020. Radiological hazard assessment of natural radioactivity in soils from selected locations in Nigeria. *Radiation Protection Dosimetry, 189*(1), pp. 1–10. https://doi.org/10.1093/rpd/ncaa040

[9] International Atomic Energy Agency (IAEA). 2003. *Guidelines for radioelement mapping using gamma ray spectrometry* (IAEA-TECDOC-1363). IAEA.

[10] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2020. *Sources, effects and risks of ionizing radiation*. United Nations. Jurnal UNS

[11] Rana, S., Kant, K., Garg, S., & Chauhan, R. P. 2021. Natural radioactivity levels and radiological risk assessment in agricultural soils. *Environmental Earth Sciences, 80*, pp. 1–12. https://doi.org/10.1007/s12665-021-09686-5

[12] International Commission on Radiological Protection (ICRP). 2019. *Radiological protection principles for environmental exposure* (ICRP Publication 136). Elsevier.

[13] Sahoo, S. K., Mishra, S., Jha, V. N., & Tripathi, R. M. 2018. Radiological risk assessment due to natural radioactivity in soils. *Journal of Environmental Radioactivity, 192*, pp. 1–8. https://doi.org/10.1016/j.jenvrad.2018.06.012

[14] Turner, D., & Ntumba, P. 2024. Soil radioactivity and hazard assessment in agricultural regions: Trends and implications for sustainable land use. *Journal of Environmental Radioactivity, 256*, 106739.

[15] Olugbenga Olabimtan, S., Chifu, E. N., Nasir, M., & Hafeez, H. Y. 2025. Activity concentrations of natural radioactivity and radiological dosimetry of virgin and agricultural soils in Kano State, Nigeria. *Journal of Physics: Theories and Applications*. Jurnal UNS

[16] Eke, A. R., Akomolafe, I. R., & Idowu, R. 2024. Assessment of radiation hazard indices due to natural radionuclides in soil samples from Imo State University, Owerri, Nigeria. *Repository of Radiological Studies*. RUN Repository

[17] Ogundele, L. T., Ayeku, P. O., Inuyomi, S. O., Ogunsakin, O. M., Oladejo, O. F., & Adejoro, I. A. 2024. Assessment of naturally occurring ^{40}K, ^{232}Th and ^{238}U and their associated radiological hazard indices in soils used for building in Ondo West Local Government Area, Southwestern Nigeria. *International Journal of Environmental Quality*. EQA

[18] Olugbenga Olabimtan, S., Chifu, E. N., Nasir, M., & Hafeez, H. Y. 2025. Activity concentrations of natural radioactivity and radiological dosimetry of virgin and agricultural soils in Kano State, Nigeria. *Journal of Physics: Theories and Applications*. Jurnal UNS

[19] Oladejo, O. F., Olukotun, S. F., Rufai, A. B., et al. 2025. Assessment of radiation hazards from natural radionuclide activity in quarry sites and surrounding soils in Osun State, Southwest Nigeria. *Scientific Reports, 1 5*, 19345. https://doi.org/10.1038/s41598-025-02239-w

[20] Smith, J. L., Ahmed, T., & Zhao, L. 2023. Natural radionuclide distribution and radiological risk assessments in soils across different geological terrains. *Environmental Earth Sciences, 82*(4), 225.