

Assessment of Soil Radioactivity Contamination Index and Health Risks in Andoni Communities, Rivers State, Nigeria

Nwanne Theresa Ilugo^{✉1}, C. P. Ononugbo², Dr. Nwii, A. A.³

¹University of Delta Department of Physics, Agbor, Nigeria

²University of Port Harcourt, Department of Physics, Choba, Rivers State, Nigeria

³Ignatius Ajuru University of Education, Department of Physics, Port Harcourt, Nigeria

[✉]E-mail: nwanne.ilugo@unidel.edu.ng (corresponding author)

ABSTRACT

Twenty-one soil samples from Andoni LGA, Rivers State, Nigeria were analyzed using a NaI (IT) gamma detector to estimate radiation hazards from anthropogenic sources. The activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K ranged from 8.86 to 33.37 Bq kg⁻¹, 0 to 26.73 Bq kg⁻¹, and 7.52 to 75.45 Bq kg⁻¹, with mean values of 22.26 Bq kg⁻¹, 8.45 Bq kg⁻¹, and 27.42 Bq kg⁻¹, respectively. These results were used to compute radiological risk parameters associated with hazards, including the Radium equivalent dose rate and excess lifetime cancer risk. The calculated indoor and outdoor annual effective dose in soil samples ranged from 0.037 to 0.129 and 0.009 to 0.032, with average values of 0.081 mSvyr⁻¹ and 0.020 mSvyr⁻¹, respectively. In contrast, the average excess lifetime cancer risk (ELCR) was 0.62 × 10⁻³, higher than the world average of 0.29 × 10⁻³. These results indicate that the study area poses no significant immediate radiological hazard from exposure to soil samples. However, the excess lifetime cancer risk (ELCR) exceeded the recommended safety limit, suggesting potential long-term health effects from prolonged exposure. Continuous environmental radiation monitoring and further investigations are therefore recommended to identify contributing factors, support effective environmental management, and protect public health.

ARTICLE INFO

Article history:

Received: 30 June, 2026

Revised: 27 July, 2026

Accepted: 11 August, 2026

Published: 30 August, 2026

Keywords:

Activity concentration;
 Andoni; Gamma radiation;
 Health Risks; Radionuclides

To cite this article: Ilugo, N. T., Ononugbo, C. P. & Nwii, A. A. (2026). Assessment of Soil Radioactivity Contamination Index and Health Risks in Andoni Communities, Rivers State, Nigeria. *Journal of Natural Science Review*, 4(3), 670-686. <https://doi.org/10.62810/jnsr.v4i3.550>

Link to this article: <https://kujnsr.com/JNSR/article/view/550>



Copyright © 2026 Author(s). This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

INTRODUCTION

The natural radionuclides found in soil, water, air, and plants, as well as the artificial radioactivity from fallout from nuclear testing and medical applications, are among the sources of radiation that humans are exposed to. External exposure to gamma radiation comes from

cosmic rays and natural radionuclides, whereas internal exposure to humans comes from ingestion through food and drink and inhalation (Augustine et al., 2014). Furthermore, the 1999 ICRP report demonstrates that man is constantly exposed to ionizing radiation from naturally occurring radioactive materials (Sokari et al., 2022), which are thought to have originated in the earth's crust or elsewhere. The primary sources of natural radiation are radionuclides from the ^{226}Ra and ^{232}Th series, as well as primordial nuclides like ^{40}K and their decay products, which are present at trace levels in all ground formations (Al-Sewaidan, 2019; Kapanadze et al., 2019). Soil is the primary source of natural radioactivity and is used as a raw material for building homes.

Natural radioactivity found in soil alters the levels of background radiation and releases gamma rays into the atmosphere. These background levels of ionizing radiation are present for all people on the planet (Kapanadze et al., 2019). Man's activities on Earth and the natural radionuclides in the soil have caused humans to be exposed to natural radiation for extended periods of time (Alzubaidi et al., 2016; Joel et al., 2019). According to Eke et al., 2015, this natural radiation makes up the majority of the annual exposure to the human population (Agar et al., 2015; Zubair M., 2020; Addo et al., 2020). Long-term radiation exposure can have detrimental radiological effects, such as DNA deformation and other bimolecular and cellular effects (Botwe et al., 2017; Ravanate et al., 2014). Exposure to uranium and thorium nuclides and their progeny can cause health risks such as lung conditions, muscle necrosis, and the development of cancerous cells, even in bone (Eke et al., 2015; Zubair M., 2020; Keith et al., 2024; Findeiβ et al., 2017).

The lithological and geological characteristics of the land determine the natural radionuclides that are present in the soil samples (Zubair M., 2020; Dhawal et al., 2014). Monitoring and evaluating the distribution of radionuclides is crucial because of their uneven distribution, the presence of radionuclides above advised threshold levels in some areas, and the related health effects (Obed et al., 2005; UNSCEAR, 2000; Dindaroglu, T., 2014; Jibiri & Okeyode 2011). To protect human life and guarantee a radiation-pollution-free environment, it is crucial that the total amount of radioactivity in an environment be precisely determined and maintained at a level as low as reasonably achievable (ALARA) (Suleman, I. K., 2024). Table 1 tabulates comparisons with other authors who conducted similar research on soil samples.

Furthermore, the research will establish baseline data on the concentrations and spatial distribution of natural radionuclides in Andoni soils. This baseline information is essential for distinguishing natural background radiation levels from future changes resulting from anthropogenic activities, environmental disturbances, or industrial development. The data generated will serve as a valuable reference for environmental monitoring programs,

radiological impact assessments, land-use planning, and policy formulation aimed at protecting public health and ensuring environmental sustainability in the region. Additionally, the findings will contribute to the broader body of knowledge on natural radioactivity in coastal environments and support future scientific investigations in Andoni and similar geographical settings.

This study aims to quantify the radiological risks associated with naturally occurring radionuclides in Andoni soils and evaluate the local population's potential exposure through external and internal pathways. External exposure arises from gamma radiation emitted by radioactive elements in the soil. In contrast, internal exposure occurs through the inhalation of resuspended soil particles and the ingestion of contaminated food, water, or other environmental media. By assessing these exposure routes, the study will provide a comprehensive understanding of the radiation dose residents receive and the corresponding health implications. It will also compute the contamination index and health risks for selected communities in Andoni Local Government Area, Rivers State, Nigeria. To achieve this, the following objectives will be carried out: calculate the radium equivalent activity (R_{eq}), the total absorbed dose rate (D), the annual effective dose (AED), external hazard indices (H_{ex}), internal hazard index (H_{in}), activity utilization index (AUI), and excess lifetime cancer risk (ELCR) due to natural radionuclides from the soil in the communities.

Table 1. Comparison of activity concentration in soil samples with other Authors

Location		Activity Concentration (Bq/kg)			Authors
		²²⁶ Ra	²³² Th	⁴⁰ K	
Ogba/Egbema/Ndoni, State, Nigeria	Rivers	22.8	18.5	215.6	Avwiri, G. O. et al. (2013)
Southwestern Nigeria		31.2	28.4	387.5	Ademola, J. A. et al. (2014)
Ekiti State, Nigeria		25.6	22.3	301.8	Isinkaye and Emeluen(2015)
Kirklareli, Turkey		37	40	667	Taskin, H. et al. (2009)
Coastal Tamil Nadu, India		43.2	61.5	489.7	Ravisankar, R. et al. (2014)
Niger Delta, Nigeria		35.4	42.8	463.9	Agbalagba, E. O. et al. (2017)
Coastal Tamil Nadu, India		47.3	68.2	512.4	Sivakumar, S. et al. (2016)
Egypt		29.8	35.6	425.3	Hassan, N. M. et al. (2019)
Gauteng Province, South Africa		58.9	71.5	580.2	Kamunda, C. et al. (2016)
Pakistan		27.6	32.4	352.7	Tufail, M. et al. (2013)
This work		3.18	2.01	5.06	

METHODS AND MATERIALS

Study Area

Andoni Local Government Area in Rivers State, Nigeria, is predominantly inhabited by the Obolo (Andoni) people, and its administrative headquarters are located in Ngo Town. The Local

Government Area encompasses numerous towns and villages, each contributing to the region's rich cultural tapestry.

It is located in southeastern Rivers State. It lies within the Niger Delta region and is bordered by Bonny Local Government Area to the west, Opobo/Nkoro Local Government Area to the north, Atlanta Ocean to the South and Akwa Ibom State to the east, it lies approximately between latitudes $4^{\circ}25'52.80''$ to $4^{\circ}32'25.51''\text{N}$ and longitudes $7^{\circ}18'29.53''$ to $7^{\circ}33'55.25''\text{E}$ It is mostly riverine and coastal with numerous creeks, rivers and mangrove forests. Andoni's location makes it important for fishing, transportation, and coastal trade.

Sample Collection and Preparation

Twenty-one soil samples were chosen at random from seven Andoni Local Government Area communities. During the rainy season, all sampling communities were chosen over those with a high concentration of farming and industrial activity. A trowel was used to gather soil samples from a $0.5\text{m} \times 0.5\text{m}$ area down to a depth of 25cm. The samples were then put in plastic bags, duly labeled, and sealed. Initially, the soil samples were allowed to air-dry for a week before being placed in an oven set to 105°C to remove any remaining moisture. The samples were crushed and sieved using a 2mm mesh after drying to get rid of lumps, stones, and organic materials. The collected soil samples were transported to the National Institute of Radiation Protection and Research Laboratory, University of Ibadan.

Gamma Spectroscopy

The sodium iodide (NaI(Tl)) Spectrometer was used to analyze all samples using gamma spectroscopy. The ORTEC 456 digiBase multichannel analyzer (MCA) was connected to a 2"x2" sodium iodide device called the NaI(Tl). A USB cable connected the digiBase to a computer. The ORTECMestro software was used on the computer to accumulate and analyze the gamma-ray spectrum. 10800 seconds was the counting (accumulation) time. To lessen the impact of background radiation, the detector was placed inside a cylindrical lead shield that was 15 cm thick. For calibration, the International Atomic Energy Agency's standard materials (IAEA, 2003) were utilized. The software was used to calculate the activity concentrations of potassium-40 (K-40), thorium-232 (Th-232), and radium-226 (Ra-226) from the counting spectra. The radionuclide activity concentrations were estimated using the peak, which corresponds to 1460 keV for ^{40}K , 1764.5 KeV (214 Bi) for ^{226}Ra , and 2614.5 KeV (208Ti) for ^{232}Th . The background counts were determined by counting an empty container of the same dimensions as those containing the samples and subtracting from the gross count. The activity content of the sample was evaluated by the net area under the photo peaks using:

$$C (\text{Bq kg}^{-1}) = K C_n \quad (1)$$

Where C (Bq kg^{-1}) is the specific activity concentration of the radionuclides in the sample, C_n is the count rate under the corresponding peak value, and K is the calibration factor.

$$K = \frac{1}{\varepsilon P_\gamma M_s}$$

where:

ε = detector efficiency

P_γ = gamma-ray emission probability

M_s = sample mass (kg)

Radiological risk estimation

Absorbed Dose Rate (D)

The energy deposited in a medium by ionizing radiation is measured by the term "absorbed dose". Since $1 \text{ Gy} = 1 \text{ J Kg}^{-1}$, it is equivalent to the energy deposited per unit mass of medium, as is the unit J/Kg or gray. For the uniform distribution of naturally occurring radionuclides (^{238}U , ^{232}Th , and ^{40}K), the absorbed dose rates (D) from gamma radiation in the air at a height of one meter above the ground surface are computed using an equation.

$$D(\text{nGyh}^{-1}) = 0.462 A_{\text{Ra}} + 0.604 A_{\text{Th}} + 0.0417 A_{\text{K}} \quad (2)$$

Where A_{Ra} , A_{Th} , and A_{K} are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K , respectively (UNSCEAR, 2000).

The absorbed dose of radiation depends on the energy absorbed, not on the types of radiation or the absorbing material.

Annual Effective Dose

The dose quality of the stochastic health impact of low-level radiation on human tissue is represented by the radiation risk in relation to the air absorbed dose rate. Two principal conversion factors provided by UNSCEAR (2000) were taken into consideration when calculating the annual effective dose from D . The first is 0.7 SvG/y , which converts the absorbed dose in the air into an effective dose (conversion coefficient); the second is 0.42 and 0.58 in and outdoor occupancy factors, which assume that Nigerians return to work by 8 am and close at 5 pm. Using the following formulas, the effective dose in and out was calculated in mSv/y (UNSCEAR, 2000).

$$\text{Outdoor AEDE } (\text{mSvy}^{-1}) = D(\text{nGyh}^{-1}) \times 8760 \text{ h} \times 0.8 \times 0.7 \times 10^{-6} \quad (3)$$

$$\text{Indoor AEDE } (\text{mSvy}^{-1}) = D(\text{nGyh}^{-1}) \times 8760 \text{ h} \times 0.2 \times 0.7 \times 10^{-6} \quad (4)$$

Radium Equivalent Activity (R_{aeq})

According to Suresh Gandhi et al., (2013), the Radium Equivalent is a widely used index that compares the specific activities of materials containing ^{226}Ra , ^{232}Th , and ^{40}K by a single quantity that accounts for the radiation hazards associated with them. The radium equivalent activity index (R_{aeq}) was computed using the equation (UNSCEAR, 2000).

$$R_{aeq} = A_{Ra} + 1.43 A_{Th} + 0.077 A_K \quad (5)$$

Where A_{Ra} , A_{Th} , and A_K are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K respectively. It is assumed in the above equation that 10 Bq kg⁻¹ of ^{238}U , 7 Bq kg⁻¹ of ^{232}Th , and 130 Bq kg⁻¹ of ^{40}K produce equal gamma doses (UNSCEAR, 2000).

Annual Gonadal Dose Equivalent (AGDE)

The gonads, bone marrow, and bone surface cells are among the organs that UNSCEAR considers to be of interest because of their rapid cell division (UNSCEAR, 2000; Akortia et al., 2012). A measure of the genetic significance of the annual dose that the reproductive organs of the population receive is the annual gonadal equivalent dose, or AGDE. Using the relation (Avwiri et al., 2015), the annual gonadal dose equivalent (AGDE) caused by the activities of ^{226}Ra , ^{232}Th , and ^{40}K was calculated.

$$AGDE(\text{mSv/yr}) = 3.09 A_{Ra} + 4.18 A_{Th} + 0.314 A_K \quad (6)$$

Where A_{Ra} , A_{Th} , and A_K are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K (in Bq/Kg), respectively, in soil samples.

Activity Utilization Index (AUI)

The parametric model that allows us to calculate the dose rates of the radionuclides (K , Ra , and Th) in the air from soil samples is called the Activity Utilization Index. This is given as,

$$AUI = \left(\frac{A_{Ra}}{50 \text{ Bq/Kg}} \right) F_{Ra} + \left(\frac{A_{Th}}{50 \text{ Bq/Kg}} \right) F_{Th} + \left(\frac{A_K}{500 \text{ Bq/Kg}} \right) F_K \quad (7)$$

In this case, the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K are represented by A_{Ra} , A_{Th} , and A_K . F_{Ra} , F_{Th} , and F_K are the fractional contributions from the actual concentrations of these radionuclides. According to Mgbeokwere et al. (2021), F_{Ra} , F_{Th} , and F_K are 0.462, 0.604, and 0.041 for radium, thorium, and potassium, respectively.

Representative Gamma Index (I_γ)

The Representative Gamma Index (I_γ) is a radiological metric that evaluates the gamma radiation levels of building materials to determine their safety. It does this by analyzing the natural radioactivity of the materials, especially from isotopes such as potassium-40 (^{40}K),

thorium-232 (^{232}Th), and radium-226 (^{226}Ra). The representative gamma index is given as (NEA-OECD, 1979; Jibiri et al., 2014).

$$I\gamma = \frac{A_{\text{Ra}}}{150} + \frac{A_{\text{Th}}}{100} + \frac{A_{\text{K}}}{1500} \quad (8)$$

Where A_{Ra} , A_{Th} , and A_{K} are the specific activity concentrations of radioisotopes in Bq/Kg respectively. ($I\gamma$) must be ≤ 1 for the radiation hazard to be completely insignificant.

External and Internal Hazard Indices (H_{ex} and H_{i})

The External Hazard (H_{ex}) and Internal Hazard Index (H_{i}) are both used to assess the radiological safety of materials (especially, building materials) that contain naturally occurring radionuclides such as radium -226 (^{226}Ra), thorium -232 (^{232}Th), and potassium -40 (^{40}K), H_{ex} and H_{i} can be expressed from the equation (Senthilkumar et al., 2010) and (UNSCEAR, 2000).

$$H_{\text{ex}} = \frac{A_{\text{Ra}}}{370} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \quad (9)$$

$$H_{\text{i}} = \frac{A_{\text{Ra}}}{185} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \quad (10)$$

Where ^{226}Ra , ^{232}Th and ^{40}K are the contents of radioisotopes in Bq/Kg in each sample.

Excess Lifetime Cancer Risk (ELCR)

The excess lifetime cancer risk is a measure of the likelihood that a population will develop an additional cancer within a lifetime following radionuclide exposure. The formula below is used to calculate it (Taskin et al, 2000).

$$\text{ELCR} = \text{AEDE} \times \text{D.L} \times \text{RF} \quad (11)$$

Where AEDE is the annual effective dose equivalent, DL is the duration of life (70yrs), and RF is the risk factor (0.05 Sv^{-1}). For stochastic effects, ICRP 70 uses a value of 0.05 Sv^{-1} .

FINDINGS

Table 2 presents the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K , along with their radium equivalent values, in the soil samples. Table 3 shows the associated radiation hazard parameters calculated.

Table 2. Specific activity of ^{226}Ra , ^{232}Th and ^{40}K and radium equivalent activity (Bq/kg) in soil samples from Andoni LGA of Rivers State

SAMPLE LOCATION	^{226}Ra	^{232}Th	^{40}K	Raeq
NGO 1	24.72	8.15	7.52	36.96
NGO 2	27.60	4.23	13.10	34.66
NGO 3	26.50	7.19	14.31	37.87
UNYEADA 1	20.87	12.06	45.13	41.59
UNYEADA 2	21.83	4.23	34.21	30.51

UNYEADA 3	19.65	6.71	30.25	31.25
ASARAMA 1	27.12	1.29	24.50	30.85
ASARAMA 2	22.31	3.25	51.19	30.90
ASARAMA 3	24.22	5.32	28.23	34.00
ATABA 1	28.56	6.19	11.16	38.27
ATABA 2	32.89	12.00	23.29	51.84
ATABA 3	29.62	10.30	18.51	45.77
OYOROKOTO 1	20.39	26.75	25.72	60.62
OYOROKOTO 2	33.37	5.21	49.42	44.63
OYOROKOTO 3	31.25	15.30	33.50	55.71
DEMA 1	20.39	14.02	16.01	41.67
DEMA 2	18.25	12.22	22.32	37.44
DEMA 3	16.78	11.61	15.28	34.57
IBOT-USUT 1	8.86	5.21	36.64	19.13
IBOT-USUT 2	9.82	0.00	75.45	15.63
ISOT-USUT 3	10.48	6.20	33.46	21.92
MEAN	22.64	8.45	27.42	35.30
UNSCEAR	35	30	400	370

Table 3. Radiation hazard indices of soil samples from Andoni LGA of Rivers State

S/N	SAMPLE ID	D (nGyh ⁻¹)	AGED (mSvyr ⁻¹)	I _γ (Bqkg ⁻¹)	AEDE (mSvyr ⁻¹)		ELCR ×10 ⁻³	H _{ex}	H _{in}	AUI
					Outdoor	Indoor				
1	NGO 1	16.660	112.810	0.210	0.020	0.080	0.71	0.010	0.167	0.327
2	NGO 2	15.850	107.080	0.265	0.019	0.077	0.67	0.094	0.168	0.307
3	NGO 3	17.180	116.430	0.307	0.020	0.083	0.73	0.100	0.174	0.333
4	UNYEADA 1	18.810	129.070	0.210	0.023	0.090	0.80	0.110	0.169	0.342
5	UNYEADA 2	14.070	95.880	0.235	0.017	0.068	0.60	0.082	0.140	0.255
6	UNYEADA 3	14.390	98.265	0.164	0.017	0.069	0.61	0.085	0.138	0.265
7	ASARAMA 1	14.330	96.886	0.230	0.017	0.070	0.61	0.083	0.157	0.268
8	ASARAMA 2	14.405	98.597	0.236	0.017	0.070	0.61	0.083	0.144	0.250
9	ASARAMA 3	15.580	105.942	0.240	0.019	0.076	0.66	0.092	0.157	0.290
10	ATABA 1	17.399	117.639	0.318	0.021	0.084	0.74	0.103	0.181	0.340
11	ATABA 2	23.414	159.103	0.338	0.028	0.114	0.99	0.140	0.229	0.450
12	ATABA 3	20.668	140.390	0.477	0.025	0.100	0.88	0.124	0.204	0.400
13	OYOROKOTO1	26.650	182.900	0.205	0.032	0.129	0.11	0.164	0.219	0.510
14	OYOROKOTO2	20.625	140.409	0.408	0.025	0.100	0.88	0.121	0.211	0.375
15	OYOROKOTO3	25.075	171.035	0.370	0.030	0.122	0.11	0.150	0.235	0.470
16	DEMA 1	18.555	126.635	0.268	0.023	0.090	0.79	0.113	0.168	0.360
17	DEMA 2	16.740	114.480	0.250	0.020	0.081	0.71	0.100	0.150	0.320
18	DEMA 3	15.400	105.178	0.174	0.019	0.074	0.65	0.090	0.140	0.300
19	IBOT-USUT 1	8.770	60.660	0.083	0.010	0.043	0.37	0.052	0.075	0.150
20	IBOT-USUT 2	7.680	54.035	0.180	0.009	0.037	0.33	0.040	0.069	0.100
21	IBOT-USUT 3	9.980	68.774	0.129	0.012	0.048	0.42	0.059	0.088	0.174
	MEAN	16.773	114.390	0.252	0.020	0.081	0.62	0.095	0.161	0.314
	UNSCEAR	57	300	1.0	1.0	1.0	0.29	1.0	1.0	1.0

D = Absorbed dose (nGy h^{-1}), 1γ = Gamma Index (Bq Kg^{-1}), AGED = Annual Gonadal Equivalent dose (mSv yr^{-1}), AEDE = Annual Effective dose Equivalents (mSv yr^{-1}), ELCR = Excess Lifetime Cancer risk, H_{in} and H_{ex} = Internal and External hazard Index

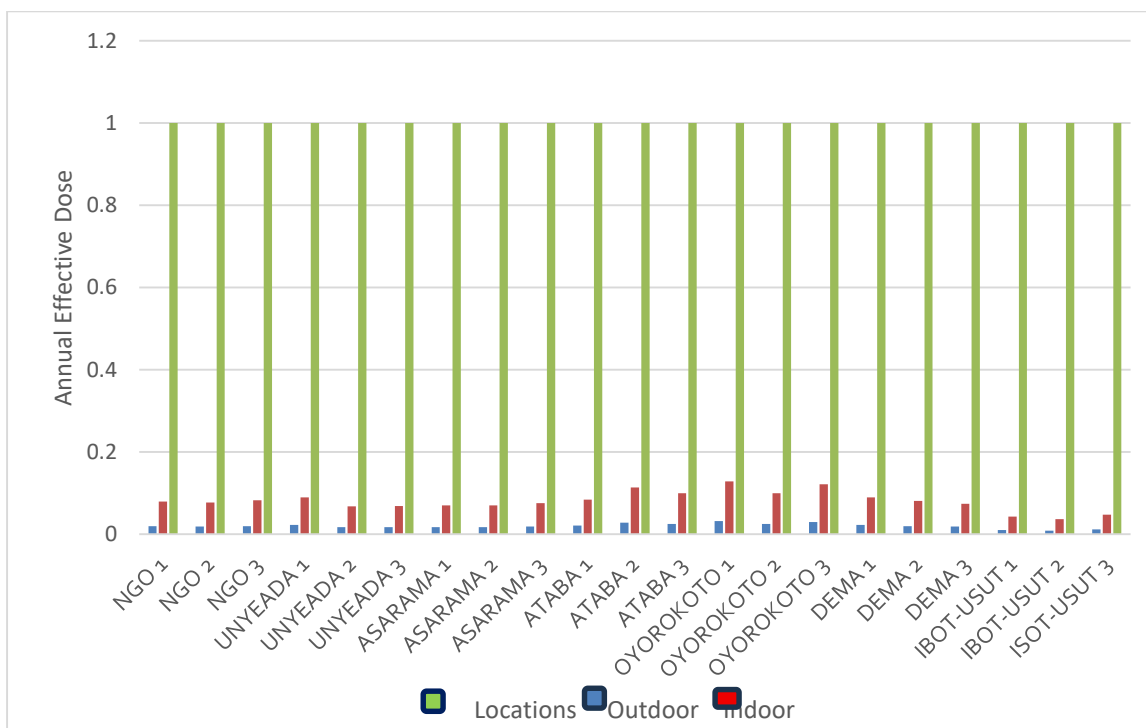


Figure 1. Comparison of Annual Effective Dose in Soil with world average in all the locations

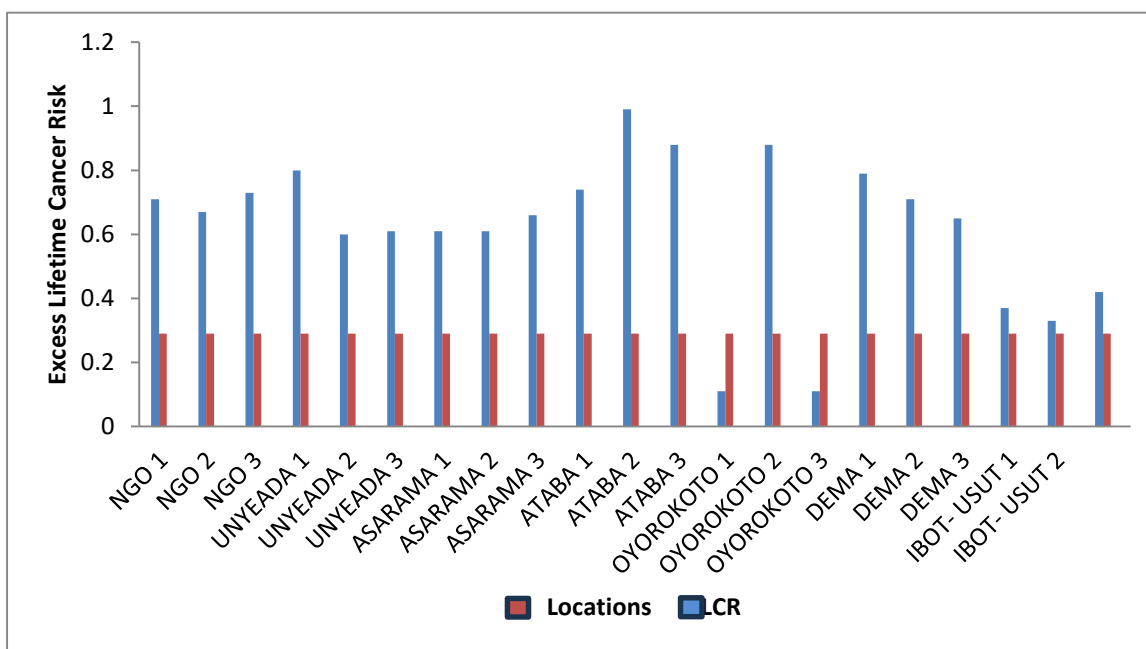


Figure 2. Comparison of Excess Lifetime Cancer Risk in Soil with world average in all the locations

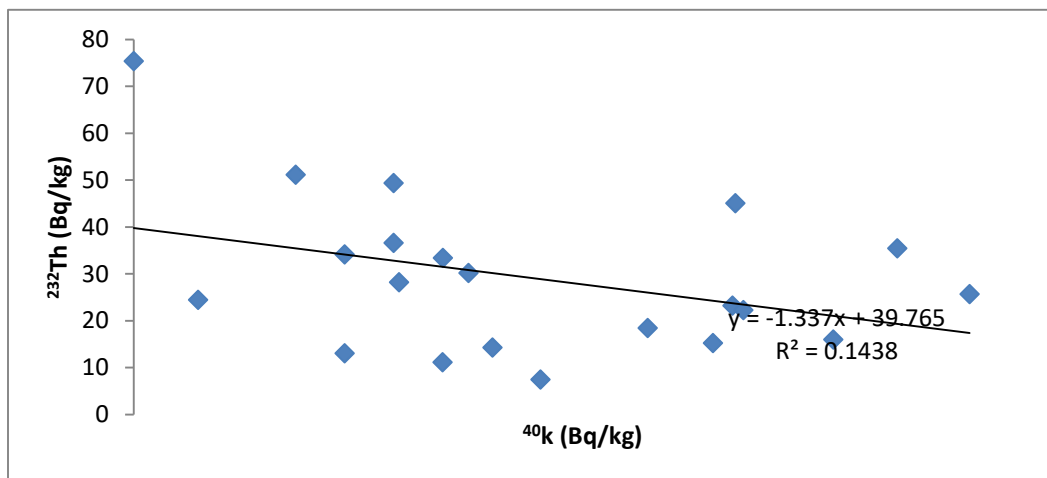


Figure 3. Correlation of ^{232}Th with ^{40}K in soil samples

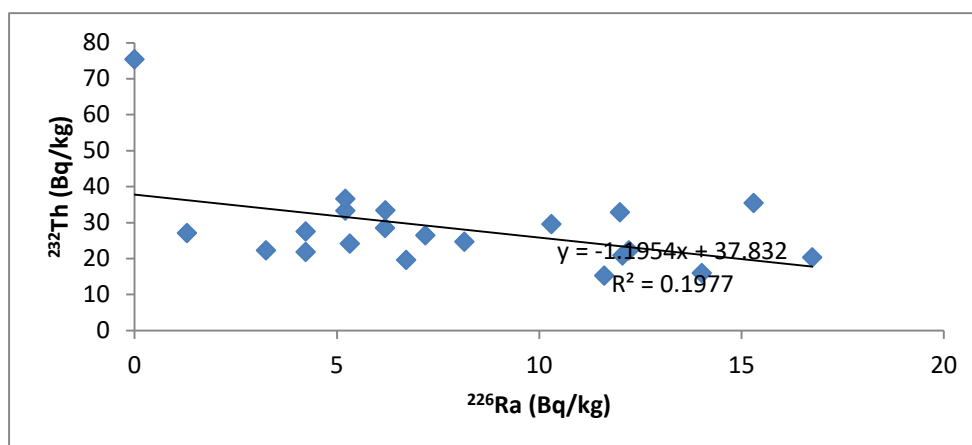


Figure 4. Correlation of ^{232}Th with ^{226}Ra in soil samples

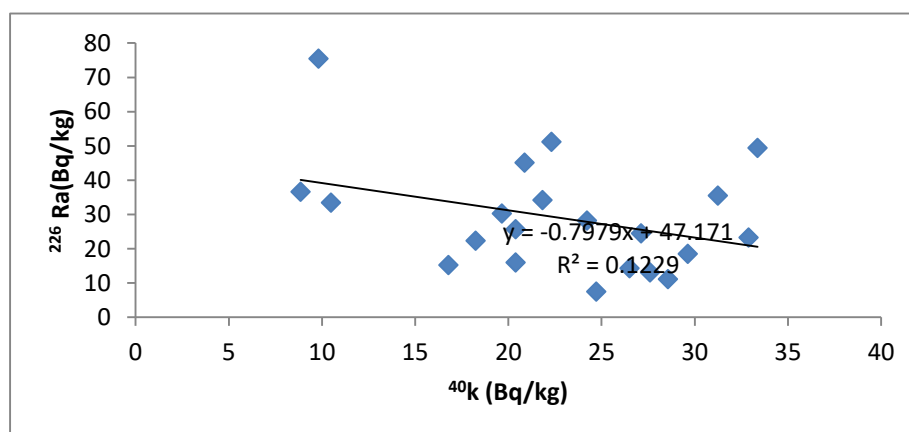


Figure 5. Correlation of ^{226}Ra with ^{40}K in soil samples

DISCUSSION

The activity concentrations of ^{226}Ra , ^{232}Th , ^{40}K , and radium equivalent in the soil samples are determined and shown in Table 1. The average activity concentration ranges for ^{226}Ra , ^{232}Th , and ^{40}K are 8.86 to 33.37 (mean 22.26 Bq kg⁻¹), 0 to 26.73 (mean 8.45 Bq kg⁻¹), and 7.52 to 75.45 (mean 27.42 Bq kg⁻¹), respectively. The slight variation in the distribution of ^{226}Ra , ^{232}Th , and ^{40}K observed can be attributed to various land uses, such as residential, mining, and farming (Nde et al., 2021). Conversely, ^{232}Th activity concentrations were lower than those of ^{226}Ra and ^{40}K . Because ^{232}Th is naturally present in soil and its activity concentration in phosphatic fertilizers is extremely small (Tabar et al., 2017), its comparatively low concentration in the investigated soil may be due to the soil's parent materials (Abedin et al., 2019; Gad, A et al., 2019).

In slightly and moderately alkaline soils, ^{226}Ra is mostly present in an available form and is easily leached by water (Kekeklidze et al., 2017). The mean results for ^{226}Ra , ^{232}Th , and ^{40}K in soil samples from all locations are lower than the global averages reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR): 35 Bq kg⁻¹, 30 Bq kg⁻¹, and 400 Bq kg⁻¹, respectively. This indicates the area is radiologically safe for living and agricultural purposes. We used the measured radium, thorium, and potassium activities from soil samples to compute the various hazard indices and absorbed dose, as shown in Table 2.

The concentrations of ^{226}Ra , ^{232}Th , and ^{40}K (Bq/kg) in the present study were lower than those reported by Osman et al., 2022 (19.98 Bqkg⁻¹), Menshikova et al., 2021 (25.49 ± 1.05 Bqkg⁻¹), and Ahmed et al., 2021 (144.3 ± 4), respectively.

Radium equivalent (Raeq) in soil samples ranged from 15.63 to 60.62 with a mean value of 35.30 Bq kg⁻¹. The results from Amanjeet et al., 2017 (93.41 Bq kg⁻¹); Ayeni et al., 2022 (114.65 Bq kg⁻¹); Ononugbo et al., 2017 (147.8 Bq kg⁻¹); and Gbarato et al., 2020 (14.85 Bq kg⁻¹) were higher than those in the present study. In this study, none of the sampled locations reported values higher than the permissible limit of 370 Bq kg⁻¹ recommended by OECD (1979).

The observed absorbed dose rate in soil samples ranged from 7.680 to 30.650 nGy h⁻¹, with an average of 16.773 nGy h⁻¹. It is observed that the absorbed rate for all the samples were below the world permissible limit of 59 nGyh⁻¹(UNSCEAR, 2000) and lower than previously reported for the study area (113.58 ± 7.62 nGyh⁻¹) (Ononugbo et al., 2016); (32.99 nGyh⁻¹) (Esi, 2017), indicated that the soil samples within the study areas were free of radiological threat and they were within the normal background environment (Eke et al., 2022). Annual Gonadal Equivalent Dose (AGED) ranged from 54.035 to 182.900 mSvyr⁻¹, with an average of 114.390 mSvyr⁻¹, which was below the world average of 300.0 mSvyr⁻¹. This implied that the gonadal values may pose no threat to the bone marrow and bone surface cells of community residents. The indoor and outdoor annual effective dose in soil samples ranged from 0.037 to 0.129 and 0.009 to 0.032,

with average values of 0.081 mSvyr^{-1} and 0.020 mSvyr^{-1} , respectively. The average outdoor annual effective dose was also below the worldwide average value of 1 mSvyr^{-1} (UNSCEAR, 2000). The internal hazard index from the sampling points ranged from 0.069 to 0.235 Bq kg^{-1} , with an average value of 0.161, while the external hazard index ranged from 0.040 to 0.164 with an average value of 0.095 Bqkg^{-1} . The values of the indices (H_{ex} , H_{in}) must be less than 1.0 for the radiation hazard to be insignificant.

Because both the internal and external hazard indices were less than 1, the radiation hazard is insignificant. The calculated representative index ranged from 0.083 to 0.477, with an average of 0.252. Values of the representative index ($I_{\text{r}} \leq 1$) correspond to an annual effective dose of less than or equal to 1 mSv . The excess lifetime cancer risk ranged from 0.11×10^{-3} to 0.99×10^{-3} , with a mean of 0.62×10^{-3} . However, the calculated average excess lifetime cancer risk (ELCR) was greater than the global average of 0.29×10^{-3} (Taskin et al. (2009)), suggesting that people who reside in or are regularly exposed to contaminated areas are at a markedly higher risk of getting cancer in their lifetime. Due to their frequent contact with soil, vulnerable groups like children, farmers, and workers are especially at risk. The histogram analysis of radionuclide concentrations revealed that radium (Ra-226) and potassium (K-40) showed a moderate to wide distribution, with average values of 22.26 Bq kg^{-1} and 27.42 Bq kg^{-1} , respectively. In comparison, thorium (Th-232) showed a positively skewed distribution with zero or low values and a mean of 8.45 Bq kg^{-1} . The variability in the results suggested localized enrichment of radium and potassium in certain areas, possibly influenced by geographical or anthropogenic factors.

The correlation coefficient among measured ^{226}Ra , ^{232}Th , and ^{40}K activity concentrations in soil (Figures 3 to 5) was shown for the studied area. The correlation analysis showed weak positive relationships among the radionuclides, with R^2 values of 0.122 for radium versus potassium, 0.197 for thorium versus radium, and 0.143 for thorium versus potassium. These low R^2 values indicated that the radionuclides likely originate from different sources or were influenced by varying environmental and geological processes.

CONCLUSION

The study found that concentrations of naturally occurring radionuclides in the sampled area were moderate for ^{226}Ra , ^{232}Th , and ^{40}K , while ^{232}Th concentrations were comparatively low. The evaluated radiological hazard parameters, including the absorbed dose rate, annual effective dose equivalent, external hazard index, and internal hazard index, were all below internationally recommended permissible limits. These results suggest that the study area does not currently pose a significant radiological hazard to the local population through direct exposure to terrestrial gamma radiation. Nevertheless, the estimated excess lifetime cancer risk (ELCR) exceeded the recommended safety threshold, indicating the possibility of long-term

stochastic health effects associated with prolonged exposure. Although the immediate radiological risk appears minimal, the elevated ELCR highlights the importance of sustained environmental radiation monitoring and comprehensive investigations into potential contributing factors. These measures are essential for early risk detection, effective environmental management, and protecting public health in affected communities.

Author Contributions

- N. T. Ilugo conceptualized and supervised the study.
- C. P. Ononugbo investigated and analyzed data.
- A. N. W. wrote the manuscript with input from all authors.
- All authors reviewed and approved the final version.

Acknowledgements

We highly appreciate the efforts of all the community development committee (CDC) presiding officers for granting us access to collect the various soil samples

Funding Information

No funding is available for the manuscript.

Conflict of Interest Statement

The authors declare that they have no conflict of interest

Data Availability Statement

All data generated or analyzed during this study are included in this published article (Tables 2–3).

REFERENCES

- Abedin, M. J., Karim, M. R., Hossain, S., Deb, N., Kamal, M., Miah, M. H. A., & Khandaker, M. U. (2019). Spatial distribution of radionuclides in agricultural soil in the vicinity of a coal-fired brick kiln. *Arabian Journal of Geosciences*, 12, Article 236. <https://doi.org/10.1007/s12517-019-4384-9>
- Addo, M. A., Lomotey, J. S., Osei, B., & Appiah, K. (2022). Measurement of natural radioactivity in soil dust samples along roadways in high commercial areas of the Ketu South District of the Volta Region, Ghana. *Radiation Protection and Environment*, 43(1), 6–12.
- Ademola, J. A., Bello, A. K., & Adejumobi, A. C. (2014). Determination of natural radioactivity and hazard assessment in soil samples from selected areas of Nigeria. *Journal of Radiation Research and Applied Sciences*, 7(2), 249–255. <https://doi.org/10.1016/j.jrras.2014.02.006>

- Agar, O., Eke, C., Boztosun, I., & Korkmaz, M. E. (2015). Determination of naturally occurring radionuclides in soil samples of Ayranci, Turkey. *Journal of Physics: Conference Series*, 590, 012042. <https://doi.org/10.1088/1742-6596/590/1/012042>
- Agbalagba, E. O., Avwiri, G. O., & Chad-Umoren, Y. E. (2017). Radiological assessment of natural radionuclides and associated hazard indices in soils from oil-producing areas of the Niger Delta region, Nigeria. *Environmental Earth Sciences*, 76, Article 565. <https://doi.org/10.1007/s12665-017-6882-0>
- Al-Sewaidan, H. A. (2019). Natural radioactivity measurements and dose rate assessment of selected ceramic and cement types used in Riyadh, Saudi Arabia. *Journal of King Saud University – Science*, 31(4), 987–992. <https://doi.org/10.1016/j.jksus.2019.04.001>
- Alzubaidi, G., Hamid, F., & Abdul Rahman, I. (2016). Assessment of natural radioactivity levels and radiation hazards in agricultural and virgin soil in the state of Kedah, north of Malaysia. *The Scientific World Journal*, 2016, 1–9. <https://doi.org/10.1155/2016/9673124>
- Amanjeet, K., Kumar, S., Singh, J., & Bajwa, B. S. (2017). Assessment of natural radioactivity levels and associated dose rates in soil samples from the historical city Panipat, India. *Journal of Radiation Research and Applied Sciences*, 10(3), 283–288. <https://doi.org/10.1016/j.jrras.2017.06.001>
- Avwiri, G. O., Egieya, J. M., & Ononugbo, C. P. (2013). Radiometric assay of hazard indices and excess lifetime cancer risk due to natural radioactivity in soil profile in Ogba/Egbema/Ndoni Local Government Area of Rivers State, Nigeria. *Academic Research International*, 4(5), 54–65.
- Ayeni, D. A., & Adebisi, F. M. (2022). Evaluation of natural radioactivity and radiation hazards of soil around petroleum products marketing company using gamma ray spectrometry. *Tanzania Journal of Science*, 48(2), 304–312.
- Botwe, B. O., Schirone, A., Delbono, I., et al. (2017). Radioactivity concentrations and their radiological significance in sediments of the Tema Harbour (Greater Accra, Ghana). *Journal of Radiation Research and Applied Sciences*, 10(1), 63–71. <https://doi.org/10.1016/j.jrras.2016.11.006>
- Dhawal, S. J., Phadatare, M. R., Kulkarni, G. S., & Pawar, S. H. (2014). Gamma radiation levels in the villages of South Konkan, Maharashtra, India. *Environmental Earth Sciences*, 72, 511–523. <https://doi.org/10.1007/s12665-013-2996-8>
- Eke, B. C., Jibiri, N. N., Anisimwu, B. C., Orji, C. E., & Emelue, H. U. (2015). Baseline measurements of natural radioactivity in soil samples from the Federal University of Technology, Owerri, South-East, Nigeria. *British Journal of Applied Science & Technology*,

5(2), 142–149.

- Eke, B. C., Ukwuihe, U. M., & Akomolafe, I. R. (2022). Evaluation of activity concentration of natural radionuclides and lifetime cancer risk in soil samples at two tertiary institutions in Owerri, Imo State, Nigeria. *International Journal of Radiation Research*, 20, 671–678.
- Esi, O. E., Edomi, O., & Odedede, O. (2017). Evaluation of radiological hazard indices in soil samples and excess lifetime cancer risk around Delta Steel Company Ovwian-Aladja, Delta State. *Journal of Scientific and Engineering Research*, 4(8), 117–127.
- Findeiß, M., & Schäffer, A. (2017). Fate and environmental impact of thorium residues during rare earth processing. *Sustainable Metals*, 3, 179–189.
<https://doi.org/10.3390/susmet3030179>
- Gad, A., Saleh, A., & Khalifa, M. (2019). Assessment of natural radionuclides and related occupational risk in agricultural soil Southeastern Nile Delta, Egypt. *Arabian Journal of Geosciences*, 12, Article 188. <https://doi.org/10.1007/s12517-019-4326-6>
- Gbarato, O. L., Sokari, S. A., & Ononugbo, C. P. (2020). Radiological hazard and excess lifetime cancer risk associated with sediments from coastal communities of Okrika, Nigeria: Evaluation of potentials for use as building materials using gamma-ray spectroscopy. *Journal of African Contemporary Research*, 11(1), 60–75.
- Hassan, N. M., Ishikawa, T., Hosoda, M., Sorimachi, A., Sahoo, S. K., Janik, M., & Tokonami, S. (2019). Assessment of natural radioactivity and associated radiological hazards in soil samples from Egypt. *Environmental Monitoring and Assessment*, 191(4), Article 1–13.
<https://doi.org/10.1007/s10661-019-7355-2>
- Isinkaye, M. O., & Emelue, H. U. (2015). Natural radioactivity measurements and evaluation of radiological hazards in sediment of Oguta Lake, South East Nigeria. *Journal of Radiation Research and Applied Sciences*, 8(3), 459–469. <https://doi.org/10.1016/j.jrras.2015.05.001>
- Jibiri, N. N., & Okeyode, I. C. (2011). Activity concentration of natural radionuclides in the sediments of Ogun River, Southwestern Nigeria. *Radiation Protection Dosimetry*, 147(4), 555–564. <https://doi.org/10.1093/rpd/ncr332>
- Joel, E. S., Maxwell, O., & Adewoyin, O. O. (2019). Investigation of natural environmental radioactivity concentration in soil of coastal area of Ado-Odo/Ota, Nigeria and its radiological implications. *Scientific Reports*, 9, Article 4219.
<https://doi.org/10.1038/s41598-019-40644-2>
- Kamunda, C., Madhuku, M., & Mathuthu, M. (2016). Assessment of radiological hazards from gold mine tailings in Gauteng Province, South Africa. *International Journal of Environmental Research and Public Health*, 13(1), 138.

<https://doi.org/10.3390/ijerph13010138>

- Keith, S., & Wohlers, D. W. (2024). *Addendum to the toxicological profile for thorium*. Agency for Toxic Substances and Disease Registry.
- Kekelidze, N., Jakhutashvili, T., Tutberidze, B., Tulashvili, F., Akhalkatsishvili, M., & Mtsariashvili, L. (2017). Radioactivity of soils in Mtskheta-Mtianeti region (Georgia). *Annals of Agrarian Science*, 15, 304–311. <https://doi.org/10.1016/j.aasci.2017.08.002>
- Obed, R. I., Farai, I. P., & Jibiri, N. N. (2005). Population dose distribution due to soil radioactivity concentration levels in 18 cities across Nigeria. *Journal of Radiological Protection*, 25(3), 305–312. <https://doi.org/10.1088/0952-4746/25/3/005>
- Organisation for Economic Co-operation and Development. (1979). *Exposure to radiation from natural radioactivity in building materials: Report of a group of experts of the OECD Nuclear Energy Agency*. OECD Publishing.
- Ononugbo, C. P., & Mgbemere, C. J. (2016). Dose rate and annual effective dose assessment of terrestrial gamma radiation in Notore Fertilizer Plant. *International Journal of Emerging Research in Management & Technology*, 5(9), 1–6.
- Osman, R., Dawood, H. Y., Melegy, A., El-Bady, S. M., Saleh, A., & Gad, A. (2022). Distributions and risk assessment of the natural radionuclides in the soil of Shoubra El Kheima, South Nile Delta, Egypt. *Atmosphere*, 13(1), 98. <https://doi.org/10.3390/atmos13010098>
- Ravanat, J. L., Breton, J., Douki, T., et al. (2014). Radiation-mediated formation of complex damage to DNA: A chemical aspect overview. *British Journal of Radiology*, 87, 20130715. <https://doi.org/10.1259/bjr.20130715>
- Ravisankar, R., Chandrasekaran, A., Vijayagopal, P., Venkatraman, B., Eswaran, P., Rajalakshmi, A., & Suganya, M. (2014). Natural radioactivity and radiological hazard assessment in soil samples of coastal Tamil Nadu, India using gamma-ray spectrometry. *Applied Radiation and Isotopes*, 97, 67–74. <https://doi.org/10.1016/j.apradiso.2014.02.011>
- Senthilkumar, B., Dhavamani, V., Ramkumar, S., & Philominathan, P. (2010). Measurement of gamma radiation levels in soil samples from Thanjavur using γ -ray spectrometry and estimation of population exposure. *Journal of Medical Physics*, 35, 48–53. <https://doi.org/10.4103/0971-6203.62271>
- Sivakumar, S., Chandrasekaran, A., Ravisankar, R., Ravikumar, S. M., Jebakumar, P. P., Vijayalakshmi, I., & Vijayagopal, P. (2016). Measurement of natural radioactivity and evaluation of radiological hazard indices in coastal sediment and soil samples, Tamil Nadu, India. *Journal of Radiation Research and Applied Sciences*, 9(3), 238–246. <https://doi.org/10.1016/j.jrras.2016.03.002>

- Sokari, S. A., Ononugbo, C. P., & Gbarato, O. L. (2022). Radiological health risk from gamma radiation of coastal communities in Okrika Local Government Area of Rivers State, Nigeria. *Asian Journal of Physical and Chemical Sciences*, 10(1), 38–59.
<https://doi.org/10.9734/AJOPACS/2022/v10i130149>
- Suresh Gandhi, M., Ravisankar, R., Rajalakshmi, A., Sivakumar, S., Chandrasekaran, A., & Pream Anand, D. (2014). Measurements of natural gamma radiation in beach sediments of northeast coast of Tamil Nadu, India by gamma-ray spectroscopy with multivariate statistical approach. *Journal of Radiation Research and Applied Sciences*, 7, 7–17.
<https://doi.org/10.1016/j.jrras.2013.12.004>
- Tabar, E., Yakut, H., Saç, M. M., Taşköprü, C., İçhedef, M., & Kuş, A. (2017). Natural radioactivity levels and related risk assessment in soil samples from Sakarya, Turkey. *Journal of Radioanalytical and Nuclear Chemistry*, 313, 249–259.
<https://doi.org/10.1007/s10967-017-5301-4>
- Taskin, H., Karavus, M., Ay, P., Topuzoglu, A., Hidiroglu, S., & Karahan, G. (2009). Radionuclide concentrations in soil and lifetime cancer risk due to gamma radioactivity in Kırklareli, Turkey. *Journal of Environmental Radioactivity*, 100(1), 49–53.
<https://doi.org/10.1016/j.jenvrad.2008.10.012>
- Tufail, M., Akhtar, N., Waqas, M., & Khalid, S. (2013). Natural radioactivity hazards of building bricks fabricated from soil of two districts of Pakistan. *Journal of Radiological Protection*, 33(2), 369–380. <https://doi.org/10.1088/0952-4746/33/2/369>
- United Nations Scientific Committee on the Effects of Atomic Radiation. (2000). *Sources and effects of ionizing radiation: UNSCEAR 2000 report to the General Assembly, with scientific annexes* (Annex B: Exposures from natural radiation sources). United Nations.
- Zubair, M. (2020). Measurement of natural radioactivity in several sandy-loamy soil samples from Sijua, Dhanbad, India. *Heliyon*, 6, e03430.
<https://doi.org/10.1016/j.heliyon.2020.e03430>