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ABSTRACT: A total of 30 soil samples from different sampling points at Imo State University (IMSU), Owerri, Nigeria were collected for the study. The activity concentrations of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) were measured in the samples by gamma-ray spectrometry using NaI (TI) detector. Absorbed dose rate (D), annual effective dose (AED), radium equivalent activity (Ra_{eq}), and radiological hazard index parameters (activity utilization index [AUI], external hazard index [H_{ex}], internal hazard index [H_{in}], and excess lifetime cancer risk [ELCR]) due to the naturally occurring radionuclides were determined. The mean activity of ^{238}U, ^{232}Th, and ^{40}K were found to be 20.32 ± 3.22, 22.55 ± 0.68, and 91.63 ± 1.54 Bqkg^{-1} which were lower than the world average reference mean values of 33, 45, and 420 Bqkg^{-1}for ^{238}U, ^{232}Th, and ^{40}K, respectively, as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The average value of D, Ra_{eq}, AUI, ELCR, H_{ex}, and H_{in} in the soil samples was 26.86 ± 1.97 nGyh^{-1}, 59.62 ± 4.14 Bqkg^{-1}, 0.42 ± 0.03, 0.14 ± 0.01 (×10^{-3}), 0.16 ± 0.01, and 0.22 ± 0.02, respectively. The annual effective dose to the general public was 33.07 ± 2.40 µSvy^{-1}. This value lies well below the average worldwide reference value of 0.7 mSvy^{-1}, as reported by UNSCEAR. Soil samples from IMSU pose no significant radiological health hazards to the university community.

KEYWORDS: Radiation dose, NaI(TI) detector, radionuclides, cancer risk, Owerri

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Introduction

Primordial radionuclides with long half-lives have been part of the Earth's crust and they remain significant sources of natural ionizing radiation to the human population.[1-3] Radiation is classified into 2 depending on the sources: natural and artificial.[4] Naturally Occurring radiation comes mainly as terrestrial gamma radiation from naturally occurring radionuclide materials (NORMs) in the Earth's crust[5-7] or as cosmic rays from space.[8] In contrast, artificial radiation arises from medical radiological imaging or nuclear industrial fallouts.[4]

Natural radionuclides in the Earth's crust are significant terrestrial radiation sources. Those predominantly found in the soil include ^{238}U, ^{232}Th, and ^{40}K.[1,9,10] The natural radioactivity from soil comes from ^{238}U, ^{232}Th decay series, and non-decay ^{40}K.[1,11,12] They are often at a low concentration level that might not cause harmful biological effects.[1,10] However, anthropogenic activities in some environments have enhanced the concentration level of the radioactivity in soil,[13,14] which could increase the background radiation in the environment because soil serves as a significant source of background radiation exposure to the human population and also a medium of transferring radionuclides into our environment.[11,15] These suggest that soil is a significant indicator of radioactivity contamination in our environment[4,16] and should be appropriately and regularly investigated.

Due to the natural radionuclides in the soil and man's activity with the Earth, humans have continuously prolonged exposure to natural radiation.[17,18] This natural radiation forms the major component of the total annual exposure to the human population.[4,8,19,20] Prolonged radiation exposure can cause harmful radiological effects, ranging from DNA deformation to other bimolecular and cellular effects.[3,21] Exposure to uranium and thorium nuclides and their progenies can cause health hazards such as lung diseases, muscle necrosis, and generation of cancerous cells even in the bones.[4,8,22,23] The natural radionuclides in the soil samples vary and depend on the lithological and geological nature of the land.[8,24]

The natural radioactivity in soil and terrestrial radiation exposure from the environment depends mainly on geological and geographical parameters. It changes in different soil levels of each region in the earth's crust.[1,25] Some other factors, such as mineralogy, organic concentration, and geochemical composition of the soil, can also affect the activity concentration of the radionuclides in the soil.[12] Considering the non-uniformly distribution of radionuclides in the soil[26] and the fact that most of these radionuclides can cause a harmful effect,[3,21] it is imperative to have a perfect understanding of the soil radioactivity concentration level and determine the radiological risks due to exposure of the human population.

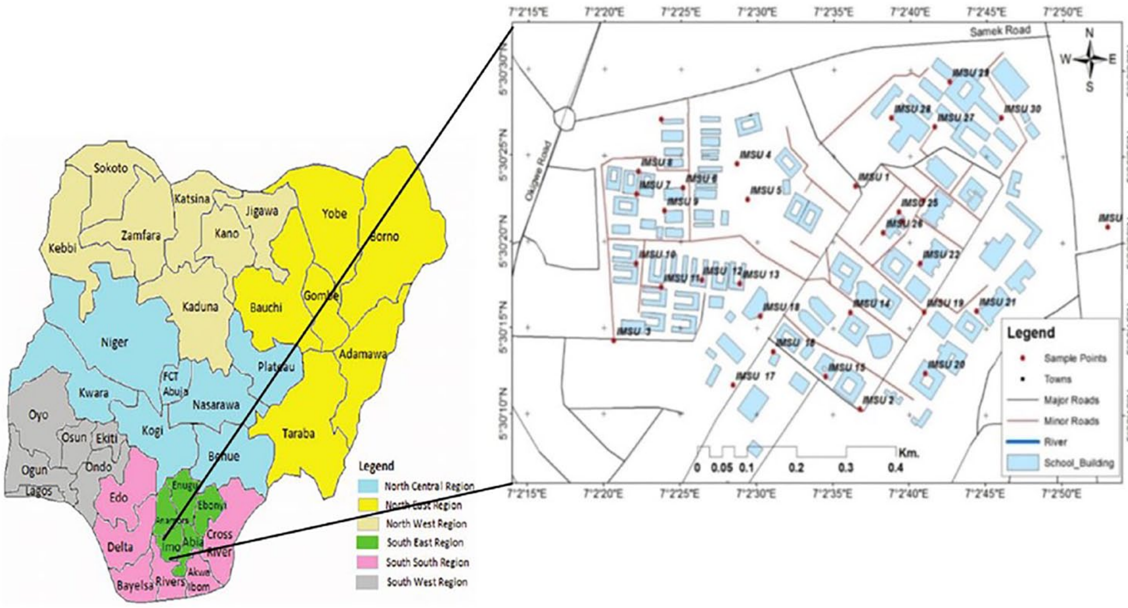

Figure 1. Map of the study location.

Imo State University (IMSU) is a densely populated institution situated at the center of Owerri City, Nigeria, with many industrial and human activities. In the interest of workers, and students, the measurement of natural radioactivity concentration in soil within such an environment is important.[20,27] In the past few years, there has been an increase in the campaigns all over the world on research on radionuclides and natural radioactivity concentration in soil due to the harmful health effect it might pose on humans as a result of both natural and anthropogenic activities.[18,28-30] As referenced in this study, several works have been done on radionuclide and radioactivity concentrations. Still, there are no available data on the radioactivity concentration level of soils from IMSU, Nigeria. Thus, this study will contribute significant data to the existing literature on the measurement of radioactivity concentration levels in soils of the study area.

The study aimed to assess radiation hazard indices due to natural radionuclides (^{238}U, ^{232}Th, and ^{40}K) in soil samples collected from 30 locations in IMSU, Nigeria. To achieve this aim, the following objectives will be carried out: calculate the radium equivalent value (Ra_{eq}), the total absorbed dose rate (D), the annual effective dose (AED), external hazard indices (H_{ex}), internal hazard indices (H_{in}), activity utilization indices (AUI), and excess lifetime cancer risk (ELCR) due to natural radionuclides from the soil in the university.

Material and Method

Study area

Imo State University is in Owerri Metropolis in Imo State, South-Eastern Nigeria. The map of the study area is presented in Figure 1. The university is on a latitude of 5.5080°N and a longitude of 7.0423°E. The environmental catchment area of the study location is about 104 km^2, which cuts across Owerri Municipal, Owerri North, and Owerri West. IMSU accommodates an average daily population above 15 000, including students, staff, and visitors, as seen from the daily report at the school entrance gate. It is a famous institution in Owerri due to its location and population density. It is also at the base of the dip slope from Okigwe (the center of mining in Imo State) to Owerri. This suggests that most radionuclides washed off by water floods from the rocks and mining sites from Okigwe might settle in Imo State University and its environs.

The study area is slightly sloped flat land, partly covered with sandy, loamy, stony, and clay soil. It has a moderately dry climate with an average monthly temperature of 24°C to 29°C, with rainfall from March to July and September to October. The dry season is dominated by harmattan breeze and moderate sun intensity from December to February and August.

Sample collection

Soil samples were collected from 30 sampling points in the natural, uncultivated grass-covered level areas within the region, as stipulated by International Atomic Energy Agency (IAEA) recommendations.[31] The samples were collected on a sunny day in March 2022 after clearing each sampling point's surface of stones, pebbles, vegetation, and roots. Each soil sample was collected at a depth of 15 cm beneath the surface and packed in a labeled polythene bag for preparation and gamma spectroscopic analysis.

Sample preparation

All collected soil samples were transported to the laboratory, and all visible unwanted materials were removed using a wooden tongue. The samples were first air-dried under ambient temperature (30°C) for 1 week and were later subjected to a higher temperature using a drying oven at 105°C to eliminate any moisture. Each sample was crushed using a mechanical potter and sieved with a 2.00 mm mesh to ensure sample homogeneity. About 0.2 kg of each homogeneous sample was weighed into a cylindrical container of negligible mass and correctly labeled with indelible ink for easy identification.[4,32] The cylindrical containers used for the package were washed with borehole water (5 times) and rinsed thoroughly with distilled water. The packaged samples were allowed in the laboratory for at least 4 weeks so natural radionuclides and their progenies could attain secular radioactive equilibrium.[4,8,32] Afterwards, the samples were gathered in a big plastic carrier and transported to the Radiation and Health Physics Research Laboratory, Department of Physics, University of Ibadan, Nigeria, for gamma-ray spectrometry analysis.

Gamma-ray spectrometry analysis

The gamma-ray spectrometry analysis was conducted at the radiation and health physics research laboratory, Department of Physics, University of Ibadan, Nigeria. Each sample was counted for a total of 36 000 seconds. The detector employed for the radioactivity measurements was a 76 mm × 76 mm NaI(Tl) detector crystal (802 Series, Canberra Inc.) coupled to a Canberra series 10 Plus multichannel analyzer (MCA) of model no: 1104 via a preamplifier. The system had an adequate lead shield that reduced the background radiation by 95%. The energy resolution of the NaI(Tl) detector was 8% at 0.662 MeV (^{137}Cs). As this study aimed to determine the activity concentration of ^{238}U, ^{232}Th, and ^{40}K radionuclides in the soil samples, the ^{238}U and ^{232}Th series and ^{40}K activities were considered as the amount of these radionuclides that would enter the air from the soil, so the energy values upon which the measurement was to be based were initially determined. The radionuclides (^{238}U and ^{232}Th) activity concentrations were determined using the gamma energy of their progenies that was noticed during the decay series as 1.760 MeV for ^{226}Ra (^{238}U) and 2.615 MeV for ^{232}Th. The activity concentration of ^{40}K was determined using only its gamma energy of 1.460 MeV. The activity concentrations of radionuclides in the samples were estimated using equation (1).[4]

$$C\left(Bqkg^{-1}\right) = \frac{C_n}{\varepsilon P_\gamma M_s t} \tag{1}$$

where C is the radionuclide activity concentration of soil samples given in Bqkg^{-1}, C_n represents the count rate under the corresponding peak, ε is the detector's efficiency at the specific gamma-ray energy, $P\gamma$ is the absolute transition probability of the specific gamma-ray, M_s is the soil sample mass in kg, and t is the counting time in seconds.

A gamma-ray detector's detection limit (DL) specifies its operational capabilities without the effect of the sample.[33] This calculation was performed using equation (2).

$$DL\left(Bqkg^{-1}\right) = 4.65\frac{(C_b)^{1/2}}{t_b}k \tag{2}$$

where t_b in the second represents the background counting time, C_b is the total background count in the corresponding peak, and k is the conversion factor given in equation (1). The present study's measurement system showed that soil samples' detection limits were 16.96, 4.43, and 3.65 Bqkg^{-1} for ^{40}K, ^{232}Th, and ^{238}U, respectively. Any activity concentrations lower than these numbers are considered below the detector's detection limit (BDL).

Radiological hazard indices

Radium equivalent: Radium equivalent activity (Ra$_{eq}$) is one of the most widely used hazard indices in comparing radionuclides (^{238}U, ^{232}Th, and ^{40}K) in any material by a single quantity that considers the hazard associated with them.[18,29,31,34] The radium equivalent is calculated using equation (3).[8,35,36]

$$Ra_{eq}\left(Bqkg^{-1}\right) = C_U + 1.43C_{Th} + 0.077C_K \tag{3}$$

where C_K, C_U, and C_{Th} are the activity concentrations in Bqkg^{-1} of ^{40}K, ^{238}U, and ^{232}Th, respectively.

Absorbed dose rate

The absorbed dose rate in the air from exposure to natural primordial radionuclides was evaluated using the activity concentration of radionuclides. The absorbed dose rate (D [nGyh^{-1}]) in the air helps us quantify the amount of radiation absorbed by a body at 1 m above the ground due to ^{238}U, ^{232}Th, and ^{40}K. The absorbed dose rate in the air was calculated using equation (4) as given in the UNSCEAR 2000 report.[1,8,37]

$$D\left(\text{nGy}h^{-1}\right) = 0.0417C_k + 0.462C_U + 0.604C_{Th} \tag{4}$$

where C_K, C_U, and C_{Th} are the activity concentrations in Bqkg^{-1} of ^{40}K, ^{238}U, and ^{232}Th, respectively.

Annual effective dose (μSvy^{-1}): it was calculated from the absorbed dose rate using equation (5)

$$AED\left(outdoor\right) = D\left(nGyh^{-1}\right) \times 8760hy^{-1} \times 0.7SvGy^{-1} \times 0.2 \times 10^{-3} \tag{5}$$

where AED is the annual effective dose equivalent (μSvy^{-1}), and D is the absorbed dose rate in the air, $0.7SvGy^{--1}$ is the conversion coefficient and 0.2 is the outdoor occupancy factor.[1,4,8]

Radiological hazard indices (H_{ex} and H_{in}): The harmful gamma radiation effects caused by radionuclides present in these soil samples were estimated by calculating the different hazard indices. Although the total activity concentrations of the exact indication of total radiation hazards have been assessed, these hazard indices also guide the choice of the right materials for building hurts, bricks, and other materials for human habitation. Two hazard indices were employed: the external hazard index (H_{ex}) and the internal hazard index (H_{in}). Both indices were calculated using equations (6) and (7).[8]

$$H_{ex} = \frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (6)$$

$$H_{in} = \frac{C_U}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (7)$$

Where C_U, C_{Th}, and C_K are as described in equation (3). Radiation hazard from soil samples is considered negligible if the value of both indices is less than unity.[1]

Activity utilization index (AUI): This is a significant health index that estimates the excess external and indoor gamma radiation from soil and other building materials.[8]

$$AUI = \frac{C_U}{150} + \frac{C_{Th}}{100} + \frac{C_K}{1500} \quad (8)$$

Where C_U, C_{Th}, and C_K are as described in equation (3).

Excess lifetime cancer risk (ELCR): The excess lifetime cancer risk is evaluated using the equation (9)

$$ELCR = AED \times LE \times RF \quad (9)$$

Where AED is the annual effective dose equivalent as contained in equation (5),

LE is the life expectancy (assumed to be 70 years in this study),[34] and RF is the risk factor of fatal cancer per Sievert. According to the International Commission on Radiological Protection (ICRP) 103 report, the value of 0.057 was used for stochastic effect for the public.[38,39]

Statistical analysis

The IBM Statistical Package for Social Science (SPSS-27) computer program was used to analyze data. The present study calculated and reported statistical parameters such as mean, maximum, and minimum. The values obtained were reported as means ± SD (standard deviation), and $P < .05$ was accepted for all comparisons. Pearson correlation was used to evaluate the level of correlation of activity concentrations obtained and absorbed dose, effective dose, and other radiological hazard indices, as presented in Table 5.

Results and Discussion

Activity concentration

The estimated activity concentration of naturally occurring radionuclides ^{238}U, ^{232}Th, and ^{40}K in soil samples were given in Table 1. The radioactivity concentration obtained from this study ranged from BDL to 31.53 Bqkg^{-1} for ^{238}U, from BDL to 37.15 Bqkg^{-1} for ^{232}Th and from 20.90 to 127.15 Bqkg^{-1} for ^{40}K. The spatial distribution of the primordial radionuclides from the studied location is an indication that the evaluated radionuclides are not concentrated in one location, as the report showed a high value for one radionuclide and a low value for the others but unequally distributed within the campus of the institution. The average radioactivity concentrations of ^{238}U, ^{232}Th, and ^{40}K found in soil samples were (20.32 ± 3.22, 22.55 ± 0.68, and 91.63 ± 1.54) Bqkg^{-1}, respectively. The activity concentration of radionuclides in soil samples from IMSU is within the report of Eke et al[34] on the top soil samples from Imo State Polytechnic. In addition, the mean activity concentration of natural radionuclides in soil samples at the 2 tertiary institutions in Owerri, as reported by Eke et al[34] is comparable. Although the activity concentration of radionuclides in soil samples from IMSU is far higher than the values reported by Popoola et al[40] the average values are lower than the world's mean radioactivity concentration of (35, 45, and 420) Bqkg^{-1}for ^{238}U, ^{232}Th, and ^{40}K, respectively.[1] This is shown in Table 2, which compares the radioactivity concentration calculated in this study with other related studies within Nigeria and globally. The present finding showed that ^{40}K has the maximum average radioactivity concentration and mark maximum at all sampling points except at 2 points, IMSU 16 (Faculty of Law) and IMSU 22 (Agricultural Science Department). Potash feldspar minerals in the studied area may be responsible for the enhanced ^{40}K recorded in the present study. Since IMSU is at the base of the dip slope from Okigwe (the center of mining in Imo State) to Owerri. This suggests that migration of weathered radionuclides from the surrounding rocks might have settled in Imo State University and its environs, increasing the activity concentration in radionuclides of the studied area. The activity concentration of ^{40}K obtained from the present research corroborates the findings of Isinkaye.[41]

Similarly, the results of Egunyinka et al[42] on the activity concentration of ^{40}K agree with the present study. Also, the soil radionuclides' activity concentrations were comparable to other related studies conducted within and outside Nigeria.[4,43-51] Eke et al[4] and Olagbaju et al[51] obtained lower activity concentrations of ^{226}Ra (^{238}U) compared to the present study. Egunyinka et al[42] and Ugbede et al[47] recorded higher activity concentrations of ^{226}Ra (^{238}U) compared to the present study.

Radiological dose assessment and radiological hazard indices

The dosimetry parameters, such as radium equivalent activity (Ra_{eq}), absorbed dose rate (D), and annual effective dose (AED), were recorded in Table 3. The calculated radium equivalent value ranges from 33.62 ± 3.46 to 81.66 ± 3.80 Bqkg^{-1}, with an average value of 59.62 Bqkg^{-1}. The estimated average value of Ra_{eq} obtained in this study is appreciably lower than the world recommended value of 370 Bqkg^{-1} 1 and the result

Table 1. The estimated radioactivity concentration of ^{238}U, ^{232}Th and ^{40}K in $Bqkg^{-1}$.

SAMPLE ID	SAMPLE LOCATION	^{238}U	^{232}TH	^{40}K
IMSU 1	Nursery and Crèche Staff School	18.24 ± 2.09	28.86 ± 0.53	91.45 ± 1.21
IMSU 2	Agricultural / vet nary medicine	20.22 ± 3.45	33.67 ± 0.61	71.19 ± 1.30
IMSU 3	Bookshop entrance	14.30 ± 2.22	19.22 ± 0.67	111.19 ± 1.41
IMSU 4	Old ETF building	12.50 ± 3.10	27.30 ± 0.59	97.10 ± 1.62
IMSU 5	Mass communication department	5.00 ± 4.33	37.15 ± 0.63	105.54 ± 1.58
IMSU 6	Survey and geo-informatics department	27.14 ± 4.10	20.11 ± 0.72	98.11 ± 1.67
IMSU 7	Computer-based test (CBT) centre	21.14 ± 2.48	27.15 ± 0.81	100.24 ± 1.39
IMSU 8	Law library	18.33 ± 3.10	34.10 ± 0.74	97.40 ± 1.43
IMSU 9	Computer science department	10.32 ± 3.58	22.25 ± 0.55	87.11 ± 1.54
IMSU 10	Main Library	20.10 ± 2.57	10.24 ± 0.57	98.44 ± 1.67
IMSU 11	Academic staff office	27.11 ± 3.10	15.13 ± 0.72	115.72 ± 1.58
IMSU 12	Microbiology department	15.78 ± 3.74	18.00 ± 0.84	122.99 ± 1.69
IMSU 13	Theatre arts department	18.93 ± 4.20	16.98 ± 0.73	73.97 ± 1.66
IMSU 14	Public health department	28.47 ± 3.35	BDL	66.90 ± 1.63
IMSU 15	Zoology department	23.10 ± 2.17	20.11 ± 0.69	101.55 ± 1.55
IMSU 16	Faculty of law	28.91 ± 3.37	15.55 ± 0.77	20.90 ± 1.64
IMSU 17	Business administration extension	20.10 ± 4.10	29.33 ± 0.81	84.53 ± 1.59
IMSU 18	New ETF building	16.44 ± 4.65	30.10 ± 0.87	91.30 ± 1.68
IMSU 19	Agric economics extension	22.10 ± 2.55	24.55 ± 0.72	87.10 ± 1.62
IMSU 20	Science Building	12.15 ± 3.10	17.04 ± 0.59	112.23 ± 1.55
IMSU 21	Information management technology	27.85 ± 2.78	32.40 ± 0.64	97.11 ± 1.42
IMSU 22	Agric science department	30.10 ± 3.93	24.44 ± 0.74	25.47 ± 1.46
IMSU 23	Building department	31.53 ± 4.20	28.15 ± 0.82	127.15 ± 1.46
IMSU 24	Food science technology department	28.50 ± 4.15	15.21 ± 0.89	110.12 ± 1.59
IMSU 25	Nutrition and dietetics department	18.50 ± 3.15	18.63 ± 0.73	122.39 ± 1.59
IMSU 26	Faculty of social science	27.40 ± 2.73	14.79 ± 0.57	57.80 ± 1.33
IMSU 27	Faculty of education	16.55 ± 2.43	19.48 ± 0.61	91.12 ± 1.58
IMSU 28	Faculty of engineering	28.90 ± 3.72	25.53 ± 0.75	84.55 ± 1.67
IMSU 29	Economics department	19.77 ± 4.13	27.19 ± 0.61	100.55 ± 1.47
IMSU 30	Fine and applied arts department	BDL	23.94 ± 0.74	97.73 ± 1.46
Minimum estimated value		**BDL**	**BDL**	**20.90 ± 1.64**
Maximum estimated value		**31.53 ± 4.20**	**37.15 ± 0.63**	**127.15 ± 1.46**
Mean estimated value		**20.32 ± 3.22**	**22.55 ± 0.68**	**91.63 ± 1.54**

Table 2. Comparison of average natural radioactivity concentration and radiological parameters evaluated in this study with results from some related studies around the globe.

S/N	LOCATION	^{238}U	^{232}TH	^{40}K	RA_{EQ}	D	AUI	AED	H_{EX} AND H_{IN}	ELCR × 10^{-3}	REFERENCE
1	Imo State University, Nigeria.	20.32	22.55	91.63	59.62	26.86	0.42	33.07 132.01	0.16 0.22	0.14	Present study
2	World mean value	33.00	45.00	420	370.00	60.00	2.00	70.00 460.00	1.00 1.00	0.29	United Nations Scientific Committee on the Effects of Atomic Radiation[1]
3	Greater Accra Ghana	34.00	30.00	320.00	83.00	39.00	–	47.00	0.20 –	–	Botwe et al[3]
4	FUTO Nigeria	17.88	22.82	90.18	–	25.99	–	31.89	– –	–	Eke et al[4]
5	Richards Bay, South Africa	28.26	31.56	138.07	85.87	38.89	–	290.00	0.23	–	Masok et al[10]
6	East coast of Tamilnadu	3.80	26.23	328.00	–	32.91	0.38	40.00	0.18 0.19	–	Sivakumar et al[12]
7	Rize province Turkey	24.50	51.80	344.99	125.00	56.90	–	69.80	0.34 –	–	Durusoy and Yildirim[15]
8	Ado-Odo/Ota Nigeria	40.44	94.44	134.25	185.82	81.32	1.53	860.00	0.50 –	–	Joel et al[18]
9	Ayranci, Turkey	25.00	50.00	228.00	114.95	52.56	–	51.82	0.64 –	–	Ogar et al.[19]
10	Volta Region, Ghana	112.00	14.60	141.00	144.80	66.90	–	90.00	– –	–	Addo et al[20]
11	Rize province Turkey	85.75	51.08	771.57	218.20	110.69	1.60	136.00	0.59 –	0.48	Dizman et al[25]
12	Western Ghats	36.30	107.80	231.90	208.30	91.44	1.47	112.30	0.56 0.66	0.39	Manigandan and Shekar[37]

Abbreviations: AUI, activity utilization index; D, absorbed dose.

Table 3. Calculated dosimetry quantities (radium equivalent ($Bqkg^{-1}$), absorbed dose ($nGyh^{-1}$) and annual effective dose (μSvy^{-1})).

SAMPLE ID	RA_{EQ}	ABSORBED DOSE	AED OUTDOOR
IMSU 1	66.55 ± 2.94	29.70 ± 1.34	36.42 ± 1.64
IMSU 2	73.85 ± 4.42	32.67 ± 2.02	40.07 ± 2.48
IMSU 3	50.34 ± 3.29	22.88 ± 1.49	28.06 ± 1.83
IMSU 4	59.02 ± 4.07	26.34 ± 1.86	32.30 ± 2.28
IMSU 5	66.25 ± 5.33	29.18 ± 2.45	35.79 ± 3.00
IMSU 6	63.45 ± 5.26	28.81 ± 2.40	35.33 ± 2.94
IMSU 7	67.68 ± 3.75	30.37 ± 1.69	37.25 ± 2.07
IMSU 8	74.59 ± 4.27	33.16 ± 1.94	40.67 ± 2.38
IMSU 9	48.87 ± 4.50	21.87 ± 2.05	26.82 ± 2.51
IMSU 10	42.32 ± 3.51	19.61 ± 1.62	24.05 ± 1.99
IMSU 11	57.66 ± 4.25	26.52 ± 1.93	32.52 ± 2.37
IMSU 12	50.99 ± 5.07	23.33 ± 2.31	28.61 ± 2.83
IMSU 13	48.91 ± 5.37	22.11 ± 2.45	27.12 ± 3.00
IMSU 14	33.62 ± 3.46	15.96 ± 1.62	19.57 ± 1.99
IMSU 15	59.68 ± 3.28	27.08 ± 1.11	33.21 ± 1.36
IMSU 16	52.76 ± 4.60	23.63 ± 2.09	28.98 ± 2.56
IMSU 17	68.55 ± 5.38	30.55 ± 2.45	37.47 ± 3.00
IMSU 18	66.51 ± 6.02	29.61 ± 2.74	36.31 ± 3.36
IMSU 19	63.91 ± 3.70	28.70 ± 1.68	35.20 ± 2.06
IMSU 20	45.16 ± 4.06	20.62 ± 1.85	25.29 ± 2.27
IMSU 21	81.66 ± 3.80	36.51 ± 1.73	44.78 ± 2.12
IMSU 22	67.01 ± 5.12	29.74 ± 2.92	36.47 ± 3.58
IMSU 23	81.58 ± 5.49	36.91 ± 2.50	45.27 ± 3.07
IMSU 24	58.73 ± 5.55	26.97 ± 2.52	33.08 ± 3.09
IMSU 25	54.56 ± 4.32	24.94 ± 1.96	30.58 ± 2.40
IMSU 26	53.00 ± 3.65	24.02 ± 1.66	29.46 ± 2.40
IMSU 27	51.42 ± 3.42	23.24 ± 1.56	28.50 ± 1.91
IMSU 28	71.92 ± 4.92	32.32 ± 2.24	39.64 ± 2.84
IMSU 29	66.39 ± 5.19	29.78 ± 2.39	37.71 ± 2.93
IMSU 30	41.76 ± 1.18	18.56 ± 0.51	23.50 ± 0.63
Min value	**33.62**	**15.56**	**19.57**
Max value	**81.66**	**36.91**	**45.27**
Mean value	**59.62**	**26.86**	**33.07**

Abbreviations: AED, annual effective dose; Ra_{eq}, radium equivalent activity.

from other related studies, as shown in Table 2. The absorbed dose values in Table 3 were found in the range of 15.96 ± 1.62 to 36.91 ± 2.50 nGyh^{-1} with an average of 26.86 nGyh^{-1}. The absorbed dose obtained in this study is lower than the world's recommended value of 59 nGyh^{-1} and within the range of other related studies, as shown in Table 2. The calculated AED value was shown in Table 3, the value ranged from 19.57 ± 1.99 to 45.27 ± 3.07 µSvy^{-1}. The average value for outdoor estimated was 33.07 µSvy^{-1}. The calculated AED was lower than the world's recommended values of 480 µSvy^{-1} (0.48 mSvy^{-1}),[1] as presented in Table 3. Also, the annual effective dose of soil samples from the present research is less than 1.0 mSvy^{-1}, the ICRP 2007 recommended value for the members of the public.[39,52]

The estimated radiological index parameters such as H_{ex}, H_{in}, AUI, and ELCR were recorded in Table 4. The values of the external hazard index (H_{ex}) and internal hazard index (H_{in}) ranged from 0.09 ± 0.01 to 0.22 ± 0.01 and 0.11 ± 0.00 to 0.31 ± 0.03, respectively, with associated average values of 0.16 and 0.22. The H_{ex} and H_{in} values estimated in this study were in line with the world's recommended value of <1 (less than unity), as shown in Table 3. The activity utilization index shown in Table 4 has a value ranging from 0.23 ± 0.02 to 0.58 ± 0.04 with an average value of 0.42, which is in line with the results

Table 4. Radiological hazard parameters (H_{ex}, H_{in}, AUI, and ELCR).

SAMPLE ID	H_{EX}	H_{IN}	AUI	ELCR × 10^{-3} (ESTIMATED WITH OUTDOOR AED ONLY)
IMSU 1	0.18 ± 0.01	0.23 ± 0.01	0.47 ± 0.02	0.15 ± 0.01
IMSU 2	0.20 ± 0.01	0.25 ± 0.02	0.52 ± 0.03	0.16 ± 0.01
IMSU 3	0.14 ± 0.01	0.17 ± 0.01	0.36 ± 0.02	0.11 ± 0.01
IMSU 4	0.16 ± 0.01	0.19 ± 0.02	0.42 ± 0.03	0.13 ± 0.01
IMSU 5	0.18 ± 0.01	0.19 ± 0.03	0.48 ± 0.04	0.15 ± 0.01
IMSU 6	0.17 ± 0.01	0.24 ± 0.03	0.45 ± 0.04	0.14 ± 0.01
IMSU 7	0.18 ± 0.01	0.24 ± 0.02	0.48 ± 0.03	0.14 ± 0.01
IMSU 8	0.20 ± 0.01	0.25 ± 0.02	0.53 ± 0.03	0.16 ± 0.01
IMSU 9	0.13 ± 0.01	0.16 ± 0.02	0.35 ± 0.03	0.10 ± 0.01
IMSU 10	0.11 ± 0.01	0.17 ± 0.02	0.30 ± 0.02	0.09 ± 0.01
IMSU 11	0.16 ± 0.01	0.23 ± 0.02	0.41 ± 0.03	0.12 ± 0.01
IMSU 12	0.14 ± 0.01	0.18 ± 0.02	0.37 ± 0.03	0.11 ± 0.01
IMSU 13	0.13 ± 0.01	0.18 ± 0.03	0.35 ± 0.04	0.10 ± 0.01
IMSU 14	0.09 ± 0.01	0.17 ± 0.02	0.23 ± 0.02	0.08 ± 0.01
IMSU 15	0.16 ± 0.01	0.22 ± 0.01	0.42 ± 0.02	0.14 ± 0.00
IMSU 16	0.14 ± 0.01	0.22 ± 0.02	0.36 ± 0.03	0.11 ± 0.01
IMSU 17	0.19 ± 0.01	0.24 ± 0.03	0.48 ± 0.04	0.15 ± 0.01
IMSU 18	0.18 ± 0.02	0.22 ± 0.03	0.47 ± 0.04	0.15 ± 0.01
IMSU 19	0.17 ± 0.01	0.23 ± 0.02	0.45 ± 0.03	0.14 ± 0.01
IMSU 20	0.12 ± 0.01	0.15 ± 0.02	0.33 ± 0.03	0.10 ± 0.01
IMSU 21	0.22 ± 0.01	0.30 ± 0.02	0.57 ± 0.03	0.18 ± 0.01
IMSU 22	0.18 ± 0.01	0.26 ± 0.02	0.46 ± 0.03	0.14 ± 0.01
IMSU 23	0.22 ± 0.01	0.31 ± 0.03	0.58 ± 0.04	0.18 ± 0.01

(Continued)

Table 4. (Continued)

SAMPLE ID	H_{EX}	H_{IN}	AUI	ELCR × 10^{-3} (ESTIMATED WITH OUTDOOR AED ONLY)
IMSU 24	0.16 ± 0.01	0.24 ± 0.03	0.42 ± 0.04	0.14 ± 0.01
IMSU 25	0.15 ± 0.01	0.20 ± 0.02	0.39 ± 0.03	0.13 ± 0.01
IMSU 26	0.14 ± 0.01	0.22 ± 0.02	0.37 ± 0.02	0.11 ± 0.01
IMSU 27	0.14 ± 0.01	0.18 ± 0.02	0.37 ± 0.02	0.11 ± 0.01
IMSU 28	0.19 ± 0.01	0.27 ± 0.02	0.50 ± 0.02	0.16 ± 0.01
IMSU 29	0.18 ± 0.01	0.23 ± 0.03	0.47 ± 0.04	0.15 ± 0.01
IMSU 30	0.13 ± 0.00	0.11 ± 0.00	0.30 ± 0.01	0.09 ± 0.00
Min value	**0.09**	**0.11**	**0.23**	**0.08**
Max value	**0.22**	**0.31**	**0.58**	**0.18**
Mean value	**0.16**	**0.22**	**0.42**	**0.14**

Abbreviatios: AUI, activity utilization index; H_{ex}, external hazard index; H_{in}, internal hazard index.

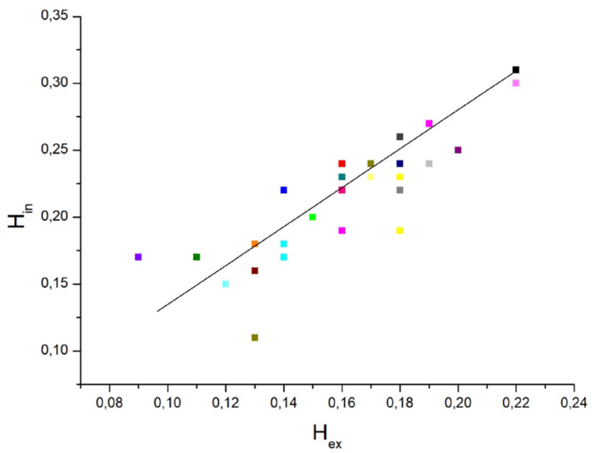

Figure 2. Correlation between the internal hazard index and external hazard index.

from other related studies and also less than the world recommended value of 2 as shown in Table 2. Figure 2 shows a strong relationship between the internal hazard index (H_{in}) and the external hazard index (H_{ex}). The excess lifetime cancer risk (ELCR) was calculated with estimated outdoor values of AED, recorded in Table 4. The range of ELCR recorded is 0.08 ± 0.01 (×10^{-3}) to 0.18 ± 0.01 (×10^{-3}), with the corresponding average value of 0.14 × 10^{-3}. The ELCR value is lower than the world mean value of 0.29 × 10^{-3}, as shown in Table 2. This implies that the radiation level measured in this study area may not pose serious radiological health hazards, and several research works have also confirmed that the health risk of exposure to low natural radiation doses may be insignificant.[53-56]

Pearson's correlation analysis

Table 5 presents the result of the correlation analysis. Pearson correlation analysis of activity concentrations of radionuclides, absorbed dose, effective dose, and the radiological parameters revealed strong relationships among these parameters. The findings revealed a significant correlation between the activity concentrations ^{232}Th and all the radiological parameters. This implies that an increase in the activity concentrations of ^{232}Th radionuclide in the soil sample of IMSU could result in exposure to the community. Similarly, there was a strong correlation between the activity concentrations ^{238}U and the radiological parameters except for radium equivalent (Ra_{eq}) and activity utilization index (AUI). The results of the present study agreed with the findings of Mbonu and Ben[57] who reported the radiation hazard indices due to natural radioactivity in soil samples from Orlu, Imo State, Nigeria. The authors revealed that the activity concentrations of radionuclides in soil samples from the studied locations were below the safe limit. Even though the mean activity concentration of ^{40}K was more than ^{232}Th and ^{238}U, there was no significant correlation between it and the radiological parameters.

Conclusion

All the activity concentrations of the radionuclides ^{238}U, ^{232}Th, and ^{40}K measured in this study were below the average world values of 33 Bqkg^{-1}, 45 Bqkg^{-1}, and 420 Bqkg^{-1}, respectively.[1] The average radium equivalent of 59.62 Bqkg^{-1} obtained from the present study was lower than the 370 Bqkg^{-1} recommended by the International Commission on Radiation Protection (ICRP). Moreover, the absorbed dose, the annual effective dose, the activity utilization index, the external hazard index, and the internal hazard index were lower than the global recommended mean value. The ELCR average value estimated was lower than the global recommended value. From the results of this study, all the radiological parameters estimated were below the permissible limits set by international professional bodies, including UNSCEAR and ICRP. These results indicate that the soil

Table 5. Correlation analysis between activity concentrations of radionuclides and their radiological parameters.

ACTIVITY CONC.	ABSORBED DOSE	AED OUTDOOR	H_{EX}	H_{IN}	RA_{EQ}	AUI
K-40						
P. Correlation	.049	.052	.049	–.119	.016	.081
Sig. (2-tailed)	.804	.795	.805	.546	.936	.681
Th-232						
P. Correlation	.779**	.779**	.814**	.466*	.809**	.826**
Sig. (2-tailed)	.000	.000	.000	.012	.000	.000
U-238						
P. Correlation	.397*	.394*	.342	.743**	.364	.315
Sig. (2-tailed)	.036	.038	.075	.000	.057	.102

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

samples from the investigated area pose no serious radiological health hazards to the human population.

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