



Human exposure levels to ionizing radiation in Agbara Industrial Estate: an impact of Industrial activities in Nigeria

Joseph O. Bodunrin · Oladele S. Ajayi · James A. Oke 

Received: 20 July 2020 / Accepted: 30 November 2020 / Published online: 6 January 2021
© The Author(s), under exclusive licence to Springer Nature Switzerland AG part of Springer Nature 2021

Abstract A total of fifty-five soil samples were collected from four locations, namely, residential, industrial, dumpsite, and sewage in Agbara industrial estate, Ogun state, Nigeria. The samples were analyzed using a high purity germanium detector (HPGe) to measure the activity concentration of radionuclides. Background radiation measurements were also taken at each point where soil samples were collected using Geiger Muller (GM) counter. The mean activity concentrations measured in the soil samples were 171.33 for ^{40}K , 9.11 for ^{232}Th , and 5.05 for ^{226}Ra in Bq/kg. The mean absorbed dose rate in the air due to radionuclides (^{40}K , ^{232}Th , and ^{226}Ra) in the soil is calculated to be 14.77 nGy/h, and the mean annual effective dose equivalent (AEDE) is 0.02 mSv/year. The mean equivalent dose rate (EDR) from GM counter for background radiation is 0.22 $\mu\text{Sv/h}$, and the mean annual effective dose rate (AEDR) is 0.39 mSv/year. These values are below the world average values, except EDR and AEDR with mean values higher than the world standard. The comparison of radiation dose rates revealed that radionuclides contributed 6.7% to background radiation. The equivalent dose ($\text{ED}_{\text{organs}}$) for various organs of the body was calculated,

and results showed that values do not pose any immediate health hazard. The excess lifetime cancer risk (ELCR) due to exposure to background radiation indicated that the dwellers and industrial workers in the study area may develop cancer over a lifetime due to accumulated dose.

Keywords Radionuclides · Background radiation · Equivalent dose · Excess lifetime cancer

Introduction

Industrialization can be beneficial and detrimental to man and his environment. The Earth's crust possesses some natural resources that enhance industrialization which tends to develop the human race. These resources are commonly explored to a great level by spontaneous and artificial activities, which tend to degrade the environment frequently (Lone et al. 2008). The environment is subjected to degradation due to pollution as a result of anthropogenic activities that deteriorate the quality of air, soil, and water, posing a great risk to human health (McGrath et al. 2001). Natural radionuclides are spontaneous in nature and are readily available in our environment. These radionuclides can be technically enhanced by human activities such as industrialization and agricultural activities. The widespread of radionuclides in the environment exists in numerous geological formations (water, soils, air, plants, rocks, and earth crust) (Unsclear 2000). Soil radionuclide activity

J. O. Bodunrin · J. A. Oke (✉)
Department of Physics, University of South Africa, Florida, 1709,
Science Campus, Christiaan de Wet and Pioneer Avenue,
Johannesburg, South Africa
e-mail: okeayodele28@outlook.com

J. O. Bodunrin · O. S. Ajayi
Department of Physics, School of Sciences, Federal University of
Technology, Akure PMB 704, Nigeria

concentration is one of the main factors of the naturally occurring radiation.

Soil radionuclides can be influenced by human activities, in addition to natural sources. The concentration of radionuclides in the soil is studied to have an in-depth understanding of their spatial distribution. Long-term exposure to radionuclides such as thorium and radium through inhalation and direct exposure is of severe health and environmental concerns today in the world (Bickerstaff and Walker 2001). Linkages between serious health effects like chronic diseases and respiratory-related ones that could induce high mortality and exposure to radionuclides have been established by previous studies (Lü et al. 2015). Health challenges like acute leucopenia, anemia, necrosis of the mouth, and chronic lung diseases are associated with long-term exposure to thorium (Agency 1991; Taskin et al. 2009), while radium causes weakening of the bone, cranial, and nasal tumors. Other diseases as a result of radionuclide exposure include leukemia, cataracts, sterility, atrophy of the kidney, cancer of skin, lungs, pancreas, kidney, and bone (Oke et al. 2020; Taskin et al. 2009).

The radiation of radionuclide emanating from the soil contributed some percentage to background radiation which increases the level of human exposure and health risk. Also, the contribution of cosmic rays to background radiation is not left out as 90% of human exposure arises from a natural source of radiation (Oladele et al. 2018). Geiger Muller (GM) counter is one of the suitable devices for background radiation measurement due to its ability to detect and measure radiation instantaneously; however, it cannot differentiate sources of radiation. A high dose of background radiation is detrimental to various organs of the human body. Ionizing radiation is highly energetic particles with high penetrating power. Cell structures are altered when ionizing radiation passed through biological cells (Emelue 2014). High-level gamma radiation exposure causes cancers and mutation (Saad-El-Din et al. 2014) in humans and other kinds of diseases (Taskin et al. 2009). Therefore, the knowledge of background radiation in a particular environment enables one to understand the level of radiation and radiological health hazards associated with exposure.

Several researchers have reported high and low dose rates of a different environment, particularly in industrial areas in Nigeria. Agbalagba (2017) evaluated the dose rate of background radiation in the industrial area of Warri. His result indicated a higher level of

radiation dose in the area (Agbalagba 2017). James et al. (2013) carried out their work at Idu industrial area (James et al. 2013). Their work shows that the area is not of great concern. Agbalagba et al. (2016) studied the level of radiation in Ughelli metropolis owing to industrial activities in the environment and reported a high level of radiation dose in the area (Agbalagba et al. 2016). Ramli et al. (2014) also studied the levels of radiation in Keffi and Akwanga towns and found that the radiation dose rate is below the recommended limit (Ramli et al. 2014).

Despite the efforts in carrying out researches in industrial areas of Nigeria, no data have been recorded on the assessment of background radiation in Agbara industrial estate, which makes its selection of interest and necessity. This work was conducted to ascertain the safety of the dwellers and industrial workers of the study area due to exposure to background radiation as a result of industrial activities, which has never been considered nor evaluated. It is therefore of interest to provide knowledge on the ionizing radiation exposure levels in Agbara Industrial Estate, owing to industrial activities to evaluate possible health hazards to safeguard the environment. The data obtained in this study will be documented for future purposes.

Materials and methods

Study area

Agbara estate is situated in Ado-odo otta LGA between $3^{\circ} 00'$ and $3^{\circ} 15'$ latitude and $6^{\circ} 15'$ and $6^{\circ} 5'$ longitude of Ogun State, Nigeria. The estate comprises three phases which are recreational, residential, and commercial (industries) areas. The industrial areas are located on a 188.289 ha of land, which is 41.55% of the total 454.1 ha of Agbara estate. The industries found in this area are multinational companies, which produce most of the consumables in the country. Some of these companies are Nestle Nig PLC, Beta Glass Nigeria PLC, Pharma Deko (Nig.) PLC, Vitamalt PLC, Reckitt Benckiser Nigeria Ltd., Lotus Plastic, Evans Medical Nigeria PLC, DIL/Maltex (Nig.) PLC, Henley Industries, Cometstar Cables Ltd, Pace Factory, Glaxo-Smith-kline Nigeria PLC, etc. Most of these companies belong to the pharmaceutical, food, and beverages group. The estate also comprises of three phases of residential areas. The residential phase one presently accommodates over five

thousand dwellers, while more than fifty thousand people come to the various companies for daily businesses and transactions or the other. The other phases (two and three) are yet to be developed which was estimated to accommodate over fifteen thousand dwellers each. The wastes from both the commercial and residential areas are linked into a sewage treatment plant through sewage pipes, which treats both industrial and domestic wastes, respectively before liquidating the treated waste into the Ologe Lagoon through a stream (Bodunrin and Ajayi 2017). The map of Nigeria, Ogun State, and Ado-odo Ota LGA showing the study area is depicted in Fig. 1.

Sample collection

Fifty-five (55) soil samples were taken from the study area. Twenty-five were from residential, fifteen from industrial, ten from dumpsites, and five from the sewage area of the study area. Each point in which samples were collected was marked 1.0 m × 1.0 m and carefully cleared of unwanted particles to a depth of few centimeters. Afterward, the samples were collected randomly from several points and thoroughly homogenized to obtain a composite soil sample of the same location. The soil

samples were packed into Polyethylene bags, tightly sealed, and were labeled accordingly. The information on the labeled soil samples includes location, point name, and point code. The soil samples were air-dried, pulverize, and sieved with a 2-mm standard net. The samples were placed in Marinelli beaker containers and weighed to 200 g. The containers were covered, sealed with PVC tape, and kept for a month to establish secular equilibrium among ²²⁶Ra (long-lived parent nuclides) and ²³²Th (short-lived daughters) (Oke et al. 2020) before analysis with the high-purity germanium detector (HPGe).

The in situ background radiation measurement was taken at each point where soil samples were collected using a Geiger Muller (GM) counter (Kindenoo blue Geiger PG-15) and a Global Positioning System (GPS) to determine the equivalent dose rate (EDR) and coordinate of each point, respectively. The measurements were taken at about 1 m above the ground level at 55 points where soil samples were taken. Three (3) readings were taken at each point at intervals of 2 min, making a total of 165 readings and the average value of each point was recorded.

The information on the soil samples and coordinates are presented in Table 1.

LOCAL MAP OF THE STUDY AREA

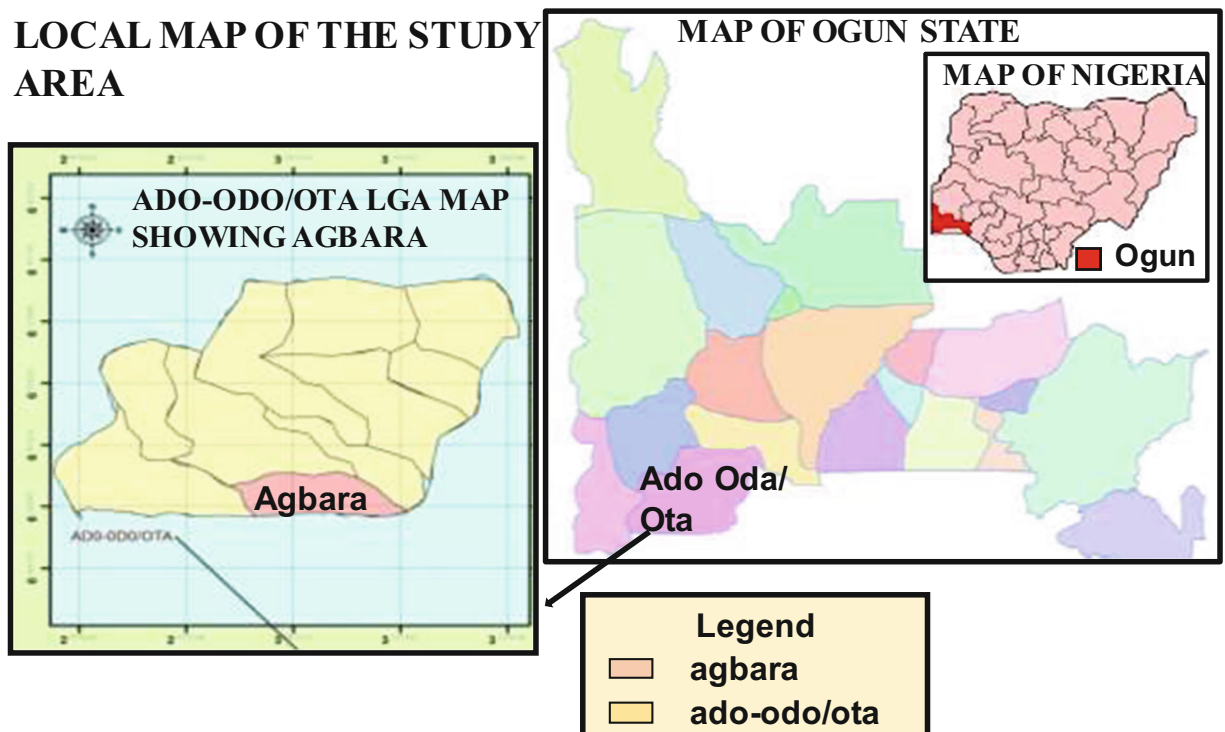


Fig. 1 Map of Nigeria, Ogun State, and Ado-odo Ota LGA showing the study area (Agbara)

Table 1 Sample locations, point names, point codes, coordinates, radionuclide activity concentrations, and background equivalent dose rates

Location	S/N	Point name	Point code	Longitude	Latitude	Activity concentration in Bq/kg			EDR ($\mu\text{Sv/h}$)
						^{40}K	^{232}Th	^{226}Ra	
Residential	1	Benin rd 1	L1	3.0926445129	6.5094160399	96.43 ± 14.46	7.52 ± 1.13	4.87 ± 0.73	0.14 ± 0.02
	2	Benin rd 2	L2	3.0899949934	6.5125917124	293.01 ± 43.95	3.57 ± 0.53	2.00 ± 0.31	0.24 ± 0.03
	3	Unilever PLC 1	L3	3.0843229921	6.5098122096	397.51 ± 59.63	9.50 ± 1.43	5.37 ± 0.81	0.22 ± 0.03
	4	Unilever PLC 2	L4	3.0829029967	6.5068667213	167.06 ± 25.06	10.96 ± 1.64	7.08 ± 1.06	0.20 ± 0.01
	5	Unilever PLC 3	L5	3.0787617712	6.5146199231	210.21 ± 31.53	9.93 ± 1.49	9.83 ± 1.47	0.14 ± 0.02
	6	Unilever Warehouse	L6	3.0783550141	6.5162754293	79.64 ± 11.95	17.73 ± 2.66	6.80 ± 1.02	0.14 ± 0.01
	7	Dear gate	L7	3.0780838091	6.5171710387	310.15 ± 46.52	6.58 ± 0.99	2.11 ± 0.32	0.17 ± 0.01
	8	Komex hotel	L8	3.0785812731	6.5171709615	292.76 ± 43.91	3.19 ± 0.48	2.86 ± 0.43	0.22 ± 0.04
	9	Ago eto block ind.	L9	3.0811124648	6.5087486085	300.42 ± 45.06	7.99 ± 1.20	5.53 ± 0.83	0.18 ± 0.01
	10	Oppcomesa, Ago eto	L10	3.0781927797	6.5199662774	374.77 ± 56.22	4.63 ± 0.69	3.21 ± 0.48	0.28 ± 0.02
Dumpsite	11	Area 4	L11	3.0745328722	6.5234637782	132.13 ± 19.82	6.44 ± 0.97	2.97 ± 0.45	0.17 ± 0.02
	12	Area 8a	L12	3.0779399123	6.5224811417	296.32 ± 44.45	7.83 ± 1.17	6.22 ± 0.93	0.15 ± 0.01
	13	Area 8b	L13	3.0789625152	6.5258642362	666.55 ± 10.13	8.54 ± 1.28	4.02 ± 0.60	0.19 ± 0.01
	14	Area 8c	L14	3.0821373299	6.5260808364	137.34 ± 20.60	2.89 ± 0.43	1.76 ± 0.26	0.15 ± 0.02
	15	Area 8d	L15	3.0840637871	6.5253658744	92.25 ± 13.84	5.02 ± 0.75	7.98 ± 1.20	0.12 ± 0.02
	16	Area 4	L16	3.0747648998	6.5234657833	107.53 ± 10.13	9.95 ± 1.49	5.66 ± 0.89	0.17 ± 0.07
	17	Area 1	L17	3.0758934595	6.5456784333	421.69 ± 63.25	8.09 ± 1.21	2.83 ± 0.42	0.18 ± 0.05
	18	Opp. Agbara hotel	L18	3.0779399123	6.5224811417	61.23 ± 9.18	6.66 ± 1.00	4.65 ± 0.67	0.18 ± 0.01
	19	Komex hotel	L19	3.0773542567	6.5214563892	246.33 ± 36.95	12.05 ± 1.81	6.22 ± 0.93	0.18 ± 0.01
	20	Area 1a	L20	3.0773427683	6.5243587934	152.33 ± 22.85	7.17 ± 1.08	3.55 ± 0.53	0.16 ± 0.02
	21	Area 1	L21	3.0765498765	6.5246788654	320.15 ± 14.02	4.19 ± 0.63	2.41 ± 0.36	0.17 ± 0.01
	22	Kurogboji 1	L22	3.0853624449	6.5027955499	273.65 ± 41.05	6.26 ± 0.94	3.01 ± 0.45	0.13 ± 0.01
	23	Kurogboji 2	L23	3.0862125917	6.5025602061	151.72 ± 22.76	8.21 ± 1.23	4.77 ± 0.71	0.09 ± 0.01
	24	Kurogboji 3	L24	3.0862668496	6.5025059201	82.96 ± 12.44	9.31 ± 1.40	3.10 ± 0.45	0.11 ± 0.01
	25	Kurogboji 4	L25	3.0859141342	6.5026326263	103.29 ± 15.49	7.56 ± 1.13	5.77 ± 0.87	0.11 ± 0.02
	26	Jamaica 1	L26	3.0832278111	6.5020541222	139.75 ± 20.96	13.48 ± 2.02	7.48 ± 1.12	0.19 ± 0.02
	27	Jamaica 2	L27	3.0833362033	6.5017374895	74.06 ± 11.11	5.01 ± 0.75	4.60 ± 0.69	0.27 ± 0.01
	28	Jamaica 3	L28	3.0832638954	6.5014842095	100.20 ± 15.03	12.36 ± 1.85	4.75 ± 0.71	0.27 ± 0.02
	29	Jamaica 4	L29	3.0832909129	6.5007786062	96.80 ± 14.52	13.01 ± 1.95	6.99 ± 1.05	0.23 ± 0.02
	30	Jamaica 5	L30	3.0840505342	6.5000728817	131.05 ± 19.66	10.80 ± 1.62	5.88 ± 0.88	0.20 ± 0.01

Table 1 (continued)

Location	S/N	Point name	Point code	Longitude	Latitude	Activity concentration in Bq/kg			EDR (µSv/h)
						⁴⁰ K	²³² Th	²²⁶ Ra	
Sewage	31	Jamaica 6	L31	3.0841138606	6.5001633325	109.42 ± 16.41	6.20 ± 0.93	3.34 ± 0.50	0.20 ± 0.01
	32	Jamaica 7	L32	3.0833091984	6.5019726936	68.10 ± 10.21	16.72 ± 2.51	7.22 ± 1.08	0.24 ± 0.02
	33	Jamaica 8	L33	3.0841140546	6.5013302845	91.54 ± 13.73	11.68 ± 1.75	5.23 ± 0.78	0.24 ± 0.02
	34	Jamaica 9	L34	3.0833091701	6.5018008169	72.14 ± 11.16	8.32 ± 1.25	3.65 ± 0.55	0.23 ± 0.03
	35	Jamaica 10	L35	3.0868465293	6.5073364583	121.52 ± 18.23	15.80 ± 2.37	6.85 ± 1.03	0.23 ± 0.02
	36	Sewage 1	L36	3.0595632437	6.5103567342	87.13 ± 13.07	10.43 ± 1.56	6.96 ± 1.04	0.23 ± 0.03
	37	Sewage 2	L37	3.0595503449	6.5103457352	113.88 ± 17.08	7.64 ± 1.15	6.94 ± 1.04	0.23 ± 0.02
	38	Sewage 3	L38	3.0595503563	6.5103431736	81.52 ± 12.23	5.51 ± 0.83	1.61 ± 0.24	0.23 ± 0.02
	39	Sewage 4	L39	3.0595503896	6.5103434342	72.14 ± 10.82	7.45 ± 1.12	5.03 ± 0.75	0.23 ± 0.03
	40	Sewage 5	L40	3.0959550344	6.5103471739	90.21 ± 13.53	12.83 ± 1.92	9.39 ± 1.41	0.23 ± 0.02
Industrial	41	Stone company	L41	3.0957237338	6.5307010098	106.18 ± 15.93	5.15 ± 0.77	6.51 ± 0.98	0.16 ± 0.01
	42	GSK	L42	3.0798012392	6.5103228451	156.53 ± 23.48	9.56 ± 1.43	5.41 ± 0.82	0.33 ± 0.02
	43	P&G	L43	3.0798021397	6.5103245456	340.67 ± 51.10	11.31 ± 1.69	3.49 ± 0.52	0.33 ± 0.04
	44	Eko supreme	L44	3.0815009473	6.5060347046	267.48 ± 40.12	5.89 ± 0.88	1.53 ± 0.23	0.35 ± 0.03
	45	Flour mill	L45	3.0829985674	6.5380125387	316.76 ± 47.51	7.30 ± 1.94	7.52 ± 1.13	0.20 ± 0.01
	46	Stone company 2	L46	3.0732468566	6.5346556736	77.28 ± 11.59	14.54 ± 2.18	5.13 ± 0.77	0.18 ± 0.05
	47	P&G 2	L47	3.0780565438	6.5015832457	90.62 ± 13.59	12.70 ± 1.91	10.17 ± 1.53	0.30 ± 0.01
	48	P&G 3	L48	3.0780542679	6.5015845476	125.83 ± 18.88	13.74 ± 1.06	2.49 ± 0.37	0.31 ± 0.06
	49	Afri fertilizer 1	L49	3.0762959047	6.5306765234	137.05 ± 20.56	12.34 ± 1.85	1.60 ± 0.24	0.22 ± 0.02
	50	Afri fertilizer 2	L50	3.0767746515	6.5325315727	57.88 ± 8.68	8.99 ± 1.35	2.79 ± 0.42	0.24 ± 0.02
Mean	51	GSK 2	L51	3.0776759152	6.5114629897	103.74 ± 15.56	6.48 ± 0.97	8.85 ± 1.37	0.29 ± 0.07
	52	GSK 3	L52	3.0944086452	6.5116862933	72.00 ± 10.80	15.10 ± 2.26	8.16 ± 1.22	0.26 ± 0.02
	53	Stone Company	L53	3.0872266141	6.5085576213	90.62 ± 13.59	14.24 ± 2.14	6.04 ± 0.91	0.14 ± 0.02
	54	Flourmill	L54	3.0950753433	6.4978003498	125.83 ± 18.87	8.13 ± 1.22	5.91 ± 0.89	0.24 ± 0.03
	55	Nestle	L55	3.0957723012	6.5006316394	137.05 ± 10.52	6.78 ± 1.02	1.89 ± 0.28	0.22 ± 0.03
						171.33 ± 24.80	9.11 ± 1.36	5.05 ± 0.76	0.22 ± 0.02

HPGe analysis of radionuclide

HPGe computerized system with a resolution of 1.8 keV at 1.33 MeV of ^{60}Co was utilized to measure the activities of ^{40}K , ^{232}Th , and ^{226}Ra in the soil samples. Relative efficiency of 40% was utilized, and a multichannel analyzer and gamma spectrometer were connected to the detector. The efficiency and energy of the system were calibrated prior to sample measurement. The calibration ensures both qualitative and quantitative analysis of the measured samples. A standard calibration of mixed radionuclide in a 1.0-L container, a density of 1.0 g cm^{-3} , and a volume of 1000 mL with serial number NW 146 were utilized (Deutscher Kalibrierdienst (DKD-3), QSA Global GmbH, Germany). For energy calibration, a combination of channel number and the standard calibration spectrum were used in observing the principal gamma-ray peaks. The efficiency calibration was also accomplished by attaining a typical spectrum to calculate the total absorption count rate with a statistical uncertainty of less than 1% at 95% assurance. The counting rate was then determined by the energies at the photo peaks for estimating the efficiency. The efficiency at other peaks was then calculated by deducing its values from a plotted graph of each energy efficiency against peak energies.

Afterward, the soil samples were inserted into the detector, inside a cylindrical Lead shield of thickness, internal diameter, and height of 5 cm, 24 cm, and 60 cm, respectively. MAESTRO 32 software was used to study the data. The concentration of the radionuclide was determined using the gamma emission lines presented in Table 2. A counting time of 10 h was utilized to obtain a spectrum for each sample. The theoretical determination of these radionuclides and the uncertainties associated with measurements can

Table 2 Gamma ray emission lines of radionuclide

Radionuclide	Gamma ray emission line
^{40}K	1460.8 keV (10.7%)
^{232}Th	^{208}Tl at 583 keV (30.1%)
	^{228}Ac at 911 keV (26.6%)
	^{212}Pb at 238.6 keV (43.3%)
^{226}Ra	^{214}Pb at 351.9 keV (35.8%)
	^{214}Bi at 609.3 keV (44.8%)

be found elsewhere (Nguyen and Zsigrai 2006; Zsigrai et al. 2015).

The activity concentrations of radionuclides in soil samples were examined using Eq. 1 (Tzortzis et al. 2003):

$$A_c = N_{\text{sam}}/M \times P_E \times T_c \times \varepsilon \quad (1)$$

where A_c is activity concentration, N_{sam} is radionuclide net counts, M is mass of the sample, P_E is gamma-ray emission probability, T_c is sample counting time, and ε is detector efficiency.

MapInfo 6.0 software was adopted for the spatial distribution of activity concentration of radionuclide as depicted in Fig. 2.

GM counter measurement of radiation

The in situ background radiation measurement was performed using a PG-15 Kindenoo GM counter with version and serial number 38.0 and 0018B2012589, respectively. The range of its measurement is 0.05–300 $\mu\text{Sv/h}$ with maximum radiation and time measurement of 250 mSv and 10 years, respectively. The detector was calibrated at the National Institute of Radiation Protection and Research, a secondary standard laboratory certified by the International Atomic Energy Agency (IAEA) and a division of the Nigerian Nuclear Regulatory Authority (NNRA). The characteristic features of this instrument are small size, flexibility of operation, and superior measurement performance which is provided by the use of low power technology.

The sievert (Sv) is the International System of Units (SI) derived unit of equivalent radiation dose, effective dose, and committed dose. One sievert is the amount of radiation needed to produce the same effect on living tissue as one gray (Gy) of high-penetration x-rays. Quantities that are measured in sieverts are designed to represent the biological effects of ionizing radiation (Cember 1969). The conversion of Gy to Sv is presented below:

$$1\text{ gray (Gy)} = 1\text{ sievert (Sv)} \quad (2)$$

Outdoor terrestrial dose assessment

Absorb dose rate (ADR) is the amount of radiation emanating from radionuclide in the soil per unit time in the air. This is direct exposure of humans to activity concentration of radionuclide. The ADR in the air at 1 m

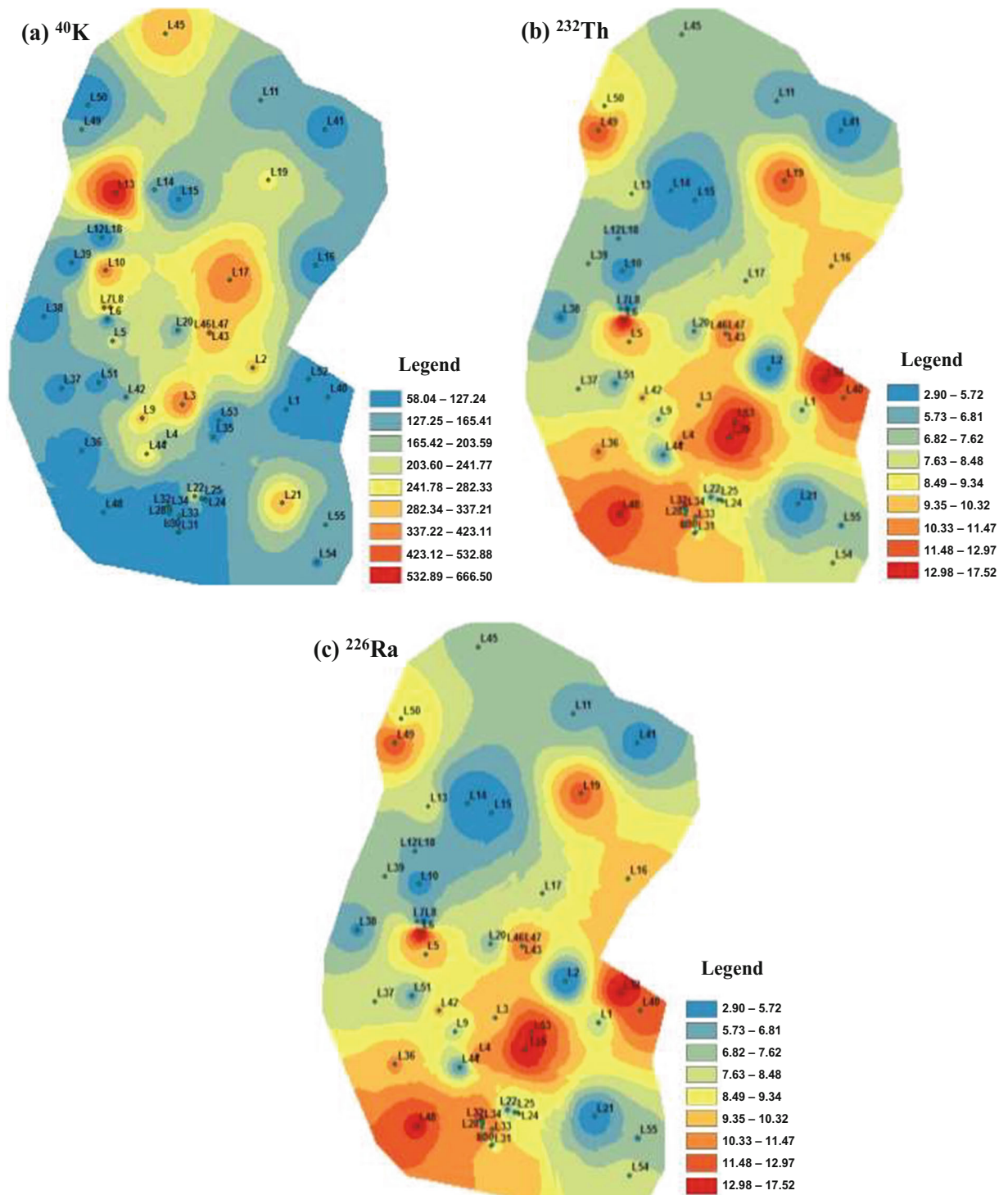


Fig. 2 Spatial distribution of a ^{40}K , b ^{232}Th , and c ^{226}Ra in the study area

above the ground surface for ^{40}K , ^{226}Ra , and ^{232}Th (Bq/kg) in soil samples was evaluated using the equation below (Suleiman et al. 2018). The dose coefficients in

units of nGyh^{-1} per Bqkg^{-1} were taken from the United Nations Scientific Committee on the Effects of Atomic Radiation report (UNSCEAR 2000).

$$\text{ADR (nGy/h)} = 0.462A_{\text{Ra}} + 0.604A_{\text{Th}} + 0.0417A_{\text{K}} \quad (3)$$

where ADR is absorbed dose rate and A_{K} , A_{Ra} , and A_{Th} are the activity concentrations of ^{40}K , ^{226}Ra , and ^{232}Th , respectively.

The annual effective dose equivalent (AEDE) is the accumulated dose rate in a year and was assessed using an outdoor occupancy factor and a conversion factor of 20% and 0.7 Sv/Gy, respectively. The equation below was used to determine the AEDE:

$$\begin{aligned} \text{AEDE (mSv/year)} &= \text{ADR (nGy/h)} \\ &\times 8760 \text{ (h/year)} \times 0.7 \\ &\times (10^3 \text{ mSv/nGy } 10^9) \\ &\times 0.2 \end{aligned} \quad (4)$$

where ADR is the absorbed dose rate and 0.2 is the outdoor occupancy factor

The maximum permissible value recommended by ICRP is 1.0 mSv/year (ICRP 1991) for radiological, epidemiological, and somatic health effects to be insignificant for the public and industrial worker as well.

Outdoor background radiation dose assessment

The equivalent dose rate (EDR) is an in situ approach of measuring ambient radiation to enable samples to maintain their original environmental features. A radiation monitor, GM counter (Kindenoo blue Geiger PG-15), was used. The GM counter detects radiations such as alpha, beta, gamma, and x-rays.

The EDR was measured with the GM counter in $\mu\text{Sv/h}$. The spatial distribution of EDR using MapInfo 6.0 software is displayed in Fig. 5.

The annual equivalent dose rate (AEDR) measures the quantity of energy absorbed by the human body in a year. Equation 4 below was used to calculate the AEDR received outdoor in mSv/year (Pourfallah et al. 2012). A 20% outdoor occupancy factor was considered translating to an occupancy factor of 0.2.

$$\begin{aligned} \text{AEDR (mSv/year)} &= \text{EDR } (\mu\text{Sv/h)} \\ &\times 8760 \text{ (h/year)} \times 0.2 \\ &\times 0.001 \text{ } (\mu\text{Sv/mSv}) \end{aligned} \quad (5)$$

where EDR is the equivalent dose rate and 0.2 is the occupancy factor.

The effective dose ($\text{ED}_{\text{organs}}$) to various organs of the body evaluates the quantity of intake radiation dose to several organs of the body and tissues. The ED_{organ} of the body due to inhalation was calculated using the equation below (Agbalagba et al. 2016; Ugbede and Benson 2018):

$$\text{ED}_{\text{organs}} \text{ (mSv/year)} = \text{AEDR} \times F_{\text{risk}} \quad (6)$$

where F_{risk} is the risk factor of organ dose from air dose. The F_{risk} for each organ of the body is presented in Table 5.

Excess lifetime cancer risk (ELCR)

ELCR reveals the possibility of having cancer over a period of time at a given level of exposure. The ELCR was assessed using the equation given below (Faromika et al. 2016):

$$\text{ELCR} = \text{AEDR}(\text{AEDE}) \times \text{DL} \times \text{RF} \quad (7)$$

where DL is the duration of life (70 years) and RF is the risk factor (0.05 Sv^{-1}). These values were recommended for the public by ICRP (ICRP 1991).

Results and discussions

Activity concentration of radionuclide in the study area

The spatial distributions of ^{40}K , ^{232}Th , and ^{226}Ra in soils of several locations (industrial, residential, dumpsite, and sewage) of the study area are displayed in Fig. 2a, b, and c, respectively. In the figures, each point with the same color falls within the same range as depicted in the legend beside each figure. Considering Fig. 2a, more than a few points are found within the color range of 58.04–127.24 Bq/kg and are distributed across all the studied locations. A point with the highest value is found within the color of 532.89–666.5 Bq/kg and is found in the residential area. In Fig. 2b, many points are found within the color range 2.90–5.72 Bq/kg and are distributed across residential, sewage, and industrial locations. The lowest points are found in dumpsite and industrial within the color range of 8.49–9.34 Bq/kg. Figure 2c shows multiple points within the color range of 1.56–3.01 Bq/kg and is distributed across residential, sewage, and industrial locations. The

lowest points fall within 3.80–4.37 Bq/kg color range and are found at the residential location.

The mean activity concentration of these radionuclides in soils of several locations has been assessed due to industrial activities and are presented and depicted in Table 3 and Fig. 3, respectively. ⁴⁰K is radioactive among natural potassium (³⁹K, ⁴⁰K, and ⁴¹K) owing to its decay process which gives rise to ⁴⁰Ca and ⁴⁰Ar (progenies) isotopes. The occurrence of ⁴⁰Ca and ⁴⁰Ar isotopes was said to be from the emissions of beta and gamma radiation, respectively, which are detrimental to human health and their environment (Ramola et al. 2008). The concentrations of ⁴⁰K ranged from 57.88 to 340.67 Bq/kg, and the mean is found to be 147.03 Bq/kg for industrial, 61.23–667.55 Bq/kg, and the mean is found to be 230.74 Bq/kg for residential, 68.10–139.75 Bq/kg, and the mean is found to be 100.46 Bq/kg for dumpsite and 72.14–113.88 Bq/kg, and the mean is found to be 88.98 Bq/kg for sewage area.

²²⁶Ra diffuses from ²³⁸U, the radioactive equilibrium is well-known among the parent ²³⁸U, and it progenies in the decay chain at a rate of the progeny half-life, and at the level of the parent decay rate. The decay process goes through ²²⁶Ra → ²²²Rn down to ²⁰⁶Pb at a rate consistent with the parent. ²²⁰Rn also diffuses from ²³²Th, ²²²Rn, and ²²⁰Rn can be formed in the air due to their gaseous nature. These radionuclides get into the atmosphere and groundwater by its presence and that of their progenies and are among the most toxic elements (Choppin et al. 2002). Thus, exposure to ²³²Th and ²²⁶Ra radiation emanating from the soil is associated with several ailments such as

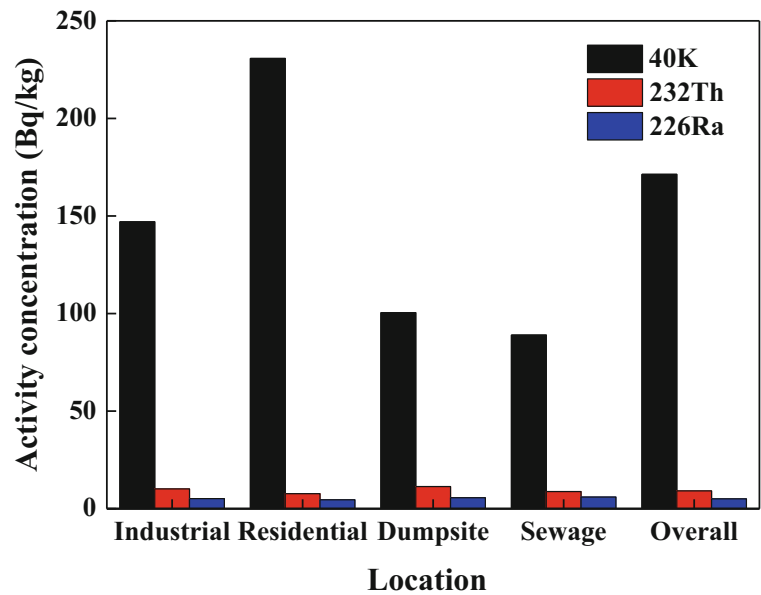
chronic hepatic cancers, lung cancer, acute leucopenia, anemia, leukemia, pancreas, kidney, and bone damage when their activity concentration exceeds the recommended dose (Agency 1991; Oke et al. 2020). The concentrations of ²³²Th in soil of the study area range within 5.15–15.10 Bq/kg and the mean is found to be 10.15 Bq/kg for industrial, 2.89–17.73 Bq/kg, and the mean is found to be 7.67 Bq/kg for residential, 5.01–16.72 Bq/kg, and the mean is found to be 11.34 Bq/kg for dumpsite and 5.51–12.83 Bq/kg, and the mean is found to be 8.77 Bq/kg for sewage location. The concentrations of ²²⁶Ra range within 1.53–8.85 Bq/kg, and the mean is found to be 5.17 Bq/kg for industrial, 1.76–9.83 Bq/kg, and the mean is found to be 4.58 Bq/kg for residential, 3.34–7.48 Bq/kg, and the mean is found to be 5.60 Bq/kg for dumpsite, 1.61–9.39 Bq/kg, and the mean is found to be 5.97 Bq/kg for sewage location. The overall activity concentration of the study area ranged from 57.88 to 667.55, 2.89 to 17.73, and 1.53 to 9.83 Bq/kg, and the mean is found to be 171.33, 9.11, and 5.05 Bq/kg for ⁴⁰K, ²³²Th, and ²²⁶Ra, respectively.

From Fig. 3, the concentrations of ⁴⁰K in all sampling locations are higher than that of ²³²Th and ²²⁶Ra. The variation in the concentrations of the studied radionuclides can be attributed to the geological conditions due to the rock formation and transport processes in the soils of the area (Oke et al. 2020; Ramola et al. 2008). From the same figure, we also observed that the concentration of ⁴⁰K is very high at the residential location, followed by the overall mean than other locations. This observation can be associated with agricultural activities that is been practice by the dwellers of the study area, which may involve the use of fertilizers as a nutrient to enhance the growth of plants and has been reported elsewhere (Faisal et al. 2015). Actually, the soil contains 0.012% of natural potassium and can be enhanced by anthropogenic activities (Ramola et al. 2008). The concentrations of ²³²Th and ²²⁶Ra at industrial, dumpsite, and sewage locations are higher than that of residential. This may be due to several industrial activities in which residues contain either ²³⁸U or ²³²Th series. We also observed that the overall mean of the radionuclides is higher than in some locations as seen in the figure. Therefore, it can be said that the increase in the concentration of ⁴⁰K in the residential, ²³²Th in the dumpsite, and ²²⁶Ra in sewage locations are major contributors to the overall mean values for ⁴⁰K, ²³²Th, and ²²⁶Ra in Agbara estate. The studied radionuclides at all points in each location of the study area are below the standard values of 400, 30, and 35 (Unsclear 2000) for ⁴⁰K, ²³²Th, and ²²⁶Ra, respectively, except points L13

Table 3 Mean activity concentration of radionuclide in soil

Locations		Activity concentration of radionuclide (Bq/kg)		
		⁴⁰ K	²²⁶ Ra	²³² Th
Industrial	Range	57.88–340.67	1.53–8.85	5.15–15.10
	Mean	147.03	5.17	10.15
Residential	Range	61.23–666.55	1.76–9.83	2.89–17.73
	Mean	230.74	4.58	7.67
Dumpsite	Range	68.10–139.75	3.34–7.48	5.01–16.72
	Mean	100.46	5.60	11.34
Sewage	Range	72.14–113.88	1.61–9.39	5.51–12.83
	Mean	88.98	5.97	8.77
Overall	Range	57.88–666.55	1.53–9.83	2.89–17.73
	Mean	171.33	5.05	9.11

Fig. 3 Mean activity concentration of ^{40}K , ^{232}Th , and ^{226}Ra at each location



(Area 8b) and L17 (Area 1) with higher concentrations of ^{40}K in the residential location (see Table 1).

Assessment of outdoor terrestrial dose

The mean values of radionuclide ADR and AEDE at each location in the study area are presented in Table 4. The ADR at each location within the study area ranged from 9.02 to 22.50 nGy/h, and the mean is found to be 14.43 nGy/h for industrial, 8.21–24.57 nGy/h, and the mean is found to be 16.18 nGy/h for residential, 8.05–17.49 nGy/h, and the mean is found to be 13.39 nGy/h for dumpsite, 7.40–15.45 nGy/h, and the mean is found

to be 11.52 nGy/h for sewage area. The values of ADR in the study area ranged within 7.40–34.68 nGy/h with an overall mean of 14.77 nGy/h. The highest (24.57 nGy/h) and lowest (7.40 nGy/h) value corresponding to L3 (Unilever PLC 1) and L38 (Sewage 3) points are found in residential and sewage areas, respectively, of the study area. All the measured ADR in soil samples were found to be lower than the world average value (54 nGy/h) (Unsear 2000) (see Table 1).

The lower value of ADR in the study area led to the evaluation of AEDE to have in-depth knowledge about the annual implication of ADR in Agbara estate due to industrial activities. Therefore, AEDE is dependent on ADR.

Table 4 Mean dose rate from radionuclide and background radiation

Location		Radiation dose rate			
		ADR (nGy/h)	AEDE (mSv/year)	EDR ($\mu\text{Sv/h}$)	AEDR (mSv/year)
Industrial	Range	9.02–22.50	0.01–0.03	0.16–0.33	0.28–0.58
	Mean	14.43	0.02	0.27	0.46
Residential	Range	8.21–34.68	0.01–0.04	0.09–0.24	0.16–0.42
	Mean	16.18	0.02	0.16	0.29
Dumpsite	Range	8.05–17.49	0.01–0.02	0.19–0.27	0.33–0.47
	Mean	13.39	0.02	0.23	0.40
Sewage	Range	7.40–15.45	0.01–0.02	0.23–0.23	0.40–0.40
	Mean	11.52	0.01	0.23	0.40
Overall	Range	7.40–24.47	0.01–0.04	0.09–0.35	0.16–0.58
	Mean	14.77	0.02	0.22	0.39

For radiological, epidemiological, and somatic health effects to be insignificant for the public and industrial worker as well, ICRP set the maximum permissible limit as 1.0 mSv/year (ICRP 1991). The values of AEDE in the study area ranged within 0.01–0.04 mSv/year and an overall mean to be 0.02 mSv/year (see Table 4). In comparison with ICRP acceptable limit, the annual dose levels of all locations were below the limit set for both the industrial workers and the public.

Figure 4a and b shows the mean dose rate of radionuclide (ADR and AEDE, respectively) at each location in the study area. Figure 4a shows a higher mean value of ADR at residential followed by industrial, dumpsite, and sewage locations. It was also confirmed that the mean value of ADR at residential location is higher than the overall mean, while others are lower. The higher ADR was due to the higher values of ⁴⁰K at each point in the residential area, which contributed more to the overall mean for ADR in Agbara estate as a result of agricultural activities. From Fig. 4b, the same mean values were obtained for AEDE at residential, industrial, and dumpsite locations. The overall mean value is also the same with these locations, while the mean value at the sewage location is lower. The dwellers of these locations of higher dose rates will be more exposed to radiation than the locations with lower dose rates.

Assessment of outdoor background radiation dose

A total of 165 measurements were taken across the 55 points in the study area, translating to three readings per point, and the average of each point was recorded. Generally, the average EDR for each point ranged from 0.09

to 0.35 μSv/h. The average value for Eko supreme (L44) shows the highest EDR, while that of Kurogboji (L23) was the lowest (see Table 1). Figure 5 shows the spatial distribution of EDR. From the figure, several points are distributed across residential, sewage, and industrial locations within the color range of 0.095–0.124 μSv/h as seen in the legend beside the figure. The lowest points are found within 0.153–0.180 μSv/h color range and are found across residential, sewage, and industrial locations.

The data for the background radiation dose rate (EDR) from several points in Agbara estate are presented in Table 1, and the calculated mean of several locations is presented in Table 4. From Table 4, the EDR at each location within the study area ranged within of 0.16–0.35 μSv/h and mean is found to be of 0.27 μSv/h for industrial, 0.09–0.24 μSv/h, and the mean is found to be 0.16 μSv/h for residential, 0.19–0.27 μSv/h, and the mean is found to be 0.23 μSv/h for dumpsite, 0.23–0.23 μSv/h, and the mean is found to be 0.23 μSv/h for sewage area. The values of EDR in all the 55 points ranged between 0.09 and 0.35, and the overall mean is found to be 0.22 μSv/h. The mean values of all locations in the study area are higher than 0.13 μSv/h recommended by ICRP (James et al. 2013). Comparing the levels of EDR with the standard value of 0.13 μSv/h and values of each point, the result shows that only four points in two locations, Area 8d (L15), Kurogboji 2 (L23), Kurogboji 3 (L24), and Kurogboji 4 (L25) (see Table 1) have EDR lower than the value of the standard background radiation. The EDR of other locations were above the standard value. The four points that have lower EDR than the standard value were located in the residential location of the study area.

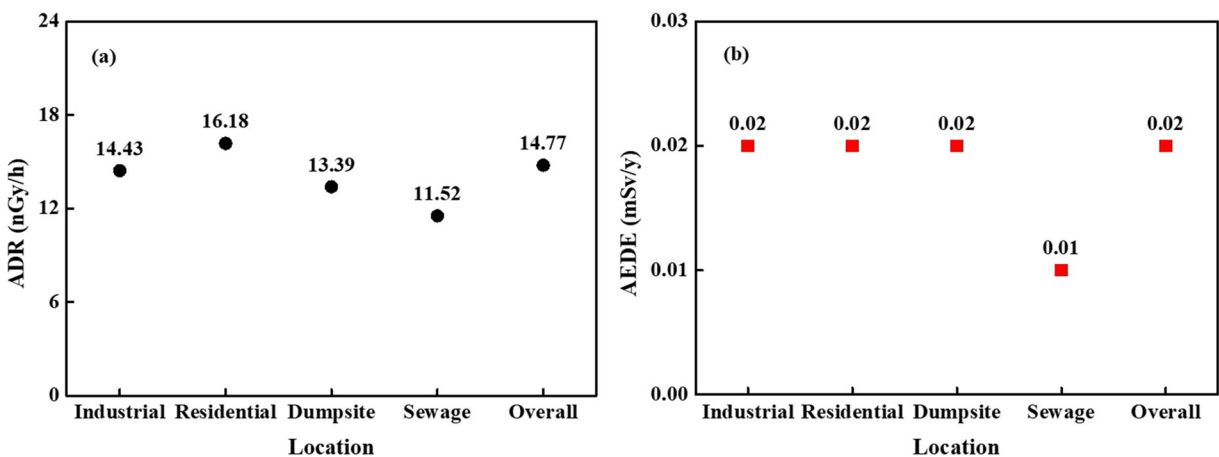
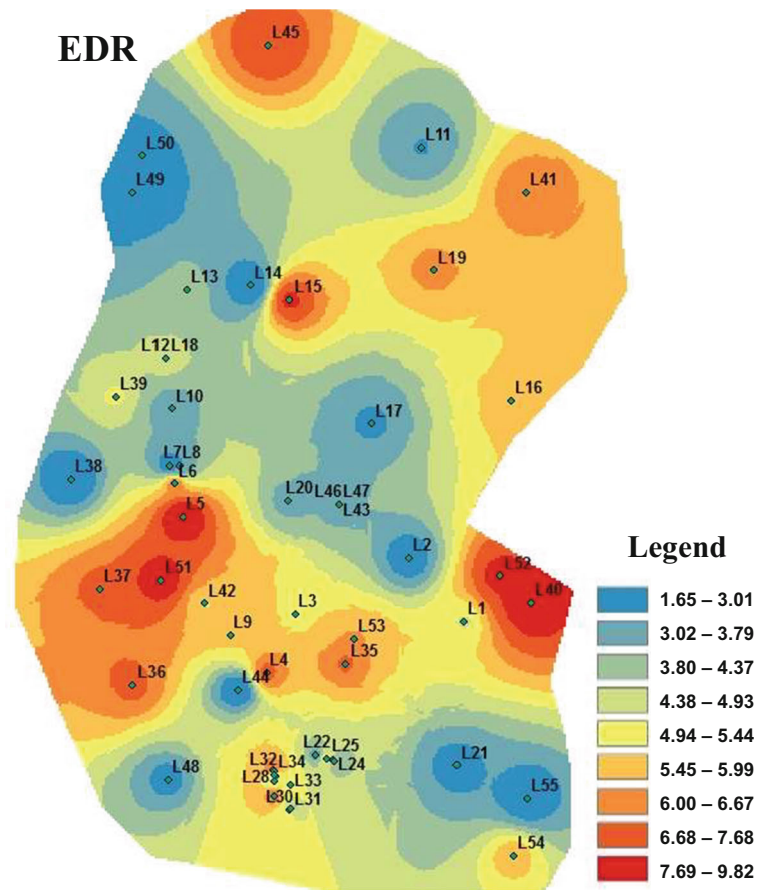


Fig. 4 Mean of radionuclide. a Absorb dose rate and b annual effective dose equivalent at each location

Fig. 5 Spatial distribution of background EDR in the study area



The AEDR was considered based on higher values of EDR measured at each location in the study area. The AEDR mean values of several locations are presented in Table 4. AEDR is the measure of the quantity of energy absorbed by the human body annually. The mean AEDR at each location ranged from 0.28 to 0.58 mSv/year, and the mean is found to be 0.46 mSv/year for industrial, 0.16 to 0.42 mSv/year, and the mean is found to be 0.29 mSv/year for residential, 0.33–0.47 mSv/year, and the mean is found to be 0.40 mSv/year for dumpsite, 0.40–0.40 mSv/year, and the mean is found to be 0.40 mSv/year for sewage location. The AEDR of all locations ranged within 0.16–0.61 mSv/year and an overall mean of 0.39 mSv/year. The obtained values are higher than the world average of 0.07 mSv/year (Unsclear 2000). The AEDR follows the same trend as observed in EDR at different locations.

Figure 6a and b shows the mean plots of background EDR and AEDR, respectively, at each location in the study area. From the same figures, it was observed that the highest EDR and AEDR are found in the industrial,

followed by dumpsite and sewage, and residential is the least. Thus, the increased dose rate in the industrial location contributed more to the overall mean values for EDR in Agbara estate. The workers and dwellers around these areas of increased EDR will be more exposed than those areas with lower EDR of background radiation. The highest mean values in these locations are mainly due to industrial activities. Although, all the measured mean values of EDR for several locations in the study area are not significantly different due to the geographical nature of the area (see Fig. 6). An extra-terrestrial source such as cosmic rays also contributes to EDR but depending on the function of altitude and latitude. The increase in altitude increases the exposure levels to cosmic rays due to a decrease in shielding effects of the atmosphere. Based on the deflection of high-velocity charged constituent particles of the radiation across the Earth's magnetic field, the shielding effects decrease with an increase in the latitude of north and south of the equator (Cember 1969). Taking the above and the values of EDR into

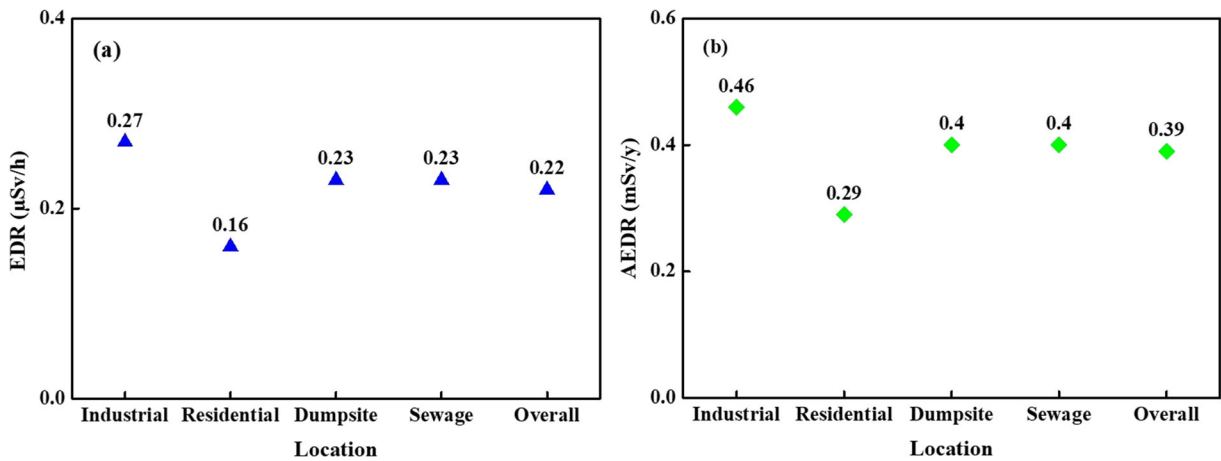


Fig. 6 Mean of background. **a** Equivalent dose rate and **b** annual equivalent dose rate at each location

consideration, cosmic radiation contributed little or no effect due to the geographical location of the Agbara industrial estate. Cosmic radiation constituent could have been completely attenuated before attaining the maximum altitude of the study area. The report of UNSCEAR (2000) on exposure to natural radiation confirmed that the level of cosmic radiations constituent rapidly decreases from the altitude of 10–20 km to small or nothing at the sea level (Oladele et al. 2018).

ED_{organs} helps to evaluate the amount of radiation that affects a particular organ. To calculate the effect on some organs of the body that absorbs radiation, an effective radiation dose and the risk factor for different organs are used (see Table 5), because the increase in the risk of cancer is different for different organs, even if the amount of radiation absorbed is the same. The ED_{organs} for various organs of the body were evaluated and are presented in Table 5. The values of ED_{organs} for liver, kidney, testes, ovaries, lungs, bone marrow, and bone marrow are 0.1794, 0.2418, 0.3198, 0.2262, 0.2496, 0.2691, and 0.2652 mSv/year, respectively. The calculated results are within the

Table 5 F_{risk} and ED_{organs} values for organs of the body

Organs	F _{risk} (Agbalagba 2017)	ED _{organs} (mSv/year)
Liver	0.46	0.1794
kidney	0.62	0.2418
Testes	0.82	0.3198
Ovaries	0.58	0.2262
Lungs	0.64	0.2496
Bone marrow	0.69	0.2691
Whole body	0.68	0.2652

acceptable value of 1.0 mSv/year (Agbalagba et al. 2016; Ugbede and Benson 2018) and do not pose any instant hazard to the dwellers and workers of the study area. Figure 7 shows the percentage distribution of ED_{organs} for various organs of the body due to background radiation exposure in the area. The results show that testes and ovaries are most and least sensible to radiation with the percentages of 18.26% and 10.24%, respectively.

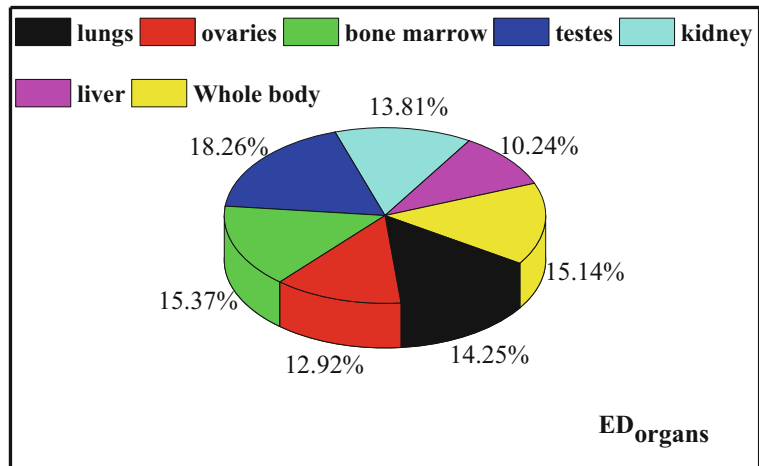
Excess lifetime cancer risk (ELCR)

ELCR was evaluated due to low exposure risk to predict if there is a possibility of developing cancer over a lifetime. The ELCR was calculated using overall mean AEDR and AEDR owing to exposure to radionuclide and background radiation, respectively. The overall value for ELCR ranged within 0.04×10^{-3} – 0.14×10^{-3} with a mean of 0.07×10^{-3} for radionuclide and ranged within 0.56×10^{-3} – 2.03×10^{-3} with a mean of 1.37×10^{-3} for background radiation. The obtained mean value of ELCR for background radiation is higher than the world average of 0.29×10^{-3} (UNSCEAR 2000), indicating there are possibilities of developing cancer by the dwellers and workers who intend to live all their life in the study area.

Comparison of dose rates

Figure 8a represents the comparison of mean ADR and EDR at each location. As seen in the figure, the ADR was converted from nGy/h to μSv/h in order to make the comparison easier. The EDR was evaluated using GM counter to measure the background radiation at each point

Fig. 7 Percentage distribution of ED_{organs} to various organs of the body owing to background radiation exposure



in the study area. While ADR was evaluated by adding the multiplications of mean activity concentration of each radionuclide and its conversion factor (see Eq. 3). Considering the same figure, EDR » ADR at all locations. This observation is due to the fact that Geiger Muller counter measures all radiation detectable irrespective of their source, while ADR was calculated due to radiation from radionuclide in the soil. The comparison of mean AEDE and AEDR at each location in the study area is also depicted in Fig. 8b. The mean values of AEDR » AEDE at each location, as a result of several sources of radiation. Also, AEDR and AEDE followed a similar trend with EDR and ADR. This was due to the fact that AEDR and AEDE were calculated putting into consideration EDR and ADR, which means that AEDR and AEDE depend on EDR and ADR, respectively. The percentage contribution of radionuclides in the air was

calculated taking into consideration the overall mean value of ADR to that of EDR of ambient radiation. The percentage contribution of radionuclides in the air was calculated to be 6.7% for ADR to background radiation.

The obtained results owing to background radiation showed a significant increase in radiation levels at Agbara industrial estate when compared with those of other locations of the world (see Table 6). The increased levels of background radiation should be of great concern as the majority of these industrial workers and people transacting businesses in the study area spends more than eight hours per day outdoors. Predictably, continual exposure to these high levels of radiation may cause lung cancer and other forms of cancers in the future. Furthermore, the industrial workers and dwellers of this area can have several diseases associated with long-term exposure owing to the condensation of

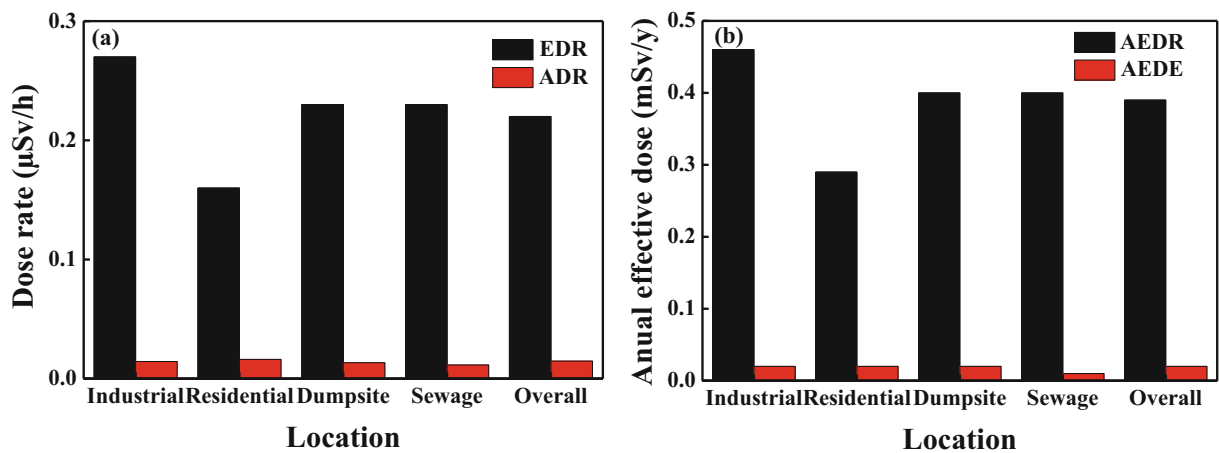


Fig. 8 Comparison of mean. **a** Dose rates of radionuclide and background radiation. **b** Annual effective doses of radionuclide and background radiation at each location

Table 6 Comparison of present study area with other location of the world

Study area	⁴⁰ K (Bq/kg)	²³² Th (Bq/kg)	²²⁶ Ra (Bq/kg)	Dose rate		Annual effective dose (mSv/year)		Reference
				ADR (nGy/h)	EDR (μSv/h)	AEDE	AEDR	
Adana, Turkey	297.5	21.1	21.7	19.25	0.054	0.02	0.082	Degerlier et al. (2008)
Epe, Nigeria	216.3	5.778	9.010	71	0.118	0.09	0.144	Oke et al. (2020)
Bangladesh	423	51	45	81	0.117	0.10	0.205	Abedin et al. (2019)
Uttarakhand, India	549	69	76	20.74	0.22	0.221	0.39	Anamika et al. (2020)
Suez, Egypt	128.9	14.57	13.79	54	0.06	0.066	0.07	Diab et al. (2019)
Kastamonu, Turkey	431.43	27.17	37.4	14.7	0.055	0.02	0.067	Kam and Bozkurt (2007)
Kirklareli, Turkey	667	28	37	14.7	0.118	0.02	0.144	Taskin et al. (2009)
Idu, Nigeria	171.33	9.11	5.05	54	0.117	0.02	0.205	James et al. (2013)
Present study	400	30	35	54	0.06	0.066	0.07	Unsear (2000)

radioactive elements as rain and underground water constituent, as these serve as drinking water and source of water for agriculture purposes.

Conclusion

We have assessed the dose rates of natural radionuclides and background radiation using calculated ADR and GM counter, respectively. The mean values of ADR and AEDE of radionuclides in the soil samples were within the world average. The mean values of EDR and AEDR of ambient radiation were found higher than the world average values at all locations. The comparison of dose rates reveals that ADR of radionuclide in the soils contributed 6.7% to background radiation in the area. The result from ED_{organs} for various organs of the body does not pose any immediate human health hazard. The ELCR owing to background radiation exposure indicates that the dwellers and industrial workers in the study area may develop cancer over a lifetime.

The following needs to be considered to safeguard the environment due to the long-term exposure to background radiation, which has been predicted to have a future effect on the industrial workers and dwellers of the study area.

- 1 Operators of companies should liaise with the government to develop a procedure to reduce the radionuclide concentrations to prevent an increase in background radiation.
- 2 Proper monitoring exercise should be carried out by the operating companies, and government agencies to checkmate the possible rise in the background radiation of the study area.
- 3 Further research on both natural and artificial radionuclides in drinking water, plants and animals, effluent, and sediment should be conducted to evaluate their levels of contamination in the environment.

Acknowledgments The authors appreciate the effort of Mr. Oyata Nicholas of the Ghana Atomic Energy Commission (G.A.E.C) for soil sample analysis.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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*(7). <https://doi.org/10.1007/s12517-019-4355-7>.
- Agbalagba, O. E. (2017). Assessment of excess lifetime cancer risk from gamma radiation levels in Effurun and Warri city of Delta state, Nigeria. *Journal of Taibah University for Science* *11*(3):367–380. <https://doi.org/10.1016/j.jtusci.2016.03.007>.
- Agbalagba, O. E., Avwiri, G. O., & Ononugbo, C. P. (2016). GIS mapping of impact of industrial activities on the terrestrial background ionizing radiation levels of Ughelli metropolis and its environs, Nigeria. *Environmental Earth Sciences*, *75*(21), 1–10. <https://doi.org/10.1007/s12665-016-6216-y>.
- Agency, N. F. E. P. (1991). Guidelines and standards for environmental pollution control in Nigeria. *Federal Environmental Protection Agency (FEPA)*.
- Anamika, K., Mehra, R., & Malik, P. (2020). Assessment of radiological impacts of natural radionuclides and radon exhalation rate measured in the soil samples of Himalayan foothills of Uttarakhand, India. *Journal of Radioanalytical and Nuclear Chemistry*, *323*(1), 263–274. <https://doi.org/10.1007/s10967-019-06876-0>.
- Bickerstaff, K., & Walker, G. (2001). Public understandings of air pollution: the 'localisation' of environmental risk. *Global Environmental Change*, *11*(2), 133–145.
- Bodunrin, J. O., & Ajayi, O. S. (2017). Natural radioactivity measurements to determine the radiation hazards from surface soil and effluents In Agbara Industrial Estate, Ogun State, Nigeria. *International Journal of Innovative Research and Advanced Studies (IJIRAS)*, *4*(11).
- Cember, H. (1969). *Introduction to health physics*.
- Choppin, G., Liljenzin, J.-O., & Rydberg, J. (2002). *Radiochemistry and nuclear chemistry*. Butterworth-Heinemann.
- Degerlier, M., Karahan, G., & Ozger, G. (2008). Radioactivity concentrations and dose assessment for soil samples around Adana, Turkey. *Journal of Environmental Radioactivity*, *99*(7), 1018–1025. <https://doi.org/10.1016/j.jenvrad.2007.12.015>.
- Diab, H. M., Ramadan, A., & Monged, M. H. E. (2019). Environmental assessment of radionuclides levels and some heavy metals pollution along Gulf of Suez, Egypt 12346–12358.
- Emelue, H. (2014). Excess lifetime cancer risk due to gamma radiation in and around Warri Refining and Petrochemical Company in Niger Delta, Nigeria. *British Journal of Medicine and Medical Research*, *4*(13), 2590–2598. <https://doi.org/10.9734/bjmmr/2014/7180>.
- Faisal, B. M. R., Majumder, R. K., Uddin, M. J., Deeba, F., Paul, D., Haydar, M. A., & Ali, M. I. (2015). Assessment of heavy metals pollution and natural radioactivity in topsoil of Savar industrial area. *Bangladesh*, *5*(5), 964–979. <https://doi.org/10.6088/ijes.2014050100091>.
- Faromika, O. P., Oke, J. A., & Ajayi, O. (2016). Dose assessment of natural radionuclide in soils of different gold mine pits at Epe, Osun State, Nigeria., *7*(1), 29–39.
- ICRP. (1991). *ICRP publication 60: 1990 recommendations of the International Commission on Radiological Protection*. Elsevier Health Sciences.
- James, I. U., Moses, I. F., & Vandi, J. N. (2013). Assessment of gamma dose rate within Idu industrial area of the Federal Capital Territory (FCT) Abuja, Nigeria, 52–55.
- Kam, E., & Bozkurt, A. (2007). Environmental radioactivity measurements in Kastamonu region of northern Turkey. *Applied Radiation and Isotopes*, *65*(4), 440–444. <https://doi.org/10.1016/j.apradiso.2006.11.005>.
- Lone, M. I., He, Z. L., Stoffella, P. J., & Yang, X. E. (2008). Phytoremediation of heavy metal polluted soils and water: progresses and perspectives. *Journal of Zhejiang University. Science. B*, *9*(3), 210–220. <https://doi.org/10.1631/jzus.B0710633>.
- Lü, J., Liang, L., Feng, Y., Li, R., & Liu, Y. (2015). Air pollution exposure and physical activity in China: Current knowledge, public health implications, and future research needs. *International Journal of Environmental Research and Public Health*, *12*(11), 14887–14897. <https://doi.org/10.3390/ijerph121114887>.
- McGrath, S. P., Zhao, F. J., & Lombi, E. (2001). Plant and rhizosphere processes involved in phytoremediation of metal-contaminated soils. *Plant and Soil*, *232*(1–2), 207–214. <https://doi.org/10.1023/A:1010358708525>.
- Nguyen, C. T., & Zsigrai, J. (2006). Basic characterization of highly enriched uranium by gamma spectrometry. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *246*(2), 417–424.
- Oke, J. A., Faromika, O. P., Aluko, J. O., & Oke, S. R. (2020). Human health hazard of elemental concentrations in soils of Epe: an implication of gold mining in Nigeria. *International Journal of Environmental Science and Technology*, *0123456789*, 4879–4894. <https://doi.org/10.1007/s13762-020-02821-x>.
- Oladele, B. B., Arogunjo, A. M., & Aladeniyi, K. (2018). Indoor and outdoor gamma radiation exposure levels in selected residential buildings across Ondo state., *16*(3). <https://doi.org/10.18869/acadpub.ijrr.16.3.363>.
- Pourfallah, T. A., Babapour, H., & Shahidi, M. (2012). Evaluation of high level environmental background radiation areas and its variation in Ramsar. *Iranian Journal of Medical Physics*, *9*(2 A), 87–92. <https://doi.org/10.22038/ijmp.2012.314>.
- Ramli, A. T., Aliyu, A. S., Agba, E. H., & Saleh, M. A. (2014). Effective dose from natural background radiation in Keffi and Akwanga towns, central Nigeria. *International Journal of Radiation Research*, *12*(1).
- Ramola, R. C., Gusain, G. S., Badoni, M., Prasad, Y., Prasad, G., & Ramachandran, T. V. (2008). 226Ra, 232Th and 40K contents in soil samples from Garhwal Himalaya, India, and its radiological implications. *Journal of Radiological Protection*, *28*(3), 379–385. <https://doi.org/10.1088/0952-4746/28/3/008>.
- Saad-El-Din, A. A., El-Tanahy, Z. H., El-Sayed, S. N., Anees, L. M., & Farroh, H. A. (2014). Study of electron spin resonance and viscosity for hemoglobin polymer after arsenic trioxide and gamma irradiation treatment. *Journal of Radiation Research and Applied Science*, *7*(4), 448–453. <https://doi.org/10.1016/j.jrras.2014.07.010>.

- Suleiman, I., Agu, M., & Onimisi, M. (2018). Evaluation of naturally occurring radionuclide in soil samples from Erena mining sites in Niger State, Nigeria. *Current Journal of Applied Science and Technology*, 27(6), 1–12. <https://doi.org/10.9734/cjast/2018/41562>.
- 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 Kirklareli, Turkey. *Journal of Environmental Radioactivity*, 100(1), 49–53. <https://doi.org/10.1016/j.jenvrad.2008.10.012>.
- Tzortzis, M., Tsertos, H., Christofides, S., & Christodoulides, G. (2003). Gamma radiation measurements and dose rates in commercially-used natural tiling rocks (granites). *Journal of Environmental Radioactivity*, 70(3), 223–235. [https://doi.org/10.1016/S0265-931X\(03\)00106-1](https://doi.org/10.1016/S0265-931X(03)00106-1).
- Ugbede, F. O., & Benson, I. D. (2018). Assessment of outdoor radiation levels and radiological health hazards in Emene Industrial Layout of Enugu State, Nigeria. *International Journal of Physical Sciences*, 13(20), 265–272. <https://doi.org/10.5897/ijps2018.4763>.
- Unsear, S. (2000). Effects of Ionizing Radiation. *United Nations, New York*, 453–487.
- Zsigrai, J., Cong, T., & Berlizov, A. (2015). Nuclear instruments and methods in physics research B Gamma-spectrometric determination of materials U in uranium-bearing. *Nuclear Instruments and Methods in Physics Research B*, 359, 137–144. <https://doi.org/10.1016/j.nimb.2015.07.047>.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.