Measurement of natural radioactivity and radiological hazard evaluation in the soil samples collected from Owo, Ondo State, Nigeria

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ABSTRACT
The activity concentrations of $^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$ in the soil samples collected from Owo Local Government of Ondo state, Nigeria, were assessed by gamma spectrometric techniques using a Na(TI) scintillation detector, encapsulated in a 5 × 5-cm-thick lead shield to reduce environmental background radiation. Results show that the ranges (and the corresponding average) of the measured activity concentrations of $^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$ are 430.15 ± 4.12 to 2100.42 ± 11.89 BqKg$^{-1}$ (1190.10 ± 373.62 BqKg$^{-1}$), 31.58 ± 2.94 to 212.11 ± 13.15 BqKg$^{-1}$ (64.64 ± 28.10 BqKg$^{-1}$), and 16.27 ± 7.10 to 203.09 ± 42.64 BqKg$^{-1}$ (110.18 ± 46.12 BqKg$^{-1}$), respectively. The average activity concentrations of the radionuclides were compared with the world average value. Radiological hazard indices of the primordial radionuclides were also calculated and compared with the recommended standard exposure limits. The absorbed dose rates estimated in the study were used to create the absorbed-dose rate map of the study area, showing the geological feature of the same. Generally, the results showed that the soil in the study area might not pose significant hazards to members of the public. However, further investigations into the level of exposure of plants and animals as well as the ingestion of radionuclide are necessary.

1. Introduction
Terrestrial radionuclides, $^{238}\text{U}$, $^{232}\text{Th}$ series, and the singly occurring $^{40}\text{K}$ are the major primordial naturally occurring radionuclide materials (NORMs) of great importance from the radiological protection point of view. Natural constituents of our environments such as rocks, soils, water, air, and food crops are found to contain NORMs in varying quantities (United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR], 2000). Because radionuclides are ubiquitous in nature, human beings cannot escape from being exposed to varying degrees of radiations that emanate from radionuclides (Aladeniyi & Aladenika, 2015). Another source of natural radiation exposure to human beings is cosmic radiations from outer space. Terrestrial radionuclides are sources of external and internal radiation exposure. External exposures occur due to gamma decay of primordial radionuclides, and internal exposures result from inhalation of airborne contaminants and by ingestion of food and water contaminated by radionuclides. Sometimes, radionuclides may find their ways into human bodies through contaminated skins and wounds. The concentration of radionuclides of terrestrial origin is dictated to a good degree by the underlying geological feature of an area, its geographical location, and its anthropogenic activities, among other factors (Ajayi, 2009; Mann, Kumar, Kumar, & Chauhan, 2017; Qureshi et al., 2014; Zaim & Atlas, 2016).

According to Chinnasakki et al. (2011), over 85% of the estimated radiation dose to the world population is from natural sources. It is an established fact that acute and chronic exposures to radiation can lead to harmful tissue reactions such as cataracts, lesions, and stochastic effects such as cancer induction and hereditary diseases (Cember & Johnson, 2012; Kaul et al., 2005). Assessment of the level of radiation exposure to the population and the distribution of activity concentration of radionuclides in the environment is important. This will not only help ascertain the possible radiological hazards posed to human health, but also help develop radiation-protection mechanisms.

Ajayi (2009) affirmed that soils are components of the human-environment, which are products of rock weathering. Studies on the activity concentration of soil are very important for assessing radiological hazards to human health. Such studies have provided reference data to compare the possible change of environmental radioactivity resulting from anthropogenic activities now or in the future. Several studies on soil radioactivity have been reported from different parts of the world (Chinnasakki et al., 2011; Issa, 2013; Kritsananuwat, Arae, Fukushima, Sahoo, & Chanyotha, 2015; Kumar, Vij, Sharma, Sarin, & Narang, 2018; Mohammed & Ahmed, 2017; Oyeyemi, Usikalu, Aizebeokhai, Achuka, &
Jonathan, 2017; Raghu, Ravisankar, Chandrasekaran, Vijayagopal, & Venkatraman, 2016; Sahin & Cavas, 2008; Sivakumar, 2014; Zaim & Atlas, 2016) with the sole aim of assessing the radiological health impact on the human population and to enrich the global data bank, which can enhance knowledge of radiation effects even at low levels of exposures. This study was aimed at determining the activity concentrations of radionuclides (\(^{40}\text{K}\), \(^{226}\text{Ra}\), and \(^{232}\text{Th}\)) in the subsurface soils of Owo Local Government Area (OLGA) of Ondo state, Nigeria. Other objectives include the assessment of radiological hazards associated with the soil samples, the annual absorbed dose rate, annual effective dose (AED) rates, radium equivalent activity (Req), annual gonad dose equivalent (AGDE), representative level index (RLI), external hazard index (Hex), internal hazard index (HI)_n, gamma activity Index (I\(\gamma\)), alpha index (I\(\alpha\)), and excess life cancer risks (ELCRs). Absorbed-dose rate mapping and geological makeup of the study area are included in the study.

2. Materials and methods

2.1. Study area

OLGA is a part of Ondo state in the southwestern region of Nigeria. It is located between latitudes 7° 00' and 7° 25' N and longitudes 5° 20' and 5° 45’E. The main lithological features of the southwestern region of Nigeria consist of amphibolites, migmatite gneisses, granites, and pegmatites. Other important rock units that are also present include schists (biotite schist), quartzite schist, quartzite schist, and muscovite schists. Migmatite, granite, schists, and quartzite are the major rocks found in the study area. Idasen, Ipele, Isuada, Iyere, Owo, Upenmen, and Uso are the major districts/areas under OLGA (Adewumi & Anifowose, 2017).

2.2. Sample collection and sample preparation

Sixty surface-soil samples were collected from the randomly selected undisturbed site (to avoid interference of man-made structures and anthropogenic activities) in the study area. At each sample site, an area of 1 × 1 m\(^2\) was marked out, and the geographic coordinates of the point were recorded using a Global Positioning System (GPS). The map with the sample location points is shown in Figure 1. A masonry trowel was used to remove the organic materials with stones from the top of the marked area. A composite of 400–500 g of soil sample was produced by digging up soil at the four corners and the center of the marked area from a depth of 5 cm. The dug-up soil samples were thoroughly mixed to produce a homogeneous sample from which the composite sample is taken as a representative sample for the site. Each sample was packaged separately into a plastic bag and labeled for identification.

The collected samples were transported to the laboratory for further treatment. The samples were first air-dried at room temperature for four to five days and then dried in a temperature-controlled oven at 105°C for 24 h to maintain a constant weight. All the dried samples were pulverized and sieved using a 2 mm mesh sieve in order to have uniform grain size. A mass of 200 g from each of the sieved
samples was placed in a plastic container and sealed for at least four weeks to established secular equilibrium between $^{226}\text{Ra}$ ($^{238}\text{U}$-series) and $^{228}\text{Ra}$ ($^{232}\text{Th}$-series) and their respective short-lived progenies (Ajayi, 2009; Issa, 2013).

### 2.3. Activity measurement

The activity concentrations of $^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$ in the prepared soil samples were measured using the gamma spectrometric technique. The gamma spectrometric system consists of a $7.62 \times 7.62$ cm Na (TI) scintillation detector (Bicron Corp model 3M/3), encapsulated in a 5.5-cm-thick lead shield to reduce environmental background radiation. The detector was coupled to a preamplifier (Bicron Corp model PA-14), an amplifier (Canberra Model, 2022), and an analogue-to-digital converter (ADC) (Canberra Model 8075), which supplied an output to a Canberra 5100 multichannel analyzer (MCA). The activity concentration of $^{40}\text{K}$ was measured from its gamma-ray energy of 1460 keV, and the transition lines of $1120.3$ keV for $^{214}\text{Bi}$ and $911$ keV for $^{228}\text{Ac}$ were applied for $^{226}\text{Ra}$ ($^{238}\text{U}$ series) and $^{228}\text{Ra}$ ($^{232}\text{Th}$ series), respectively.

A standard soil sample supplied by the International Atomic Energy Agency (IAEA), Vienna, Austria (Reference Material IAEA-375 for radionuclides and trace elements in soil), was used for the calibrations of the detector. The background radiation was considered as an empty container having the same geometry as the container of the standard sample and was counted for 25,200 s (7 h). Each of the prepared soil samples was counted for 7 h to determine the activity concentration of the radionuclides in them. The activity concentrations of the radionuclides in the samples were obtained using the comparative method according to Equation 1 (Aladeniyi & Aladenika, 2015):

$$\frac{A_S}{A_{SD}} = \frac{N_S}{N_{SD}} $$

where $A_S$ and $A_{SD}$ are the activity concentrations (Bq kg$^{-1}$) of the sample and the reference sample, respectively, and $N_S$ and $N_{SD}$ are the net count rates under the region of interest for the sample and the reference (standard) sample, respectively. The counting was performed in the Radiological Laboratory of Centre for Energy, Research and Development (CERD), Obafemi Awolowo University, Ile Ife, Nigeria.

### 3. Radiological hazard indices

In this research, the following radiological hazard indices were determined using the measured activity concentrations of $^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$ from the soil samples: absorbed dose rate (D), annual effective dose rates in air (AED), Req, and AGDE. Other radiological hazard indices calculated are RLI, Hex, $H_{IN}$, $I_\nu$, $I_\alpha$, and ELCRs.

#### 3.1. Absorbed dose rate in air

The indoor ($D_{in}$), outdoor ($D_{out}$), and total absorbed $D_{tot}$ dose rates (nGy h$^{-1}$) at a height of about 1.0 m above the surface of the ground in the study area were obtained using Equation 2, (UNSCEAR, 2000), Equation 3, (European Commission (EC), 1999), and Equation 4, respectively. It is assumed that the radionuclides are uniformly distributed and the contributions of other naturally occurring radionuclides are insignificant.

$$D_{Out} = A_K + 0.462A_{Ra} + 0.604A_{Th} $$

$$D_{In} = 0.08A_K + 0.92A_{Ra} + 1.1A_{Th} $$

And it follows that

$$D_{Tot} = D_{In} + D_{Out} $$

where $A_K$, $A_{Ra}$, and $A_{Th}$ are the activity concentrations of $^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$ measured in Bq kg$^{-1}$, respectively, in the samples. The corresponding coefficients of the radionuclides in the equations are the activity conversion factors (CFs) measured in nGy h$^{-1}$ Bq kg$^{-1}$.

Outdoor (AED$_{out}$) and indoor AED$_{in}$ annual effective doses were calculated, respectively, from $D_{Out}$ and $D_{In}$ by considering the outdoor occupancy factor of 0.2 and the indoor occupancy factor of 0.8. A CF of $0.7 \times 10^{-6}$ Sv y$^{-1}$ was used to convert the absorbed dose rates in air to effective doses using Equations 5 and 6 (UNSCEAR, 2000):

$$AED_{Out} (\text{mSv y}^{-1}) = D_{Out} \times 8760 \times 0.2 \times CF $$

$$AED_{In} (\text{mSv y}^{-1}) = D_{In} \times 8760 \times 0.8 \times CF $$

It follows that the total annual effective dose AED$_{TOL}$ was calculated using Equation 7.

$$AED_{TOL} (\text{mSv y}^{-1}) = AED_{In} + AED_{Out} $$

#### 3.2. Radium equivalent activity (Req)

Req is the index that accounts for the contribution of each of the radionuclides ($^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$) to the total dose from the material under investigation. It is actually the weighted sum of the activities of $^{40}\text{K}$, $^{226}\text{Ra}$, and $^{232}\text{Th}$ in the material with the assumption that 4810 Bq kg$^{-1}$ of $^{40}\text{K}$, 370 Bq kg$^{-1}$ of $^{226}\text{Ra}$, and 259 Bq kg$^{-1}$ of $^{232}\text{Th}$ produce the same gamma dose rate. The Req was estimated from Equation 8 (Ajayi, 2009; Srilatha, Rangaswamy, & Sannappa, 2015):

$$Req (\text{Bq kg}^{-1}) = \left( \frac{A_K + A_{Ra}}{4810 + 370 + 259} \right) \times 370 $$

It follows that

$$AED_{TOL} = AED_{In} + AED_{Out} $$

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where $A_{K}$, $A_{Ra}$, and $A_{Th}$ are the activity concentrations (Bq kg$^{-1}$) of $^{40}$K, $^{226}$Ra, and $^{232}$Th, respectively, measured in the samples. The recommended maximum activity level of the hazard index (Req) of the materials corresponding to an annual dose of 1.5 mGy is 370 Bq kg$^{-1}$ (Beretka & Matthew, 1985).

### 3.3. Annual gonad dose equivalent (AGDE)

AGDE represents the genetic relevance of the annual equivalent dose received by the gonads of the exposed population. Equation 9 (Issa, 2013) was used to estimate the AGDE due the presence of specific activities of $^{40}$K, $^{226}$Ra, and $^{232}$Th in the soil samples:

$$\text{AGDE(µSv y}^{-1}) = 0.314A_{K} + 3.09A_{Ra} + 4.18A_{Th}$$  \hspace{1cm} (9)

### 3.4. Representative level index (RLI)

RLI estimates the level of gamma radiation hazard linked with natural gamma-emitting radionuclides in construction materials. This index was calculated using Equation 10 (Ajayi, 2009; Darwish, Abul-Nasr, & El-Khayatt, 2015; Jallad, 2016; Raghu et al., 2016):

$$\text{RLI} = \left(\frac{A_{K}}{1500Bqkg^{-1}} + \frac{A_{Ra}}{150Bqkg^{-1}} + \frac{A_{Th}}{100Bqkg^{-1}}\right)$$  \hspace{1cm} (10)

### 3.5 Gamma activity index ($I_{\gamma}$) and external hazard index (Hex)

$I_{\gamma}$ and Hex are used to assess excess external gamma radiation from materials as a means of checking their suitability as construction materials. In this work, Hex and $I_{\gamma}$ were estimated using Equations 11 and 12 as proposed by Krieger (1981) and EC (1999), respectively:

$$\text{Hex} = \left(\frac{A_{K}}{4810Bqkg^{-1}} + \frac{A_{Ra}}{185Bqkg^{-1}} + \frac{A_{Th}}{259Bqkg^{-1}}\right)$$  \hspace{1cm} (11)

$$I_{\gamma} = \left(\frac{A_{K}}{3000Bqkg^{-1}} + \frac{A_{Ra}}{300Bqkg^{-1}} + \frac{A_{Th}}{200Bqkg^{-1}}\right)$$  \hspace{1cm} (12)

The limit for Hex is 1, which corresponds to the upper limit of Req (370 Bq kg$^{-1}$) for the safe use of the materials for building construction. While $I_{\gamma}$ ≤ 0.5 is equivalent to an effective dose rate of 0.3 mSv y$^{-1}$, $I_{\gamma}$ ≤ 1 is equivalent to a dose rate of 1 mSv y$^{-1}$. Many countries adopt the upper limit (1 mSv y$^{-1}$) to control the usage of such materials for construction.

### 3.6. Alpha index ($I_{\alpha}$) and internal hazard index ($H_{IN}$)

$I_{\alpha}$ and $H_{IN}$ are used to estimate excess alpha radiation due to inhalation of radon gas and its daughters emitted from materials such as soil or building materials. In this work, Equations 13 and 14 are used to determine $H_{IN}$ and $I_{\alpha}$ respectively (Najam, Majeed, Kheder, & Younis, 2017; Raghu et al., 2016; Raghu, Ravisankar, Chandrasekaran, Vijayagopal, & Venkatraman, 2017; Rautela et al., 2013):

$$\text{Hex} = \left(\frac{A_{K}}{4810Bqkg^{-1}} + \frac{A_{Ra}}{185Bqkg^{-1}} + \frac{A_{Th}}{259Bqkg^{-1}}\right)$$  \hspace{1cm} (13)

$$I_{\alpha} = \frac{A_{Ra}}{200}$$  \hspace{1cm} (14)

The standard limits set for $I_{\alpha}$ and $H_{IN}$ are 0.5 and 1, respectively.

### 3.7. Excess life cancer risk (ELCR)

The chance of developing cancer over a lifetime due to human exposure to ionizing radiation can be calculated using ELCR according to Equations 15, 16, and 17 (Darwish et al., 2015; Issa, 2013; Kaliprasad, Vinutha, & Narayana, 2017; Kolo, Aziz, Khandaker, Asaduzzaman, & Amin, 2015):

$$\text{ELCR}_{\text{Out}} = \text{AED}_{\text{Out}} \times L \times F_{R}$$  \hspace{1cm} (15)

$$\text{ELCR}_{\text{In}} = \text{AED}_{\text{In}} \times L \times F_{R}$$  \hspace{1cm} (16)

$$\text{ELCR}_{\text{TOL}} = \text{AED}_{\text{In}} + \text{AED}_{\text{Out}}$$  \hspace{1cm} (17)

where ELCR$_{\text{out}}$, ELCR$_{\text{in}}$, AED, L, and $F_{R}$ are outdoor excess life cancer risk, indoor excess life cancer risk, annual effective dose (indoor and outdoor), period of life (that is, 70 y), and fatal risk factor per Sievert (0.05 Sv$^{-1}$), respectively. ELCR$_{\text{TOL}}$ is the total excess life cancer.

### 4. Results and discussion

Tables 1 and 2 present the activity concentrations and the statistically analyzed data of the activities of $^{40}$K, $^{226}$Ra, and $^{232}$Th with the associated radiological indices. Table 3 shows the geographical coordinates and the absorbed dose level due to the presence of $^{40}$K, $^{226}$Ra, and $^{232}$Th in the soil samples collected from OLGA of Ondo state Nigeria. In this study, the measured activity concentrations of $^{40}$K, $^{226}$Ra, and $^{232}$Th range from 430.15 ± 4.12 to 2100.42 ± 11.89 Bq kg$^{-1}$ with an average value of 1190.10 ± 373.62 Bq kg$^{-1}$, from 31.58 ± 2.94 to 212.11 ± 13.15 Bq kg$^{-1}$ with an average value of 64.64 ± 28.10 Bq kg$^{-1}$, and from 16.27 ± 7.10 to 203.09 ± 42.64 Bq kg$^{-1}$ with an
average value of 110.18 ± 46.12 Bq kg⁻¹, respectively. Activity concentrations of 400 Bq kg⁻¹, 35 Bq kg⁻¹, and 30 Bq kg⁻¹ were the world average values reported by UNCEAR (2000) for 40K, 226Ra, and 232Th, respectively. It is evident that the activity concentrations of 40K obtained in all the studied samples are greater than the world average value. In addition, about 95% (57) of the total samples examined have activity concentrations of each of 226Ra and 232Th greater than the reported world average.

A comparison of the average values of the activity concentrations in this study (that is, 1190.10 Bq kg⁻¹ for 40K, 64.64 Bq kg⁻¹ for 226Ra, and 110.18 Bq kg⁻¹ for 232Th) with the corresponding average values from the results reported in Nigeria, Egypt, Malaysia, India, Turkey, and Iraq (Ajayi, 2009; Ademola, Bello, & Adejumobi, 2014; El-Gamal, Farid, Abdel Mageed, Hasabelnaby, & Hassanien, 2013; Issa, 2013; Kolo et al., 2015; Mohammed & Ahmed, 2017; Srilatha et al., 2015; Tabar et al., 2017; Zaim & Atlas, 2016) indicates that the values measured in this study are relatively higher. Meanwhile, the reported values in this study are less than the values reported in Cyprus and Turkey (Merdanoglu & Altninsy, 2006; Tzortzis, Svorakis, & Tsertos, 2004). The relatively higher activity concentration recorded in this study could be attributed to the nature of the underlying rocks in this study area.

The study of radiological characteristics of the soil samples using Shapiro-Wilk’s test (p > 0.05) and visual inspection of their histograms (Figure 2) show that the activity concentrations of 40K, 232Th, and Req in the soil samples are approximately normally distributed. The skewness and the corresponding kurtosis of activity concentration distributions of 40K, 232Th, and Req are -0.044 (SE = 0.309), -0.061 (SE = 0.608); 0.258 (SE = 0.311), -558 (SE = 0.613); and 0.214 (SE = 0.309), -0.139 (SE = 0.608), respectively. The concentration of 226Ra is not normally distributed by considering the same test as described above; it is evident that the distribution is positively skewed with a skewness of 2.764 (SE = 0.309) and a kurtosis of 11.959 (SE = 0.608), and it thus follows a lognormal distribution. This is also confirmed as the values of the geometric mean (60.38) and the median (58.58) are almost the same (Tabar et al., 2017). The test was carried out on the radiological indices, and they follow the same trend.

The absorbed dose rates \(D_{\text{nr}}\), \(D_{\text{Out}}\), and \(D_{\text{tot}}\) were calculated using Equations 2–4, respectively, and the summary of the results is presented in Table 2. The results show that the values of \(D_{\text{nr}}\) vary from 110.46 to 441.24 nGy h⁻¹ with an average value of 273.85 nGy h⁻¹. The values of \(D_{\text{Out}}\) range from 56.82 to 230.54 nGy h⁻¹ with an average value of 144.93 nGy h⁻¹. In addition, the values of \(D_{\text{tot}}\) vary from 167.27 to 671.78 nGy h⁻¹ with
an average value of 418.78 nGy h$^{-1}$. The average values of $D_{\text{in}}$, $D_{\text{Out}}$, and $D_{\text{Tot}}$ are higher by factors of 3, 2, and 5 than the world average values recommended by UNSCEAR (2000), respectively. Data presented in Table 3 were used to produce the distributions of the total absorbed ($D_{\text{Tot}}$) dose rates shown in Figure 3. The distribution of the total absorbed dose rate on the map shows that the variations of $D_{\text{Tot}}$ might have been influenced by the geology of the study area because migmatite that dominated the area is a mixture of metamorphic rocks and igneous rocks (such as granite), and there is evidence to prove that areas with higher values of $D_{\text{Tot}}$ as shown in the map have certain traces of granites (Adewumi & Anifowose, 2017).

The results obtained for the annual effective doses ($AED_{\text{Out}}$, $AED_{\text{In}}$, and $AED_{\text{Tot}}$) are summarized in Table 2. The values for $AED_{\text{Out}}$ range from 0.07 to 0.28 mSv with an average value of 0.18 mSv. The values for $AED_{\text{In}}$ range from 0.54 to 2.16 mSv with an average value of 1.34 mSv, and the total average value is 1.52 mSv. The average values of $AED_{\text{Out}}$, $AED_{\text{In}}$, and $AED_{\text{Tot}}$ for this study are higher than the corresponding worldwide average values of $AED_{\text{Out}}$ (0.07 mSv), $AED_{\text{In}}$ (0.41 mSv), and $AED_{\text{Tot}}$ (0.48 mSv) as declared by UNCEAR (2000). However, the total average value of $AED_{\text{Tot}}$ recorded in this work falls within the average worldwide range (1–10 mSv) of doses received from natural radiation sources.

The Req values were estimated due to the presence of $^{40}$K, $^{226}$Ra, and $^{232}$Th in the soil samples. The results of the estimation are summarized in Table 2. Results show that the values calculated are in the range of 111.27–500.66 Bq kg$^{-1}$ with an average value of 311.20 Bq kg$^{-1}$. The average value is observed to be higher than 205.47 Bq kg$^{-1}$ for India, 135 Bq kg$^{-1}$ for Egypt, 126 Bq kg$^{-1}$ for Thailand, 64.14 Bq kg$^{-1}$ for Turkey, and 24.92 Bq kg$^{-1}$ for Malaysia (Issa, 2013; Kolo et al., 2015; Kritsanunuvat et al., 2015; Srilatha et al., 2015; Tabar et al., 2017). However, the average value is less than 370 Bq kg$^{-1}$, the criterion limit suggested by Beretka & Matthew (1985). This implies that the soil from the study area may not pose any significant radiological hazards when used as building materials.

The results of AGDE due to the natural radionuclides in the soil samples are shown in Table 2. A comparison of the average value in this study with the world average shows that it is higher than the world average, 300 µSv y$^{-1}$ (UNSCEAR, 2000). It is found to be higher than the AGDE reported in some literature (Al-Hamarneh & Awadallah, 2009; Chandrasekaran et al., 2014; Isinkaye & Emelue, 2015). On the other hand, the average AGDE recorded in this study is found to be less than the values reported in Egypt (Arafà, 2004; El-Gamal et al., 2013).

The results of the calculated RLI are also presented in Table 2. This index varies from 0.88 to 3.58, with an average value of 2.31 and a deviation of 0.59.
The average value calculated in this study exceeds the recommended limit of 1.0. This was the trend found in the reports of Bangladesh, Nigeria, and India (Chowdhury, Kamal, Alam, Yeasmin, & Mostafa, 2006; Ajayi, 2009; Chandrasekaran et al., 2014).

$I_y$ and Hex determined are presented in Table 2. The values for $I_y$ range between 0.44 and 1.79 with an average value of 1.15, and the Hex values vary between 0.3 and 1.35 with an average value of 0.84. The average value of $I_y$ is greater than the recommended limit (unity) by a factor of 1.15 units. In addition, the average value of Hex is found to be lower than the limit of 1 (unity) (EC (European Commission), 1999; Krieger, 1981). However, the soil from the study area may not pose any significant
hazards due to external gamma radiation to members of the public.

$I_\alpha$ and $H_{IN}$ determined are presented in Table 2 using Equations 13 and 14. The values of $I_\alpha$ range between 0.16 and 1.06 with an average value of 0.32, while the values of $H_{IN}$ vary from 0.42 to 1.93 with an average value of 1.02. The average value of each of the two quantities is not expected to be greater than unity for the safe use of soil as building materials (Beretka & Matthew, 1985; Krieger, 1981) and for the land to be safe for planting and other human activities. While the average value of $I_\alpha$ recorded in this study is less than unity, the average value of $H_{IN}$ is slightly higher than unity; therefore, the soil from the study area may not pose internal radiation hazards due to inhalation of radon gas and its progenies. However, further investigation could be carried out to ascertain the level of activity concentrations of the soil at different depths (> 5cm). The current study is restricted to the topsoil of the study area.

Results of ELCR are presented in Table 2. The values of total ELCR, $ELCR_{Tot}$, calculated from $ELCR_{Out}$ and $ELCR_{In}$ are also shown in Table 2. The values of $ELCR_{Tot}$ vary between $2.14 \times 10^{-3}$ and $8.57 \times 10^{-3}$ with an average value of $5.32 \times 10^{-3}$ and a standard deviation of $1.33 \times 10^{-3}$. The average value is higher than the world average value recommended by UNSCEAR (2000) by a factor of 3.6 units. The relatively higher values of ELCR observed in this work may be due to the high concentrations of the natural radionuclides in the soil samples, which are directly dependent on the geological composition of the study area. The higher values recorded in the current study agree with the earlier study on a commercial water sachet produced and sold in the study area as reported in the work of Aladeniyi and Aladenika (2015).

The higher values of ELCR indicated here call for further investigation regarding the level of ingestion of radionuclides by plants and animals in this geographical location. Apart from water and direct
contact, plants and animals are the paths to human beings through which ingestion of radionuclides can occur.

5. Conclusion

Activity concentrations and radiological hazard indices of the natural radionuclides $^{40}$K, $^{226}$Ra, and $^{232}$Th in the soil samples collected from OLGA, Ondo state, Nigeria, have been assessed. The study became necessary because an earlier radiological study conducted on sachet packaged water produced and used in the study area indicated that the activity concentrations of natural radionuclides in the water samples are higher than the recommended safe level. In addition, the total radiation dose a human being is exposed to is a summation of internal and external radiation exposure. The following are some of the findings in this study.

- Activity concentrations of $^{40}$K, $^{226}$Ra, and $^{232}$Th from the soil samples examined in this study are observed to be higher than the world average values recommended by UNSCEAR (2000). The results also indicate that they are higher than the values recorded in some countries.

- The average values of $D_{\text{inv}}$, $D_{\text{out}}$, and $D_{\text{Tot}}$ for the soil samples are higher than the world average by factors ranging between 2 and 5 units.

- While the average values of some radiological indices such as Req, Hex, and $I_{p}$ fall below the recommended limits, others such as RLI and $I_{p}$ are slightly higher than the recommended safe limits.

- The average values of AGDE and ELCR$_{\text{Tot}}$ calculated in this study are higher than the world average values of 300 $\mu$Sv$^{-1}$ and $1.45 \times 10^{-3}$, respectively.

- The use of soil for building from the study area may not pose any serious radiological hazards to the inhabitants of the area. However, further investigation is required to ascertain the activity concentration of the study area at different depths. It is also important to examine the level of radionuclide ingestion by animals and plants found in the study area.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ademola, A. K., Bello, A. K., & Adejumobi, A. C. (2014). Determination of natural radioactivity and hazard in soil samples in and around gold mining area in Itagumodi, south-western, Nigeria. Journal of Radiation Research and Applied Sciences, 7, 249–255.

Adevuumi, A. J., & Anifowose, Y. B. (2017). Hydrogeologic characterization of Owo and its environs using remote sensing and GIS. Applied Water Science, 7, 2987–3000.

Ajayi, O. S. (2009). Measurement of activity concentrations of $^{40}$K, $^{226}$Ra and $^{232}$Th for assessment of radiation hazards from soils of the southwestern region of Nigeria. Radiation and Environmental Biophysics, 48, 323–332.

Aladeniyi, K., & Aladenika, A. K. (2015). Radiological study of sachet-packaged water: A case study of the products in Owo local government area of Ondo State, Nigeria. Journal of Radiological Protection, 35, N19.

Al-Hamarneh, I. F., & Awadallah, M. I. (2009). Soil radioactivity levels and radiation hazard assessment in the highlands of northern Jordan. Radiation Measurements, 44, 102–110.

Arafa, W. (2004). Specific activity and hazards of granite samples collected from the Eastern Desert of Egypt. Journal of Environmental Radioactivity, 75, 315–327.

Beretka, J., & Matthew, P. J. (1985). Natural radioactivity of Australian building materials, industrial wastes, and by-products. Health Physics, 48, 87–95.

Cember, H., & Johnson, T. E. (2012). Introduction to health physics. Health Physics, 102. doi:10.1097/01.HP.0000410056.48665.1F

Chandrasekaran, A., Ravisankar, R., Senthilkumar, G., Thillaivelavan, K., Dhinakaran, B., Vijayagopal, P., … Venkatraman, B. (2014). Spatial distribution and lifetime cancer risk due to gamma radioactivity in Yelagiri Hills, Tamilnadu, India. Egyptian Journal of Basic and Applied Sciences, 1, 38–48.

Chinnasaikki, S., Chopra, M., Kumar, S., Arora, V., Sartandel, S. J., Bara, S. V., … Bajwa, B. S. (2011). Assessment of natural radioactivity in soil samples and comparison of the direct and indirect measurement of environmental air kerma rate. Journal of Radioanalytical and Nuclear Chemistry, 289, 885–892.

Chowdhury, M. I., Kamal, M., Alam, M. N., Yeasmin, S., & Mostafa, M. N. (2006). Distribution of naturally occurring radionuclides in soils of the southern districts of Bangladesh. Radiation Protection Dosimetry, 118, 126–130.

Darwish, D. A. E., Abul-Nasr, K. T. M., & El-Khayatt, A. M. (2015). The assessment of natural radioactivity and its associated radiological hazards and dose parameters in granite samples from South Sinai, Egypt. Journal of Radiation Research and Applied Sciences, 8, 17–25.

EC (European Commission). (1999). Radiological protection principles concerning the natural radioactivity of building materials. Radiation Protection 112, Directorate General Environment. Luxembourg: Nuclear Safety and Civil Protection.

El-Gamal, H., Farid, M. E. A., Abdel Mageed, A. I., Hasabelnaby, M., & Hassanien, H. M. (2013). Assessment of natural radioactivity levels in soil samples from some areas in Assiut, Egypt. Environmental Science and Pollution Research, 20, 8700–8708.

Isinkaye, M. O., & Emelue, H. U. (2015). Natural radioactivity measurements and evaluation of radiological hazards in the sediment of Oguta Lake, South East Nigeria. Journal of Radiation Research and Applied Sciences, 8, 459–469.

Issa, S. A. M. (2013). Radiometric assessment of natural radioactivity levels of agricultural soil samples collected in Dakahlia, Egypt. Radiation Protection Dosimetry, 156, 59–67.

Jallad, K. N. (2016). Radiation hazard indices and excess lifetime cancer risk in sand from the northern and eastern regions of Kuwait. Environmental Earth Sciences, 75, 1–10.

Kaliprasad, C., Vinutha, P., & Narayana, Y. (2017). Natural radionuclides and radon exhalation rate in the soils of Cauvery River Basin. Air, Soil and Water Research, 10, 117862211774694.
Kaul, A., Becker, D., Brix, G., Dalheimer, A., Dietze, A., Doerfel, H. R., … Weiss, W. (2005). Group VIII : Advanced materials and technology - Radiological protection. (A. Kaul & D. Becker, Eds.). Berlin: Springer-Verlag.

Kolo, M. T., Aziz, S. A. B. A., Khandaker, M. U., Asaduzzaman, K., & Amin, Y. M. (2015). Evaluation of radiological risks due to natural radioactivity around lynes advanced material plant environment, Kuantan, Pahang, Malaysia. *Environmental Science and Pollution Research*, 22, 13127–13136.

Krieger, V. R. (1981). Radioactivity of construction materials. *Betonwerk Fertigteile Techn.*, 47, 468–473.

Kritsanawat, R., Arae, H., Fukushima, M., Sahoo, S. K., & Chanyotha, S. (2015). Natural radioactivity survey on soils originated from southern part of Thailand as potential sites for nuclear power plants from the radiological viewpoint and risk assessment. *Journal of Radioanalytical and Nuclear Chemistry*, 305, 487–499.

Kumar, A., Vij, R., Sharma, S., Sarin, A., & Narang, S. (2018). Assessment of radionuclide concentration and exhalation studies in the soil of lesser Himalayas of Jammu and Kashmir, India. *Acta Geophysica*, 66, 1–8.

Mann, N., Kumar, A., Kumar, S., & Chauhan, R. P. (2017). Measurement of radium, thorium, potassium and associated hazard indices from the soil samples collected from Northern India. *Indoor and Built Environment*, 27, 1420326 × 1769613.

Merdanoglu, B., & Altinsoy, N. (2006). Radioactivity concentrations and dose assessment for soil samples from Kestanbol granite area, Turkey. *Radiation Protection Dosimetry*, 121, 399–405.

Mohammed, R. S., & Ahmed, R. S. (2017). Estimation of excess lifetime cancer risk and radiation hazard indices in southern Iraq. *Environmental Earth Sciences*, 76. doi:10.1007/s12665-017-6616-7

Najam, L. A., Majeed, F. A., Kheder, M. H., & Younis, S. A. (2017). Estimation of the Radiological Hazard Effects for Soil Samples of Nineveh Province. *International Journal of Physics*, 5, 33–56. doi:10.12691/ijp-5-2-4

Oyeyemi, K. D., Usikalu, M. R., Aizebeokhai, A. P., Achuka, J. A., & Jonathan, O. (2017). Measurements of radioactivity levels in part of Ota Southwestern Nigeria: Implications for radiological hazards indices and excess lifetime cancer-risks. *Journal of Physics: Conference Series*, 852. doi:10.1088/1742-6596/852/1/012042

Qureshi, A. A., Tariq, S., Din, K. U., Manzoor, S., Calligaris, C., & Waheed, A. (2014). Evaluation of excess lifetime cancer risk due to natural radioactivity in the river's sediments of Northern Pakistan. *Journal of Radiation Research and Applied Sciences*, 7, 438–447.

Raghu, Y., Ravisankar, R., Chandrasekaran, A., Vijayagopal, P., & Venkatraman, B. (2016). Assessment of natural radioactivity and radiological hazards in brick samples used in Tiruvannamalai District, Tamilnadu, India, with a statistical approach. *Health Physics*, 111, 265–280.

Raghu, Y., Ravisankar, R., Chandrasekaran, A., Vijayagopal, P., & Venkatraman, B. (2017). Assessment of natural radioactivity and radiological hazards in building materials used in the Tiruvannamalai District, Tamilnadu, India, using a statistical approach. *Journal of Taibah University for Science*, 11, 523–533.

Rautela, B. S., Gusain, G. S., Yadav, M., Sahoo, S. K., Tokonami, S., & Ramola, R. C. (2013). Natural radionuclide analysis in Chhattarpur area of southeastern coastal area of Odisha, India. *Acta Geophysica*, 61, 1038–1045.

Sahin, L., & Cavas, M. (2008). Natural radioactivity measurements in soil samples of central Kutahya (Turkey). *Radiation Protection Dosimetry*, 131, 526–530.

Sivakumar, R. (2014). An assessment of natural radioactivity levels and radiation hazards in the soil of Coonoor, South India. *Environmental Earth Sciences*, 72, 5063–5071.

Srilatha, M. C., Rangaswamy, D. R., & Sannappa, J. (2015). Measurement of natural radioactivity and radiation hazard assessment in the soil samples of Ramanagara and Tumkur districts, Karnataka, India. *Journal of Radioanalytical and Nuclear Chemistry*, 303, 993–1003.

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.

Tzortzis, M., Svoukis, E., & Tsertos, H. (2004). A comprehensive study of natural gamma radioactivity levels and associated dose rates from surface soils in Cyprus. *Radiation Protection Dosimetry*, 109, 217–224.

UNSCEAR. (2000). *Sources and effects of ionizing radiation, United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 2000 report to the general assembly, with scientific annexes* (UNSCEAR 2000 Report, Vol. I). New York, NY. doi:10.1097/00004032-199907000-00007

Zaim, N., & Atlas, H. (2016). Assessment of radioactivity levels and radiation hazards using gamma spectrometry in soil samples of Edirne, Turkey. *Journal of Radioanalytical and Nuclear Chemistry*, 310, 959–967.