Original Research Article

Assessment of Natural Radioactivity and Associated Dose Rates in Surface Soils around Oluwa Glass Industry Environments, Igbokoda, Ondo State, Southwestern Nigeria.

ABSTRACT

Assessment of natural radioactivity of surface soils in Oluwa Glass industry environment of Igbokoda, Ondo state, Nigeria was carried out by means of well-calibrated NaI(TI) that is well shielded with a detector coupled to a computer resident quantum MCA2100R multichannel analyzer with an aim to measure the concentrations of ^{40}K,^{238}U and ^{232}Th radionuclides in the soil samples as well as to estimate the absorbed dose rate, annual effective dose and excess lifetime cancer risk in the study area.

The activity concentrations in the soil samples ranged from 153.74 to 228.13 Bq kg^{-1} with a mean value of 194.69± 17.40 Bq kg^{-1} for ^{40}K, from 9.40 to 14.07 Bq kg^{-1} with a mean of 11.49 ±2.10 Bq kg^{-1} for ^{238}U and from 8.42 to 12.08 Bq kg^{-1} with a mean value of 9.94 ± 1.05 for ^{232}Th respectively. The mean absorbed dose rate was 19.73 ± 18.43 $nGyh^{-1}$, the annual effective dose was 24.20 ± 8.31 μSvy^{-1} and the excess lifetime cancer risk was 0.085. The activity concentration of ^{40}K reported in the present study is higher than the value of 58.69 Bq kg^{-1} for ^{40}K reported for soil samples collected from parts of Sagamu, Southwestern, Nigeria. The mean absorbed dose rate, mean annual effective dose and mean excess lifetime cancer risk reported in this present study were lower than the world average values of 54.00 $nGyh^{-1}$, 66.00 μSvy^{-1} and 0.29 respectively. Thus, the results obtained showed that the study area is free from radiological contamination.

Keywords: Radioactivity, Absorbed Dose Rate, Annual Effective Dose, Excess Lifetime Cancer Risk, Igbokoda, Nigeria.

1.0 Introduction

All living creatures have been and are still being, exposed to various degrees of radiation. Nonetheless, most people are not aware of all the natural and man-made sources of radiation in our environment. The natural sources of radiation have been present since the earth was formed. In the last century, we have added to this natural background radiation some artificial sources **[1]**. Radioactivity and its sources have been part and parcel of everyday life from time immemorial. However, radiation exposure to a large population with dose about 1.5 Sv increases cancer incidence and mortality **[2].** These radiations are from either natural or artificial sources. Naturally occurring radioactive materials (NORMs) such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are generally the

terrestrial background radiations which are the main external sources of irradiation to the human body **[2].** However, humankind can be exposed to radiation originating from artificially radioactive sources such as cesium (^{137}Cs) present in the earth's environment as a result of nuclear weapon testing or nuclear fallout from nuclear wastes **[2].** Radionuclides that are ingested through consumption of food and water or as inhaled radioactive gases (internal exposure) are also sources of irradiation.

Oluwa Glass Industry located at Igbokoda area of Ondo State is a typical example of the United Nation Nuclear Regulatory Commission identified problem cited above [1]. Oluwa Glass Industry is owned by the Ondo State Government and has been temporarily shut down due to financial mismanagement. Glass production involves the extensive usage of ionizing radiation and as such there may be improper handling of gauge sources, spillage and release of radioactive materials from pressurized system, unauthorized disposal of waste, emergency and natural disasters, fire, explosion and transportation accidents are some of the potential contamination channels that can lead to extremely large internal or external radiation doses to the exposed individual of the public. Of recent, the study area and its environs are basically used for farming, since the abandonment of glass productions. Therefore, it is necessary to measure the activity concentrations of the natural radionuclides in the soil samples around the abandoned Oluwa Glass Industry so as to estimate the radioactivity levels exposed to humans, plants and other organisms in the study area and also estimate the absorbed dose rate, annual effective dose in the soil samples and evaluate the health-cancer risk according to International Commission for Radiological Protection (ICRP) standard (dose equivalent in Sv/year).

2.0 Materials and Methods

2.1 Geographical description of the study area

Igbokoda is the headquarter of Ilaje Local Government Area of Ondo State, Southwestern Nigeria. It has geographical coordinates of $6^0 21' 0''$ North and $4^0 48' 0''$ East, it has an area of 1,318 km^2 and a population of 290, 615 **[3]**. There are several raw materials found in the area which include petroleum, glass sand, salt, Bitumen, Cassava, Banana, etc. The occupational activities of the majority include fishing, farming and trading **[3]**. The study area belongs to the geological land scale of Benin formation which consists of continental gravels, sands, subordinate silt and clay lenses and the land masses are also less than 15 metres above sea level which makes absorption of radioactive materials from the abandoned industry site easier to the water table of the area **[1]**. Oluwa-glass Industry is an abandoned glass industry with a growing population residing around and carrying out daily farming activities within the abandoned industrial environments.

Fig. 1: Showing the study area (Oluwa Glass Industry in Igbokoda, Ondo State, Nigeria)

2.2 Samples collection

A total of 20 soil samples were collected for the present study and these points of the collection were marked out using a Global Positioning System (GPS) device. Soil samples were collected from depths of 5 cm at different locations within the sample site. At the collection point, all samples were wrapped in separate black plastic bags and were well labelled with a paper marking tape. The samples were then transported to the laboratory for preparation.

Below is the GPS representation of locations of the samples.

Table 1: Samples location mapped out by GPS

Soil Samples	GPS (Location)
S1	N 06^0 23′ 37.7′ ′ , E 004^0 46′ 23.6′ ′
S2	N 06^0 23′ 37.8′ ′ , E 004^0 46′ 23.4′ ′
S3	N 06^0 23′ 37.9′ ′ , E 004^0 46′ 23.2′ ′
S4	N 06^0 23′ 37.8′ ′ , E 004^0 46′ 23.0′ ′
S5	N 06^0 23′ 38.0′ ′ , E 004^0 46′ 22.8′ ′
S6	N 06^0 23′ 38.1′ ′ , E 004^0 46′ 22.5′ ′
S7	N 06^0 23′ 38.2′ ′ , E 004^0 46′ 22.3′ ′
S8	N 06^0 23′ 38.2′ ′ , E 004^0 46′ 22.0′ ′
S9	N 06^0 23′ 38.4′ ′ , E 004^0 46′ 21.7′ ′

S10	N 06^0 23′ 38.6′ ′ , E 004^0 46′ 21.3′ ′
S11	N 06^0 23′ 35.4′ ′ , E 004^0 46′ 20.4′ ′
S12	N 06^0 23′ 35.6′ ′ , E 004^0 46′ 20.1′ ′
S13	N 06^0 23′ 35.9′ ′ , E 004^0 46′ 20.8′ ′
S14	N 06^0 23′ 35.1′ ′ , E 004^0 46′ 20.3′ ′
S15	N 06^0 23′ 35.3′ ′ , E 004^0 46′ 20.7′ ′
S16	N 06^0 23′ 32.6′ ′ , E 004^0 46′ 21.2′ ′
S17	N 06^0 23′ 32.4′ ′ , E 004^0 46′ 21.6′ ′
S18	N 06^0 23′ 32.8′ ′ , E 004^0 46′ 21.4′ ′
S19	N 06^0 23′ 32.9′ ′ , E 004^0 46′ 21.5′ ′
S20	N 06^0 23′ 33.5′ ′ , E 004^0 46′ 21.7′ ′

2.3 Samples preparation

Soil samples were well mixed after removing extraneous materials such as roots, pieces of stones and gravels. Samples were then weighed, dried and transferred into an electric oven at 110^{0}C for 4 days until a constant dry weight was obtained. The dried samples were then crushed using mortar and pestle, after crushing and mixing thoroughly, soil samples were shaken in a sieve shaker using the 2-mm mesh size. The samples were later scaled in 200 g each in a radon tight container for a minimum of 28 days so as to reach secular equilibrium between radon and its daughter nuclides before radiometric counting **[4]**.

2.4 Activity concentrations

The activity concentrations of the soil samples were measured using a well calibrated NaI(TI) and well-shielded detector coupled to a computer resident quantum MCA2100R multichannel analyzer for 36,000 s. An empty container under identical geometry was also counted for the same time. The 1460 KeV gamma-radiation of ^{40}K was used to determine the concentration of ^{40}K in the sample. The gamma transition energy of 1764.5 KeV ^{214}Bi was used to determine the concentration of ^{238}U, while the gamma transition energy of 2614 KeV ^{208}TI was used to determine the concentration of ^{232}Th while ^{137}Cs was detected by its 661.6 KeV gamma transition. The activity concentrations in the samples may be determined using equation (1) [5].

$$C_s = \frac{C_\alpha}{P_\gamma(\frac{M_s}{V_s})\varepsilon_\gamma t_c}\ (BqKg^{-1}) \qquad (1)$$

Where C_s is the sample concentration, C_α is the net peak energy, ε_γ is the efficiency of the detector for a γ-energy of interest, M_s/V_s is the sample mass per volume of soil, t_c is the total counting time and P_γ is abundance of the γ-line in a radionuclide.

The efficiency calibration of the detector was done using a reference standard mixed source traceable to Analytical Quality Control Service (AQCS, USA), which has certified activities of the selected radionuclide and has a geometrical configuration identical to sample container. The standard reference sample from the International Atomic Energy Agency (IAEA) traceable to source Ref No. IAEA-152 were used for efficiency calibration of the detector used in the study. The standard sources contained ten known radionuclides. The energy

calibration was also performed by using the peaks of the radionuclide present in the standard sources. The channel number is proportional to energy; the channel scale was then converted to an energy scale. This produces an energy calibration curve, i.e., energy versus channel. The measurements were carried out at the Radiation Measurement Laboratory of Ladoke Akintola University of Technology, Ogbomosho, Osun State, Nigeria in October 2017.

The estimated absorbed dose rate (D) in $\mathrm{nGyh^{-1}}$ due to the radionuclide concentration was done according to the equation **[6]**:

$$\mathrm{D} = 0.042\mathrm{S_K} + 0.429\mathrm{S_U} + 0.666\mathrm{S_{Th}} \quad (2)$$

Where D is the estimated absorbed dose rate in $nGyh^{-1}$ due to the specific radionuclide concentration. S_K, S_{Th} and S_U are for ^{40}K, ^{232}Th and ^{238}U respectively in $Bqkg^{-1}$ at 1 m above the ground.

The annual effective dose H_E (μSvy^{-1}) received by a member of the public at the study area was calculated using equation **[2]**:

$$\mathrm{H_E(\mu Svy^{-1})} = \mathrm{D(nGyh^{-1})XO_cXF_cX8760X10^{-3}} \quad (3)$$

Where O_c is the outdoor occupancy factor taken as 0.2 and F_c is taken as 0.7, which is the coefficient of conversion used in translating the absorbed dose rate to effective dose incurred by adult **[1]**. Eight thousand seven hundred and sixty hours per year was used and the factor converting nano (10^{-9}) to milli (10^{-3}).

The Excess Lifetime cancer risk (E_L) was estimated using the following equation **[7]**:

$$\mathrm{E_L} = \mathrm{H_E(\mu Svy^{-1})XD_LXR_F(Sy^{-1})} \quad (4)$$

Where D_L is the average duration of life (estimated to be 70 years) and R_F is the Risk Factor taken as 0.05 for the general public. This calculation of E_L helps to project carcinogenic effects that are characterized by estimating the probability of individuals for a specific lifetime from projected intakes and exposures to naturally occurring radionuclides in a study area **[8]**.

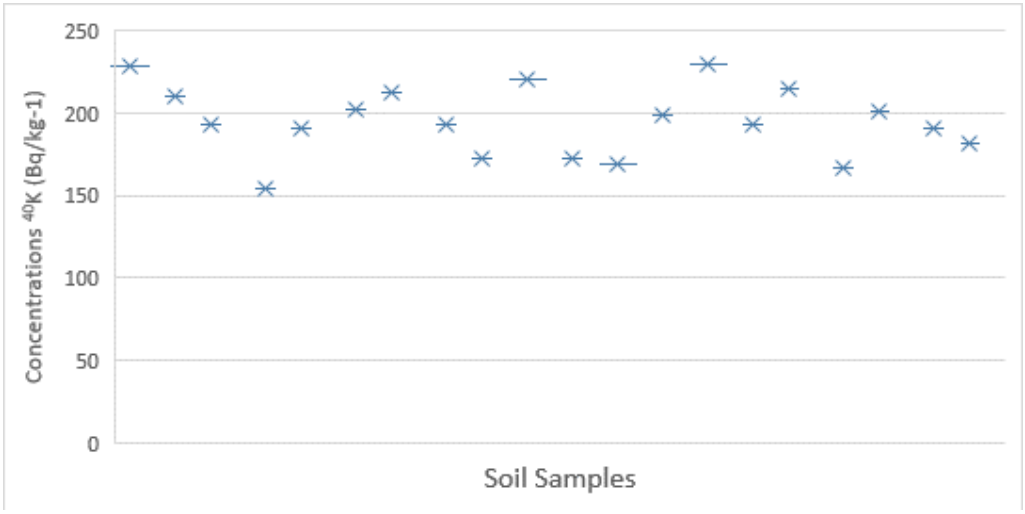
3.0 Results and discussions

The activity concentrations of natural radionuclides (^{40}K, ^{238}U and ^{232}Th) in soil samples collected from the present study area are shown in Table 2. The activity concentrations of ^{40}K range from 153.74 to 228.13 Bq kg^{-1} with a mean value of 194.69±17.40 Bq kg^{-1}; the activity concentrations of ^{238}U range from 9.40 – 14.07 Bq kg^{-1} with a mean value of 11.49±2.10 Bq kg^{-1} and the activity concentrations of ^{232}Th range from 8.42 – 12.08 Bq kg^{-1} with a mean value of 9.94±1.05 Bq kg^{-1}. The activity concentrations of ^{40}K were higher than the values for ^{232}Th and ^{238}U in the study. The values reported were lower than the world average values of 410.0 Bq kg^{-1} for ^{40}K, 25.0 Bq kg^{-1} for ^{238}U and 28.0 Bq kg^{-1} for ^{232}Th **[2]**. The mean values reported were also lower than the mean values of 12 – 31 Bq kg^{-1} for ^{238}U, 14 – 36 $Bqkg^{-1}$ for ^{232}Th and 267 - 867 Bq kg^{-1} for ^{40}K reported for Tehran-Iran **[10]**. The values reported were also lower than the values of 470.4 Bq kg^{-1} for ^{40}K, 48.8 $Bqkg^{-1}$ for ^{238}U and 6.9 $Bqkg^{-1}$ for ^{232}Th respectively reported for surface soils of Ondo city, Ondo State, Nigeria **[9]**. The average activity concentrations of ^{40}K reported in the present study is higher

than the value of 58.69 Bqkg^{-1} for ^{40}K reported for Soil Samples Collected from Parts of Sagamu, Southwestern, Nigeria **[11]**.

Table 2: Activity concentrations of radionuclides in soil from the study area

Soil Samples	^{40}K (Bqkg^{-1})	^{238}U (Bqkg^{-1})	^{232}Th (Bqkg^{-1})
S1	228.13±14.18	11.43±5.40	10.03±3.56
S2	210.66±12.30	11.34±4.50	11.06±1.60
S3	193.18±24.01	11.25±2.11	12.08.91
S4	153.74±13.80	9.40±3.56	8.86±0.43
S5	191.18±14.50	12.25±2.71	10.08±0.89
S6	201.67±18.20	12.22±4.50	10.11±1.05
S7	212.16±20.30	12.19±1.74	10.13±2.33
S8	192.53±15.40	10.86±1.09	9.28±1.72
S9	172.90±13.20	9.52±0.98	8.42±1.50
S10	220.09±22.40	11.61±3.70	10.93±0.93
S11	172.38±21.50	12.03±2.50	10.75±1.56
S12	168.52±19.60	10.63±4.01	8.99±1.98
S13	198.37±20.45	11.35±1.55	9.03±1.04
S14	229.71±16.92	14.07±3.82	10.69±0.79
S15	193.39±20.40	12.19±4.13	9.09±2.13
S16	215.10±15.51	13.97±2.90	10.22±1.34
S17	166.46±23.20	10.28±0.85	8.61±0.88
S18	201.04±17.50	11.73±1.08	11.31±1.02
S19	191.24±21.24	11.08±1.36	10.17±2.20
S20	181.43±18.50	10.43±1.62	9.03±0.57
Range	153.74 – 228.13	9.40 – 14.07	8.42 – 12.08
Mean	194.69±17.40	11.49±2.10	9.94±1.05



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165 Fig. 2: Distribution of ^{40}K in the soil samples from the study area

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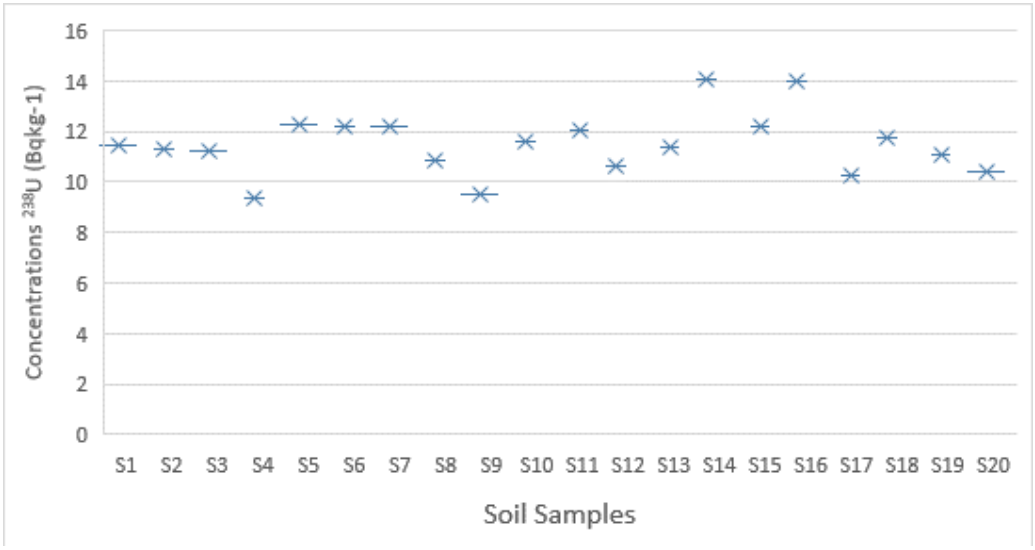

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168 Fig. 3: Distribution of ^{238}U in the soil samples from the study area

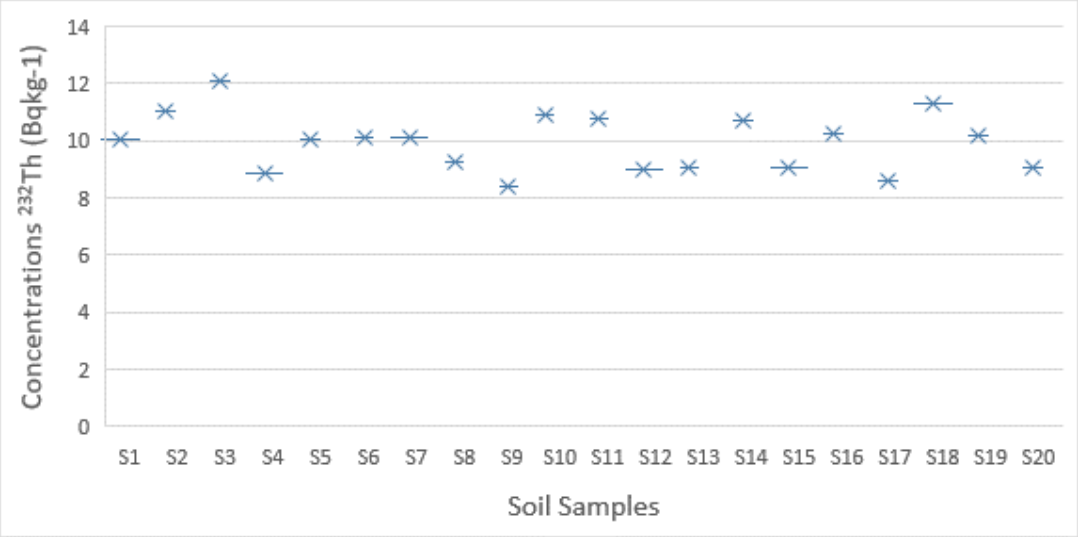

Fig. 4: Distribution of ^{232}Th in the soil samples from the study area

The estimated absorbed dose rate due to the terrestrial gamma rays at 1 m above the ground are shown in Table 3. The range of 16.39 to 22.80 $\mathrm{nGyh^{-1}}$ with an average value of 19.73 $\mathrm{nGyh^{-1}}$ were reported which is lower than 59 $\mathrm{nGyh^{-1}}$, the world average **[2]**. The value reported for this present study is also lower than the value of 45.36 $nGyh^{-1}$ reported for surface soils in Ondo City, Ondo State, Nigeria **[9]**. The estimated absorbed doses rate in the present study were higher in some locations reported for Bethlehem Province, West Bank, Palestine **[12]**.

The annual effective dose equivalent (H_E) received by individuals was calculated to estimate the dose received by a member of the public in the study area as shown in Table 3. The range of 20.10 – 27.97 $\mu\mathrm{Svy^{-1}}$ with a mean value of 24.20 $\mu\mathrm{Svy^{-1}}$ was calculated. The mean value reported is lower than the mean value of 42.07 $\mu\mathrm{Svy^{-1}}$ reported for Sagamu, Southwestern Nigeria **[11]**. The value represents 36.54% of the average value of 54 $\mu\mathrm{Svy^{-1}}$.

The Excess Lifetime cancer risk (E_L) was estimated as shown in Table 3. This is to project carcinogenic effects that are characterized by estimating the probability of individuals for a specific lifetime from projected intakes and exposures to naturally occurring radionuclides in a study area **[8]**. The values reported range from 0.070 – 0.098 with a mean value of 0.085. The value reported for this study is lower than the value reported for Sagamu, Southwestern Nigeria, and is also lower than the value of 0.29 **[2]**. The excess lifetime cancer risk was lower than that reported for Palestine **[12]**. The distribution of radionuclides from the study area were shown in Figures 2 – 4.

Table 3: Absorbed dose rate (D), annual effective dose (H_E) and excess life-time cancer risk from the study area

Soil Samples	D ($nGyh^{-1}$)	H_E (μSvy^{-1})	E_L
S1	21.16±10.21	25.96±09.35	0.091
S2	21.08±18.06	25.85±06.13	0.090

S3	20.99±16.22	25.74±07.33	0.090
S4	16.39±14.04	20.10±10.70	0.070
S5	20.00±12.82	24.53±11.39	0.086
S6	20.44±17.99	25.07±09.18	0.088
S7	20.89±11.08	25.62±11.16	0.090
S8	18.92±15.50	23.21±10.81	0.081
S9	16.96±18.62	20.80±07.29	0.073
S10	21.50±15.21	26.37±06.92	0.092
S11	19.56±21.80	23.99±12.45	0.084
S12	17.63±19.37	21.62±08.42	0.076
S13	19.21±20.97	23.56±13.91	0.082
S14	22.80±18.50	27.97±11.84	0.098
S15	19.41±24.78	23.80±10.21	0.083
S16	21.83±11.83	26.78±08.71	0.094
S17	17.14±12.63	21.02±11.42	0.074
S18	21.01±23.56	25.76±11.27	0.090
S19	19.56±13.96	23.99±10.40	0.084
S20	18.11±18.07	22.21±12.74	0.078
Range	16.39 - 22.80	19.96 – 22.80	0.070 – 0.098
Mean	19.73±18.43	24.20±11.40	0.09
UNSCEAR (2000)	54.00	66.00	0.29

The average values of radionuclides from the present study area were compared with the recommended World average values by UNSCEAR (2000) and the values reported for Ondo City, Ondo State, Nigeria (2016) as shown in Table (4) below:

S/N		^{40}K (BqKg^{-1})	^{238}U (BqKg^{-1})	^{232}Th (BqKg^{-1})
1	World Average (UNSCEAR, 2000)	410.0	25.0	28.0
2	Ondo City, Ondo State, Nigeria (2016)	470.4	48.4	6.9
3	Present Study	194.69	11.49	9.94

4.0 Conclusion

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th in the soil samples collected at various locations of Oluwa Glass Industry area, Igbokoda, Ondo State Southwestern Nigeria were measured using a well calibrated NaI(TI) and well shielded detector coupled to a computer resident quantum multichannel analyzer. The activity concentrations of ^{40}K were higher than the values for ^{232}Th and ^{238}U in the study, which shows that ^{40}K contributes mostly to the presence of natural radionuclides at the study area. The activity concentrations of ^{40}K reported in the present study is higher than the value of 58.69 Bqkg^{-1} for ^{40}K reported for Soil Samples Collected from some parts of Sagamu, Southwestern, Nigeria. The activities of natural radionuclides reported in this present study were lower than the world average

values. The mean activity concentration values reported were also lower than the mean values reported for Tehran-Iran. The values reported were also lower than the values reported for surface soils of Ondo city, Ondo State, Nigeria. This lower values reported may be attributed to the non-operation of the glass industry close to two decades ago and the geological land scale of the area which is of Benin formation consisting continental gravels, sands, subordinate silt and clay lenses, the land are also less than 15 metres above sea level which makes absorption of radioactive materials from the abandoned industry site easier to the water table of the area **[13]**.

The estimated absorbed dose rate due to the terrestrial gamma rays at 1 m above the ground reported is lower than the world average and is also lower than the value reported for surface soils in Ondo City, Ondo State, Nigeria. The estimated absorbed dose rate in the present study were higher in some locations reported for Bethlehem Province, West Bank, Palestine. The annual effective dose equivalent (H_E) and Excess Lifetime cancer risk (E_L) reported for the present study area were lower than the value*s* reported for Sagamu, Southwestern Nigeria and also lower than the world average value. Therefore, the results obtained showed that the study area may be free from radiological contamination. Our deduction, finally is that most of the naturally occurring radioactive nuclei have already decayed to stable nuclei (safe level) as at the time of carrying out this study.

5.0 Recommendation

There is need to extend this study to cover the entire Igbokoda. This is due to variations of human activities along the riverine area of the study area. Also, different types of crops (such as roots and tubers, fruits, legumes, vegetables and cereals) and weeds grown in the area of study should be collected and analyzed, the water of the study area should also be studied for the presence of radioactive elements. There is also need to enforce existing public health law, to safeguard the lives of the inhabitants and aquatic lives.

6.0 References

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APPENDICES

APPENDIX A

When an unstable nucleus (^{40}K, ^{238}U, or ^{232}Th) in the soil decays, it does so by several routes, or by a sequence of decays via a line of daughter products.

Single decays:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He \quad \text{(A1)}$$

$$^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + \beta^{-} + \overline{\nu} \quad \text{(A2)}$$

$$^{A}_{Z}X \rightarrow {}_{Z-1}{}^{A}Y + \beta^{+} + \overline{\nu} \quad \text{(A3)}$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z}Y + \gamma \quad \text{(A4)}$$

In reaction (A4), the electron emission is due to an Auger process or an internal conversion.

Most single radioactive decays have branching ratios out of every *N* decays. The probability for a decay per unit time is a constant and is denoted by λ. λ is a property of the ^{40}K, ^{238}U, or ^{232}Th nuclei and is independent of the soil environment considered at Igbokoda, Ondo State, Nigeria.

For *N(t)* nuclei in the soil at the chosen Igbokoda site at time *t*, the number which decay in time *t* is:

$$\frac{dN(t)}{dt} = -\lambda N(t) = \frac{-1}{\tau} N(t), \quad \text{(A5)}$$

Where $\tau = \left({}^{1}/_{\lambda}\right)$ is the lifetime of the nucleus. Hence, we have:

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{-{}^{t}/_{\tau}}, \quad \text{(A6)}$$

Where N_0 is the number of nuclei at time *t* = 0.

Half-life $\left(T_{\frac{1}{2}}\right)$ of a radioactive nucleus at any time *t* is the time required for half of the nuclei present at that time *t* to decay or disintegrate.

$$N = \frac{1}{2} N_0 = N_0 e^{-\lambda T_{\frac{1}{2}}} \quad \text{(A7)}$$

$$ln\left(\frac{1}{2}\right) = -\lambda T_{\frac{1}{2}} \quad \text{(A8)}$$

$$T_{\frac{1}{2}} = {}^{0.693}/_{\lambda} = 0.693\ \tau\ (s) \quad \text{(A9)}$$

The strength or activity *C(t)* of a radioactive element in the soil samples collected is the number of decays that occur per second. That is,

$$C(t) = \frac{-dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t} \quad \text{(A10)}$$

SI units of *C(t)* are:

(i) $Curie = Ci = 3.7\ X\ 10^{10}\ decays/s$

(ii) $Becquerel = Bq =$ 1 decay/s.

Parallel decay paths:

If alternate modes of decay exist, each with decay constant λ_i, then the total number of active nuclei *N(t)* decreases as ${}^{dN}/_{dt} = -(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \cdots)$. The total activity thus has a half-life expressed as:

$$T_{\frac{1}{2}} = {}^{0.693}/_{(\sum \lambda_i)}$$

$$= {}^{0.693}\Big/_{\left(\sum \frac{1}{\tau_i}\right)} \quad \text{(A11)}$$

Sequential decay paths:

If the decay (daughter) products are radio-active, they can also decay to give intermediate concentrations of products N_A, N_B, N_C, ---- . That is,

A $\underset{\lambda_A}{\rightarrow}$B $\underset{\lambda_B}{\rightarrow}$ C → ------ etc.

$$\frac{dN_A(t)}{dt} = -\lambda_A N_A(t)$$ (A12)

$$\frac{dN_B(t)}{dt} = \lambda_A N_A(t) - \lambda_B N_B(t)$$ (A13)

From equations (A12) and (A13), we get:

$$N_A(t) = N_A(t=0)e^{-\lambda_A t}$$

$$\frac{dN_B(t)}{dt} = \lambda_A N_A(t=0) - \lambda_B N_B(t)\, e^{-\lambda_A t} - \lambda_B N_B(t)$$ (A14)

On solving equation (A14), we get:

$$N_B(t) = N_A(t)\left(ae^{-\lambda_A t} + be^{-\lambda_B t}\right),$$ (A15)

Where *a* and *b* are constants.

$$N_B(t) = \frac{\lambda_A N_A(t=0)}{(\lambda_B - \lambda_A)}\left[e^{-\lambda_A t} - e^{-\lambda_B t}\right] + N_B(t=0)\, e^{-\lambda_B t}$$ (A16)

The activity $C_B(t)$ of daughter nucleus *B* of ^{40}K, ^{238}U, or ^{232}Th for any value of initial concentration $N_B(t=0)$ is found to be:

$$C_B(t) = \frac{\lambda_A \lambda_B N_A(t=0)}{(\lambda_B - \lambda_A)}\left[e^{-\lambda_A t} - e^{-\lambda_B t}\right] + \lambda_B N_B(t=0)\, e^{-\lambda_B t}$$ (A17)

Gamma (γ) ray decay:

An excited nucleus of ^{40}K, ^{238}U, or ^{232}Th decays through the emission of electromagnetic radiation (or photons) of specific energies (E>40 KeV). The energy of the γ rays reflect specific nuclear states or reactions. γ-emission often occurs after β-decay.

Characteristics of X-ray emission:

Interactions between the electronic energy levels of an atom and an excited nucleus produce X-rays/photons in the energy range of 10 – 50 KeV. In general, the transitions are characteristics of the product nucleus/atom.

Neutron emission:

Nuclei that produce neutrons after reactions have very short lifetimes ($\backsim 10^{-22}$s), hence, stable radioisotopes are not available as neutron sources. See the following neutrons-producing nuclear reactions:

$$^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

$$^{226}_{88}Ra + {}^{9}_{4}Be \rightarrow {}^{234}_{92}U + {}^{1}_{0}n$$

$$^{241}_{95}Am + {}^{9}_{4}Be \rightarrow {}^{249}_{99}Es + {}^{1}_{0}n$$

$$^{242}_{96}Cm + {}^{9}_{4}Be \rightarrow {}^{250}_{100}Fm + {}^{1}_{0}n$$

APPENDIX B

347 Table B1: Derived Nuclear Units.

Unit	Symbol	Definition	Derivation
Becquerel	Bq	Activity of a radioactive element or source	S^{-1}
Gray	Gy	Absorbed dose ionizing radiation	$J.Kg^{-1}$
Sievert	Sv	Dose equivalent	$J.Kg^{-1}$

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349 Table B2: Non-SI Radiation Units.

Name or Purpose	Definitions/Relationships
Exposure:	1 Roentgen (R) = Amount of radiation which will create 1 esu of charge per cm^3 of dry air at 1 atm and 273K. 1 esu = 3.33 X 10^{-10}C; 1 cm^3 air ≡ 1.293 mg. 1 Roentgen (1 R) = 2.58 X 10^{-4} C/Kg.
Dose:	1 Gy = 1 J/Kg 1 Rad = 100 erg/g 1 Rad = 0.01 Gy
Dose Equivalent:	Sv = Gy X Q 1 Rem = 1 Rad X Q = 0.01 Sv

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354 Table B3: Atomic and Nuclear Data for ^{40}K, ^{238}U and ^{232}Th.

Element	Atomic Number (Z)	Mass Number (A)	Density (g/cm^3)	μ/s = mass attenuation coefficient (cm^2/g) (30 KeV)
Potassium (K)	19	39.102	0.862	3.50
Uranium (U)	92	238.03	18.95	-
Thorium (Th)	90	232.038	11.66	-

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356 Thus, it can be deduced from our results, that ^{40}K, ^{238}U and ^{232}Th naturally occurring
357 radionuclides, to a very great extent, had already decayed to stable nuclei as at the time of
358 carrying out this research on the chosen site at Igbokoda, Ondo State, Nigeria.