

Environmental risks assessment of kaolin mines and their brick products using monte carlo simulations

Article

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1 **Environmental Risks Assessment of Kaolin Mines and their Brick Products using Monte**
2 **Carlo Simulations**

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14 **Abstract**

15
16 This study aimed to assess the radiological health implications to humans due to the use of kaolin
17 from kaolin mines in Nigeria. A calibrated RS-125 spectrometer was used *in-situ* to monitor the
18 activities of ⁴⁰K, ²³⁸U, ²³²Th and dose-rate of kaolin minefields in Ilorin-south and Ilorin-west,
19 Nigeria. The *in-situ* monitoring and measurements were done in 90 locations selected at random
20 in the study areas. The *in-situ* measurements were consolidated via laboratory analysis of 48
21 samples of Kaolin bricks using lead-shielded NaI(Tl) detector. The estimated average values for
22 all radiological hazard parameters for the in-situ measurements of Ilorin-west are higher than that
23 of Ilorin-south minefield. However, the opposite was the case with the laboratory analysis of the
24 bricks. This apparent conundrum was due to the higher values of ²³⁸U observed in the samples of
25 bricks from Ilorin-south. Additionally, the measured activities of the primordial radionuclides in
26 the Kaolin bricks from both mines are lower than the on-site measurements. This was attributed

27 to the contribution from other terrestrial materials on-site. The 5th, 50th, and 95th percentiles of
28 the cumulative probabilities for the excess lifetime cancer risk using the Monte Carlo simulation
29 are 167.00×10^{-6} , 281.00×10^{-6} , 414.00×10^{-6} for Ilorin-west (*in-situ*), 104.00×10^{-6} , 232.00×10^{-6} ,
30 392.00×10^{-6} for Ilorin-south (*in-situ*), 706.00×10^{-6} , $1,250.00 \times 10^{-6}$, $1,900.00 \times 10^{-6}$ for Ilorin-west
31 (Lab), and 742.00×10^{-6} , $1,480.00 \times 10^{-6}$, $2,460.00 \times 10^{-6}$ for Ilorin-south (Lab), respectively.
32 Therefore, the cancer risks are within the acceptable limits for both mining sites. This study is
33 useful in developing radiation risk assessment models for decision makers in different fields of
34 environmental sciences.

35 **Keywords:** Kaolin, Gamma ray spectrometry, Natural radionuclides, Radiological hazards,
36 Environmental risk assessment.

37 **Article Highlights:**

- 38 • The laboratory measured activity concentrations of ^{40}K , ^{238}U and ^{232}Th in all the locations
39 are lower than their respective *in-situ* measurements.
- 40 • The estimated average values for all radiological hazard parameters for the *in-situ*
41 measurements of Ilorin-west are higher than that of Ilorin-south minefield. However, the
42 opposite was the case with the laboratory analysis of the bricks.
- 43 • The cancer risk assessment using the Monte Carlo simulations reveals values that are
44 mostly within the recommended permissive limits

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49 1. Introduction

50 Kaolin, also known as china clay, typically contains about 85 percent of kaolinite that is
51 formed through weathering of the mother rock under favorable conditions. Additionally, kaolin
52 typically contains small amounts of mica, feldspar, illite and quartz. Due to its good physical,
53 mineralogical and chemical characteristics, Kaolin is extensively utilized as a raw material in
54 production of ceramics, cements, paints, refractory bricks, tiles, papers, drugs, toothpastes,
55 fabrics, rubbers and plastics (Turhan, 2009). The Raw Materials Research and Development
56 Council (RMRDC) of Nigeria has drawn attention to the numerous benefits of kaolin production
57 in Nigeria and put the estimated annual national demand at over 360,000 tones (Dailytrust, 2018;
58 Leadership, 2018). This demand is usually met by locally mined Kaolin. In Nigeria, because
59 bricks prepared from Kaolin are cheap, easy to produce and have good geotechnical properties,
60 they are widely used as raw materials for building and construction (Dailytrust, 2018;
61 Leadership, 2018).

62 All raw materials used for building and construction resulting from weathering of mineral
63 rocks, such as limestone, laterite and kaolin, often contain considerable level of radioelements
64 like ^{238}U , ^{232}Th , their daughter elements and the non-series ^{40}K . These radionuclides are usually
65 inherited from the parent rock during pedogenesis. Since the presence of these naturally
66 occurring radioelements in the building and construction materials contributes to radiation
67 exposure, information about the level of these natural radionuclides in building materials
68 becomes very important in assessing the possible radiological hazards to human health.
69 Knowledge about the concentration of these radionuclides is also very important in developing
70 standards and rules that will help to check and manage the use of these mineral soils as building
71 materials (Janković et al., 2018; Turhan, 2009).

72 In Nigeria, the activities of ^{238}U , ^{234}Th and their progenies together with the non-series
73 ^{40}K in different materials used for building and construction from diverse locations of the country
74 have been reported (Ajibola et al., 2021; Orosun et al., 2019, 2020; Omeje et al., 2018;
75 Adagunodo et al., 2018; Isinkaye et al., 2015; Usikalu et al., 2014, 2016, 2019; Ajayi et al.,
76 2012; Ademola et al., 2008; Farai and Ademola, 2001). Unfortunately, beside the work of
77 Olusola et al. in 2013, where they investigated the geochemical and mineralogy of the Kaolin, no
78 work has been carried out in Kwara on the assessment of natural radionuclides despite the
79 growing level of Kaolin mining and usage for construction in Nigeria. Cancer incidence in Ilorin
80 could be attributed to over exposure to elevated level of background ionizing radiation from the
81 use of mined mineral soils such as the kaolin for building purposes because epidemiological
82 studies have shown a strong correlation between cancer incidence and exposure to enhanced
83 level of ionizing radiation (IARC, 1988). Hence, the aim of this present work is to assess the
84 radiological risk at the mine sites and relate this to the human health risk of kaolin bricks
85 exported from the mine for use in construction.

86 2. Material and Methods

87 2.1. Study Area

88 The study areas are Fufu village in Ilorin-south and Akerebiata area of Ilorin-west in
89 Kwara State, Nigeria. The latitudes/Longitudes description of the location are $8^{\circ}20'$ N and $8^{\circ}50'$
90 N and $4^{\circ}25'$ E and $4^{\circ}65'$ E as shown in figures 1a, 1b and 1c. Ilorin town is known to have
91 sedimentary rock base, and has both primary/secondary laterites and alluvial deposits (Orosun et
92 al., 2020a; Ajadi et al., 2016; Oyegun, 1985). The collection of basement-complex rocks in the
93 study area resulted in the numerous ferruginous groups of soils of high percentage of clay
94 content. The soils originate from Igneous and metamorphic rocks which is typical of basement



106
107 Map data © 2019 CNES/Airbus, Maxar Technologies

108 **Fig. 1c. Base map of Ilorin-south Kaolin mining field showing the sampling locations.**

109

110 2.2. Field Survey

111 In-situ quantitative measurements of ^{40}K , ^{232}Th , ^{238}U activities and the radiation dose
112 exposures at the two biggest Kaolin mines in Kwara state was carried out using gamma
113 spectrometer (Super SPEC RS-125, Canadian Geophysical Institute). This instrument employed
114 a large 2.0 x 2.0 NaI crystal which offered superior unified design with a large detector with
115 good sensitivity. Activity determination of the radionuclide heads were made at
116 approximately 1m above the topsoil in keeping with previous studies (Adagunodo et al., 2018,
117 Orosun et al., 2019). The RS-125 gamma spectrometer was calibrated by manufacturer and
118 initialized for use in Nigeria. Calibration was completed on 1 x 1 m test pads that stored 5min
119 spectra accumulation on potassium, uranium and thorium pads and 10 min accumulation on the
120 background pad. The equipment has a very high degree of accuracy with probable errors in
121 measurement of about $\pm 5\%$ (Radiation Solution Inc., 2015; Oyeyemi et al., 2017; Adagunodo et
122 al., 2018, Orosun et al., 2019). Further details of the spectrometry methods can be found in
123 previous studies (Radiation Solution Inc., 2015; Oyeyemi et al., 2017; Adagunodo et al., 2018,
124 Orosun et al., 2019).

125 At the Ilorin-south mine site, 50 spatially random sample points were recorded together
126 with their standard deviations. At the Ilorin-west mine site, 40 randomly selected sample points
127 were assessed. For more accuracy, the readings were repeated 5 times at each sample location.
128 The geographical coordinates and elevations of each of the sampling points were recorded using
129 a GPSMAP78 global positioning system.

130 **2.3. Sample preparation and Gamma-Ray Spectrometry**

131 Twenty-four (24) samples each were collected randomly from blocks/bricks made with
132 the kaolin soil from the mining sites. This brings the total samples to 48. The samples were
133 collected in a rubber test containers of about 10 ml each using a plastic trowel. These samples
134 were sent to the laboratory where they were screened to remove macroscopic traces of glass,
135 rubber, hair, animal and plant matter to ensure that the materials to be analysed are free from
136 non-mineral contaminants. The samples were ground using agate mortar and sieved through a 1
137 mm sieve mesh and stored in labelled plastic containers (Marinelli cylindrical beakers) and kept
138 for 40 days to ensure secular radioactive equilibrium before the Gamma-Ray spectrometry. The
139 detector that was used for the radioactivity measurements is a 3 x 3 inch lead-shielded NaI(Tl)
140 detector produced by Princeton Gamma Tech. USA. The NaI(Tl) detector is coupled to Gamma
141 Spectacular (GS-2000-Pro) Multichannel Analyzer (MCA) through a preamplifier. The linearity
142 of the detector was tested and found to be satisfactory. RSS8 gamma source set, Spectrum
143 Techniques LLC, USA, were used for the energy resolution calibration. The spectral data from
144 the standard gamma sources were obtained with an energy range of 511 – 2,620 KeV (Orosun et
145 al., 2020; Isinkaye, 2018). The detection efficiency calibration was carried out using standard
146 reference materials IAEA-RGK-1, IAEA-RGU-1, and IAEA-RGTh-1 consisting of known
147 activities of ^{40}K , ^{238}U and ^{232}Th . The resolution of the detector at 662 keV of ^{137}Cs is 8% full

148 width at half maximum (FWHM). Each sealed sample were placed on the shielded NaI(Tl)
149 detector and counted for 18000 seconds. The empty control container was also counted for the
150 same counting time of 18000 seconds to determine the background distribution spectrum.
151 Canberra S100 gamma ray acquisition software was used for the gamma counting process after
152 which the spectra information was retrieved and the analysis was carried out using the
153 comparative method i.e. The specific radioactivity “C_x” in the sample and the corresponding
154 specific radioactivity “C_s” in the standard material are related by;

$$155 \quad C_x = C_s \frac{M_s A_x}{M_x A_s} \quad 1$$

156 where, C_x = concentration of specific radioactivity in the sample, C_s = specific activity
157 concentration of the standard, M_s = mass of the standard, M_x = mass of the sample, A_s = area of
158 the standard and A_x = area of the sample.

159 This data analysis software subtracted a linear net background distribution from the
160 corresponding net peaks area for a particular radionuclide in the spectra of the samples. The
161 activity concentration of ²¹⁴Bi (determined from its 1764.5 keV γ-ray peak) was selected to
162 provide an estimate of ²³⁸U in the samples, while 2614.7 keV of ²⁰⁸Tl was chosen as an indicator
163 of ²³²Th. ⁴⁰K was determined by measuring the 1460 KeV γ-rays emitted during its decay
164 (Orosun et al., 2020; Isinkaye, 2018; Joel et al., 2018a; Omeje et al., 2020). The minimum
165 detectable activity for ⁴⁰K, ²³⁸U and ²³²Th was 0.0255, 0.00737 and 0.00737 Bqkg⁻¹, respectively,
166 for the NaI(Tl) detector used in this study.

167 **3. Results and Discussion**

168 **3.1. In situ Activity concentration**

169 The statistical summary of the *in situ* measured activity concentrations of ^{238}U , ^{232}Th , ^{40}K
 170 and the gamma dose rate (*DR*) together with their standard deviation (*SD*) for Kaolin mines in
 171 Ilorin-west and Ilorin-south are shown in Tables 1 and 2 respectively. From Table 1, the highest
 172 values of the activity concentration of ^{40}K , ^{238}U , ^{232}Th and *DR* for Ilorin-west are 782.50 ± 27.04 ,
 173 69.16 ± 3.62 , $66.99 \pm 5.72 \text{ Bqkg}^{-1}$ and $81.92 \pm 7.16 \text{ nGyh}^{-1}$, respectively, while their
 174 corresponding lowest values are 156.50 ± 2.10 , 1.24 ± 0.12 , $22.33 \pm 1.60 \text{ Bqkg}^{-1}$ and $45.92 \pm$
 175 2.14 nGyh^{-1} , respectively. From Tables 2, the highest values of the activity concentration of ^{40}K ,
 176 ^{238}U , ^{232}Th and *DR* for Ilorin-south are 532.10 ± 30.17 , 132.15 ± 13.22 , $69.02 \pm 3.01 \text{ Bqkg}^{-1}$ and
 177 $88.30 \pm 6.92 \text{ nGyh}^{-1}$, respectively, while their corresponding lowest values are 31.30 ± 1.15 , 1.24
 178 ± 0.01 , $5.28 \pm 1.02 \text{ Bqkg}^{-1}$ and $13.90 \pm 1.13 \text{ nGyh}^{-1}$, respectively. The mean values of the
 179 measured activity concentration of ^{40}K , ^{238}U , ^{232}Th and *DR* for the Ilorin-west (Akerebiata)
 180 Kaolin mine field were found to be 492.19 , 35.63 , 44.07 Bqkg^{-1} and 63.28 nGyh^{-1} respectively.
 181 While the mean values for the measured activity concentrations of ^{40}K , ^{238}U , ^{232}Th and *DR* for
 182 the Ilorin-south (Fufu) were 263.55 , 52.24 , 31.29 Bqkg^{-1} and 54.71 nGyh^{-1} , respectively. The
 183 mean values of ^{40}K , ^{232}Th and *DR* for the Kaolin mine site in Ilorin-west are higher than that of
 184 the estimated mean values for Ilorin-south. In contrast, the mean value of ^{238}U for Ilorin-west is
 185 less than the estimated mean value for Ilorin-south.

186 According to the International Commission on Radiological Protection ([ICRP, 1991](#)),
 187 International Atomic Energy Agency ([IAEA, 1996](#)) and United Nations Scientific Committee on
 188 the Effects of Atomic Radiation ([UNSCEAR, 2000](#)) report, the recommended values for general
 189 populace for exposure to ^{40}K , ^{238}U , ^{232}Th and *DR* are given as 420.00 , 32.00 , 45.00 Bqkg^{-1} and
 190 59.00 nGyh^{-1} , respectively. The estimated mean values of ^{40}K , ^{238}U and *DR* for the Kaolin mine
 191 site in Ilorin-west were higher than the recommended global average values. These values are

192 cause for concern since considerable increase in the concentration of the radionuclides causes
193 increase in the level of the background radiation which may render the mineral soil unfit for use
194 in building and construction purposes. Even though the average value of ^{232}Th for the Ilorin-west
195 mine field is less than the recommended global average of 45.00 Bqkg^{-1} , it was observed that the
196 50% (20 out of 40) measured values were higher than the reported global average values. For the
197 Kaolin mine field in Ilorin-south, only the estimated mean value of ^{238}U is higher than its
198 corresponding recommended limit. The mean values of ^{40}K , ^{232}Th and DR were lower than their
199 global averages.

200 To further study the distribution of these measured radionuclides and the gamma dose
201 rate, Surfer™ version 15 was used to plot 3D maps for the two mine fields (Figures 2 to 9). Two
202 colors (green and red) were adopted to reflect areas with values within and greater than the
203 recommended limits. Red colour which is commonly used to signify danger, represent areas with
204 values higher than the recommended average while green field represents areas within the
205 recommended limits. The 3D maps revealed that the Ilorin-west mine field is blessed with ^{40}K
206 and ^{238}U which in turn contributes to the outdoor gamma dose rate. The enhancement of the dose
207 rate caused by these radionuclides is evident in Figure 5 wherein, more red fields are seen. The
208 3D maps also revealed that the Ilorin-south mine field is rich in ^{238}U (Figure 7).

209 Comparing the mean values of ^{40}K , ^{238}U , ^{232}Th and DR for the two studied fields with
210 selected studies from literatures, as shown in Table 4, it was revealed that these average values
211 obtained in this study compare well with the values reported for Ifonyintedo (Kaolin, Nigeria)
212 (Adagunodo et al., 2018), as well as Asa (Granite, Nigeria) (Orosun et al., 2019 and 2020), and
213 Ilorin (Laterite, Nigeria) (Orosun et al., 2020b).

214 **Table 1. Descriptive Statistics of the in-situ measured activities of ^{40}K , ^{238}U , ^{232}Th and DR of**
 215 **Kaolin mining field in Akerebiata area of Ilorin-west LGA.**

216

Stat	DR (nGyh ⁻¹)	^{40}K (Bqkg ⁻¹)	^{238}U (Bqkg ⁻¹)	^{232}Th (Bqkg ⁻¹)
Minimum	45.92±2.30	156.50±23.10	1.24±0.40	22.33±3.10
Maximum	81.92±11.20	782.50±72.20	69.16±11.40	66.99±7.20
Median	62.90±1.70	438.20±35.70	35.82±6.20	45.07±1.80
Mode	N/A	657.30±21.10	35.82±2.10	29.23±2.30
Range	36.00	626.00	67.92	44.66
Sum	2531.12	19687.70	1425.30	1762.86
Mean ± SD	63.28±10.48	492.19±156.90	35.63±17.66	44.07±13.94
Standard Error	1.66	24.81	2.79	2.20
Standard Deviation (SD)	10.48	156.90	17.66	13.94
Sample Variance	109.82	24617.22	311.80	194.29
Kurtosis	-0.98	-0.89	-0.32	-1.22
Skewness	0.12	0.03	-0.08	0.14
Coefficient of Variation	16.56	31.88	49.56	31.63
Count	40.00	40.00	40.00	40.00

217

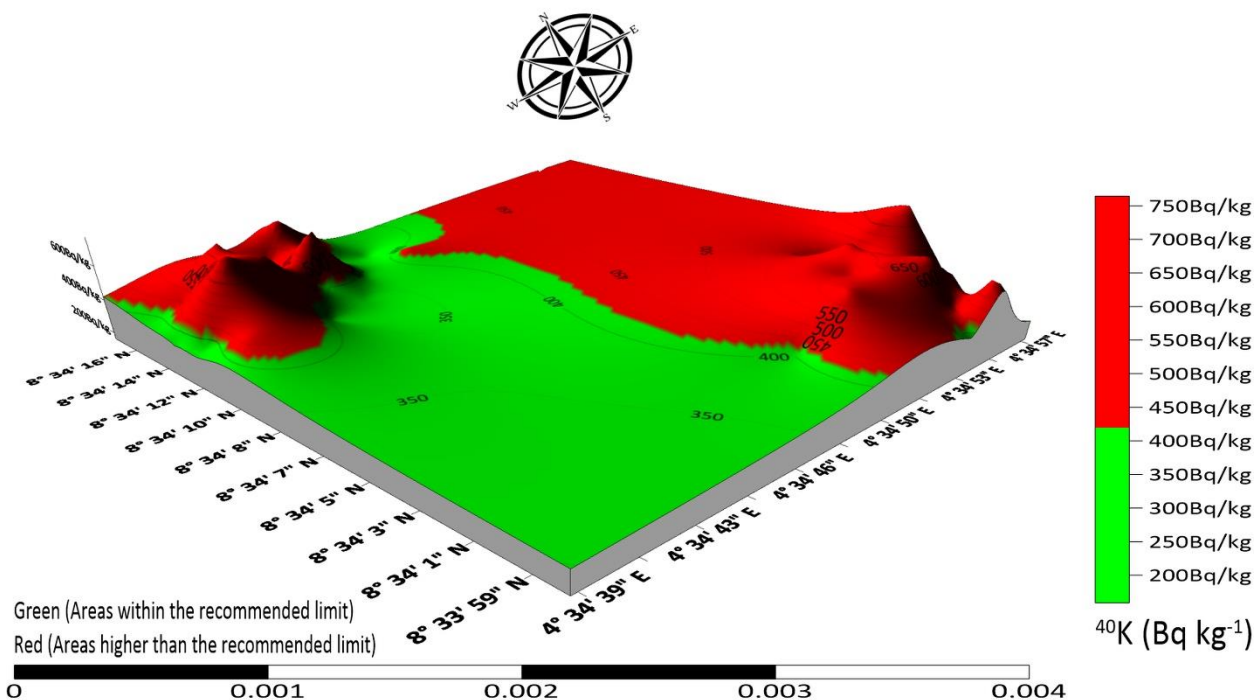
218

219 **Table 2 Descriptive Statistics of the in-situ measured activities of ^{40}K , ^{238}U , ^{232}Th and DR of**
 220 **Kaolin mining field in Fufu area of Ilorin-south LGA.**

221

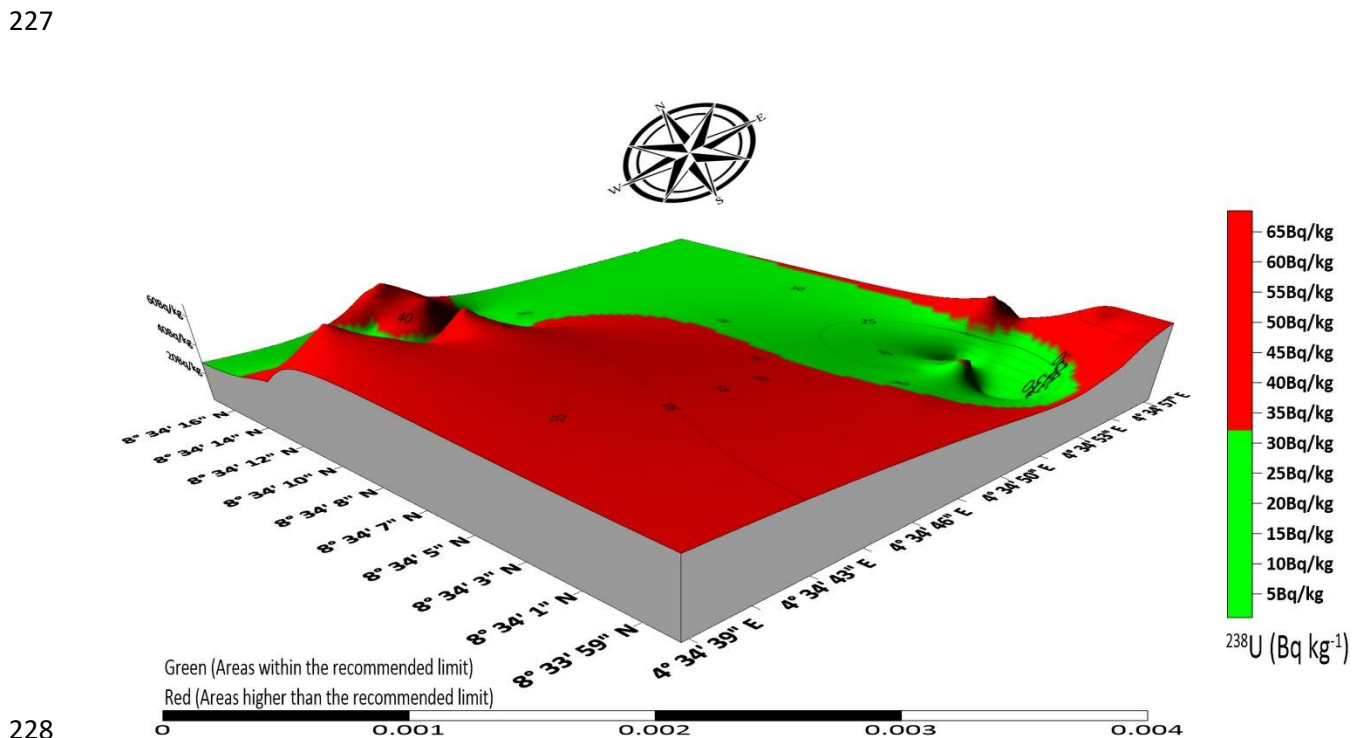
Stat	DR (nGyh ⁻¹)	^{40}K (Bqkg ⁻¹)	^{238}U (Bqkg ⁻¹)	^{232}Th (Bqkg ⁻¹)
Minimum	13.90±2.30	31.30±4.20	1.24±0.40	5.28±1.30
Maximum	88.30±21.20	532.10±150.40	132.10±11.30	69.00±13.20
Median	54.80±12.10	250.40±48.70	49.40±3.20	29.40±4.30
Mode	54.80±12.10	156.50±23.20	38.29±3.60	29.20±4.10
Range	74.40	500.80	130.86	63.72
Sum	2735.30	13177.30	2612.02	1562.74
Mean ± SD	54.71±16.68	263.55±145.18	52.24±27.01	31.25±15.60
Standard Error	2.36	20.53	3.82	2.21
Standard Deviation (SD)	16.68	145.18	27.01	15.60
Sample Variance	278.22	21076.93	729.32	243.21
Kurtosis	0.05	-0.97	0.71	0.35
Skewness	-0.18	0.26	0.73	0.60
Coefficient of Variation	30.49	55.09	51.70	49.90
Count	50.00	50.00	50.00	50.00

222



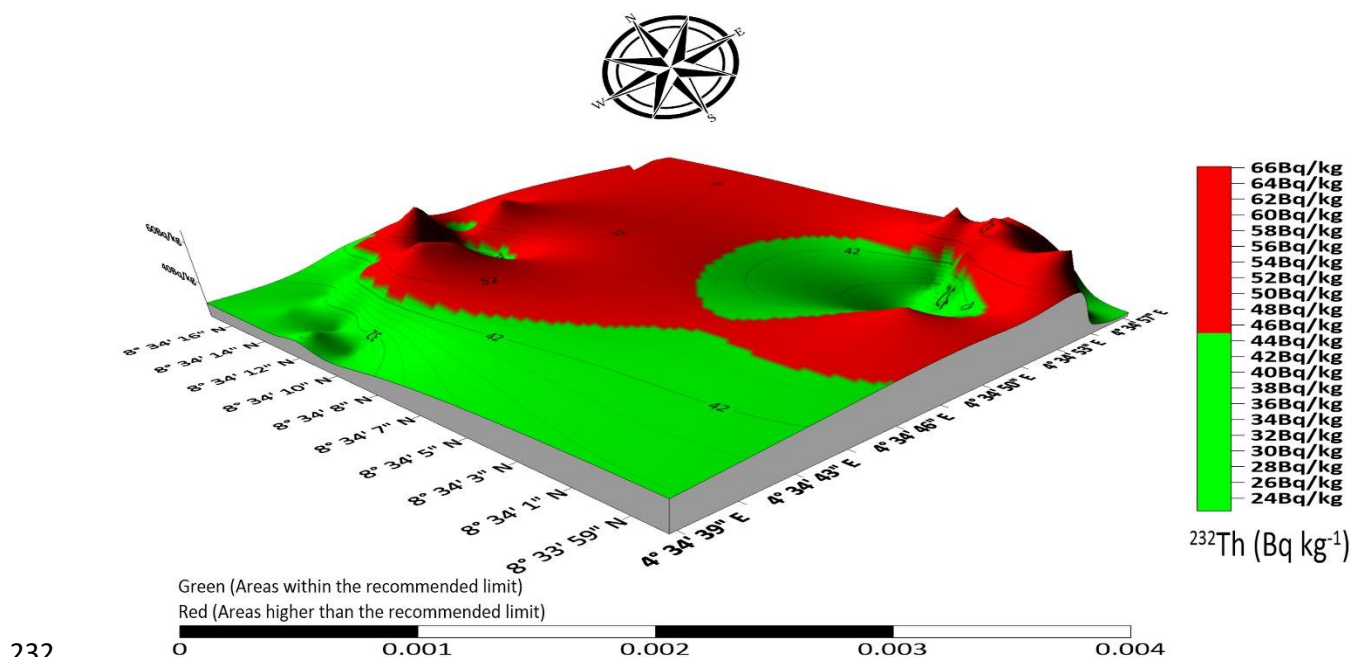
223

224 **Fig. 2. Isopotassium 3D map of Ilorin-west Kaolin mining field (Red colour represents**
 225 **areas with values higher than the recommended global average value of 450.00 Bqkg⁻¹**
 226 **while the green field represents areas within the recommended limits).**

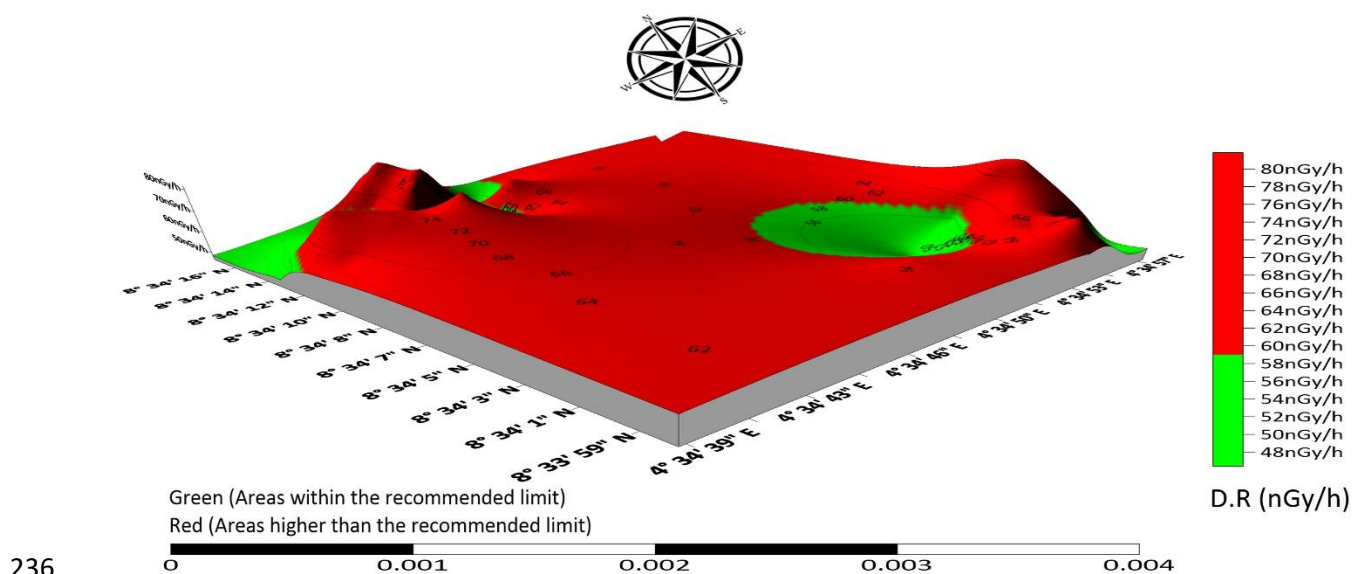


228

229 **Fig. 3. Isouranium 3D map of Ilorin-west Kaolin mining field (Red colour represents areas**
 230 **with values higher than the recommended global average value of 32.00 Bqkg⁻¹ while the**
 231 **green field represents areas within the recommended limits).**

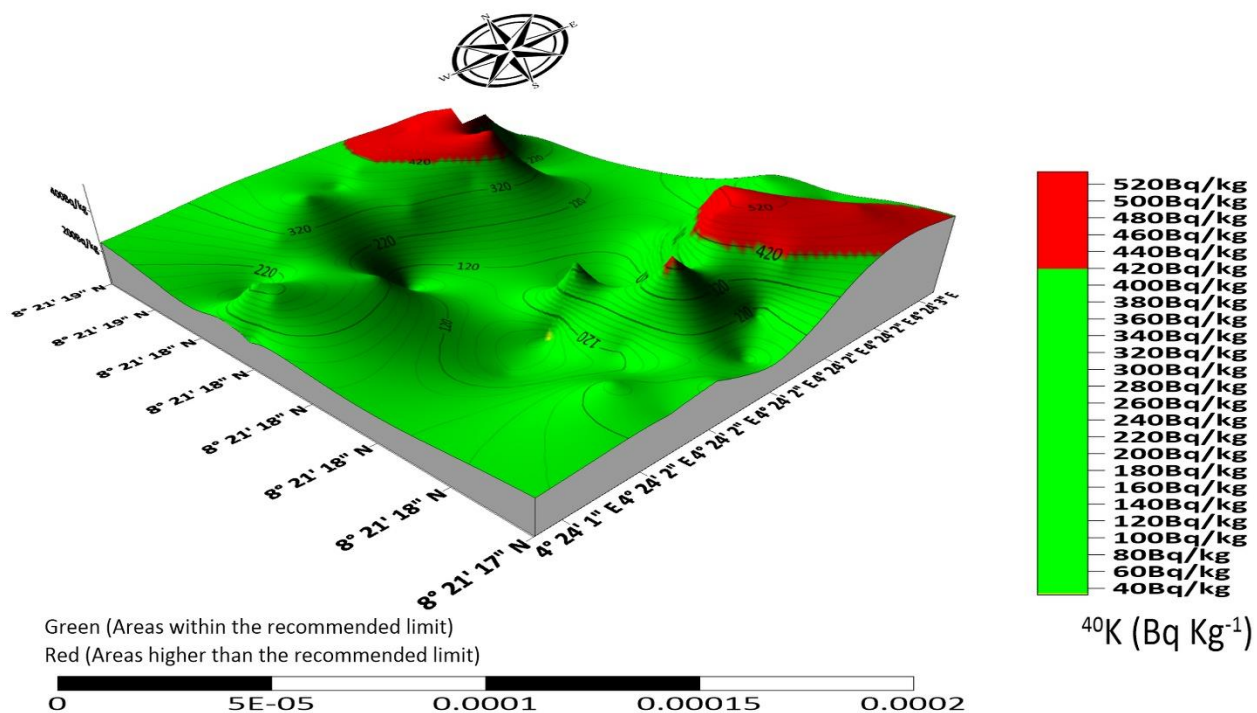


233 **Fig. 4. Isothorium 3D map of Ilorin-west Kaolin mining field (Red colour represents areas**
 234 **with values higher than the recommended global average value of 45.00 Bqkg⁻¹ while the**
 235 **green field represents areas within the recommended limits).**



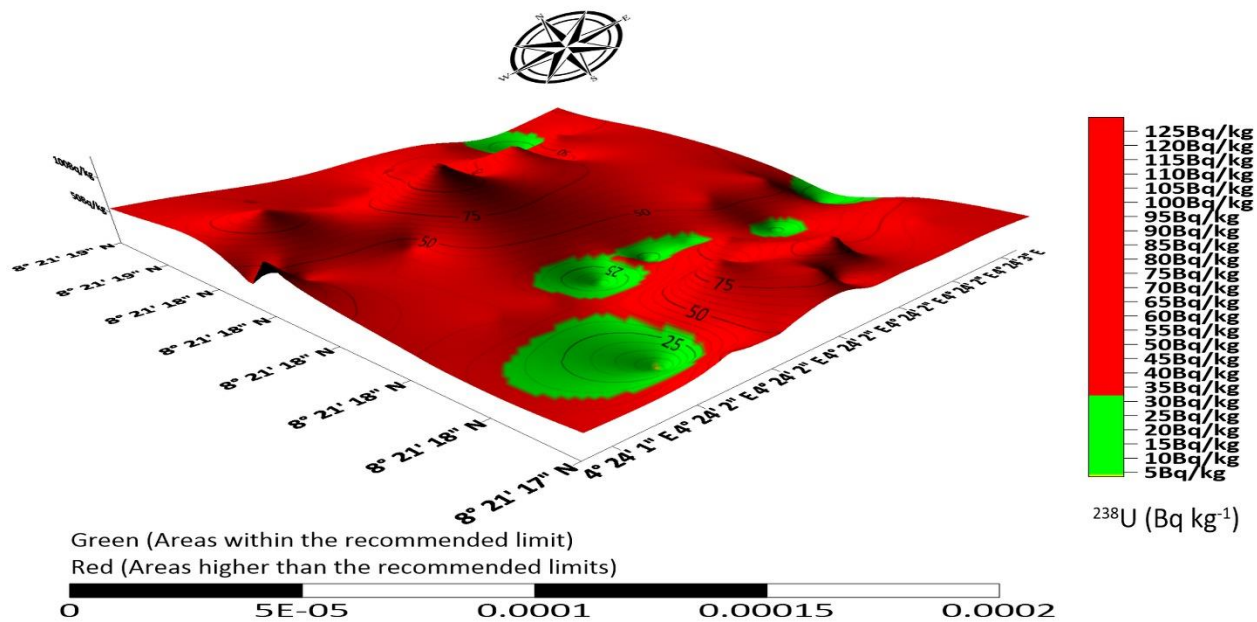
237 **Fig. 5. Isodoserate 3D map of Ilorin-west Kaolin mining field (Red colour represents areas**
 238 **with values higher than the recommended global average value of 59.00 nGyh⁻¹ while the**
 239 **green field represents areas within the recommended limits).**

240



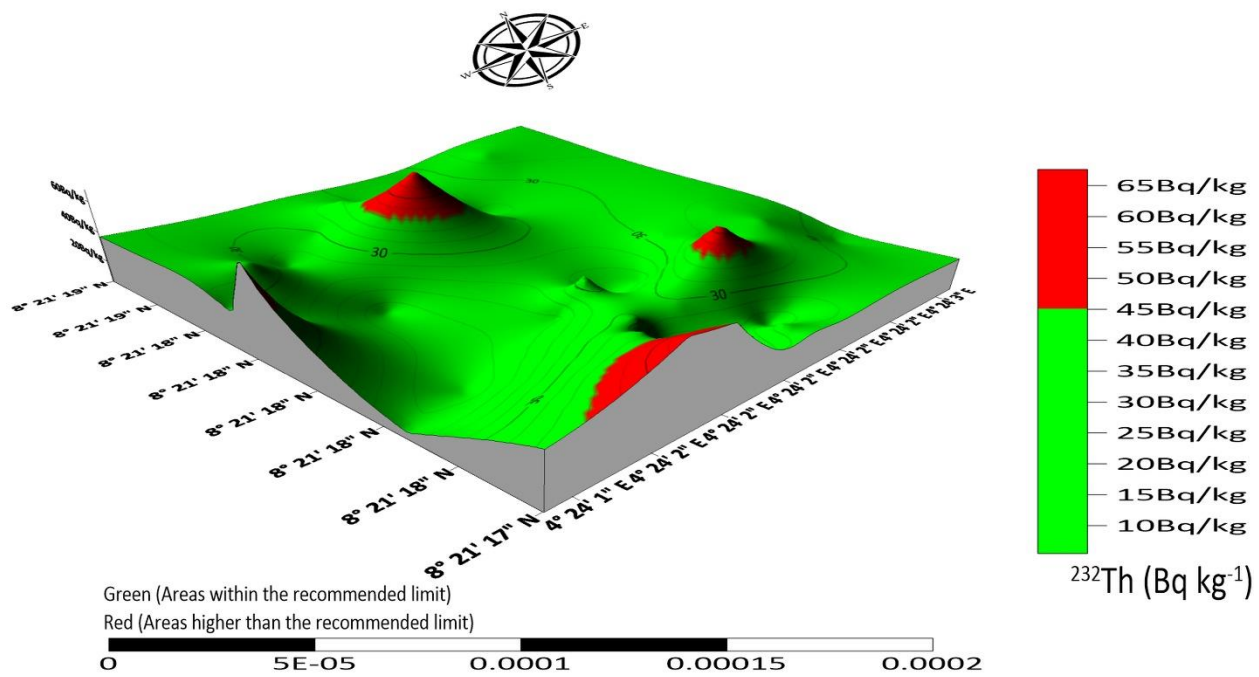
241

242 **Fig. 6. Isopotassium 3D map of Ilorin-south Kaolin mining field (Red colour represents**
 243 **areas with values higher than the recommended global average value of 450.00 Bq/kg while**
 244 **the green field represents areas within the recommended limits).**



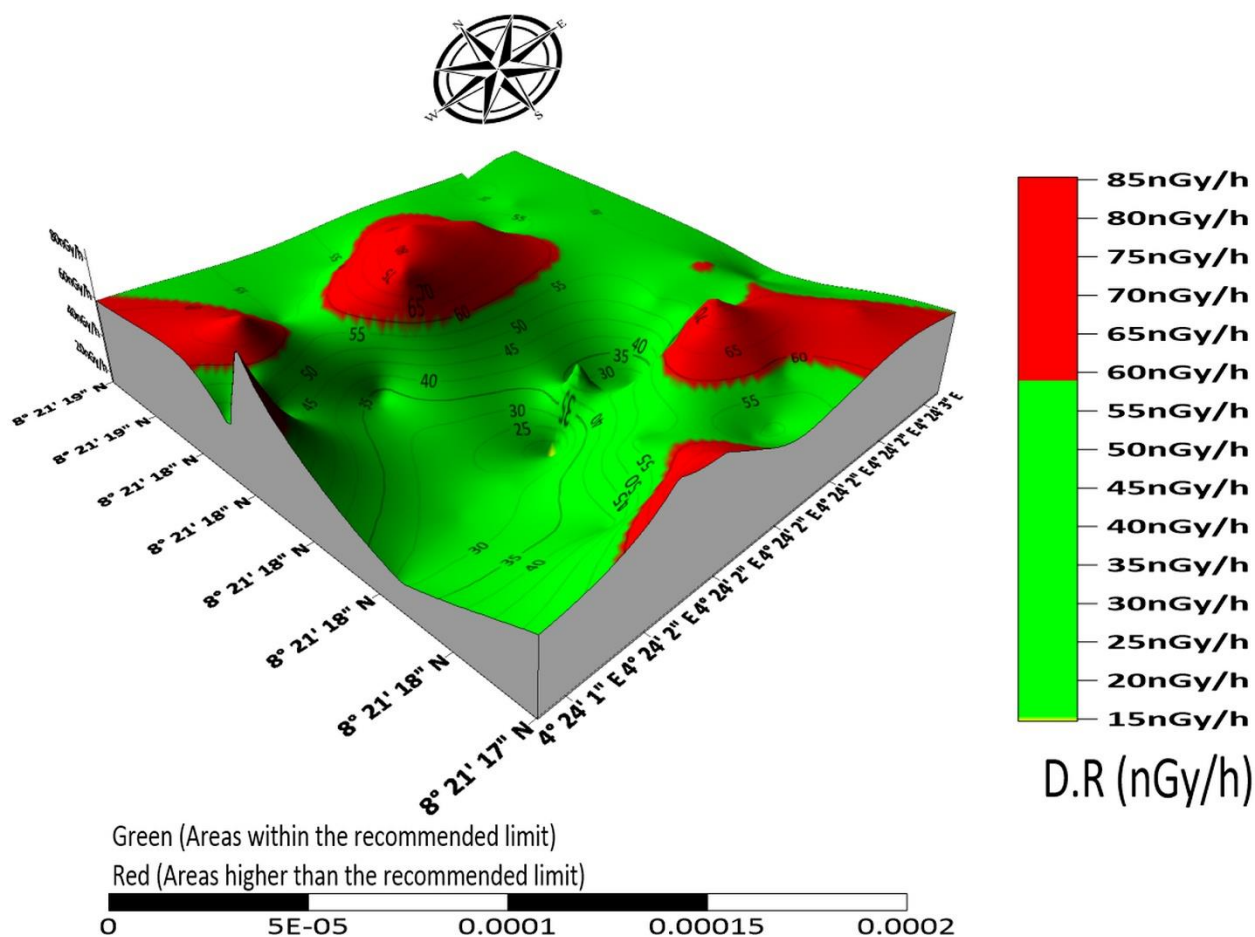
245

246 **Fig. 7. Isouranium 3D map of Ilorin-south Kaolin mining field (Red colour represents areas**
 247 **with values higher than the recommended global average value of 32 Bq/kg while the green**
 248 **field represents areas within the recommended limits).**



249

250 **Fig. 8. Isothorium 3D map of Ilorin-south Kaolin mining field (Red colour represents areas**
 251 **with values higher than the recommended global average value of 45.00 Bq/kg while the**
 252 **green field represents areas within the recommended limits).**



253
254 **Fig. 9. Isodoserate 3D map of Ilorin-south Kaolin mining field (Red colour represents areas**
255 **with values higher than the recommended global average value of 59.00 nGy/h while the**
256 **green field represents areas within the recommended limits).**

257
258 **3.2. Radioactivity content in the selected soil samples from the study areas**

259 Since *in situ* measurements are insufficient for quantitative determination of activity
260 concentrations, we consolidated our measurements with laboratory analyses. The summary of the
261 radioactivity content in the sampled blocks/bricks made with soils collected from the mining
262 sites is presented in Table 3. The activity concentration of ^{40}K appeared to be far higher than that
263 of ^{232}Th and ^{238}U . This tendency was observed at all study locations. The results for all
264 radionuclide heads studied (i.e. ^{238}U , ^{232}Th and ^{40}K) were skewed moderately; this means that the

265 spread is moderately asymmetric, because most of the measure of the asymmetry of their
 266 probability distribution is in the range of -2 and +2 about their means.

267 The mean values of the measured activity concentration of ^{40}K , ^{238}U and ^{232}Th for the Ilorin-west
 268 (Akerebiata) Kaolin minefield were 189.28, 23.80 and 32.40 Bqkg^{-1} respectively. While the
 269 mean values for the measured activity concentrations of ^{40}K , ^{238}U and ^{232}Th for the Ilorin-south
 270 (Fufu) are 92.34, 42.73 and 27.06 Bqkg^{-1} respectively. The mean values of ^{40}K and ^{232}Th for the
 271 Kaolin minefield in Ilorin-west are higher than that of the estimated mean values for Ilorin-south.
 272 However, the mean value of ^{238}U for Ilorin-west is less than (about half) the estimated mean
 273 value for Ilorin-south. This is in accord with the *in situ* measurements. Interestingly, all the *in*
 274 *situ* measurements were higher than their respective measured activity concentrations of ^{40}K ,
 275 ^{238}U and ^{232}Th in all the locations. This may be attributed to contribution by other terrestrial
 276 materials on-site to the gamma ray detection during the course of *in situ* measurements.

277 **Table 3 Statistical summary of the measured activity concentrations of ^{40}K , ^{238}U , ^{232}Th in**
 278 **samples collected from mining site using 3 x 3 inch NaI[Tl].**

SAMPLE LOCATION	SAMPLE STAT	^{40}K (Bqkg^{-1})	^{238}U (Bqkg^{-1})	^{232}Th (Bqkg^{-1})
				279 280
ILN-WEST	MIN	118.23 ± 13.20	12.57 ± 3.50	22.56 ± 6.20 281
	MAX	299.40 ± 91.10	36.82 ± 8.20	48.38 ± 9.10 282
	SKEW	1.52	0.65	1.60 283
	MEAN±SD	189.28 ± 96.70	23.80 ± 6.22	32.40 ± 13.96
ILN-SOUTH	MIN	48.36 ± 4.70	10.80 ± 2.20	2.56 ± 1.20
	MAX	129.40 ± 67.20	86.82 ± 25.10	54.38 ± 13.70
	SKEW	-0.74	1.26	0.48
	MEAN±SD	92.34 ± 19.96	42.73 ± 9.44	27.06 ± 6.02
GLOBAL AVERAGE		420.00	32.00	45.00

284 **Table 4 Comparison of the mean activity concentration and dose rate with other studies.**

Material	^{238}U (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Dose rate (nGy h^{-1})	Location	References
Soil	19.16	48.56	1146.88	89.6	India	Chandrasekaran et al. (2014).
Kaolin	82	94.8	463.6	117.7	Turkey	(Turhan, 2009).
Clay	39.3	49.6	569.5	74.1	Turkey	(Turhan, 2009).
Floor ceramic	101.22	87.53	304.57	213.98	Iraq	(Amana, 2017).
Wall ceramic	102.12	70.9	328.6	178.4	Iraq	(Amana, 2017).
Kaolin	964.7	251.6	58.9	58.1	Eqypt	(El-Dine et al., 2004).
Phosphogypsum	206.8	99.1	15.1	154.6	Brazil	(Mazzilli and Saueia, 1999).
Kaolin	38.2	65.1	93.9	59.6	Nigeria (Ifonyintedo)	(Adagunodo et al., 2018).
Granite	11.51	15.42	441.06	32.72	Nigeria	(Orosun et al., 2020).
Granite	18.15	42.86	570.91	60.11	Nigeria	(Orosun et al., 2019).
Laterite	43.89	38.79	81.38	46.44	Nigeria	(Orosun et al., 2020b).
Kaolin	35.63	44.07	492.19	63.28	Nigeria (Ilorin- west)	Present study (<i>In situ</i>)
Kaolin	52.24	31.29	263.55	54.71	Nigeria (Ilorin- south)	Present study (<i>In situ</i>)
Kaolin	23.8	32.4	189.28	38.32	Nigeria (Ilorin- west)	Present study
Kaolin	42.73	27.06	92.34	39.87	Nigeria (Ilorin- south)	Present study
Soil and Rock	32	45	420	59	Global Average	(UNSCEAR, 2000).

285

286 **3.3. Evaluation of the Radiological Impact Parameters**287 **3.3.1. Radium Equivalent Activity (Ra_{eq})**

288 The radiation exposure has been defined in terms of radium equivalent activity (Ra_{eq}) in
289 Bqkg^{-1} to evaluate the specific activity of substance having differing amounts of ^{238}U , ^{232}Th and
290 ^{40}K because the distribution of these radionuclides in the Kaolin is not uniform. The assumption
291 is that 0.7 Bqkg^{-1} of ^{232}Th , 1 Bqkg^{-1} of ^{238}U and 13 Bqkg^{-1} of ^{40}K produces equal radiation dose
292 rates. This permits the use of a solitary index to represent the gamma dose due to different
293 mixture of ^{238}U , ^{232}Th and ^{40}K in the Kaolin. The Ra_{eq} was calculated using equation (2)
294 (UNSCEAR, 2000; Orosun et al. 2018, 2018a):

$$Ra_{eq} = C_U + 1.43C_{Th} + 0.077C_K \quad 2$$

296 C_U , C_{Th} and C_K are the activity concentrations in $Bqkg^{-1}$ for ^{238}U , ^{232}Th and ^{40}K respectively. The
 297 recommended average value for it is $370 Bqkg^{-1}$ (UNSCEAR, 2000; ICRP, 1991; IAEA, 1996).
 298 The maximum, minimum and mean values for the Ra_{eq} obtained for *in situ* measurements are
 299 175.45, 98.10 and $136.55 Bqkg^{-1}$ respectively, for the Ilorin-west Kaolin minefield and 193.49,
 300 32.61 and $117.28 Bqkg^{-1}$ respectively, for the Ilorin-south Kaolin mine field. For the laboratory
 301 gamma spectrometry results, the Ra_{eq} values ranges between $117.57 - 53.93 Bqkg^{-1}$ with mean
 302 value of $84.70 Bqkg^{-1}$ for Ilorin-west location, and ranges between $168.31 - 41.87 Bqkg^{-1}$, with a
 303 mean value of $88.54 Bqkg^{-1}$. All the measured values (both laboratory and *in situ*) for the two
 304 mine sites are less than the recommended limit.

305 3.3.2. Radiation Hazard Indices

306 The internal radiation hazards (H_{int}) and the external radiation hazard (H_{ext}) were
 307 calculated using equations (3) and (4);

$$308 \quad H_{int} = \left(\frac{C_U}{185}\right) + \left(\frac{C_{Th}}{259}\right) + \left(\frac{C_K}{4810}\right) \quad 3$$

$$309 \quad H_{ext} = \left(\frac{C_U}{370}\right) + \left(\frac{C_{Th}}{259}\right) + \left(\frac{C_K}{4810}\right) \quad 4$$

310 C_U , C_{Th} and C_K are defined in equation (2).

311 Both H_{int} and H_{ext} have to be less than 1 for it to be considered as low radiation hazard. Natural
 312 radionuclides in mineral soils produce external radiation to which the general populaces are
 313 exposed. The mean values of H_{int} and H_{ext} for the Ilorin-west are 0.47 and 0.37 for *in situ*
 314 measurements and 0.29 & 0.23 for bricks samples lab gamma spectrometry respectively. While

315 for Ilorin-south, the mean values were found to be 0.46 and 0.32 for *in situ* and 0.36 & 0.24
 316 respectively. These values are within the permissible value of unity.

317 **3.3.3. Absorbed Dose Rate**

318 Generally, at about 1m above the ground level, naturally occurring radionuclides are
 319 assumed to have a uniform distribution. The outdoor dose rate (DR) at about 1 m above the
 320 ground was obtained *in situ* using the RS-125 gamma spectrometer and indoor absorbed dose
 321 (for bricks used for building purposes) was calculated using equation 5 (Omeje et al., 2021;
 322 Akinyose et al., 2018; Adagunodo et al., 2018; Orosun et al., 2017; UNSCEAR, 2000).

323 The Kaolin from both Ilorin-west and Ilorin-south are used basically for building
 324 purposes. It implies that, the indoor radiation dose rate in a particular building with wall
 325 thickness of about 20 cm and room size $2.8 \times 4 \times 5$ m, is given by:

$$326 \quad D_i(nGy h^{-1}) = 0.92C_u + 1.1C_{Th} + 0.08C_K \quad 5$$

327 The *in situ* mean values of D_o (DR) and the D_i for the Ilorin-west is 63.28 and 72.67
 328 $nGyh^{-1}$ respectively, while for Ilorin-south, the mean values were found to be 54.71 ± 16.68 and
 329 $76.47 \pm 18.24 nGyh^{-1}$ respectively (see Table 5). As expected, these mean values of D_o for
 330 Ilorin-west are higher than that of Ilorin-south mine field. However, the opposite was the case
 331 with D_i . This apparent conundrum was primarily due to the high values of ^{238}U observed in the
 332 samples of bricks from Ilorin-south (i.e. the mean concentration of ^{238}U of Ilorin-south is almost
 333 twice the mean value obtained for bricks samples from Ilorin-west). The mean value of D_i for
 334 both Ilorin-west and Ilorin-south are less than the recommended limit of $84.00 nGyh^{-1}$ given by
 335 (UNSCEAR, 2000). This follows that indoor gamma radiation exposure risk is relatively low for

336 the Kaolin soils, but the publics might not be considered safe from indoor exposure to ionizing
 337 radiation, since no amount of radiation is safe for stochastic effects.

338 3.3.4. Annual Effective Dose (AED)

339 The annual effective dose received indoor and outdoor by a member of the general public
 340 was calculated using dose rates. Dose conversion factor of 0.7 SvGy^{-1} and occupancy factor for
 341 outdoor and indoor as 0.2 and 0.8 were used (UNSCEAR, 2000; Isinkaye et al., 2015; Omeje et
 342 al., 2021).

$$343 \quad AED_{out} (mSvy^{-1}) = D_o \times 8760 \times 0.7 \times 0.2 \times 10^{-6} \quad 6$$

$$344 \quad AED_{in} (mSvy^{-1}) = D_i \times 8760 \times 0.7 \times 0.8 \times 10^{-6} \quad 7$$

345 The mean values for the AED_{out} and AED_{in} for Ilorin-west are 0.08 and 0.36 mSv y^{-1} respectively,
 346 while that of Ilorin-south are 0.07 and 0.38 mSv y^{-1} respectively. While the mean AED_{out} for
 347 Ilorin-west is above the global limits provided by UNSCEAR (2000), the mean AED_{out} for Ilorin-
 348 south is approximately equal to the recommended limit of 0.07 mSvy^{-1} . The mean values of the
 349 AED_{in} for both Ilorin-west and south are lower than the recommended limit of 0.41 mSvy^{-1} .

350 3.3.5. Excess Lifetime Cancer Risk (ELCR)

351 The Excess Lifetime Cancer Risk ($ELCR$) was calculated using equation (8):

$$352 \quad ELCR = AED \times DL \times RF \quad 8$$

353 AED is the indoor Annual Equivalent Dose Equivalent, DL represents the mean human lifespan
 354 (given as 70 years) and RF is the stochastic Risk Factor in Sv^{-1} . The fatal cancer risk (RF) per
 355 Sievert is given as 0.05 set by ICRP for the public (UNSCEAR, 2000; Orosun et al., 2018). All

356 the values estimated for the *ELCR* (i.e. for both Ilorin-west and south) were below the
 357 recommended limits of 3.75×10^{-3} .

358 3.3.6. Annual Gonadal Equivalent Dose (AGED)

359 An increase in annual gonadal equivalent dose (*AGED*) has been reported to increase the
 360 likelihood of developing leukemia that can be fatal to humans. The annual gonadal equivalent
 361 dose (*AGED*) for the residents using the bricks for building and construction was calculated
 362 using equation (9) (UNSCEAR, 2000; Orosun et al., 2018; Usikalu et al., 2017):

$$363 \quad \text{AGED } (\mu\text{Sv } y^{-1}) C = 3.09 C_U + 4.18 C_{Th} + 0.314 C_K \quad 9$$

364 The *AGED* mean values estimated for the residents using the Kaolin bricks for building were
 365 evaluated and found to be only slightly lower than the recommended limit of $0.3 \text{ mSv } y^{-1}$ (see last
 366 column of Table 6). However, the estimated *AGEDs* for the *in situ* measurements were higher
 367 than the recommended $0.3 \text{ mSv } y^{-1}$. These high values obtained for *AGED* increase our fear over
 368 the use of these kaolin soils for building and construction purposes.

369 3.3.7. Representative Level Index (RLI)

370 The *RLI* was estimated using equation 10 (UNSCEAR, 2000; Orosun et al., 2018):

$$371 \quad RLI = \frac{C_u}{150} + \frac{C_{Th}}{100} + \frac{C_k}{1500} \leq 1 \quad 10$$

372 The mean *RLI* for the kaolin mine fields were estimated and to be 1.01 and 0.84 or *in situ*
 373 measurements, and 0.61 & 0.62 for the lab results respectively for Ilorin-west and south. The
 374 mean *RLI* for Ilorin-west is greater than the recommended limit of unity while that of Ilorin-
 375 south is close to 1. This shows that care should be taken in the use of these kaolin soils for
 376 building purposes.

377 Tables 5 and 6 shows the summary of the evaluated hazard risk parameters for the
 378 measured activity concentrations. The contributions of the measured radionuclides (^{40}K , ^{238}U and
 379 ^{232}Th) to the radiological hazard parameters were displayed in Figures 10 and 11. It was observed
 380 that ^{40}K and ^{234}Th were the main contributors to the radiological hazards for Ilorin-west while
 381 ^{238}U is the chief contributor to radiological hazards from Ilorin-south kaolin mine field. These
 382 radionuclides have been noted for their notorieties and contributions to background ionizing
 383 radiation which is linked with various kinds of cancers, liver diseases and ruthless health related
 384 harms which could eventually lead to death.

385 **Table 5 Summary of the estimated D_o , D_i , AED , $ELCR$ and RLI for the measured activity**
 386 **concentrations.**

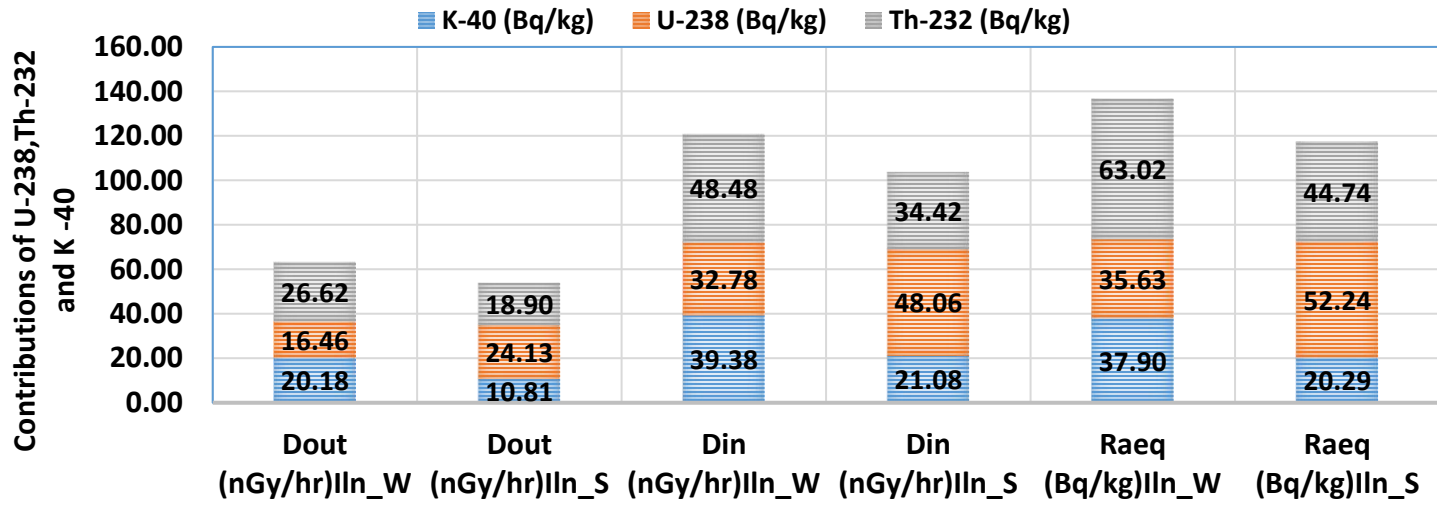
LOCATION	STAT	D_o ($n\text{Gyh}^{-1}$)	AED_{out} ($m\text{Svy}^{-1}$)	$ELCR$ ($\times 10^{-3}$)	RLI
	MIN	45.92	0.06	0.20	0.71
ILN-WEST	MAX	81.92	0.10	0.35	1.32
<i>In situ</i>	MEAN \pm STDEV	63.28 \pm 10.48	0.08 \pm 0.01	0.27 \pm 0.05	1.01 \pm 0.17
	MIN	13.90	0.02	0.06	0.23
ILN-SOUTH	MAX	88.30	0.11	0.37	1.35
<i>In situ</i>	MEAN \pm STDEV	54.71 \pm 16.68	0.07 \pm 0.02	0.23 \pm 0.07	0.84 \pm 0.25
	LIMIT	59.00	0.07	3.75	≤ 1
LOCATION	STAT	D_i ($n\text{Gyh}^{-1}$)	AED_{in} ($m\text{Svy}^{-1}$)	$ELCR$ ($\times 10^{-3}$)	RLI
	MIN	45.84	0.22	0.79	0.39
ILN-WEST	MAX	99.11	0.49	1.70	0.83
	MEAN \pm STDEV	72.67 \pm 16.64	0.36 \pm 0.13	1.25 \pm 0.36	0.61 \pm 0.18
	MIN	38.88	0.19	0.67	0.30
ILN-SOUTH	MAX	143.56	0.70	2.46	1.16
	MEAN \pm STDEV	76.47 \pm 18.24	0.38 \pm 0.29	1.31 \pm 0.44	0.62 \pm 0.21
	LIMIT	84.00	0.41	3.75	≤ 1

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392 **Table 6 Summary of the estimated H_{ext} , H_{int} , Ra_{eq} and $AGED$ for the measured activity**
393 **concentrations**

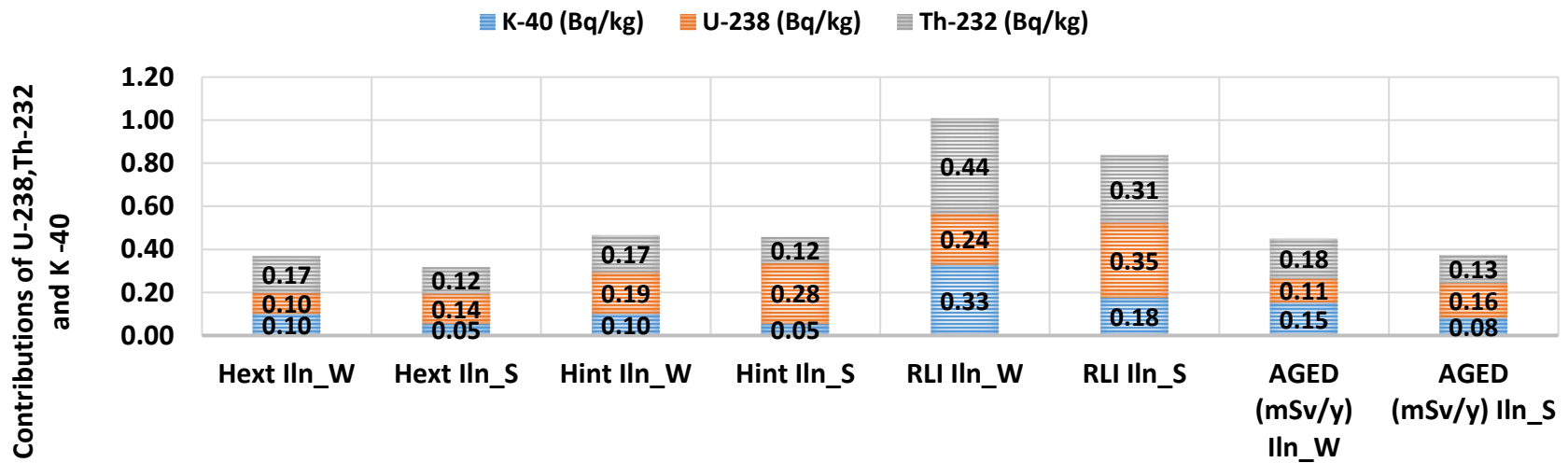
LOCATION	STAT	H_{ext}	H_{int}	Ra_{eq} (Bqkg ⁻¹)	$AGED$ (mSvy ⁻¹)
	MIN	0.27	0.32	98.10	0.32
ILN-WEST	MAX	0.48	0.64	175.45	0.59
<i>In situ</i>	MEAN±STDEV	0.37±0.06	0.47±0.09	136.55±23.20	0.45±0.07
	MIN	0.09	0.12	32.61	0.10
ILN-SOUTH	MAX	0.53	0.84	193.49	0.59
<i>In situ</i>	MEAN±STDEV	0.32±0.10	0.46±0.16	117.28±36.25	0.37±0.11
	LIMIT	≤1	≤1	370.00	0.30
LOCATION	STAT	H_{ext}	H_{int}	Ra_{eq} (Bqkg ⁻¹)	$AGED$ (mSvy ⁻¹)
	MIN	0.15	0.18	53.93	0.17
ILN-WEST	MAX	0.32	0.42	117.57	0.36
	MEAN±STDEV	0.23±0.08	0.29±0.09	84.70±21.87	0.27±0.08
	MIN	0.11	0.18	41.87	0.14
ILN-SOUTH	MAX	0.46	0.69	168.31	0.51
	MEAN±STDEV	0.24±0.11	0.36±0.11	88.54±22.41	0.27±0.10
	LIMIT	≤1	≤1	370.00	0.30

394



395
396 Fig. 10. Contributions of ^{40}K , ^{238}U and ^{232}Th to D_o , D_i and Ra_{eq} (Iln-W = Ilorin-west and Iln-S = Ilorin-south)

397



398
399 Fig. 11. Contributions of ^{40}K , ^{238}U and ^{232}Th to H_{ext} , H_{in} , RLI and $AGED$ (Iln-W = Ilorin-west and Iln-S = Ilorin-south).

400 3.4 Monte Carlo Simulation (MCS)

401 The result of the Monte Carlo simulation performed using Oracle Crystal Ball package
402 version 11.1.2.4.850 for both mining sites is presented in Table 8 and figures 12a – d. The level
403 of risk signifying the 95th percentile, mean, 5th percentile and other level of probability of
404 interest, were determined based on the distribution of the output (Orosun et al., 2020c;
405 Changsheng et al., 2012; Saghi et al., 2019; Orosun, 2021; NRC, 1994; USEPA, 1997). The
406 evaluation of the minimum probable risk (P 5% = best case scenario) reveals that about 167, 104,
407 706 and 742 individuals in a population of 1 million (10^6) are projected to develop cancer in
408 Ilorin-west (*in-situ*), Ilorin-south (*in-situ*), Ilorin-west (Lab), and Ilorin-south (Lab) respectively.
409 However, the results of the maximum probable risk assessment (P 95% = worst-case scenario)
410 reveals that about 414, 392, 1,900 and 2,460 individuals in a population of 1 million (10^6) are
411 projected to develop cancer in Ilorin-west (*in-situ*), Ilorin-south (*in-situ*), Ilorin-west (Lab), and
412 Ilorin-south (Lab) respectively. Similarly, the most probable risk estimation (50%) reveals that
413 the most likely outcomes are 281, 232, 1,250 and 1,480 individuals in a population of 1 million
414 (10^6) are likely to develop cancer in Ilorin-west (*in-situ*), Ilorin-south (*in-situ*), Ilorin-west (Lab),
415 and Ilorin-south (Lab) respectively. This follows that the mean, P 5% and P 95% cumulative
416 probabilities for the cancer risk for both mining sites are within the recommended value of
417 $3,750.00 \times 10^{-6}$ (UNSCEAR, 2000). Based on the obtained results, there is no substantial
418 environmental or radiological health hazard in the study areas. The results also reveal that
419 inhabitant living around or using the Kaolin from Fufu area of Ilorin-south are the most
420 vulnerable. The outcomes of this research have a potential in order to develop radiation risk
421 assessment models applicable for stakeholders and decision makers for further environmental
422 studies.

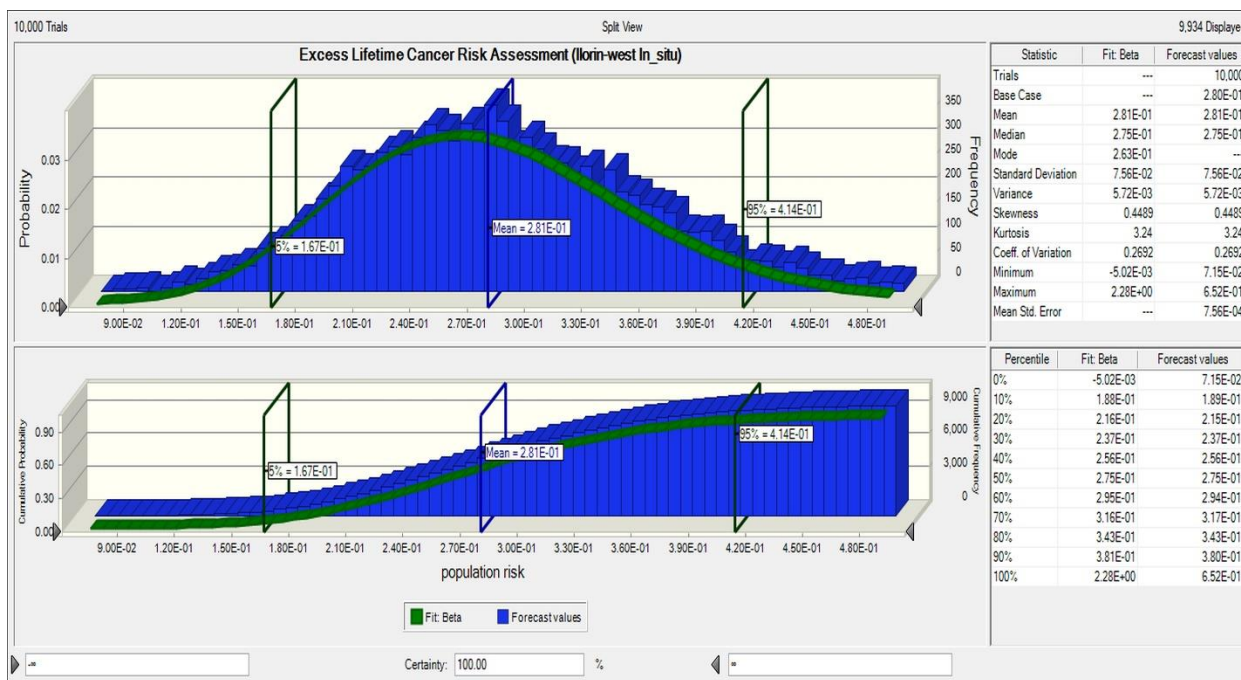
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425 **Table 8 Summary of the Monte Carlo simulation**

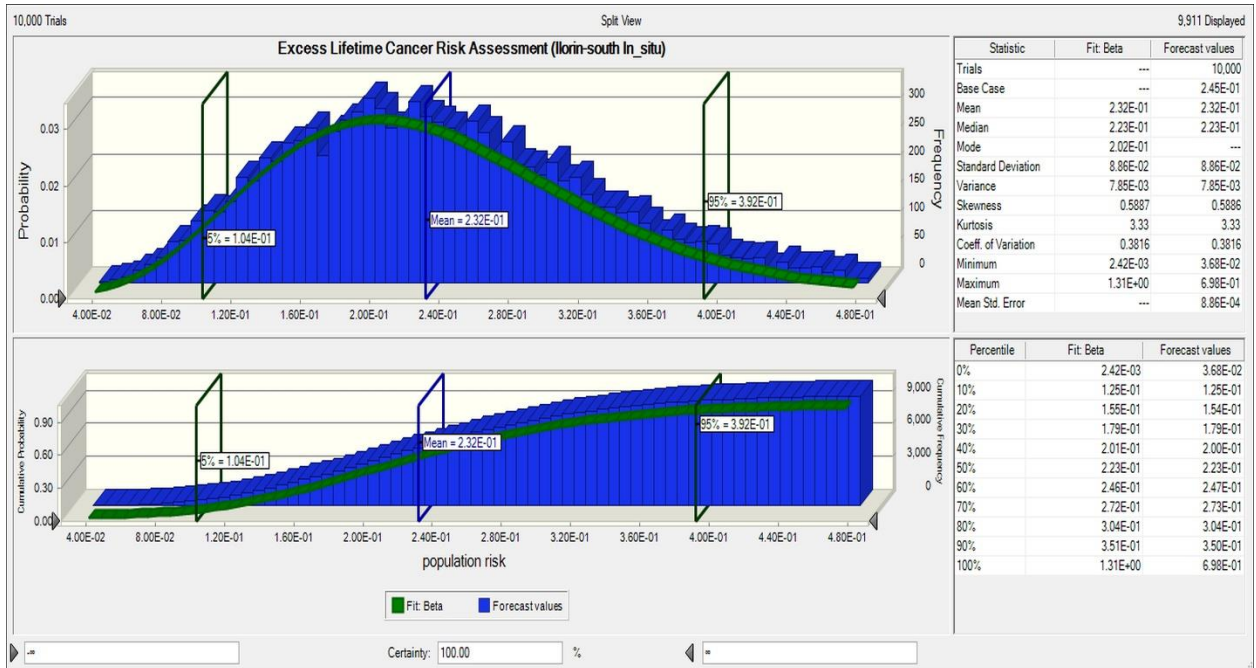
	<u>Excess Lifetime Cancer Risk (ELCR) ($\times 10^{-6}$)</u>		
	5%	Mean (50%)	95%
Ilorin-west (<i>in-situ</i>)	167.00	281.00	414.00
Ilorin-south (<i>in-situ</i>)	104.00	232.00	392.00
Ilorin-west (Lab)	706.00	1,250.00	1,900.00
Ilorin-south (Lab)	742.00	1,480.00	2,460.00

426



427

428 (a) Ilorin-west *in-situ* cancer risk (indicating the mean, P 5% and P 95% cumulative
429 probabilities for the cancer risk)



430

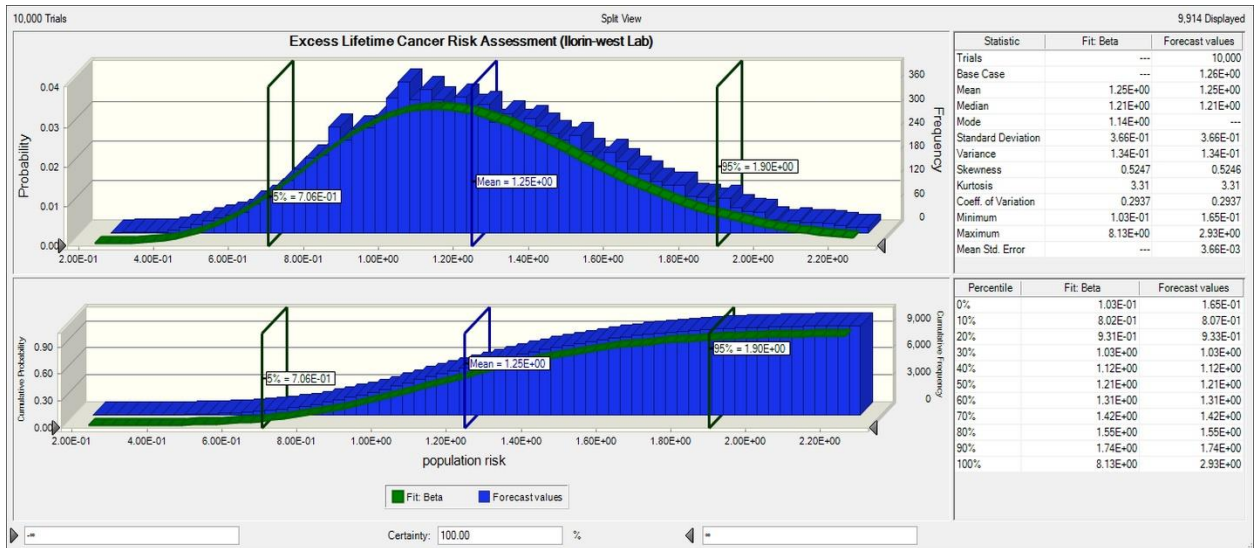
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(b) Ilorin-south *in-situ* cancer risk (indicating the mean, P 5% and P 95% cumulative probabilities for the cancer risk)

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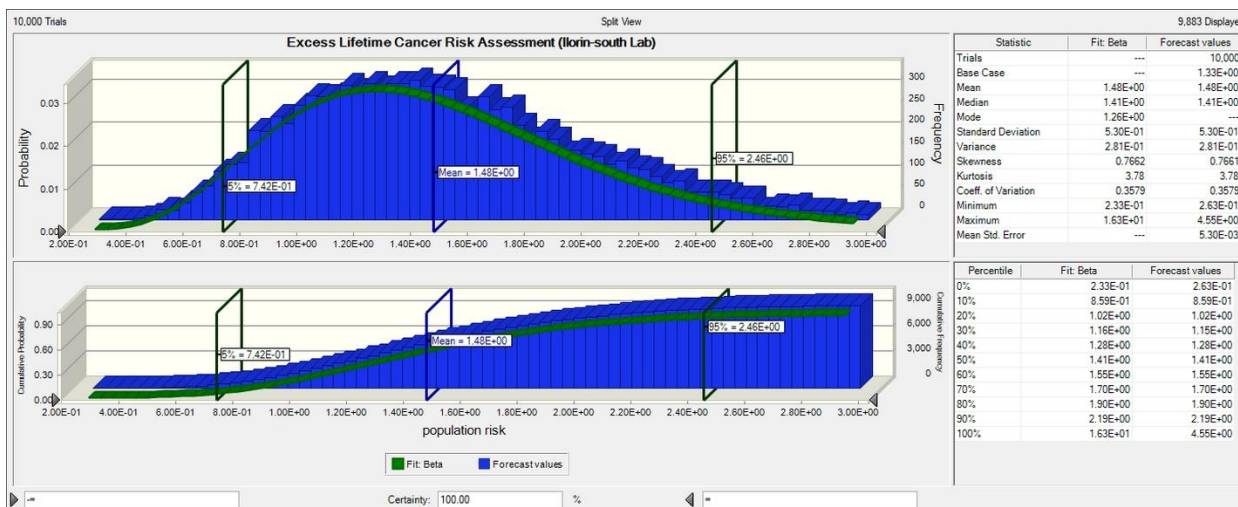
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(c) Ilorin-west Lab cancer risk (indicating the mean, P 5% and P 95% cumulative probabilities for the cancer risk)

438



439

440 (d) Ilorin-south Lab cancer risk (indicating the mean, P 5% and P 95% cumulative
441 probabilities for the cancer risk)

442 Figure 12. Cumulative probability plot of the Excess Lifetime Cancer Risk associated with
443 the measured radionuclides at the Kaolin mining sites. (a) Ilorin-west *in-situ* cancer risk, (b)
444 Ilorin-south *in-situ* cancer risk, (c) Ilorin-west Lab cancer risk and (d) Ilorin-south Lab
445 cancer risk.

446 4. Conclusions

447 The estimated mean values (both *in situ* and lab results) of ^{40}K , ^{234}Th and DR for the Kaolin
448 minefield in Ilorin-west are higher than that of Ilorin-south. However, the mean value of ^{238}U for
449 Ilorin-west is less than the estimated mean value for Ilorin-south. Also, all the measured activity
450 concentrations of ^{40}K , ^{238}U and ^{232}Th in all the locations are lower than their respective *in situ*
451 measurements. The mean values estimated for all radiological parameters for Ilorin-west were
452 comparably higher than that of Ilorin-south mine field for *in situ* measurements. This shows that
453 the Ilorin-west Kaolin mine field poses more significant source of radiation hazard. However, the
454 opposite was the case with the laboratory analysis of the bricks. This unexpected twist was
455 mainly due to the high values of ^{238}U observed in the samples of bricks from Ilorin-south (i.e. the

456 mean concentration of ^{238}U of Ilorin-south is almost twice the mean value obtained for bricks
457 samples from Ilorin-west). The mean values of all the hazard parameters for the bricks from both
458 Ilorin-west and Ilorin-south are less than the recommended limits. The cancer risk assessment
459 using the Monte Carlo simulations reveals values that are mostly within the recommended limits.
460 Therefore, the risk of cancer inducement due to radiation exposure is within the acceptable limits
461 for both mining sites.

462 **Declarations:**

- 463 • **Conflict of Interests:** The authors declare that they have no conflict of interest.
- 464 • **Data availability:** The data supporting the findings of this study are available on request
465 from the corresponding author.
- 466 • **Consent for publication:** All authors have read and agreed to the published version of
467 the manuscript.
- 468 • **Consent to participate:** Not applicable.
- 469 • **Ethics approval:** Not applicable.
- 470 • **Animal research:** Not applicable.
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- 477 • **Author contribution:** M.M.O. conceived and designed the research work, performed the
478 Monte Carlo Simulations, and wrote the paper. M.M.O., T.B.A and C.A.O. collect the
479 data, performed the risks analysis and compilation of the work. M.T and M.V contributed
480 to the writing and final editing of the manuscript. M.R.U. and K.J.O. supervised the work
481 and final editing of the manuscript.

482 **References**

- 483 Adagunodo et al. (2018). Radioactivity and radiological hazards from a kaolin mining field in
484 Ifonyintedo, Nigeria. *MethodsX*, 5, 362–374.
- 485 Ademola, A.K.; Hammed, O.S.; and Adejumobi, C.A. (2008). Radioactivity and dose assessment
486 of marble samples from Igbeti mines, Nigeria. *Radiation Protection Dosimetry*, 132(1),
487 94–97. doi:10.1093/rpd/ncn279
- 488 Ademola, A.K.; Hammed, O.S.; and Adejumobi, C.A. (2008). Radioactivity and dose assessment
489 of marble samples from Igbeti mines, Nigeria. *Radiation Protection Dosimetry*, 132(1),
490 94–97. doi:10.1093/rpd/ncn279.
- 491 Ajadi et al. (2016). Effect of effluents discharge on public health in Ilorin Metropolis, Nigeria.
492 *Ethiopian Journal of Environmental Studies and Management*, 9(4), 389.
- 493 Ajayi J.O.; Balogun B.B.; and Olabisi O. (2012). Natural Radionuclide Contents in Raw
494 Materials and the Aggregate Finished Product from Dangote Cement Plc, Obajana, Kogi

- 495 State, North Central Nigeria. *Research Journal of Environmental and Earth Sciences*,
496 4(11), 959-961, 2012 ISSN: 2041- 0492
- 497 Ajibola et al. (2021). Assessment of Annual Effective Dose Associated with Radon in Drinking
498 Water from Gold and Bismuth Mining area of Edu, Kwara, North-central Nigeria,
499 *Pollution*, 7(1): 231-240.
- 500 Akinyose et al. (2018). Radiological Impacts of Natural Radioactivity in Locally Produced
501 Tobacco Products in Ibadan, Oyo State, Nigeria. *Momona Ethiopian Journal of Science*
502 (MEJS), 10(1), 59-75. <http://dx.doi.org/10.4314/mejs.v10i1.5>.
- 503 Amana M.S. (2017). Radiation hazard index of common imported ceramic using for building
504 materials in Iraq, *Aust. J. Basic. Appl. Sci.* 11(10), 94–102.
- 505 Chandrasekaran et al. (2014). Spatial distribution and life time cancer risk due to gamma
506 radioactivity in Yelagiri Hills, Tamilnadu, India, *Egypt. J. Basic Appl. Sci.*, 1, 38–48.
- 507 Changsheng et al. (2012). Monte Carlo Simulation-Based Health Risk Assessment of Heavy
508 Metal Soil Pollution: A Case Study in the Qixia Mining Area, China, *Human and*
509 *Ecological Risk Assessment: An International Journal*, 18:4, 733-750. DOI:
510 10.1080/10807039.2012.688697.
- 511 Dailytrust, (2018). “how Nigeria can exploit untapped kaolin deposits”. Available at
512 [https://www.dailytrust.com.ng/how-nigeria-can-exploit-untapped-kaolin-deposits-](https://www.dailytrust.com.ng/how-nigeria-can-exploit-untapped-kaolin-deposits-265327.html)
513 [265327.html](https://www.dailytrust.com.ng/how-nigeria-can-exploit-untapped-kaolin-deposits-265327.html) (Accessed on 22nd February, 2019)
- 514 El-Dine et al. (2004). Radioactivity in local and imported kaolin types used in Egypt, *Appl.*
515 *Radiat. Isot.*, 60, 105–109.

- 516 Farai I.P.; and Ademola J.A. (2001). Population dose due to building materials in Ibadan,
517 Nigeria, *Radiat.Prot. Dosim.* 95, 69-73
- 518 IAEA (1996). Radiation protection and the safety of Radiation sources. International Atomic
519 Energy Agency, Wagramerstrsse 5, P. O Box 100, A1400 Vienna, Austria. IAEA-RPSR-
520 1 Rev 1.
- 521 IARC (1988) International Agency for Research on Cancer, Monograph on the Evaluation of
522 Carcinogenic Risks to Humans: Man Made Mineral Fibres and Radon, vol. 43. IARC
523 Monograph, Lyon, France. [https://publications.iarc.fr/Book-And-Report-Series/Iarc-](https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Man-Made-Mineral-Fibres-And-Radon-1988)
524 [Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Man-Made-](https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Man-Made-Mineral-Fibres-And-Radon-1988)
525 [Mineral-Fibres-And-Radon-1988](https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Man-Made-Mineral-Fibres-And-Radon-1988). Accessed 26 January 2021.
- 526 ICRP (1991). Recommendations of the International Commission on Radiological Protection
527 1990 (ICRP) Publication No. 60. *Annals of the ICRP* 21: 1-201. Elberg. pp119-13.
- 528 Isinkaye O.M.; Jibiri N.N.; and Olomide A.A. (2015). Radiological health assessment of natural
529 radioactivity in the vicinity of Obajana cement factory, North Central Nigeria. *J Med*
530 *Phys.*, 40(1), 52-59.
- 531 Isinkaye, O.M. (2018). Distribution and multivariate pollution risks assessment of heavy metals
532 and natural radionuclides around abandoned Iron-ore mines in North Central Nigeria.
533 *Earth Systems and Environment*, 2, 331–343. doi:10.1007/s41748-018-0035-0.
- 534 Janković, B.Ž.; Janković, M.M.; Marinović-Cincović, M.M.; Todorović, D.J; and Sarap, N.B.
535 (2018). Thermal analysis testing and natural radioactivity characterization of kaolin as
536 building material. *Journal of Thermal Analysis and Calorimetry*, 133(1), 481–487.
537 doi:10.1007/s10973-018-7159-1

- 538 Joel et al. (2018a). Assessment of natural radionuclides and its radiological hazards from tiles
539 made in Nigeria. *Radiation Physics and Chemistry*. 144: 43–47.
540 doi:10.1016/j.radphyschem.2017.11.003.
- 541 Kayode et al. (2015). Delineation of the subsurface geological structures of Omu-Aran area,
542 south-western Nigeria, using aeromagnetic data. National Physics Conference 2014
543 (PERFIK 2014) AIP Conf. Proc., 1657, 040012-1–040012-5. doi: 10.1063/1.4915173.
- 544 Leadership (2018). “kaolin as nigerias untapped goldmine” Available at
545 <https://leadership.ng/2018/08/15/kaolin-as-nigerias-untapped-goldmine/> (Accessed on
546 22nd February, 2019)
- 547 Mazzilli B.; and Saueia C. (1999). Radiological implications of using phosphogypsum as a
548 building material in Brazil, *Radiat. Prot. Dosim.*, 86 (1), 63–67.
- 549 NRC. (1994). *Science and Judgment in Risk Assessment*. National Research Council.
550 Washington, DC, USA Plum LM, Rink L.
- 551 Olusola J.O.; Suraju A.A.; and Nurudeen A. (2013). Geochemical and Mineralogical Studies of
552 Kaolinitic Clays in Parts of Ilorin, Southwestern Basement Rock Area, Nigeria. *Universal*
553 *Journal of Geoscience*, 2(7), 212-221.
- 554 Omeje et al. (2018). Natural radioactivity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in
555 commercial building materials and their lifetime cancer risk assessment in Dwellers,
556 *Human and Ecological Risk Assessment: An International Journal*, 24(8), 2036-2053.

- 557 Omeje et al. (2020). Spatial distribution of gamma radiation dose rates from natural
558 radionuclides and its radiological hazards in sediments along river Iju, Ogun state
559 Nigeria. *MethodsX*. 7: 101086.
- 560 Omeje et al. (2021). Measurements of Seasonal Variations of Radioactivity Distributions in
561 Riverine Soil Sediment of Ado-Odo Ota, South-West Nigeria: Probabilistic Approach
562 Using Monte Carlo, *Radiation Protection Dosimetry*, 2021: ncab027.
563 <https://doi.org/10.1093/rpd/ncab027>.
- 564 Orosun et al. (2017). Natural radionuclide concentration and radiological impact assessment of
565 soil and water from Dadinkowa Dam, Northeast Nigeria. *Journal of the Nigerian
566 Association of Mathematical Physics*, 42 (1), 307 – 316.
- 567 Orosun et al. (2018). Radiological Safety of Water from Hadejia River. *IOP Conf. Series: Earth
568 and Environmental Science*, 173(2018), 012036 doi:10.1088/1755-1315/173/1/012036.
- 569 Orosun et al. (2018b). Measurement of Natural Radionuclides Concentration and Radiological
570 Impact Assessment of Fish Samples from DadinKowa Dam, Gombe State Nigeria.
571 *African Journal of Medical Physics*, 1(1): 25-35.
- 572 Orosun et al. (2019). Natural Radionuclides and Radiological Risk Assessment of Granite
573 Mining Field in Asa, North-central Nigeria, *MethodsX*. 6, 2504-2514.
- 574 Orosun et al. (2020). Dataset on radioactivity measurement of Beryllium mining field in
575 Ifelodun and Gold mining field in Moro, Kwara State, North-central Nigeria, *Data in
576 Brief*, 31, 105888. <https://doi.org/10.1016/j.dib.2020.105888>.

- 577 Orosun et al. (2020). Radioactivity levels and transfer factor for granite mining field in Asa,
578 North-central Nigeria. *Heliyon*. 6(6). e04240.
579 <https://doi.org/10.1016/j.heliyon.2020.e04240>.
- 580 Orosun et al. (2020a). Magnetic susceptibility measurement and heavy metal pollution at an
581 automobile station in Ilorin, North-Central Nigeria, *Environ. Res. Commun.*, 2(2020),
582 015001. <https://doi.org/10.1088/2515-7620/ab636a>
- 583 Orosun et al. (2020c). Monte Carlo approach to risks assessment of heavy metals at automobile
584 spare part and recycling market in Ilorin, Nigeria, *Sci. Rep.*, 10 (2020) 22084.
585 <https://doi.org/10.1038/s41598-020-79141-0>.
- 586 Orosun et al. (2021). Assessment of ambient gamma radiation dose and annual effective dose
587 associated with radon in drinking water from gold and lead mining area of Moro, North-
588 Central Nigeria, *Journal of Radioanalytical and Nuclear Chemistry*, (2021).
589 <https://doi.org/10.1007/s10967-021-07644-9>.
- 590 Orosun, M. M. (2021). Assessment of Arsenic and Its Associated Health Risks Due to Mining
591 Activities in Parts of North-Central Nigeria: Probabilistic Approach Using Monte Carlo,
592 *Journal of Hazardous Materials*, 412 (2021): 125262.
- 593 Orosun, M. M.; Usikalu, M.R.; Kayode, K. J. (2020b). Radiological hazards assessment of
594 laterite mining field in Ilorin, North-central Nigeria. *International Journal of Radiation*
595 *Research*. 18(4), 895-906.
- 596 Oyegun, R.O. (1985). The use and waste of water in a third world city. *Geo Journal*, 10 (2), 205-
597 210.

- 598 Oyeyemi et al. (2017). Measurements of radioactivity levels in part of Ota Southwestern Nigeria:
599 Implications for radiological hazards indices and excess lifetime cancer-risks. *Journal of*
600 *Physics: Conference Series*, 852, 012042. doi:10.1088/1742-6596/852/1/012042.
- 601 Radiation Solution Inc. (2015). RS-125/230 User Manual, Revision 1.05-December 2015,
602 Firmwave Version 5v95, Part Number D-1009, (2015) pp 7.
- 603 Saghi et al. (2019). Estimate the effective dose of gamma radiation in Iran cities: lifetime cancer
604 risk by Monte Carlo simulation model. *Environmental Geochemistry and Health*. 41:
605 2549–255. doi:10.1007/s10653-019-00300-y.
- 606 Turhan, Ş. (2009). Radiological impacts of the usability of clay and kaolin as raw material in
607 manufacturing of structural building materials in Turkey. *Journal of Radiological*
608 *Protection*, 29(1), 75–83. doi:10.1088/0952-4746/29/1/005
- 609 UNSCEAR (2000). Sources, effects and risks of ionization radiation, United Nations Scientific
610 Committee on the Effects of Atomic Radiation. Report to The General Assembly, with
611 Scientific Annexes B: Exposures from Natural Radiation Sources New York.
- 612 USEPA. (1997). *Guiding Principles for Monte Carlo Analysis*. Washington, DC, USA.
- 613 Usikalu et al. (2016). Assessment of geogenic natural radionuclide contents of soil samples
614 collected from Ogun State, South western, Nigeria, *International Journal of Radiation*
615 *Research*, 14(3), 355-361.
- 616 Usikalu et al. (2017). Assessment of radiological parameters of soil in Kogi State, Nigeria,
617 *Environmental Forensics*, 18(1), 1-14.

618 Usikalu et al. (2019). Radiation dose assessment of soil from Ijero Ekiti, Nigeria, Cogent
619 Engineering, 6, 1586271.

620 Usikalu M.R.; Akinyemi M.L.; and Achuka J.A (2014). Investigation of radiation levels in soil
621 samples collected from selected locations in Ogun State, Nigeria, IERI Procedia, 9, 156-
622 161. DOI: 10.1016/j.ieri.2014.09.056