Assessment of radiological risk from the soils of artisanal mining areas of Anka, North West Nigeria

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Assessment of radiological risk was carried out on twenty soil samples collected from agricultural, mining and mine processing areas in Anka, Zamfara State, North Western Nigeria. The measurement of activity concentration of $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ was performed using the gamma-ray spectrometer equipped with a high purity germanium detector. The values of the activity concentration of $^{226}\text{Ra}$ ranged from 24.69±4.26 to 82.20±15.62 Bq kg$^{-1}$, with a mean of 47.06±14.01 Bq kg$^{-1}$; $^{232}\text{Th}$ ranged from 22.52±3.44 to 159.47±16.81 Bq kg$^{-1}$, with a mean of 75.97±9.11; while $^{40}\text{K}$ ranged from 22.52±3.44 to 159.47±16.81 Bq kg$^{-1}$, with a mean of 75.97±9.11. The concentration of the Radium equivalent in the study area ranged from 60.41 to 307.30 Bq kg$^{-1}$, with a mean value of 172.33 Bq kg$^{-1}$. The absorbed dose rate in air was calculated and the values ranged between 26.80 and 135.02 nGy h$^{-1}$, with a mean of 76.64 nGy h$^{-1}$. The external hazard index was computed and the values ranged from 0.163 to 0.830, with a mean of 0.465. This value is within the safe limit of 1. The annual effective dose rate was calculated from the activity concentration with the minimum value of 32.87 μSv y$^{-1}$, while the maximum was 165.58 μSv y$^{-1}$, with a mean of 93.99 μSv y$^{-1}$, which is higher than the world average of 80 μSv y$^{-1}$ but less than the recommended annual effective dose safe limit of 1 mSv y$^{-1}$. Therefore, the soil does not constitute radiological threat to the local population in the environment.

Key Words: Anka, artisanal mining, radioactivity, radiological, radionuclide, soil.

INTRODUCTION

Naturally occurring radionuclides within certain environmental matrix are able to assume hazardous radiological proportions as the activity concentrations of radioactive materials in the Earth’s environment vary according to the geological formation. This is largely responsible for the uneven distribution of radionuclides and natural resources in the earth environment. The soil serves as a means of migration for transportation of radionuclides to the environment, it is considered the principal indicator to the radiological contamination in the

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in the environment (Elsaman et al., 2018).

A huge occurrence of about forty to fifty various types of untapped sub-soil resources buried under the soil in Nigeria has been reported (Merem et al., 2017). Anka, is noted for crude mineral mining and processing by artisans alongside farming and cattle rearing (Salisu et al., 2016; Plumlee et al., 2013). Minerals, such as gold, copper, lead and zinc are mined and pre-processed in Anka and environs. These minerals deposits exist in alluvial and eluvia forms, with some occurring as vein within the meta-sediments of the area. Anka came under the radar following the discovery of rise in ill health and mortality rates amongst children in the isolated communities by health workers in the area. Investigation by Lo et al., (2012), suggested that the mining and processing of lead-rich ore inside villages in Anka led to soil contamination and that the polluted soil and ore dust were probably the main sources of lead exposure affecting children resident in ore-processing villages.

The environment where artisanal mining and processing activities are carried out is considered a major source of exposure to varying degrees of ionizing radiation. This radiation emanates from natural radionuclides present in rocks, soils, plants and water bodies and mining and mineral processing increase the concentration of the end products. The measurement of gamma radiation dose from environmental sources is of significance because radiation of natural origin is the principal contributing factor to the external dose globally (UNSCEAR, 1988).

Therefore, as the spread of radioactive elements in the earth environment is unequal and the concentration enhanced during mining activities, the knowledge of their level of concentration and distribution within the environment plays a major role in radiation safety. This work seeks to evaluate the activity concentrations and absorbed dose from $^{226}$Ra, $^{232}$Th and $^{40}$K in the soils within artisanal mining and processing areas of Anka. It was recommended by Innocent et al., (2013), that periodic radiological assessment of proper radiation monitoring of the mining sites. Apart from complementing the previous findings, the result would be used to assess the radiological risk from natural radionuclides in the study area.

MATERIALS AND METHODS

Study area

With a population of 263,400 (Buba, 2016). Anka falls between latitude 11°51’N and 12°08’N, and longitude 5°51’E and 6°08’E. (Figure 1). However, samples were collected from mining and mine processing sites in Dareta, Abare, Dan Kampani and Daki Talkwas. The Anka River is the main water body in the study area; it lies about one kilometer to the north of the town and numerous seasonal streams dissect the landscape, pouring into the major river, the Anka river (Figure 1).

The geology of Anka is characterized by the Anka schist belt that hosts the lead mineralization, and the lead-copper-silver-gold polymetallic association. Anka is well known for artisanal gold exploitation for several decades and the mineral is hosted by schists, phyllites and quartzites associated with sub-regional structural elements subsidiary to the Anka fault (Waziri et al., 2013).

Sampling technique and sample preparation

Twenty (20) soil samples were systematically collected within 50 m from mining and mine processing sites as well as agricultural land. The samples were collected at an average depth of 10 cm. The samples were transferred to the Material Science laboratory at the Centre for Energy Research and Training, Zaria, where they were prepared. The samples were dried in an oven at about 120 to 150°C and ground into fine powder, using agate mortar and pestle, made of 99% silica to avoid contamination. The ground sample was sieved to 250 μm. 200 g of the prepared samples was packaged and transferred to the laboratory of National Institute for Radiation Protection and Research for laboratory analysis. The samples were weighed again, packaged and sealed in plastic cylindrical beakers, where they were stored for 28 days to allow for secular equilibrium between $^{238}$U and $^{232}$Th with their daughters, prior to the analysis.

Sample analysis

Sample analysis was undertaken at the National Institute of Radiation Protection and Research, University of Ibadan, Nigeria. Measurement of activity concentration of $^{226}$Ra, $^{232}$Th and $^{40}$K was carried out with the gamma-ray spectrometer equipped with a high purity germanium (HPGe) detector enclosed in a 10 cm cylindrical multilayer graded shield. The application of this method is based on the secular equilibrium between uranium and thorium with their daughter isotopes. Prior to the sample analysis, the background gamma radiation at the laboratory was measured with an empty sample container under similar environmental conditions. The value was later subtracted during the computation of the activity concentration.

Data analysis

Activity concentration

Calculations of number of counts per second for the photpeak and activity concentrations of each detected radionuclides was based on the concept secular equilibrium being. The activity concentration in Bq kg$^{-1}$ (A) in the samples was obtained as follows (Uosif et al., 2015).

$$A = \frac{N_{2}}{\varepsilon \eta m} \quad (1)$$

Where, $N_{2}$ is net counts per second (CPS) = (sample CPS – background CPS), $\varepsilon$ is the abundance of the γ-line in a radionuclide, $\eta$ is the measured efficiency for each gamma-line observed, and the mass of the sample in kilograms is denoted by m.

The 1764.8 keV of $^{214}$Bi gamma line was used to determine the activity concentration of $^{226}$Ra while the activity concentration of $^{232}$Th was determined with 2614 keV of $^{208}$Tl gamma line. The gamma line of $^{40}$K was determined directly from 1460.8 keV gamma line.
Figure 1. Map of Anka, Zamfara State, North Western Nigeria.

Radinium equivalent ($Ra_{eq}$)

The radiological health effect can be determined by evaluating the radium equivalent effect because it is a measure of radiation hazard. This allows for uniformity in terms of radiation exposure and the comparison of the specific activity of materials containing different amounts of $^{226}$Ra, $^{232}$Th and $^{40}$K (Mohamed et al., 2016; Uosif et al., 2015). $Ra_{eq}$ is evaluated on the basis that the gamma dose rate produced by $370 \text{ Bq kg}^{-1}$ of $^{226}$Ra, $259 \text{ Bq kg}^{-1}$ of $^{232}$Th and $4810 \text{ Bq kg}^{-1}$ of $^{40}$K is the same (Mohamed et al., 2016).

$$Ra_{eq} = A_{Ra} + 1.43 \ A_{Th} + 0.077 \ A_{K}$$

(2)

where, $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in the samples.

Calculation of absorbed dose rate ($D$)

The outdoor absorbed dose rate at a height of 1 m above the ground level from terrestrial sources of gamma radiation can be determined by measuring the specific activity concentrations of the $^{226}$Ra, $^{232}$Th and $^{40}$K in soil samples using the formula (Mohamed et al., 2016)

$$D \ (nGy^{-1}) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_{K}$$

(3)

Where, $D$ is given in nGy h$^{-1}$, $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the specific
Table 1. Specific activity, radium equivalent, absorbed dose, Hazard index and annual equivalent dose rate for soil samples from Anka.

| Sample code | Activity concentration (Bqkg⁻¹) | Raeq (Bqkg⁻¹) | Absorbed dose (nGyh⁻¹) | Hexp (µSv y⁻¹) |
|------------|--------------------------------|---------------|-------------------------|----------------|
|            | ²²⁶Ra | ²³²Th | ⁴⁰K | | |
| SL1 | 57.87±14.79 | 327.06±57.52 | 361.53±166.56 | 553.40 | 239.36±46.02 | 1.494 |
| SL2 | 55.62±15.91 | 102.61±11.70 | 542.64±156.93 | 244.14 | 110.30±20.96 | 0.659 |
| SL3 | 43.39±13.23 | 222.67±33.95 | 1052.34±305.67 | 442.84 | 198.42±39.36 | 1.196 |
| SL4 | 31.40±6.29 | 325.22±45.23 | 342.19±100.49 | 522.81 | 225.21±34.42 | 1.412 |
| SL5 | 26.11±8.19 | 22.52±3.44 | 27.20±8.03 | 60.41 | 26.80±6.20 | 0.163 |
| SL6 | 24.69±4.26 | 39.02±7.30 | 173.55±50.51 | 93.85 | 42.21±8.48 | 0.253 |
| SL7 | 54.55±13.80 | 55.66±7.91 | 174.39±50.75 | 147.57 | 66.09±13.27 | 0.399 |
| SL8 | 42.46±10.58 | 346.99±50.49 | 794.38±231.38 | 599.82 | 262.32±45.03 | 1.620 |
| SL9 | 60.10±15.03 | 88.47±11.75 | 332.73±96.46 | 212.23 | 74.31±13.70 | 0.573 |
| SL10 | 47.06±12.79 | 34.59±4.84 | 106.52±31.09 | 104.73 | 95.08±18.06 | 0.283 |
| SL11 | 28.28±14.27 | 54.62±7.40 | 184.79±53.83 | 104.73 | 47.08±10.13 | 0.283 |
| SL12 | 34.84±15.35 | 64.25±8.43 | 439.55±127.23 | 120.62 | 53.76±13.31 | 0.326 |
| SL13 | 54.53±14.51 | 73.32±8.56 | 194.63±56.56 | 160.56 | 73.23±17.49 | 0.434 |
| SL14 | 53.02±14.32 | 111.16±11.84 | 123.70±36.18 | 174.36 | 77.59±14.23 | 0.471 |
| SL15 | 75.38±16.72 | 362.30±35.49 | 542.16±159.20 | 221.50 | 96.79±15.28 | 0.598 |
| SL16 | 31.17±13.82 | 209.07±36.53 | 940.66±274.38 | 635.22 | 276.26±35.80 | 1.715 |
| SL17 | 17.99±1.24 | 92.43±12.25 | 85.91±25.57 | 402.57 | 179.90±39.89 | 1.087 |
| SL18 | 23.84±3.48 | 193.14±25.76 | 508.27±148.88 | 156.78 | 67.72±9.04 | 0.423 |
| SL19 | 51.05±10.69 | 63.33±8.52 | 299.24±86.71 | 339.17 | 148.87±23.38 | 0.916 |
| SL20 | 18.72±2.02 | 234.62±32.90 | 761.69±221.86 | 164.65 | 74.31±13.70 | 0.445 |
| Min | 17.99±1.24 | 22.52±3.44 | 27.28±8.03 | 60.41 | 23.05±2.99 | 0.163 |
| Max | 75.38±16.72 | 362.30±35.57 | 1052.34±305.67 | 635.22 | 297.54±55.21 | 1.715 |
| Mean | 41.60±11.06 | 151.15±21.09 | 380.34±116.41 | 273.10 | 121.78±21.89 | 0.737 |

Activity concentration of ²²⁶Ra, ²³²Th and ⁴⁰K, respectively.

External hazard index (Hexp)

The external hazard index (Hexp) is widely used to reflect external exposure. It provides a solitary index that expresses the gamma yield from various combinations of ²²⁶Ra, ²³²Th and ⁴⁰K in the sample. It is defined as follows (Mohamed et al., 2016):

\[ H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810} \]  

Annual effective dose rate (AEDR)

The Annual effective dose rate (µSv y⁻¹) was computed as described by Mohamed et al., (2016). The evaluation of year-long effective dose rates, the conversion factor from absorbed dose in air to the effective dose (0.7 SvGy⁻¹) and outdoor occupancy factor (0.2) given by Duruso and Yildirim (2017) and Mohamed et al. (2016).

\[ AEDR \text{ (µSv y}^{-1} \text{)} = D \text{ (nGy h}^{-1} \text{)} \times 8760 \text{ (h}^{-1} \text{)} \times 0.14 \text{ (SvGy}^{-1} \text{)} \times 10^{-3} \]  

RESULTS AND DISCUSSION

The measurement of the radioactivity levels of ²²⁶Ra, ²³²Th and ⁴⁰K in soil samples collected from Anka was determined using the HPGe detector. These values including the Raeq, D, Hexp, and AEDR are presented on Table 1. The values of the activity concentration of ²²⁶Ra ranged from 17.99±1.24 (Abare) to 75.38±16.72 (Dareta) Bqkg⁻¹, with a mean of 41.60±1.06 Bqkg⁻¹. ²³²Th ranged from 22.52±3.44 Bqkg⁻¹ (Abare) to 362.30±57.52 Bqkg⁻¹ (Dareta), with a mean of 151.15±21.09; while ⁴⁰K ranged from 27.2±8.03 (Abare) to 1052.34±305.67 Bqkg⁻¹ (Dareta), with a mean of 380.34±116.41 Bqkg⁻¹.

A summary of the activity concentration of ²²⁶Ra, ²³²Th and ⁴⁰K is presented in Figure 2. Dareta accounted for the highest concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K while Abare recorded the lowest values. Analysing the results obtained in this study, the mean activity concentrations for ²²⁶Ra and ²³²Th are higher than the world average of 36 Bqkg⁻¹ and 30 Bqkg⁻¹, respectively (UNSCEAR, 2000).

The mean activity concentration of ⁴⁰K is lower than the world average of 400 Bqkg⁻¹ (UNSCEAR, 2000). This generally suggests that the radioactivity concentration in the study area is higher than the world average.

The Raeq in the study area ranges from 60.41 to 635.22 Bqkg⁻¹, with mean value of 273.10 Bqkg⁻¹, which falls below the permissible limit of 370 Bqkg⁻¹ set by...
The D in air values ranged between 23.05±2.99 nGy h⁻¹ and 297.54±55.21 nGy h⁻¹, with a mean of 121.78±21.89 nGy h⁻¹. This value is higher than the world average value of 60 nGy h⁻¹ (UNSCEAR, 2000), which indicates that the dose from the study area is higher than most places in the world.

The external hazard index values ranged from 0.163 to 1.715, with a mean of 0.737, which is less than the recommended limit of 1 (UNSCEAR, 2000). Generally, the radiation hazard in the study region can be assumed to be lower than the recommended limit but not insignificant as 33% of the sites showed high radiation hazard indices.

The annual effective dose rate was calculated from the soil samples with the minimum value of 32.87 µSv y⁻¹, while the maximum was 338.81 µSv y⁻¹, with a mean of 149.29 µSv y⁻¹, which is higher than the world average of 80 µSv y⁻¹. This is less than 1 mSv y⁻¹, the limit on dose from public exposure.

Comparison of natural radioactivity levels in soils of Anka with those obtained from other studies within and outside Nigeria

A comparison of activity concentration of ²²⁶Ra, ²³²Th, ⁴⁰K and Ra eq from different studies around the world and the present study has been carried out and is summarized on Table 2. For ²²⁶Ra (47.06±14.01 Bq kg⁻¹), the minimum average concentration was recorded in Utagunmodi, Nigeria (Ademola et al., 2013) while the maximum average value of 102.08±3.96 Bq kg⁻¹ obtained was reported in Kedah, Malaysia (Alzubaidi et al., 2016).

The minimum average concentration of ²³²Th of 11.41±3.28 Bq kg⁻¹ was recorded at Suez Canal region, Egypt (Fares et al., 2017) and the maximum average of 155.36 Bq kg⁻¹ was recorded in Kaduna, Nigeria (Gyuk et al., 2017). For ⁴⁰K, the minimum value of 102.8 ± 12.1 Bq kg⁻¹ was reported in Utagunmodi, Nigeria while the maximum average of 505.1 ± 7.1 Bq kg⁻¹ was reported in Utagunmodi, Nigeria (mining site) Ademola et al., 2013).
Table 2. Comparison of activity concentration and radium equivalent for soil of Anka with those of other regions/countries.

| Country/region                  | Activity concentration (Bq kg⁻¹) | Raₑq (Bq kg⁻¹) | Reference               |
|---------------------------------|----------------------------------|----------------|-------------------------|
|                                 | Ra-226                           | Th-232         | K-40                    |
| Panipat, India                  | 30.24 ± 0.53                     | 29.89 ± 0.61   | 291.06 ± 0.57           | 93.41 | Kumar et al. (2017) |
| Malnichera Bangladesh           | 55.25 ± 4.68                     | 125.27 ± 5.81  | 497.91 ± 43.83          | 269.24 ± 16.06 | Miah et al. (2012) |
| Zamfara, Nigeria                | 12.12 ± 1.37                     | 60.117 ± 1.98  | 426.51 ± 9.67           | -    | Innocent et al. (2013) |
| Kaduna, Nigeria                 | 62.28                            | 155.36         | 459.56                  | -    | Gyuk et al. (2017) |
| Balad, Iraq                     | -                                | -              | -                       | 33.24 | Assie et al. (2016) |
| Kedah, Malaysia                 | 102.08 ± 3.96                    | 133.96 ± 2.92  | 325.87 ± 9.30           | 52.15 | Miah et al. (2012) |
| Punjab, India                   | 57.64                            | 87.42          | 143.04                  | 192.76 | Singh et al. (2005) |
| Suez Canal, Egypt               | 11.63 ± 3.35                     | 11.41 ± 3.28   | 327.65 ± 80.05          | 132.14 | Fares et al. (2017) |
| Tulkarem, Palestine             | 34.5                             | 23.8           | 120.0                   | 72.0  | Assie et al. (2016) |
| Utagunmodi, Nig. Mining site    | 8.8 ± 1.9                        | 17.5 ± 2.7     | 102.8 ± 12.1            | 31.75 | Ademola et al. (2013) |
| World                           | 55.3 ± 1.2                       | 26.4 ± 2.7     | 505.1 ± 7.1             | 132.14 | Fares et al. (2017) |
| This study                      | 41.60 ± 11.09                    | 151.15 ± 21.09 | 380.34 ± 116.41        | 373.10 | UNSCEAR (2000)     |

Table 3. Comparison of absorbed dose, external hazard index and annual effective dose rate for soil of Anka with those of other regions.

| Country/region                  | Absorbed dose (nGy h⁻¹) | Hₑx | AEDR (µSv y⁻¹) | Reference               |
|---------------------------------|-------------------------|-----|---------------|-------------------------|
| Panipat, India                  | 44.16                   | -   | 54            | Kumar et al. (2017)    |
| Malnichera, Bangladesh          | 124.12 ± 2.59           | 0.601 | 152.23 ± 9.31 | Miah et al. (2012) |
| Zamfara, Nigeria                | 59.70 ± 2.23            | -   | 73            | Innocent et al. (2013) |
| Balad, Iraq                     | 17.558                  | 0.089 | 70            | Gyuk et al. (2017)    |
| Kedah, Malaysia                 | 141.62                  | 0.859 | 168           | Assie et al. (2016)   |
| Punjab and Himachal Pradesh,India| -                       | 0.52 | 87            | Singh et al. (2005)   |
| Egypt, Suez Canal               | 26.12                   | 0.14 | -             | Fares et al. (2017)   |
| Tulkarem, Palestine             | 35.5                    | 0.30 | 44            | Thabayneh et al. (2012) |
| Utagunmodi, Nig. Mining Site    | 20.4 ± 2.1              | 0.11 | 132.62        | Ademola et al. (2013) |
| World                           | 66.33 ± 4.1             | 0.36 | 439.73        | UNSCEAR (2000)        |
| This study                      | 121.78                  | 0.737 | 149.29        | UNSCEAR (2000)        |

A comparison of the average radium equivalent activity Raₑq indicates that the minimum average of 33.241 Bq kg⁻¹ was reported in Balad, Iraq ([Assie et al., 2016] whereas the maximum average of 458.785 Bq kg⁻¹ was reported in Kedah, Malaysia (Alzubaidi et al., 2016).

Table 3 summarizes the comparison of absorbed dose, external hazard index and the annual effective dose rate obtained from different studies. The average minimum absorbed dose and external hazard index were recorded in Balad, Iraq with values of 17.558 nGy h⁻¹ and 0.089 respectively (Assie et al., 2016). However, Kedah, Malaysia Alzubaidi (2016) recorded the average maximum value of 141.62 nGy h⁻¹ for absorbed dose and 0.859 for external hazard index. The average minimum of annual effective dose rate of 30 µSv y⁻¹ was recorded in Suez Canal region, Egypt (Fares, 2017) while the average maximum of 439.73 µSv y⁻¹ was recorded for mining site, Utagunmodi, Nigeria (Ademola et al., 2013). The result by the latter is however not consistent with those obtained from other studies considering the level of activity concentration of natural radionuclides from which the annual effective dose rate is evaluated. The values would have been much lower and consistent with the result of this study.

Conclusion

The gamma-ray spectrometer equipped with a HPGe detector was used in the measurement of activity concentration of ²²⁶Ra, ²³²Th and ⁴⁰K from soil samples in Anka, Zamfara State. From the result obtained in the
study area, the mean activity concentrations for $^{226}\text{Ra}$ and $^{232}\text{Th}$ are higher than the world average of 35 Bq kg$^{-1}$ and 30 Bq kg$^{-1}$, respectively (UNSCEAR, 2000). Generally, the radioactivity levels recorded in this study is higher than those recorded by Ademola et al. (2013) and Innocent et al. (2013) (Table 2). Hence, the increase in artisanal mining activities in the study area is increasing the external gamma radiation. The mean external hazard index was evaluated to be 0.737, which is less than the limit of 1. The annual effective dose rate is less than the limit on dose from public exposure (1 mSv yr$^{-1}$); this suggests that the risk of radiation hazard to humans and animals is insignificant. Hence, the soil does not constitute radiological threat to the local population in the environment.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

REFERENCES

Ademola AK, Bello AK, Adejumobi AC (2013). Determination of natural radioactivity and hazard in soil samples in and around gold mining area in Itagunmodi, south-western, Nigeria. Journal of Radiation Research and Applied Sciences 7:245-255.

Alzubaidi G, Hamid F, Abdul RI (2016). Assessment of natural radioactivity levels and radiation hazards in agricultural and virgin soil in the state of Kedah, North of Malaysia. The Scientific World Journal pp. 1-9.

Assie A, Oudah AJA, Jasmis AS, Al-Mashhadani AH (2016). Determination of natural radioactivity by gamma spectroscopy in Balad soil, Iraq. Advances in Applied Research Science 7(1):35-41.

Buba FN (2016). Analysis of the Spatial Distribution of Lead Concentration in the Soil of Anka, Zamfara State, Nigeria. Journal of Environment Pollution and Human Health 4(1):16-23.

Durusoy A, Yildirim M (2017). Determination of radioactivity concentrations in soil samples and dose assessment for Rize Province, Turkey. Journal of Radiation Research and Applied Sciences 10(4):348-352.

Elsaman R, Omer MAA, Seleem EMM, El-Taher A (2018). Natural Radioactivity Levels and Radiological Hazards in Soil Samples Around Abu Kargas Sugar Factory. Journal of Environmental Science and Technology 11:28-38.

Fares S (2017). Measurements of natural radioactivity level in black sand and sediment samples of the Temsah Lake beach in Suez Canal region in Egypt. Journal of radiation research and applied sciences 10(3):194-203.

Gyuk PM, Habila SS, Dogara MD, Kure N, Daniel HI, Handan TE (2017). Determination of Radioactivity Levels in Soil Samples At Chikun Environment of Kaduna Metropolis using Gamma Ray Spectrometry. Science World Journal 12(2):52-55.

Innocent AJ, Onimisi MY, Jonah SA (2013). Evaluation of naturally occurring radionuclide materials in soil samples collected from some mining sites in Zamfara State, Nigeria. British Journal of Applied Science and Technology 3(4):684.

Kumar A, Kumar S, Singh J, Singh P, Bajwa BS (2017). Assessment of natural radioactivity levels and associated dose rates in soil samples from historical city Panipat, India. Journal of radiation research and applied sciences 10(3):283-288.

Lo YC, Dooyma CA, Neri A, Durant J, Jefferies T, Medina-Marino A, de Ravello L, Thorughman D, Davis L, Danksi RS, Samson MY (2012). Childhood lead poisoning associated with gold ore processing: a village-level investigation-Zamfara State, Nigeria, October–November 2012. Environmental Health Perspectives 120(10):1450-1455.

Merem EC, Twumasi Y, Wesley J, Isokpehi P, Shenge M, Fageir S, Crisler M, Romorno C, Hines A, Hirse G, Ochai S, Leggett S, Nwaigboso E (2017). Assessing the Ecological Effects of Mining in West Africa: The Case of Nigeria, International Journal of Mining Engineering and Mineral Processing 6(1):1-19.

Miah A, Miah MM H, Kamal M, Chowdhury MI, Rahmatullah M (2012). Natural radioactivity and associated dose rates in soil samples of Malnichera Tea Garden in Sylhet district of Bangladesh. Journal of Nuclear and Particle Physics 2(6):147-152.

Plumlee GS, Durant JT, Mornan SA, Neri A, Wolf RE, Dooyma CA, Hageman PL, Lowers HA, Ferntette GL, Meeker GP, Benzol WM (2013). Linking geological and health sciences to assess childhood lead poisoning from artisanal gold mining in Nigeria. Environmental health perspectives 121(6):744-750.

Salisu K, Yusuf MA, Ahmed M, Mohammed MU, Umar IA (2016). Analysis of the distribution of heavy metals in the soils of Bagega mining area Zamfara State, Nigeria. Bayero Journal of Pure and Applied Sciences 9(1):150-159.

Singh S, Rani A, Mahajan RK (2005). $^{226}\text{Ra}$, $^{232}\text{Th}$ and $^{40}\text{K}$ analysis in soil samples from some areas of Punjab and Himachal Pradesh, India using gamma ray spectrometry. Radiation measurements 39(4):431-439.

Thabayneh KM, Jazzar MM (2012). Natural radioactivity levels and estimation of radiation exposure in environmental soil samples from Tulkarem Province-Palestine. Open Journal of Soil Science 2(01):7.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1988). Effects and risks of ionizing radiations. United Nations, New York.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2000). Sources and effects of ionizing radiation, 2. Uosif MM, Issa SA, El-Salam LA (2015). Measurement of natural radioactivity in granites and its quartz-bearing gold at El-Fawakher area (Central Eastern Desert). Egypt. Journal of Radiation Research and Applied Sciences 8(3):393-398.

Wazir NM, Andrews JE (2013). In vitro bioaccessibility of lead in Artisanal mining contaminated soils and sediments from the Anka area, NW Nigeria. Earth Science Research 3(1):1-13.