Assessment of Naturally Occurring Radioactive Materials (NORM) in Mining Residues and Environmental Material from Sefwi, Awaso Bauxite Mine

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Assessment of Naturally Occurring Radioactive Materials (NORM) in mining residues and environmental material from Sefwi, Awaso bauxite mine

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ABSTRACT

Gamma ray spectrometry was used to quantify level of NORM in mining residues sampled at Awaso bauxite mine and surrounding communities. The radionuclides of interest were $^{238}$U, $^{232}$Th and $^{40}$K and the radioactivity levels were determined in soil, bauxite ore, red mud and water samples from wells. The radioactivity concentrations in soil, bauxite ore and red mud $^{238}$U, $^{232}$Th and $^{40}$K were $18.01±1.96$ Bq kg$^{-1}$, $19.07±2.12$ Bq kg$^{-1}$ and $103.21±1.74$ Bq kg$^{-1}$; $39.42±4.18$ Bq kg$^{-1}$, $97.32±10.63$ Bq kg$^{-1}$ and $14.68±1.82$ Bq kg$^{-1}$; $44.85±4.79$, $64.23±6.58$ and $125.30±18.72$ Bq kg$^{-1}$. The activity levels for both $^{232}$U and $^{232}$Th were above world-wide average values while Potassium-40 levels were lower. The mean activity concentration values of $^{238}$U, $^{232}$Th and $^{40}$K in water samples were $1.49±0.45$ Bq l$^{-1}$, $3.68±0.69$ Bq l$^{-1}$ and $15.69±0.28$ Bq l$^{-1}$ respectively and were within the world average activity concentrations except for bauxite ore and red mud. The committed effective dose was $0.74$ mSv and annual effective dose estimated to be $0.136$ mSv which is below recommended dose limit of $1$ mSv year$^{-1}$ for public exposure.

1. Introduction

Mining has been identified as one of the potential sources of exposure to Naturally Occurring Radioactive Materials (NORM) and they exist in various kinds of natural sources [1]. Elevated concentrations of these radionuclides are regularly found in geological materials such as ores and igneous rocks. Human activities around such geological setting may lead to higher concentration of radionuclides in the environment and consequently further exposure to ionizing radiation. If these activities are not well managed or controlled, there is a high possibility of these radionuclides leaching into the soil and water bodies, thereby exposing both workers and members of the public [2,3].
The radioactive materials that occur naturally in the environment are potassium, thorium, and uranium decay chains [4]. The emanated radiation from soil and rock is due to both the decay of the parent radionuclides and their daughter radionuclides and also depend upon their mineral composition. Many industries, particularly the mining industries have operated for a long time without knowledge that their operations could give rise to Naturally Occurring Radioactive Materials in mining residues and environmental materials [5, 6].

If the institutes fail to control the disposal site where the NORM are being disposed, this may lead to the leaching of NORM or their release into airborne dust and into the groundwater bodies. Again, leaching of the natural radionuclides from the local sources may leads to contamination of drinking water and foodstuffs and thereby expose members of the public and workers. Institutional control may need to be maintained for a longer time since the NORM is associated with long half-lives [7].

The main objective of this study was to assess the Naturally Occurring Radioactive Materials in water and soil from the environs of Sefwi, Awaso Bauxite Mine and to estimate the health risk to both mine workers and members of the public living in the vicinity of the mining area. Specific objectives were to identify and estimate the levels of the various radionuclides associated with NORM in bauxite mining and also to estimate the NORM exposure of workers and the public due to consumption of water from the area.

2. Study areas, materials and methods

2.1. Study Area Description

Sefwi, Awaso is a town situated in the Municipality called Bibiani-Anhwiaso-Bekwai of the Western North Region of Ghana with the geographical coordinates of 6°14'0"N and 2°16'0"W. It is at an elevation of 166 meters above sea level with a population of 29,748 according to 2010 census. The habitats are predominantly peasant farmers with a few engage in artisanal mining.

2.2. Materials

2.2.1. Collection of Soil, Bauxite Ore and Red Mud Samples

Soil, mining residue and the bauxite ore were collected within the perimeter of Awaso bauxite mine and 5 km away into the surrounding communities. Simple random sampling technique was adopted where the samples were collected using manual sampling tool i.e shovel into polythene bag. This technique used to ensure that results obtained from the sample which is an aggregation from three different locations into one representative sample with single coordinate and plotted as shown in figure 1. A total of 8 samples comprising of soil, ore and red mud samples were collected at 5 cm depth using hand shovel. Labeled polythene bags were used in collection of soil, ore and red mud samples.

2.2.2 Collection of Water Samples
Eight (8) water samples were collected from wells which are the main source of water to the community. These wells are situated at random locations in the community a few kilometers away from the site of mining. The wells were purged for a while before samples were collected into cleaned 2.5 L plastic bottles. Two drops of concentrated nitric acid were added after filling the water bottles in order to ensure that radionuclides do not attach themselves to the container walls.

![Geographical location and sampling points](image)

**Fig.1** Geographical location and sampling points

### 2.3 Preparation of Soil and Water sample for Laboratory Analysis

The soil samples were air dried for 7 days and then grinded using steel ball mill into fine particles and sieved with 500 μm mesh size pore in order to have a uniform matrix size. The sieved soils were then placed in an oven to dry for 3 to 4 hours at 105 °C temperature to completely remove excess moisture from the sample. The samples were then transferred to 500 ml labelled Marinelli beakers and completely sealed and stored for 30 days in order to allow short-lived daughters of $^{238}$U and $^{232}$Th decay series to attain secular equilibrium with their long-lived parent radionuclides. This step was also important to ensure that radon was removed from the sample volume before counting. The water samples were transferred to 1 Liter Marinelli beakers and sealed without any pre-treatment. The samples were weighed and recorded. They were counted for 10 hours long enough for low level radioactive materials to form peaks.

### 2.4 Instrumentation and Calibration

In order to obtain both qualitative and quantitative results from the samples, both energy and efficiency calibration were performed for the analytical technique used, high purity germanium gamma detector, prior to the analysis. The calibration was performed using known test sources and mixed radionuclides standard respectively for energy and efficiency in order to get accurate results. For efficiency calibration, the mixed
radionuclide standard was counted for 10 hours long and a spectrum was obtained and analysed for the peak areas formed. Genie-2000 Gamma Ray Acquisition and Analysis Software was used to identify the radionuclides present in the sample with respect to their well-known gamma energies. The actual samples were counted using the same geometry as the standard used at same counting time.

2.5 Determination of the Results

2.5.1 Calculation of Activity Concentration

The following expression was used to calculate the activity concentrations for natural radionuclides in soil, water, ore and red mud samples, the:

\[ A = \frac{N_D}{p \cdot T_c \cdot \eta(E) \cdot m} \]  \hspace{1cm} (1)

Where: \( A \) is the activity concentration, \( N_D \) is the net count area of the radionuclides in the sample, \( p \) is gamma ray emission probability (gamma yield), \( \eta(E) \) is the absolute counting efficiency of the detector system, \( T_c \) is the sample counting time and \( m \) is the mass of the sample.

2.5.2 Calculation of Absorbed Dose Rate

The equation below was used to determine absorbed dose rate from soil samples [2].

\[ D_{\gamma}(nGy/h) = DCF_K \times A_K + DCF_U \times A_U + DCF_{Th} \times A_{Th} \]  \hspace{1cm} (2)

Where: \( D_{\gamma} \) is Absorbed dose rate, DCF is Dose conversion factors; 0.462, 0.0417 and 0.604 (nGy·h⁻¹/Bq·kg⁻¹) respectively for \(^{238}\)U, \(^{40}\)K and \(^{232}\)Th, and \( A \) is Activity concentration of the radionuclide.

2.5.3 Calculation of Annual Effective Dose

To estimate the annual external effective dose, three factors were taken into consideration i.e. the conversion coefficient from absorbed dose in air to effective dose, the outdoor occupancy factor of 0.2 which assumes an average duration of time someone spent outdoors (8760 hours year⁻¹) and the annual estimated average effective dose received by a member is calculated using a conversion factor of 0.7 Sv·Gy⁻¹ [1].

\[ E_{\gamma} = D_{\gamma} \times 0.2 \times 8760 \times 0.7 \]  \hspace{1cm} (3)

Where: \( E_{\gamma} \) is the Annual effective dose and \( D_{\gamma} \) is the absorbed dose rate in soil.

2.5.4 Committed Effective Dose

The committed effective dose is determined by the activity concentration of the radionuclides of \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K in a sample, the amount of water a person take in liters per year. According to [8] guideline for drinking water, an individual is recommended to take 730 L·year⁻¹ and the ingestion dose coefficient for \(^{238}\)U, \(^{232}\)Th, \(^{40}\)K is 45, 230 and 6.4 nSv·Bq⁻¹ respectively [1].

The equation below is used to calculate committed effective dose.
\[ S_{\text{ing}}(w) = I_w \sum_{j=1}^3 DCF_{\text{ing}}(U, Th, K) \times A_{sp}(w) \]  

(4)

where: \( S_{\text{ing}}(w) \) is the committed effective dose, \( A_{sp} \) is the activity concentration of the radionuclide in the sample in Bq\(^{-1}\), \( I_w \) is the intake of water in L\(\text{year}^{-1}\) and \( DCF_{\text{ing}} \) is the ingestion dose coefficient in Sv\(\text{Bq}^{-1}\).

3. Results and Discussion

Table 1 indicates the activity concentrations of \(^{238}\text{U},^{232}\text{Th}\) and \(^{40}\text{K}\) radionuclides present in the soil samples, bauxite ore and red mud collected at Awaso bauxite mine and surrounding areas. The activity concentrations were used to calculate the mean absorbed dose rate as 36.21 nGy\(\text{h}^{-1}\) and the mean annual effective dose of 0.136 mSv in the study area. The value obtained indicates that the radiation dose or exposure is within the recommended dose limit of 1 mSv for members of the public and 20 mSv for mine workers [9].

Table 1 Activity concentrations of natural radionuclides content in soil, bauxite ore and red mud samples collected from the study area, absorbed dose and effective dose

| Sample ID | Radionuclide Concentration (Bqkg\(^{-1}\)) | Absorbed dose rate (nGy\(\text{h}^{-1}\)) | Annual effective dose (mSv) |
|-----------|------------------------------------------|----------------------------------------|---------------------------|
|           | \(^{238}\text{U}\) | \(^{232}\text{Th}\) | \(^{40}\text{K}\) |                                  |                                |
| SS1       | 29.41 ± 3.22 | 32.21 ± 3.45 | 178.71 ± 18.37 | 40.49 | 0.049                        |
| SS2       | 16.96 ± 1.62 | 16.09 ± 1.53 | 56.40 ± 5.02 | 19.89 | 0.024                        |
| SS3       | 12.71 ± 1.51 | 13.52 ± 1.61 | 14.68 ± 1.82 | 14.65 | 0.017                        |
| SS4       | 12.16 ± 1.30 | 13.68 ± 1.59 | 105.94 ± 11.55 | 18.29 | 0.022                        |
| SS5       | 25.80 ± 2.63 | 28.98 ± 2.92 | 167.20 ± 16.06 | 36.40 | 0.045                        |
| SS6       | 10.98 ± 1.53 | 9.93 ± 1.62 | 96.33 ± 9.96 | 15.09 | 0.019                        |
| Red mud   | 44.85 ± 4.79 | 64.23 ± 6.58 | 125.30 ± 18.72 | 67.24 | 0.082                        |
| Ore       | 39.42 ± 4.18 | 97.32 ± 10.63 | 14.68 ± 1.82 | 77.60 | 0.095                        |

Mean 22.51±2.60 34.49±3.74 94.91±10.42 36.21 0.136
Range (Min-Max) 10.98 -44.85 9.93- 97.3 14.68 - 167.20 14.65 – 77.60 0.017 – 0.095
Figure 2 represents the activity concentration values of radionuclides ($^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$) in the entire soil samples at six different locations away from center of mining activities in the study area. The activity concentrations at SS1 and SS5 are higher compared to the rest of the sampled location points. As indicated in figure 1 SS1 and SS5 are closer to mines whilst the rest spaced further away from the mine site. All the values obtained for activity concentrations are lower as compared to the worldwide average activity concentration in soil samples being 35, 30 and 400 Bqkg$^{-1}$ for the mentioned radionuclides [1].

The activity concentrations in bauxite ore from this study as indicated in figure 3 is much higher as compared to radionuclide concentrations of natural origin found in bauxite and red mud as reported in some publications. Table 2 shows the comparison the activity concentrations of the bauxite ore in this work to those published by other investigations in different locations across the world. On the other hand, the activity concentration for $^{40}\text{K}$ is low as compared to the world average figure of 400 Bqkg$^{-1}$ [1]. The results obtained indicates that the activity concentration of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were 39.42±4.18 Bqkg$^{-1}$, 97.32±10.63 Bqkg$^{-1}$ and 14.68±1.82 Bqkg$^{-1}$ respectively in the ore sample. It also evident from this study, figure 3, that the bauxite ore is enriched with thorium in high proportion just as gold ore is enriched with uranium in studies done in Ghana.

**Table 2** Comparison of natural radioactivity concentrations of $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$ in the bauxite ores between the present study and published works in other countries.
| Description         | Activity Concentration (Bqkg⁻¹) | Country   | Reference |
|---------------------|---------------------------------|-----------|-----------|
|                     | $^{238}\text{U}$                | $^{232}\text{Th}$ | $^{40}\text{K}$ |        |
| Bauxite ore         | 70.2                            | 499       | -         | India   | [10]      |
| Bauxite ore         | 64                              | 154       | 9.4       | Brazil   | [11]      |
| Bauxite ore         | 72.8                            | 185       | 43        | Greece   | [12]      |
| Bauxite ore         | 150                             | 205       | 28.3      | Greece   | [13]      |
| Bauxite ore         | 419.0                           | 256.0     | 47.0      | Hungary  | [14]      |
| Bauxite ore         | 370.0                           | 400.0     | 63.0      | China    | [15]      |
| Bauxite ore         | 15.5-405                        | 19.9-414  | 12.8-111.6| Turkey   | [16]      |
| Bauxite ore         | 83.7                            | 107.3     | 192.0     | Saudi Arabia | [17] |
| Bauxite ore         | 39.42                           | 97.32     | 14.68     | Ghana    | Present study |

**Fig. 3** Activity concentration for natural radionuclides in bauxite ore

![Activity concentration for natural radionuclides in bauxite ore](image)

As shown in figure 4, the activity concentrations due to terrestrial gamma rays from $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in the red mud were recorded as 44.85±4.79 Bqkg⁻¹, 64.23±6.58 Bqkg⁻¹ and 185.30±18.72 Bqkg⁻¹ respectively. The figures for both $^{238}\text{U}$ and $^{232}\text{Th}$ are above world-wide acceptable limit of 35 and 30 Bqkg⁻¹ in while $^{40}\text{K}$ figure is reported to be low as compared to 400 Bqkg⁻¹ in [1]. The higher concentration of this radionuclide in the red mud suggests an increased concentration following the removal of alumina from the bauxite ore. The data indicates that the significant accumulation of $^{40}\text{K}$ occurs in alumina by the production process, resulting in very low level of the radionuclide in the red mud waste product.
Fig. 4 Activity concentration for natural radionuclides $^{232}$Th, $^{238}$U and $^{40}$K in red mud

As depicted in the Figure 5, the absorbed dose rate for the bauxite ore is higher than the one for the red mud and the soils. This is because of the higher activity concentration of radionuclides present in the sample and their dose conversion factors. Generally, the arithmetic means for absorbed dose for the samples (soil, bauxite and red mud) is $36.21 \text{nGy h}^{-1}$ and that is the energy deposited into tissue as a result of exposure to ionizing radiation.

Fig. 5 Comparison of the absorbed dose rates of the entire sample types (soils, bauxite ore and the red mud)

Figure 6 above illustrates the annual effective dose calculated for the samples and it is observed that the dose for bauxite ore is higher than the one for the red mud and the soils. The calculated annual effective dose is $0.136 \text{ mSv}$. This value is below the recommended dose limit of $20 \text{ mSv}$ for workers and $1 \text{ mSv}$ for members of the public as recommended by [9] in radiation protection principles for public radiation exposure control.
Fig. 6 Graphical representation of annual effective dose for soils, bauxite ore and the red mud

Results of water samples from the study area

Eight (8) groundwater samples were analyzed to determine the radionuclides presents and the results obtained are presented in table 3. The mean activity concentration values of $^{238}$U, $^{232}$Th and $^{40}$K for the water samples are 1.49±0.45 Bql$^{-1}$, 3.68±0.69 Bql$^{-1}$ and 15.69±0.28 Bql$^{-1}$ with ranges of 0.616 Bql$^{-1}$, 2.73-7.43 Bql$^{-1}$ and 12.16-21.64 Bql$^{-1}$ respectively and the committed effective dose is calculated to be 0.74 mSv.

Table 3 Activity concentrations and committed effective doses due to natural radionuclides in water from the study area

| Sample ID | Radionuclide Concentration (Bql$^{-1}$) | Committed effective dose (mSv) |
|-----------|----------------------------------------|-------------------------------|
|           | U-238        | Th-232      | K-40          |                               |
| WS1       | 6.16 ± 0.63  | 7.43 ± 0.35 | 13.48 ± 0.31  | 1.52                         |
| WS2       | 1.49 ± 0.55  | 2.73 ± 0.46 | 14.98 ± 0.29  | 0.58                         |
| WS3       | ND           | 3.04 ± 0.33 | 14.28 ± 0.29  | 0.57                         |
| WS4       | 1.21 ± 0.83  | 3.69 ± 0.38 | 13.57 ± 0.31  | 0.72                         |
| WS5       | 0.70 ± 0.25  | 3.73 ± 1.00 | 21.62 ± 0.20  | 0.75                         |
| WS6       | 1.00 ± 0.59  | 2.74 ± 0.42 | 17.59 ± 0.25  | 0.57                         |
| WS7       | 0.80 ± 0.43  | 2.85 ± 0.45 | 15.83 ± 0.27  | 0.58                         |
| WS8       | 0.59 ± 0.34  | 3.24 ± 2.14 | 12.16 ± 0.37  | 0.62                         |
Figure 7 represents the average activity concentration of three radionuclides in all water samples collected from the study area. The measured result shows that the activity concentration for $^{238}$U, $^{232}$Th and $^{40}$K were $1.49 \pm 0.45$ Bq l$^{-1}$, $3.68 \pm 0.69$ Bq l$^{-1}$ and $15.69 \pm 0.28$ Bq l$^{-1}$ respectively. The results show that the activity concentration for $^{238}$U is lower than the activity recommended by WHO guidelines in drinking water and the activity for $^{232}$Th is higher than the value recommendations. This is because bauxite mining is associated with thorium series than any other radionuclides series. Potassium-40 do not have the recommended value in WHO guidelines in drinking water as it is amenable to control by body.

|       | Mean       | Range       |
|-------|------------|-------------|
| $^{238}$U | $1.49 \pm 0.45$ | (Min- 0 – 6.16) |
| $^{232}$Th | $3.68 \pm 0.69$ | 2.73 - 7.43 |
| $^{40}$K  | $15.69 \pm 0.28$ | 12.16 - 21.64 |
| Activity Concentration (Bq/L) | 0 – 6.16 | 2.73 - 7.43 | 12.16 - 21.64 |

The figure 8 depicts the committed effective dose for different water samples collected from the study area. It is observed that WS1 has the highest committed effective dose than any other water samples. The value for committed effective dose depends on the activity concentration of the radionuclides, intake of water in liters per year and the ingestion dose coefficient. The average committed effective dose is calculated to be 0.74 mSv.
4. Conclusion

The results obtained from the study indicates that the radioactivity levels in soil for $^{238}$U, $^{232}$Th, and $^{40}$K for all locations where the soil samples were collected within the mine and surrounding communities were within the world activity concentration of the soil. It was also observed that the activity concentration in red mud and the bauxite ore were higher than the expected concentration of soil. The radioactivity levels in water were within the global average values for $^{238}$U, $^{232}$Th, and $^{40}$K and the committed effective dose were determined.

Declarations:

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Conflicts of interest/Competing interests

The authors declare that they have no known competing interest, financial or personal relationships that could have appeared to induced the work reported in this article.

Availability of data and material

All data pertaining this article has been presented

Code availability (Not Applicable)

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