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Evaluation of Radiation Hazard Indices Due to Naturally-Occurring Radioactive Materials in Ashaka Quarry Site and its Environs, Gombe State North-Eastern Nigeria

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Abstract

This study evaluates the radiological hazards associated with naturally occurring radioactive materials (NORM), specifically Potassium-40 (^{40}K), Radium-226 (^{226}Ra), and Thorium-232 (^{232}Th), in the Ashaka Cement Quarry and its surrounding environment in Gombe State, Nigeria. Soil and water samples were collected at different sites such as near active quarry activities and analyzed by gamma spectrometry. The results indicated that the activity concentrations in soil were generally higher than in water, and that some soil samples were slightly higher than the average concentrations in the world reported by UNSCEAR. Soil samples close to excavation areas, where possible, showed the highest concentrations, possibly a result of enrichment from mining activities. The radiological hazard indices were calculated, but are below the international safety limits; however, the elevated levels of ^{226}Ra and ^{232}Th indicate long term exposure risks, in particular the inhalation of radon gas. It is important to have continuous monitoring of the environment, as well as radiation protection for the workers and incorporation of radiation parameters in future environmental impact assessments to guarantee safety of workers and residents of the vicinity.

Keywords: Radiation, hazard indices, and NORMs, and Ashaka Quarry Site

Introduction

Naturally occurring radioactive materials (NORM) exist in the Earth's crust. They are found in rocks, soil, water, and even building materials. These materials contain radioactive elements like uranium-238 (^{23}U), thorium-232 (^{232}Th), and potassium-40 (K) which release ionizing radiation. Mining and quarrying activities can increase the level of NORM in the environment which can easily raise the risk of radiation exposure. In Nigeria, many limestone deposits have high amounts of uranium and thorium (Arogunjo et al., 2022), which break down into other harmful elements like radium-^{226}Ra and radon-^{222}Rn.

Quarry operations conducted by small-scale operators can adversely impact the environment, especially soil, water, and agricultural goods grown in proximity to quarry sites. Radionuclides are chemical elements with unstable isotopes that emit ionising radiation during their decay process. These isotopes, characterised by restricted lifespans varying from mere fractions of a second to several centuries, are designated as radioactive isotopes. During the degradation process, three types of radiation are emitted: alpha particles (α), beta particles (β), and gamma rays (γ) (Orosun et al., 2022). Subsequent emissions of radionuclides into the environment originate from industrial activities such as mining, milling, and fertiliser production (IAEA, 2014). The analysis of radionuclides in samples entails the quantitative assessment of energy spectra from gamma-ray sources and is frequently employed in astrophysical, nuclear, and geological research institutions. Gamma rays, distinguished by their high photon energy and frequency, constitute the most potent type of electromagnetic radiation. Their considerable penetrating capacity renders them physically similar to all other types of radiation.

Several studies have found high levels of radioactive materials at mining sites in Nigeria. For example, Jibiri et al. (2019) tested rocks from quarries in southwest Nigeria in which they found high levels of ^{238}U and ^{232}Th. The levels were above global safety limits. Other studies in the Middle Belt region showed the same problem (Oke et al., 2021), which had radiation hazard levels above what is allowed by safety rules. More research also shows that cement dust can carry NORM. For example, Akpan et al. (2022) found that cement dust had high radiation levels which added to background radiation in nearby areas and these findings show the need for regular testing and steps to reduce exposure. The Nigerian Nuclear Regulatory Authority (NNRA) is the body responsible for radiation safety in Nigeria. The IAEA and ICRP are other organisations with rules for staying safe around the world. They take measures to ensure their safety: They set limits to the amount of radiation that workers and the public can receive (ICRP, 2021), they wear protective gear, they have improved air exchange systems, and they use radiation shields.

The present study seeks to quantify the radiation exposure from naturally occurring radionuclides in soil samples obtained from the Ashaka quarry environment and to characterise the related radiological hazard factors. This research is motivated by the growing necessity to promote sustainable quarrying practices to reduce environmental contamination and public health hazards, particularly in communities reliant on mine for their economy.

Material and Methods

Location and geology of the Study Area

The Ashaka Cement Quarry is situated in Gombe State, Nigeria and is among the biggest cement manufacturing sites in the nation. The region has a large amount of limestone which is quarried and used to make cement. There are potential increases in exposure to NORM due to mining activity, and a radiological evaluation of the area soil and water is needed. The climate is tropical, with a pronounced wet and dry season, the mobility of radionuclides in the environment may be affected.

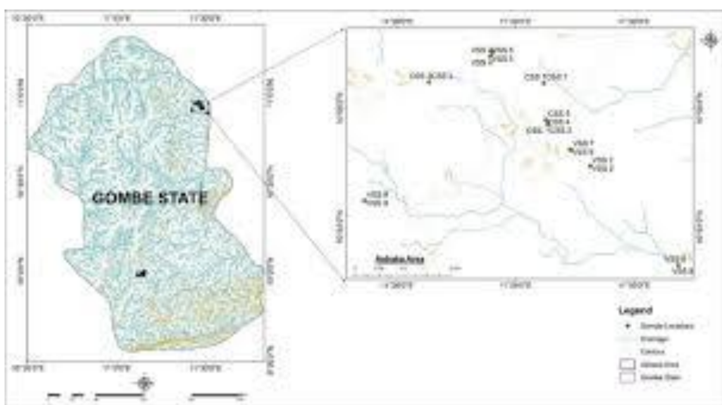

Fig.1: geographic location of Ashaka Cement Factory

Sample Collection

Samples were taken from the Ashaka Cement Quarry and its surrounding environment, totalling six samples, which included three soil samples and three water samples. Sampling locations were selected based on proximity to quarrying operations, probable exposure paths, and control sites. At each designated place where soil samples were taken, a Global Positioning System (GPS) device was utilised to ascertain the latitude and longitude.

Soil Sample Collection

Three soil samples were collected from different locations within and around the quarry site as shown in table 1. Each sample was obtained from the top 10 cm of the soil layer using a shovel to minimize contamination. The sampling points included:

1. **S1**: Soil deposit (active excavation area)
2. **S2**: Soil sample from Agricultural Farmland
3. **S3**: Control site (a location far from the quarry for comparison)

At each sampling point, approximately 2 kg of soil was collected and stored in labeled polyethylene bags to prevent moisture loss and contamination.

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Table1: Soil Samples Location

Name of location	Latitudes	Longitudes
Sabon Quarry (Ashaka)	10°55'20"N	11°27'42"E
Sabon Quarry (Ashaka)	10°54'20"N	11°27'50"E
Alheri (Ashaka)	10°56'20"N	11°28'41"E

Water Sample Collection

Water samples were obtained from diverse sources adjacent to the quarry site, as defined in Table 2, encompassing both surface and groundwater sources. The selection of water sampling sites was predicated on their probable exposure to NORM pollution. The three water sampling points included:

1. **W1**: Groundwater from a well in a nearby residential area
2. **W2**: Groundwater from a borehole within the quarry site
3. **W3**: Control sample (from a distant, unaffected water source)

Each water sample was collected in a 1-liter polyethylene bottle, pre-rinsed with the sampled water to minimize contamination. The bottles were tightly sealed, labeled, and transported to the laboratory under controlled conditions.

Table2: Water Sample Collection

Name of location	Latitudes	Longitudes
Sabon Quarry (Ashaka)	10°55'19"N	11°27'53"E
Sabon Quarry (Ashaka)	10°55'10"N	11°28'30"E
Alheri (Ashaka)	10°56'12"N	11°28'40"E

Soil Sample Preparation

The soil samples were air-dried at room temperature **for** 48–72 hours to remove moisture. Once dried, each sample was:

- Crushed and sieved through a 2 mm mesh to obtain a uniform particle size.
- Weighed and placed in a 250 ml Marinelli beaker, ensuring complete filling to maintain uniform sample geometry during gamma spectrometry.
- Sealed and stored for 28 days to allow radioactive equilibrium between radon (^{222}Rn) and its progeny before analysis.

Water Sample Preparation

The water samples were processed as follows:

- Filtered using a 0.45-micron filter to remove particulate matter.
- Acidified with 0.1 M HNO to prevent precipitation and microbial growth**.**
- Stored in 1-liter Marinelli beakers**,** sealed, and left for 28 days to ensure equilibrium between radium (^{226R}a) and radon (^{222}Rn).

Sample Analysis

In the ABU Zaria Radiation Laboratory, each fine soil and water sample was placed into a Marinelli beaker and sealed for approximately 29 days to enable the short-lived progeny of the ^{238}U and ^{232}Th decay series to attain equilibrium with their long-lived parent radionuclides. The radioactive samples were analysed using a high-resolution gamma-spectrometry system using a Sodium Iodide (NaI) detector, integrated with a computer-based modular processor and computer system. The detector was linked to an Uninterrupted Power Supply for 10 hours, during which identification and quantitative analysis of radionuclides were conducted using standard efficiency calibration.

Instrumentation and Calibration

The NaI radiation detector is connected to a Multi-Channel Analyser (MCA) module via connector pins to obtain various pulse amplitudes and differential pulse height spectra from the detector. This MCA module is connected to a Personal Computer (PC) via a PCI bus slot for data collecting and processing. The

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gamma-ray spectrometry apparatus employed for analysis comprises a highly protected and precisely calibrated 7.6 cm by 7.6 cm NaI (Tl) detector encased in a 5 cm thick lead shield to mitigate background radiation. The spectrometer underwent linearity testing and subsequent calibration for energy utilising gamma sources provided by the International Atomic Energy Agency in Vienna. This was accomplished by gathering spectral data from conventional sources with energies ranging from 0.511 to 2.62 MeV. The channel numbers of the photopeaks associated with various gamma energies were documented after 900 seconds. The energy and efficiency calibration of the gamma spectrometer was conducted utilising reference standard source material traceable to a mixed standard gamma source (ENV94084-200g) provided by Analytic Inc., Atlanta, GA, USA. The efficiency calibration curve for the NaI (Tl) detector was derived using the efficiencies calculated for ^{40}K, ^{238}U, and ^{232}Th. The detector assembly exhibits a resolution of around 8% at 0.662 MeV for ^{137}Cr.

Method of Data Analysis

Radiological Hazard Assessment

To evaluate the potential health risks associated with NORM in the Ashaka Cement Quarry, the following radiological hazard indices were calculated:

The background count was established by tallying an empty container of identical dimensions to those holding the samples and deducting this from the gross count. Each sample was counted for 36,000 seconds to minimise statistical uncertainty. Each sample was measured for a duration of 29,000 seconds. The peak area of each energy in the spectrum was utilised to calculate the activity concentrations. The formula was follow according to

$$A = \frac{C_n}{\varepsilon_\gamma \times P_\gamma \times t \times m} \quad \text{..................(1)}$$

Where $c\,n$ is the net count rate (background subtracted) under the photo peak, εγ is the absolute efficiency at the photo peak energy, Pγ is the gamma-ray emission probability, t is the counting time and m is the mass of the sample. (Rabiu et al., 2025, Gilmore et al., 2011)

Radiological Hazard Assessment

To evaluate the potential health risks associated with NORM in the Ashaka Cement Quarry, the following radiological hazard indices were calculated:

Radium equivalent activity index (Raeq)

A universal radiological index has been created to incorporate the activity levels of ^{226}Ra, ^{232}Th, and ^{40}K, reflecting their related radiation dangers (Diab et al., 2023). This index, referred to as the Radium Equivalent (Raeq) activity, is mathematically expressed according to the formula provided by UNSCEAR (2020), as detailed below:

External hazard index (H_{ex})

The External Hazard Index (Hex), which indicates external exposure, is defined as follows (UNSCEAR, 2020).

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad \text{........... (2)}$$

In addition to the external hazard index, radon and its transient decay products provide threats to the respiratory system. The internal hazard index is established to restrict the permissible maximum concentration of 226Ra to fifty percent of the threshold considered tolerable for external exposures exclusively. Internal exposure to radon and its decay products is quantified using the internal hazard index (Hin), computed based on the equation established by Ali et al. (2019).

Internal hazard index (H_{in})

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_k}{4810} \ldots\ldots\ldots (3)$$

Annual effective dose rate

To calculate the yearly outdoor effective dose rates, one must account for the conversion coefficient from absorbed radiation in air to effective dose (0.7 Sv Gy^{-1}) and the outdoor occupancy factor (0.2) as recommended by UNSCEAR (2020). Thus, the yearly effective radiation rate (mSv/year) was computed utilising the formula established by UNSCEAR (2020): Effective dose rate ($mSvyr^{-1}$) = D (ηGyh^{-1}) x 8760 hyr^{-1} x 0.7 x ($103mSv/10^9$) ηGy x 0.2.

$$Effective\ dose\ rate\ (mSvyr^{-1}) = D\ x\ 1.2264\ x10^{-3} \quad \ldots\ldots\ldots\ldots\ldots\text{.....................(4)}$$

The worldwide annual effective dose from the natural sources of radiation in areas of normal background is estimated to be $1mSvy^{-1}$ by (UNSCEAR, 2020).

Absorbed dose rate (D)

The absorbed dose rates in outdoor contexts (D), resulting from gamma radiation in the air at a height of 1 metre above the ground, were computed for the uniform distribution of naturally occurring radionuclides (226Ra, 232Th, and 40K) in accordance with UNSCEAR recommendations (2020). The conversion factors used to compute the absorbed gamma (γ) dose rate (D) in air per unit activity concentration in Bq/kg (dry weight) are 0.462 nGy/h for ^{226}Ra, 0.621 nGy/h for ^{232}Th, and 0.0417 nGy/h for ^{40}K (UNSCEAR, 2020; Ashraf et al., 2020).

$$D\ (nGyh^{-1}) = 0.462\ C_{Ra} + 0.621C_{Th} + 0.0417C_{k}. \quad \ldots\ldots\ldots (5)$$

Where D = Absorbed dose rate, $\mathbf{C_{Ra}}$ = Activity Concentration of radium, $\mathbf{C_{Th}}$ = Activity Concentration of Thorium and $\mathbf{C_{K}}$ = Activity Concentration of Potassium.

Excess Lifetime Cancer Risk (ELCR): It assesses the probability of individuals in a community developing cancer over their lifetime due to prolonged exposure to ionising radiation. The calculation use Equation (6), which correlates the ELCR to the previously established average effective dose (AED).

$$ELCR = AED \times DL \times RF \quad \ldots\ldots\ldots (6)$$

Here, DL represents a life expectancy of 70 years, while RF denotes the risk factor, which is specified as $0.05\ Sv^{-1}$ for stochastic effects.

Result and Discussion

The results of activity Concentrations of Radionuclides in Samples for the three natural radionuclides—Potassium-40 (^{40}K), Radium-226 (^{226}Ra), and Thorium-232 (^{232}Th)—in both soil and water samples from the Ashaka Cement Quarry and nearby areas are presented in Table 3.

The concentration of ^{40}K ranged from 55.37 ± 2.49 Bq/kg in Water Sample 3 to 85.38 ± 4.82 Bq/kg in Soil Sample 1. The levels are significantly lower than the one reported by UNSCEAR (2020) for the world-average for soil, which is 400 Bq/kg. This indicates that the gamma radiation hazard in the area is low due to 40K. The potassium levels are dependent on the type of rocks and minerals present in the earth's crust as potassium is abundantly found in the earth's crust (Arogunjo et al., 2022; Idris et al., 2019).

For ^{226}Ra, the values ranged from 14.02 ± 1.97 Bq/kg (Water Sample 2) to 37.19 ± 3.26 Bq/kg (Soil Sample 2). A value of 35 Bq/kg for ^{226}Ra in soil has been determined as world average, and the value of soil sample 2 is slightly higher than this value, potentially as a result of natural accumulation in the rocks or from mining operations. High levels of 226Ra is a concern because it can emit radon gas, which when inhaled over time is harmful (Salawu et al., 2021; Ononugbo et al., 2023).

The concentration of ^{232}Th ranged from 20.75 ± 2.39 Bq/kg (Water Sample 2) to 34.66 ± 2.20 Bq/kg (Soil Sample 1). According to UNSCEAR (2020), the average value per kg around the world is 30 Bq/kg. Two samples of soil exceeded this limit, Soil Sample 1 with the highest score. Thorium has strong radiation and a high level will result in a high gamma dose rate. The localization of Soil Sample 1 in the excavation area indicates that thorium rich minerals may have been brought to the surface by the mining activities (Adewoyin et al., 2020; Zakari et al., 2018).

The overall results showed that the levels of all three radionuclides were greater in soil than in water samples. This is in line with previous research indicating that soil is more efficient in retaining radioactive contaminants than water. This is particularly pronounced in tropical regions and soils have the property of retaining radionuclides to their surface through adsorption (Muhammed et al., 2024).

Table 3: Activity Concentrations of Radionuclides in Samples

No	Sample ID	K-40 (Bq/kg) ± Error	Ra-226 (Bq/kg) ± Error	Th-232 (Bq/kg) ± Error
1	Water Sample 1	79.47 ± 2.33	24.33 ± 2.09	26.68 ± 2.17
2	Water Sample 2	67.29 ± 3.27	14.02 ± 1.97	20.75 ± 2.39
3	Water Sample 3	55.37 ± 2.49	16.57 ± 1.62	23.72 ± 2.51
4	Soil Sample 1	85.38 ± 4.82	27.80 ± 3.01	34.66 ± 2.20
5	Soil Sample 2	70.92 ± 4.51	37.19 ± 3.26	24.52 ± 2.55
6	Soil Sample 3	76.39 ± 4.67	17.96 ± 1.51	34.44 ± 2.26

Detection limits: K-40: 14.54 Bq/kg, Ra-226: 3.84 Bq/kg, Th-232: 9.08 Bq/kg

All values recorded were above the minimum detection limits**:**

- ^{40}K: 14.54 Bq/kg
- ^{226}Ra: 3.84 Bq/kg
- ^{232}Th: **9.08 Bq/kg**

This is to validate the testing method, which is by gamma spectrometry, used in ABU Zaria as it is accurate and sensitive. The results can be trusted and will be useful for future radiation risk calculations.

Graphical Representation

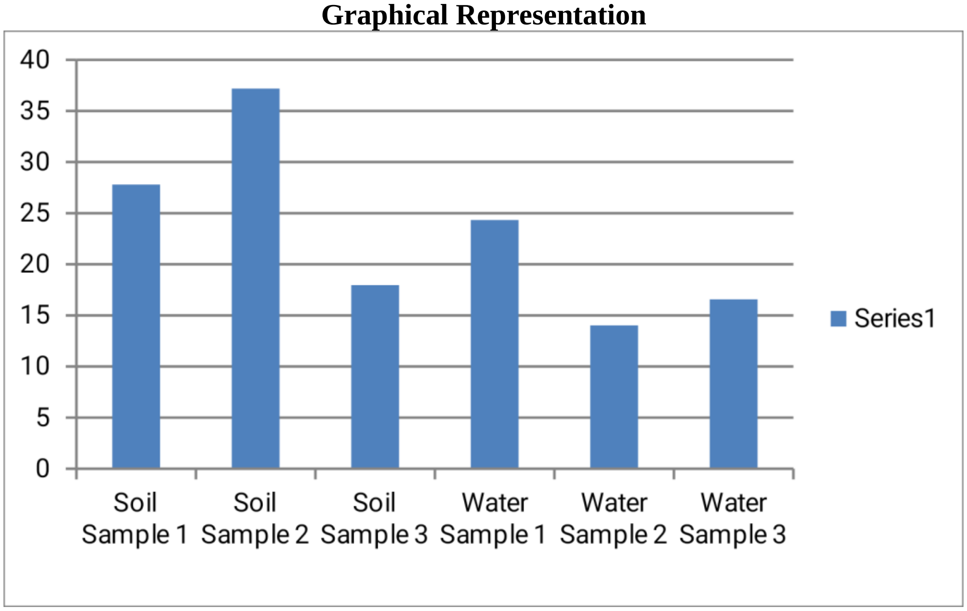

Figure1: Activity Concentration of ^40K in Soil and Water Samples

From figure 1, it is seen that Soil sample 1 (85.38 Bq/kg) had the highest concentration of Potassium-40 (^{40}K) while Water Sample 3 (55.37 Bq/kg) had the lowest concentration. The concentrations of all values are lower than the world average of 400 Bq/kg for soil (UNSCEAR, 2000).

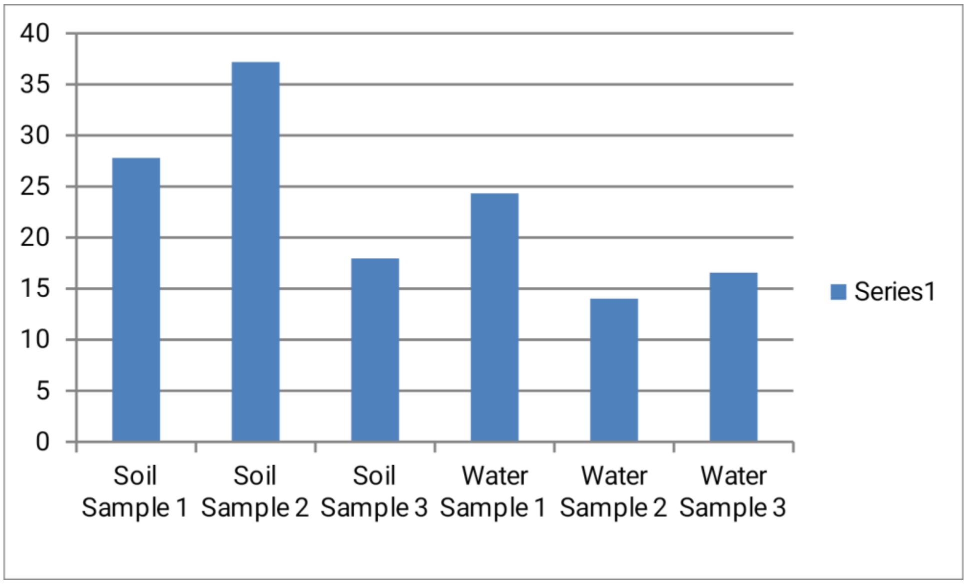

Figure 2: ***Activity Concentration of ^226Ra in Soil and Water Samples***

The highest activity was found in Soil 2 (37.19 Bq/kg) and the lowest in Water 2 (14.02 Bq/kg) as shown in fig. 2 Radium-226 (^{226}Ra). The radioactivity concentrations are lower than the soil radioactivity background concentration of 35 Bq/kg in the global average, and hence relatively low radiological risk.

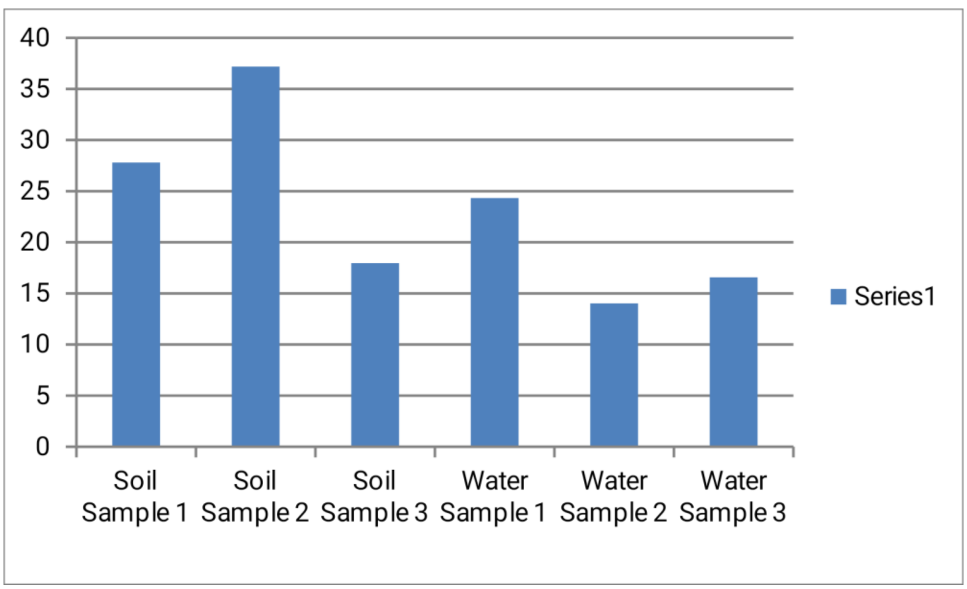

Figure 3: Activity Concentration of ^{232}Th in Soil and Water Samples

In fig 3 Thorium-232 (^{232}Th), Soil Sample 2 (34.66 Bq/kg) had the highest concentration. All values are below the w orldwide average of 30 Bq/kg for soil, except two slightly exceeding this threshold.

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Comparison with International Standards

Table 4 Comparison with International Standards

Radionuclide	UNSCEAR World Avg (Soil, Bq/kg)	Highest Observed Value
^{40}K	400	85.38 (Soil Sample 1)
^{226}Ra	35	37.19 (Soil Sample 2)
^{232}Th	30	34.66 (Soil Sample 1)

Table 4 compares the activity concentrations of radionuclides found in the Ashaka Cement Quarry area with global average values set by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2020). The focus is on three key radionuclides: Potassium-40 (^{40}K), Radium-226 (^{226}Ra), and Thorium-232 (^{232}Th).

These results show that the highest measured level of ^{40}K was 85.38 Bq/kg. This is significantly less than the world's average (400 Bq/kg) which is approximately 21% of the UNSCEAR standard. This indicates there is no significant radiation hazard in this location. This low level could be attributed to the poorly mineralised soil in the area which may be deficient in potassium minerals such as feldspar (Arogunjo et al., 2022; Salawu et al., 2021).

The highest concentration of ^{226}Ra found was 37.19 Bq/kg. Likewise, ^{232}Th was highest at 34.66 Bq/kg, compared to the UNSCEAR average of 30 Bq/kg. Both values are slightly high, but not to the extent that the limits are exceeded, hence it is worthwhile to mention, particularly near homes or farms (Idris et al., 2019; Ononugbo et al., 2023).

The problem with ^{40}K is that it is more hazardous than Radium-226 because it decays to radon gas (222Rn) which can be harmful if breathed for a prolonged period. Extensive exposure to radon has been associated with lung cancer. ^{226}Ra may also be ingested via contaminated drinking water and/or food crops grown in contaminated soil (UNSCEAR, 2020; Chidiebere et al., 2022).

Thorium-232 is also important because it gives off strong gamma radiation. This may be due to the type of rock in the quarry that is located in Soil Sample 1. Quarrying activities can expose thorium minerals like monazite, thereby increasing the radiation levels (Adewoyin et al., 2020; Zakari et al., 2018).

To summarize, the levels of ^{40}K are considered safe, while the levels of ^{226}Ra and ^{232}Th are slightly higher than the UNSCEAR average. The results of these findings do not indicate immediate health risk, but do indicate ongoing monitoring is necessary, particularly in areas where people live, work or farm close to the quarry.

Conclusion

The highest activity concentration was found for Soil Sample 1 (85.38 Bq/kg), and the lowest for Water Sample 3 (55.37 Bq/kg). All the values were found to be much lower than the average of 400 Bq/kg for the world given by UNSCEAR for the soil for ^{40}K. The concentration of ^{226}Ra in Soil Sample 2 (37.19 Bq/kg) was slightly higher than the global average (35 Bq/kg), indicating enrichment which may be from quarry operations. The activity concentration in water samples were relatively low, indicating that soil is a significant environmental path for radionuclides, with the highest result of 34.66 Bq/kg in Soil Sample 1, which is also slightly above the UNSCEAR requirement of 30 Bq/kg. The calculated hazard indices (Ra_eq, H_ex, and AEDE) were within safe limits, which means that there are no immediate radiological hazards to the general population or the environment.

This study has revealed that the background radiation levels around Ashaka Cement Quarry are generally in acceptable limits. A few soil samples, particularly those close to active quarry sites, however, have slightly elevated radiation levels. This indicates that the radiological enrichment is mild because of the mining activities. The hazard indices of the samples are all below the recommended safety limits, but there are ^{226}Ra and ^{232}Th present in the samples at concentrations just above world averages, and this is a cause for concern. These radionuclides can cause potential health effects, particularly from internal exposure due to inhalation and/or ingestion of radon and its decay products. Therefore frequent environmental monitoring and protection measures are highly recommended to minimise health risk to the quarry workers and the surrounding community in the longterm.

Recommendations

Recorded data should be kept so as to have record of radiation hazard indices due to naturally-occurring radioactive materials in ashaka quarry site and its environs. Further study is suggested on other parts of state most especially in mining sites in order to add to the existing knowledge.

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