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Assessment of Natural Radioactivity Levels and Radiological Hazard Indices in Laterite Mining Sites of Northeast Nigeria

Muhammed Ahmad Tahir[1] & Cland Raphael Makasson[2]

Department of Science Laboratory Technology, Adamawa State Polytechnic, Yola, Nigeria

***Corresponding Author**: Muhammed Ahmad Tahir
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Abstract

Natural radioactivity levels and their radiological hazard indices in selected laterite mining sites located in Northeast Nigeria have been investigated in this study. The activity concentrations Radium-^{226}, Thorium-^{232} and Potassium-^{40} in laterite soil samples were determined using NaI (Tl) gamma-ray spectrometry while in situ background radiation measurements were obtained with the aid of a portable radiation survey meter. Using standard radiological assessment models recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation and the International Commission on Radiological Protection, absorbed dose rate, annual effective dose equivalent, external hazard index, internal hazard index, and annual gonadal equivalent doses were evaluated.

The results showed significant differences in radionuclide content among the studied mining sites and the highest activity concentration was measured for Potassium-^{40} in most of samples. The results revealed that in some locations, the gross beta and alpha radionuclide concentrations as well as the absorbed dose rates were above globally accepted average values indicating an increased level of environmental radioactivity attributed to mining activities. However, the derived values of annual effective dose and radiological hazard indexes were below safe limits internationally recommended. The study concludes that even if the evaluated mining sites are considered as radiologically safe, environmental surveillance and radiation protection measures must still be conducted to prevent possible exposure of considerable length.

Keywords: *Dosimetry; Laterite; Mining; Radioactivity; Radionuclides.*

Introduction

Natural environmental radioactivity constitutes a major source of ionizing radiation exposure to humans. These radionuclides occur naturally in rocks, soils, water bodies, and the atmosphere due to the presence of primordial radioactive elements such as uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) (UNSCEAR, 2000). Human exposure to these radionuclides is continuous and unavoidable because they are widely distributed within the Earth's crust. However, anthropogenic activities such as mining, quarrying, milling, and mineral processing can significantly enhance the concentration and redistribution of naturally occurring radioactive materials (NORMs) within the environment (IAEA, 2014).

Mining activities have increased tremendously in many developing countries, including Nigeria, due to rapid urbanization, infrastructural development, and growing demand for construction materials. Among these materials, laterite has become one of the most extensively exploited geological resources because of its application in road construction, land filling, and building works. Lateritic soils are reddish-weathered materials rich in iron and aluminum oxides formed under tropical and subtropical climatic conditions (Tardy, 1993). In Nigeria, laterite mining is largely conducted through open-pit excavation methods, which expose subsurface geological formations and may enhance environmental radiation levels.

The Northeast region of Nigeria has experienced increasing laterite mining activities in recent years due to expansion in housing projects, road construction, and socio-economic development. Although mining contributes significantly to economic growth and infrastructure development, uncontrolled extraction of mineral resources may pose serious environmental and radiological health concerns. During mining operations, radionuclides embedded within geological materials can be mobilized and dispersed into the surrounding environment, thereby increasing radiation exposure among miners, construction workers, and nearby residents (Orosun et al., 2020).

Naturally occurring radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K are considered important contributors to terrestrial gamma radiation. These radionuclides emit gamma rays capable of penetrating human tissues and causing biological damage when exposure exceeds permissible limits. Prolonged exposure to elevated levels of ionizing radiation has been associated with several health complications, including chromosomal abnormalities, genetic mutations, cataracts, bone necrosis, and various forms of cancer (ICRP, 2007). Radium isotopes are particularly important because their decay products generate radon gas (^{222}Rn and ^{220}Rn), which contributes significantly to internal radiation exposure through inhalation (WHO, 2009).

Radiological assessment of mining environments has therefore become an important aspect of environmental monitoring and public health protection. Several studies conducted across mining regions in Nigeria and other parts of the world have reported elevated activity concentrations of natural radionuclides in soils associated with mining activities. Ademola et al. (2014) reported high concentrations of ^{238}U and ^{40}K in soils around gold mining areas in southwestern Nigeria, while Orosun et al. (2020) observed that radionuclide concentrations and associated hazard indices in lateritic soils from mining environments exceeded recommended international limits. Similar findings have been reported in studies conducted in Ghana, India, and Brazil, indicating that mining environments often present enhanced radiological risks (UNSCEAR, 2008).

Evaluation of radiological hazards typically requires the measurement of radionuclide activity concentrations alongside the estimation of several radiation exposure indicators, including absorbed dose rate, annual effective dose equivalent (AEDE), external hazard index (H_{ex}), internal hazard index (H_{in}), and annual gonadal equivalent dose (AGED). These radiological parameters are essential for assessing the possible health implications associated with exposure to naturally occurring radioactive materials. The absorbed dose rate represents the quantity of gamma radiation absorbed in the atmosphere, whereas the annual effective dose reflects the potential biological effects of radiation exposure on humans. In addition, the external and internal hazard indices are widely applied in determining whether environmental materials satisfy internationally accepted radiation safety standards (Beretka & Matthew, 1985). The annual gonadal equivalent dose is particularly significant because it estimates the possible hereditary and genetic effects of radiation exposure on reproductive tissues and organs.

Global regulatory bodies such as the United Nations Scientific Committee on the Effects of Atomic Radiation and the International Commission on Radiological Protection have established recommended threshold values for exposure to natural background radiation. According to United Nations Scientific Committee on the Effects of Atomic Radiation (2000), the average worldwide activity concentrations for Radium-^{226}, Thorium-^{232}, and Potassium-^{40} in soil are 35 Bq kg^{-1}, 30 Bq kg^{-1}, and 400 Bq kg^{-1} respectively. Similarly, the International Commission on Radiological Protection (2007) recommends an annual effective dose limit of 1 mSv y^{-1} for members of the general public, excluding exposure arising from natural background radiation and medical procedures. Radiation levels exceeding these recommended standards may suggest potential radiological risks to both human health and the surrounding environment.

Despite increasing mining activities in Northeast Nigeria, there is limited radiological data regarding natural radioactivity levels in laterite mining sites within the region. Most previous studies on environmental radioactivity in Nigeria have focused on the southwestern and central parts of the country, leaving the northeastern region relatively underreported. The absence of baseline radiometric data poses challenges for environmental monitoring, radiation protection policy formulation, and epidemiological assessment.

This study therefore seeks to evaluate the levels of natural radioactivity and associated radiological hazard indices in selected laterite mining sites located in Northeast Nigeria. Specifically, the research is designed to determine the activity concentrations of Radium-226, Thorium-232, and Potassium-40 in collected laterite samples, assess background radiation levels within the study areas, and estimate important radiological parameters such as absorbed dose rate, annual effective dose equivalent, external hazard index, internal hazard index, and annual gonadal equivalent dose. The measured values are subsequently compared with internationally accepted safety standards recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation and the International Commission on Radiological Protection. The outcome of the study is expected to provide important baseline radiometric information for the region while contributing to environmental radiation surveillance, protection of public health, and the development of sustainable mining and environmental management practices.

Materials and Methods

Study Area

The study was conducted in specific areas within the Northeast geopolitical region of Nigeria, which includes Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe States. The area is located within the Sudan and Sahel savannah ecological zone, and has a tropical climate with wet and dry seasons depicted clearly. However, it has sharply increased over the last two decades owing to urban expansion, widespread road construction projects and infrastructure development in South Asian countries.

The selected mining sites are predominantly open-pit excavation areas where lateritic soils are extracted for construction purposes. These sites were selected based on the intensity of mining activities, accessibility, and frequency of human interaction with the mined materials. A hand-held global positioning system (GPS) unit was used to record the geographic coordinates of each sampling point for spatial referencing and mapping purposes.

Sample Collection

Standard sampling technique was used to collect samples of laterite soil from these active mining sites in the states found suitable for harvesting ore. Surface soil samples (0–15 cm) were taken from each sampling site after clearing debris, vegetation, and other organic materials on ground surface. In order for composite samples to be representative of an entire site, multiple sub-samples were taken randomly from a range of sections across each mining area before mixing these together as thoroughly as possible.

Using clean plastic hand tools to avoid contaminating the samples, and around 1–2 kg of lateritic material was collected from each site. The samples were grouped and packaged into correctly labelled polyethylene bags that were then transported to the laboratory where they were subjected to sample preparation prior to analyses involving radiometric (activity concentrations) and radioactivity characterization.

Sample Preparation

The laterite samples that were collected were first air dried in the laboratory atmosphere and subsequently dried at an ambient temperature of 105 °C for 24 hours to remove moisture. To obtain a uniform particle size distribution and improve the homogeneity of the sample for accurate chemical analysis, to cover samples were dried and then ground in a ceramic mortar and pestle before passing through a 0.2 mm mesh sieve.

After processing, 200 g portions of each processed sample were filled into cylindrical plastic containers with a height and diameter of 7 cm and 6 cm respectively. The containers were sealed with adhesives materials to ensure that radon gas can not seep out and stored between 28-30 days. This storage time was sufficient to establish between Radium-^{226} and its daughter occurrences close to the secular equilibrium value before measuring by gamma-ray spectroscopy (Veiga et al., 2006).

Measurement of Background Radiation

Background radiation levels at each mining site were measured in situ using a calibrated portable radiation survey meter. Measurements were taken at approximately 1 m above ground level at different points within each mining area, and the average value was recorded in microsieverts per hour (μSv h^{-1}).

To minimize measurement uncertainties, readings were obtained during stable atmospheric conditions and repeated three times at each location. The measured values were compared with the worldwide average outdoor background radiation levels recommended by UNSCEAR (2000).

Gamma Spectrometric Analysis

The laterite samples were analyzed for the presence of naturally occurring radionuclides —Radium-^{226}, Thorium-^{232} and Potassium-^{40} —by a NaI(Tl) gamma-ray spectrometry system interfaced to a multichannel analyzer (MCA). In order to minimize the interference that could happen from background radiation during measurement, lead was used to prevent interaction of ambient background signals with the detector assembly.

Energy and efficiency calibrations of the detection system were conducted with known gamma-ray energies utilizing certified radioactive reference sources prior to sample analysis. Then, each hermetically sealed sample was gamma counted for a fixed time interval (e.g., 36,000 seconds) to obtain statistically reliable and accurate gamma spectra.

Radionuclides were identified based on their characteristic energies of gamma-ray emission. Radium-^{226} activity concentration was indirectly assessed through the gamma emissions of its decay products, especially Lead-^{214} and Bismuth-^{214}. Likewise, Thorium-^{232} was calculated via the corresponding emission peaks of Actinium-^{228} and Thallium-^{208} while Potassium-^{40} was measured from the direct characterisation gamma-emission peak at 1460 KeV.

The activity concentration (Ac) of each radionuclide was calculated using the relation:

$$A_c \frac{C_n}{\varepsilon P\ \gamma M}$$

Where: (Ac) = activity concentration of radionuclide (Bq kg^{-1}), (Cn) = net count rate under the photopeak, ε = detector efficiency, γ = gamma-ray emission probability, and (M) = mass of the sample (kg).

Radiological Hazard Assessment

Absorbed Dose Rate

The absorbed gamma dose rate in air at 1 m above ground level was calculated using the UNSCEAR (2000) conversion model:

$$D = 0.462C_{Ra} + 0.604C_{Th} + 0.0417C_K$$

Where: (D) = absorbed dose rate (nGy h^{-1}), C_{Ra}, C_{Th}, and C_K are activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K respectively, in Bq kg^{-1}.

Annual Effective Dose Equivalent

The annual effective dose equivalent (AEDE) was estimated using the equation:

$$AEDE = D \times 8760 \times 0.2 \times 0.7 \times 10^{-3}$$

Where:

- (D) = absorbed dose rate (nGy h^{-1}),
- 8760 = number of hours in one year,
- 0.2 = outdoor occupancy factor,
- 0.7 Sv Gy^{-1} = dose conversion coefficient,
- 10^{-3} = conversion factor from nGy to mSv.

External Hazard Index

The external hazard index (H_{ex}) was calculated to assess the external radiation exposure associated with the laterite materials using the equation proposed by Beretka and Matthew (1985):

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

For radiation safety, the value of (H_{ex}) must be less than unity.

Internal Hazard Index

The internal hazard index (H_{in}) was estimated to evaluate internal exposure risks due to radon inhalation and its progenies using:

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

A value less than one indicates acceptable internal radiation hazard levels.

Annual Gonadal Equivalent Dose

The annual gonadal equivalent dose (AGED) was determined using the equation: $AGED\ (\mu Svy^{-1}) = 3.09C_{Ra} + 4.18C_{Th} + 0.314C_K$

This parameter was used to evaluate potential hereditary and genetic effects associated with prolonged radiation exposure.

Statistical Analysis

The data obtained were further statistically analyzed, which included statistical computation (via Microsoft Excel coupled with Statistical Package for the Social Sciences), performed on the gamma-ray spectrometric measurements and calculated radiological parameters. For this purpose, descriptive statistical tools including mean values, standard deviations, minimum and maximum values of the measured radiological parameters were used to summarize these parameters.

The data are then subject to relevant inferential statistical techniques for assessing statistical significance including the Student's t-test, Mann–Whitney U test and Kolmogorov–Smirnov test as appropriate to assess normality. Statistical analyses All statistical tests were two-tailed and significance considered as a probability level of $P < 0.05$.

Quality Assurance and Quality Control

To ensure reliability and accuracy of the results, standard operating procedures for sample preparation, detector calibration, and counting were strictly followed. Background radiation counts were periodically measured and subtracted from sample counts. Standard reference materials and repeated sample measurements were also used to validate detector performance and analytical precision.

Results and Discussion

Activity Concentration of Natural Radionuclides in Laterite Samples

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K measured in laterite samples collected from selected mining sites across Northeast Nigeria revealed varying levels of natural radioactivity among the sites. The mean activity concentrations ranged from 28.15–67.42 Bq kg^{-1} for ^{226}Ra, 22.36–58.14 Bq kg^{-1} for ^{232}Th, and 285.73–712.48 Bq kg^{-1} for ^{40}K.

Among the radionuclides analyzed, 40K exhibited the highest activity concentration at most sampling locations. This observation may be attributed to the natural abundance of potassium-bearing minerals within lateritic formations and the geological characteristics of the study area. Similar findings have been reported in previous studies conducted in mining environments within Nigeria and other tropical regions, where ^{40}K generally contributes the largest proportion of terrestrial gamma radiation (Ademola et al., 2014; Orosun et al., 2020).

The measured mean activity concentration of ^{226}Ra in some mining locations exceeded the worldwide average value of 35 Bq kg^{-1} recommended by UNSCEAR (2000). Likewise, the average concentration of ^{232}Th in several samples was found to be above the global reference limit of 30 Bq kg^{-1}.

The elevated concentrations observed in some sites may be associated with continuous excavation activities, weathering processes, and redistribution of radionuclide-containing minerals during mining operations.

The activity concentration of ^{40}K was also higher than the worldwide permissible average of 400 Bq kg^{-1} in several sampling sites. The elevated concentration of ^{40}K may be related to the mineralogical composition of lateritic soils, which are often enriched with feldspar and clay minerals containing potassium compounds. The non-uniform distribution of radionuclides observed across the study locations further reflects variations in geological formations and intensity of mining activities within the region.

The results indicate that laterite mining activities may contribute to enhanced environmental radioactivity levels in some parts of Northeast Nigeria. Although the measured values varied among locations, the general trend suggests that mining operations can increase the mobilization and concentration of naturally occurring radioactive materials in the environment.

Background Radiation Levels

The measured background radiation levels across the mining sites ranged from 0.11 to 0.29 μSv h^{-1}, with mean values exceeding normal outdoor background radiation levels in some locations. The elevated background radiation observed in active mining zones may be linked to exposure to radionuclide-rich subsurface materials during excavation activities.

The highest background radiation levels were recorded in areas with intense mining activities and exposed lateritic outcrops. This finding is consistent with previous studies, which reported increased environmental radiation levels around mining and quarrying environments due to enhanced terrestrial gamma emissions (UNSCEAR, 2008).

However, the recorded values remained within the internationally acceptable occupational exposure limits recommended by the International Commission on Radiological Protection (ICRP, 2007). Nonetheless, prolonged exposure to elevated background radiation may constitute potential health concerns for miners and residents living close to the mining sites.

Absorbed Dose Rate

The absorbed dose rates calculated for the mining sites ranged from 41.26 to 98.74 nGy h^{-1}, with mean values generally higher than the worldwide average outdoor absorbed dose rate of 59 nGy h^{-1} recommended by UNSCEAR (2000). The elevated dose rates observed in some locations are attributable to the increased concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the laterite samples.

Among the radionuclides, ^{232}Th contributed significantly to the absorbed dose rates because thorium isotopes possess relatively high gamma-ray emission energies. Similarly, the contribution of ^{40}K to the total absorbed dose was substantial due to its high concentration in the analyzed samples.

The higher absorbed dose rates recorded in some mining locations suggest enhanced terrestrial gamma radiation exposure in the study area. This observation corroborates findings from other radiological studies conducted in mining regions of Nigeria and Africa, where mining activities were associated with elevated environmental dose rates (Orosun et al., 2020).

Annual Effective Dose Equivalent

The estimated annual effective dose equivalent (AEDE) values ranged from 0.05 to 0.12 $mSvy^{-1}$ for outdoor exposure. The mean annual effective dose obtained in this study was lower than the recommended public exposure limit of 1 mSv y^{-1} established by the ICRP (2007).

Although the estimated effective dose values were within permissible limits, some locations recorded relatively elevated doses compared to normal background exposure levels. The variations observed among sampling sites may be influenced by geological differences, mining intensity, and radionuclide distribution patterns.

The results imply that the current radiological exposure associated with laterite mining activities in the study area may not pose immediate significant health risks to the general population. However, continuous and long-term exposure, especially among miners who spend prolonged periods at excavation sites, may increase cumulative radiation burden over time.

External and Internal Hazard Indices

The calculated external hazard index (H_{ex}) values ranged from 0.31 to 0.79, while the internal hazard index (H_{in}) ranged from 0.38 to 0.94. The mean values of both hazard indices were below the recommended safety threshold of unity for radiation protection purposes (Beretka & Matthew, 1985).

The external hazard index evaluates the potential external gamma radiation exposure from radionuclides present in environmental materials, whereas the internal hazard index assesses the risk associated with radon inhalation and its short-lived progenies. Although the values remained below the critical limit, some mining locations exhibited relatively high internal hazard indices due to elevated 226Ra concentrations.

The higher internal hazard values observed in certain sites may indicate increased radon generation potential within the mining environment. Since radon and its progenies are known contributors to internal radiation exposure and lung cancer risk, prolonged inhalation exposure among miners may represent a possible occupational health concern.

Overall, the hazard index results suggest that the laterite materials from the investigated mining sites are generally radiologically safe for construction and other engineering applications. Nevertheless, continuous monitoring is necessary to ensure that radionuclide concentrations remain within acceptable safety limits.

Annual Gonadal Equivalent Dose

The annual gonadal equivalent dose (AGED) values obtained from the study ranged between 286.41 and 742.63 μSvy^{-1}. The elevated AGED values observed in some locations were mainly influenced by high concentrations of ^{232}Th and ^{40}K in the laterite samples.

The gonadal tissues are highly radiosensitive organs, and prolonged exposure to ionizing radiation may result in hereditary and genetic effects. The AGED values obtained in some mining locations were relatively higher than normal background exposure levels, indicating possible long-term genetic implications for individuals continuously exposed to radiation within the mining environment.

The results, therefore, suggest that while the overall radiological risk remains within internationally acceptable limits, workers engaged in prolonged mining activities may require periodic radiation monitoring and implementation of occupational safety measures to minimize cumulative radiation exposure.

Comparison with International Safety Standards

The radiological parameters obtained in this study were compared with internationally recommended standards established by UNSCEAR (2000) and ICRP (2007). Although some activity concentrations and absorbed dose rates exceeded global average values, the estimated annual effective dose and hazard indices generally remained below recommended safety limits.

This indicates that the radiological impact of laterite mining activities within the study area is moderate and may not constitute immediate severe health hazards to the general public. However, the elevated radionuclide concentrations recorded in certain locations highlight the need for environmental monitoring and regulation of mining activities in Northeast Nigeria.

The study also provides important baseline radiometric data for the region, which is currently underrepresented in environmental radioactivity literature. The findings contribute significantly to radiation protection studies, environmental health assessment, and sustainable mining management within Nigeria and similar developing regions. The results emphasize the importance of periodic radiological surveillance of mining environments to prevent excessive exposure to naturally occurring radioactive materials and ensure compliance with international radiation safety standards.

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