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Assessment of Activity Concentrations of Radionuclides (^{226}Ra, ^{232}Th and ^{40}K) and Annual Effective Doses in Water from Gold Mining Pits, Osun State, Nigeria

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Abstract: **Gold mining activities can lead to the accumulation of naturally occurring radionuclides in water sources, posing potential health risks to local communities. This study assesses the activity concentrations of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in 23 water samples collected from gold mining pits in Itagunmodi and Iperindo, Osun State, Nigeria. Using gamma-ray spectrometry, the measured activity concentrations were compared to global safety standards. The estimated annual effective dose for adult miners was also calculated to evaluate potential radiological health risks and ranged from 0.33 to 17.49 mSv/y. Results revealed varying concentrations of radionuclides, with some exceeding the recommended limits set by international regulatory bodies. The findings highlight the need for continuous monitoring and mitigation strategies to minimize radiation exposure from mining-related water sources.**

Keywords: **Radionuclides, Gold Mining, Water Contamination, Annual Effective Dose, Osun State, Gamma Spectrometry.**

1. INTRODUCTION

Gold mining is a major economic activity in many regions of Nigeria, including Osun State, where artisanal and small-scale mining is widely practiced (Ogunnowo and Ojakorotu 2023; Eludoyin et al. 2024; Awogbami et al. 2024). While gold extraction contributes significantly to local economies, it also raises environmental and health concerns, particularly due to the release of naturally occurring radioactive materials (NORMs) into surrounding ecosystems (Candeias et al. 2018; Ogundele et al. 2021; Popoola et al. 2024). Among these radionuclides, radium-226 (^{226}Ra), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are of particular interest due to their potential to cause long-term radiological health effects when present in elevated concentrations (Pandey et al. 2010; Alimam and Auvinen, 2025).

Water from mining pits often serves as a primary source of drinking and domestic water for local communities, increasing the likelihood of exposure to radioactive contaminants (Paul et al. 2022; Mohuba et al. 2022). Prolonged ingestion of water containing radionuclides can lead to internal exposure, which may result in an increased risk of radiation-induced illnesses, including cancers and other chronic health conditions (Yadav et al. 2017; Giussani et al.2020). As such, assessing the levels of radionuclides in mining-related water sources and estimating the associated annual effective doses are crucial for understanding the potential risks and ensuring compliance with international safety standards.

Previous studies have reported varying levels of radionuclide contamination in mining areas across Nigeria, yet limited data exist for Osun State, particularly in relation to gold mining pits. This study aims to fill this gap by measuring the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water samples from gold mining pits in Osun State and evaluating the radiological health risks through annual effective dose calculations. The findings will provide essential data for regulatory agencies and policymakers to develop strategies for radiation protection and environmental management in mining communities.

2. MATERIALS AND METHODS

Study Area

The study was conducted in Osun State, Nigeria, a region known for extensive artisanal and small-scale gold mining activities. The area is located within the schist belt of Southwestern Nigeria, which embraces undifferentiated schist, gneisses, and migmatites with pegmatites, schist and epidorite complex, quartzite and quartz schist, granite gneiss, amphibolite, pegmatised schist, granulite, and gneiss (Fadare, 2000). The soils of the study area are tropical ferruginous red soils from the material of basement complex of western highland. The soils are generally deep and of two types; namely, deep clayed soil formed on low smooth hill crest and upper slopes and the sandier hill wash soils on the lower slopes. The well drained clayed soils of the hill crest and slopes are very important because they provide the best soils for Cocoa (*Theobroma cacao*), Oil palm (El*aeis guineensis*), Citrus (*Gambeya Africana*) and Coffee (*Coffea brevipes*), which are the major cash crops in the area. However, mining activities had affected agricultural practices in most communities of the study area. For instance, much of the gold is found in soils of Itagunmodi series, which are some of the best soils for cocoa plantations. Thus, the first causalities of the onslaught of gold mining are the loss of rich cocoa plantations which, communities had benefited from for many decades (Adeoye, 2015). The main towns around the mining sites are Itagunmodi (18 carats alluvial gold), Iperindo (18 carats alluvial gold) (Taiwo and Awomeso, 2017; TEL, 2019)

The study area has two contrasting lithologies separated by NNE-SSW trending shear system- the Ifewara Fault Zone, which is occupied by the amphibole schist, amphibolites, talc-tremolite and pellitic rocks (Akinlalu, 2023). The eastern part has quartzite, quartz schist and amphibole schist. The gold deposit occurs in the eastern area that lies on the east of Ifewara fault zone. Gold occurs with ores such as: Pyrite, pyrrhotite and minor chalcopyrite, galena, sphalerite, magnetite and ilmenite. Adjacent to the gold bearing veins the host granite-gneiss has been hydrothermally altered to a sericite chlorite epidote assemblage (with also hematite and pyrite) (Ayantobo *et al*., 2014). Figure 4 presents the geological map of the study area.

Sample Collection

Water samples were collected from gold mining pits across different locations in Osun State. A total of 23 water samples were collected following standard sampling procedures. Each sample was collected in a 1-liter polyethylene bottle, pre-rinsed with distilled water and the respective mining pit water before collection. To prevent contamination and loss of radionuclides, nitric acid (HNO_3) was added to each sample to maintain a pH of <2. The samples were then transported to the laboratory for analysis.

Sample Preparation and Analysis

Water samples were dispensed into previously weighed 400 mL thoroughly cleaned plastic containers. The containers with their contents were weighed again to determine the weight of the sample. The containers were then covered and sealed with paper tape to prevent the escape of the gaseous radionuclides in the samples. The samples were kept for 30 days to allow for secular equilibrium between the long – lived parent radionuclides and their short – lived daughter radionuclides in the ^{238}U and ^{232}Th decay series. These water samples after attaining secular equilibrium, were counted using a NaI(Tl) detector for 10800 s at the Department of Physics, Federal University of Agriculture, Abeokuta.

Determination of Activity Concentrations

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the water samples were determined by analysing their characteristic gamma emission lines at 1,765 keV, 2,614 keV, and 1,460 keV, respectively. These concentrations were calculated using the formula in equation (1) (Breketka & Matthew, 1985)

$$AR = \frac{C_R}{n \times m} \tag{1}$$

where *AR* represents the activity concentration in becquerels per litre (Bq/L), C_R is the net count rate measured in counts per second, *n* denotes the detector efficiency, and *m* corresponds to the mass or volume of the sample.

Estimation of Annual Effective Dose

The radiological health risk associated with ingesting water contaminated with radionuclides was evaluated by determining the annual effective dose (AED). This was calculated using the equation (2) (USEPA, 1991; Meltem & Gursel, 2010).

$$AED = C \times DCF \times AW_I \quad (2)$$

where AED represents the annual effective dose in millisieverts per year (mSv/year), C is the activity concentration of the radionuclide in becquerels per litre (Bq/L), AW_I denotes the annual water intake in litres per year (L/year), and DCF refers to the dose conversion factor in millisieverts per becquerel (mSv/Bq), as recommended by the International Commission on Radiological Protection (ICRP). The value for annual water intake of adults was obtained from ICRP guidelines to ensure a thorough evaluation of exposure risks (ICRP, 1974; ICRP, 1993).

3. RESULTS AND DISCUSSION

Activity Concentrations of Radionuclides in Water Samples

The measured activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water samples from gold mining pits in Osun State are presented in Table 1 and 2. The results indicate that the activity concentrations varied across the sampled locations, with some exceeding the recommended limits of 1.00 Bq/L set by the International Atomic Energy Agency (IAEA, 2004) for drinking water.

The activity concentrations of water samples from Itagunmodi mines ranged from BDL to 47.86 Bq/L with average values of 31.19 ± 9.83, 1.49 ± 1.25 and 15.04 ± 1.40 Bq/L for ^{40}K, ^{226}Ra and ^{232}Th respectively.

Radionuclides in water samples from Iperindo mine have activity concentrations of ^{40}K ranged from 28.05 Bq/L to 44.67 Bq/L with an average value of 35.68 ± 5.99 Bq/L. The range of activity concentrations of ^{226}Ra is from 2.34 to 6.00 Bq/L with an average of 3.98 ± 1.18 Bq/L. For ^{232}Th, the activity concentration ranged from 11.26 to 50.59 Bq/L with an average of 22.05 ± 14.74 Bq/L. The average activity concentration obtained for each radionuclide was found to be above recommended value (UNSCEAR, 2000; IAEA, 2004).

Table 1. Activity concentrations of radionuclides and annual effective doses of water from mining pits, Itagunmodi.

Sample	Activity concentration (Bq/L)			*AED (mSv/y)*
	^{40}K	^{226}Ra	^{232}Th	
ITA 1	40.62	2.08	36.25	10.07
ITA 2	35.01	1.69	35.58	9.21
ITA 3	48.66	BDL	47.86	8.26
ITA 4	40.39	2.35	17.34	7.39
ITA 5	43.67	BDL	7.32	1.43
ITA 6	26.11	4.08	10.95	9.40
ITA 7	32.52	0.00	5.45	1.06
ITA 8	28.21	2.90	12.97	7.59
ITA 9	21.43	1.55	5.72	3.89
ITA 10	21.15	1.46	6.17	3.80
ITA 11	19.83	BDL	1.45	0.33
ITA 12	19.17	1.45	5.36	3.64
ITA13	28.70	1.84	3.11	4.01
Average	31.19 ± 9.83	1.49 ± 1.25	15.038 ±1.40	5.39 ± 3.41
Minimum	19.17	BDL	14.45	0.33
Maximum	40.63	40.79	47.86	10.07

BDL = below detection limit; ITA = Water from Itagunmodi mines

Table 2. Activity concentrations of radionuclides and annual effective doses of water from Iperindo mines

Sample	Activity concentration (Bq/l)			AED (mSv/y)
	40K	226Ra	232Th	
IPE 1	28.05	5.71	12.04	12.57
IPE2	42.97	6.00	37.77	17.49
IPE 3	44.67	3.64	50.59	15.33
IPE 4	38.97	4.27	15.70	10.60
IPE 5	31.01	3.56	13.05	8.83
IPE 6	30.29	4.53	11.26	10.30
IPE 7	41.04	3.10	12.62	7.95
IPE 8	35.52	2.89	13.31	7.68
IPE 9	29.41	3.76	14.05	9.35
IPE 10	34.84	2.34	40.11	11.15
Average	35.68 ± 5.99	3.98 ±1.18	22.05 ± 14.74	11.13 ± 3.19
Minimum	28.05	2.34	11.26	7.68
Maximum	44.67	6.00	50.59	17.49

IPE = water from Iperindo mines

The elevated levels of ^{226}Ra and ^{232}Th in some samples suggest significant radioactive contamination likely due to the weathering of uranium- and thorium-rich minerals associated with gold deposits. The relatively high ^{40}K concentrations may be attributed to potassium-bearing minerals present in the surrounding rock formations.

Comparison with International Safety Standards

To assess the potential health risks, the measured radionuclide concentrations were compared with global regulatory limits (Table 1 and 2). The WHO recommended limits for ^{226}Ra and ^{232}Th in drinking water are 1.0 Bq/L and 0.1 Bq/L, respectively, while the UNSCEAR guideline for ^{40}K is 10 Bq/L. Some of the sampled locations exceeded these limits, indicating potential radiological risks for communities relying on these water sources.

Annual Effective Dose Estimation

The annual effective dose (AED) due to ingestion of radionuclide-contaminated water was calculated for the adult miners **(Table 1 and 2)**

The estimated overall average annual effective dose for the water samples Itagunmodi mines is 5.39 ± 3.41 mSv/y, which is above recommended limit of 1 mSv/y for members of the public (ICRP 1991) and 0.1 mSv/y recommended for drinking water (WHO, 2000). The estimated AED in Itagunmodi is displayed in figure 1, indicating high values greater than the recommended IAEA value.

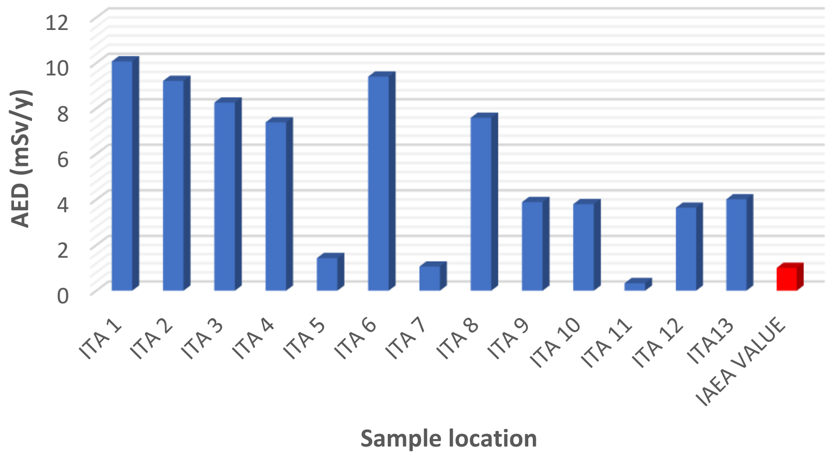

Figure 1. Estimated AED for Adult miners in Itagunmodi mines compared with IAEA value

The estimated total average annual effective dose for adult miners of Iperindo gold mines is 11.13 ± 3.19 mSv/y, which is above the recommended limit of 1 mSv/y for members of the public (ICRP, 1991) and 0.1 mSv/y recommended for drinking water (WHO, 2000). The estimated AED in Iperindo mines is shown in figure 2, indicating high values greater than the recommended IAEA value.

The estimated AED for ^{226}Ra and ^{232}Th in some samples exceeded the ICRP-recommended limit of 0.1 mSv/year for the general population. The contribution of ^{40}K to the overall AED was lower compared to ^{226}Ra and ^{232}Th, as potassium is an essential biological element with a lower radiological impact.

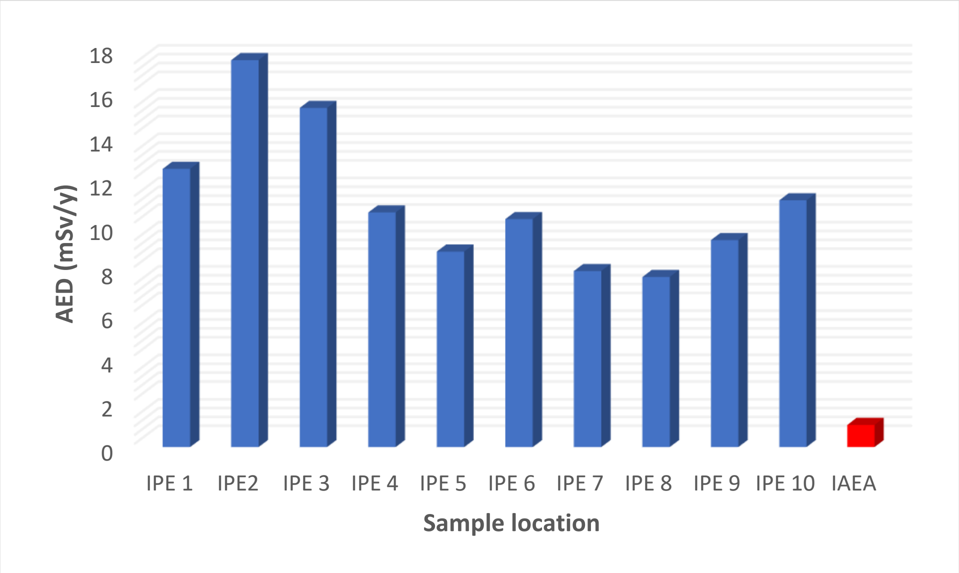

Figure 2. Estimated AED for Adult miners in Iperindo mines compared with IAEA values

Health and Environmental Implications

The findings suggest that prolonged consumption of water from certain gold mining pits could pose significant radiological health risks, particularly due to ^{226}Ra and ^{232}Th. Long-term ingestion of these radionuclides has been linked to bone cancer, leukemia, and kidney disorders.

Additionally, the presence of elevated radionuclide levels in mining pit water could indicate contamination of nearby groundwater and surface water systems, potentially affecting a larger population. This calls for regular monitoring and remediation efforts to mitigate exposure risks. Implementation of regulatory measures to enforce safe mining practices and environmental protection policies.

4. CONCLUSION

This study assessed the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water from gold mining pits in Osun State, Nigeria, and evaluated the associated annual effective doses to determine potential radiological health risks. The results revealed varying concentrations of these radionuclides, with some exceeding the IAEA and UNSCEAR recommended limits for drinking water. The estimated annual effective doses for the miners surpassed the ICRP safety threshold of 0.1 mSv/year, indicating potential health risks from prolonged ingestion.

The presence of elevated radionuclide concentrations in mining pit water highlights the need for continuous monitoring and intervention strategies to mitigate exposure risks. Effective remediation measures, such as water treatment technologies, stricter mining regulations, and public health awareness campaigns, should be implemented to protect local communities from radiation-related health hazards.

Further studies are recommended to assess the migration of radionuclides to nearby groundwater and surface water sources, as well as to explore long-term environmental and health impacts in the region. Addressing these challenges will be crucial for ensuring sustainable mining practices and safeguarding public health in gold-mining communities.

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