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Assessing Scalability of Natural Radionuclides and Associated Risks in Soils from Gold Mining Areas in Iperindo, Southwestern Nigeria

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Abstract
The environmental and health implications of artisanal gold mining activities at mining sites across Nigeria have rekindled research interest. This study aimed to assess the scalability of naturally occurring radioactive materials in gold mining sites in Iperindo, Nigeria. Soil samples were collected from three different mining sites and control locations and analyzed for natural radionuclides, mainly ^{238}U, ^{232}Th, and ^{40}K, using gamma spectrometry having a sodium iodide detector. The average activity concentration values of 61.55 ± 3.71, 72.65 ± 4.45, and 1134.99 ± 38.12 Bqkg^{-1} obtained from within the mining sites for ^{238}U, ^{232}Th, and ^{40}K, respectively, were above the world permissible values of 33.0 Bqkg^{-1} for ^{238}U, 45.0 Bqkg^{-1} for ^{232}Th, and 420.0 Bqkg^{-1} for ^{40}K. The average activity concentration values of 15.26 ± 3.19, 21.46 ± 4.27, 381.04 ± 23.36 Bqkg^{-1} estimated for ^{238}U, ^{232}Th, and ^{40}K, respectively, for the control location were, however, lower than the global permissible values. The study also evaluated other radiological parameters such as radium equivalent, dose rate, annual effective dose rate, internal and external hazard indices, and alpha and gamma indices. The obtained values were 252.83 Bqkg^{-1}, 119.98 nGyh^{-1}, 147.15 mSvy^{-1}, 0.85 Bqkg^{-1}, 0.68 Bqkg^{-1}, 0.31 Bqkg^{-1}, and 1.89 Bqkg^{-1} respectively. Except for radium equivalent, external and internal hazard risks, and alpha index, which were significantly lower than the recommended threshold, all other radiological parameters were higher than the recommended global limits. Moderate data reproducibility and a *p*-value of 0.000574 further reinforced the robustness and reliability of the results obtained in this study.

Keywords Artisanal gold mining · Iperindo · Natural radionuclides · Naturally occurring radioactive materials (NORM) · Gamma spectrometry · Radiological health hazard · Health risk

1 Introduction

Mining has been described as an age-long technique for extracting valuable metals and minerals from the Earth's surface for income and employment generation and use in industries [1, 2]. Gold remains one of the world's most mined metals, primarily because of its rarity and value, with an estimated 3000 metric tons produced globally in 2021, from 2560 metric tons produced in 2010 [3]. A 2022 report by Statista places China as the world's largest gold producer, followed by Australia, Russia, and Canada, with global gold production in 2022 increasing by just 100 metric tons compared to 2021 [3]. Gold occurs mainly as discrete particles, up to 100 μm in size, at grain boundaries between quartz and carbonates, and is generally associated with sparse, scattered pyrite (two generations), pyrrhotite, and rarer base-metal sulfides [4, 5].

Gold has good corrosion resistance, is ductile and malleable, and possesses good chemical reactions, thus making it suitable for industrial applications such as gold leafing, electrical connectors, and infrared shielding [5, 6]. Gold is also used primarily by financial investors for jewelry, coins, and investment purposes [7, 8]. Gold is mined globally on every continent except Antarctica and has been identified by the United Nations (UN) as one of the fundamental drivers of attaining most of the UN Sustainable Development Goals (SDGs) through sustainable artisanal and small-scale gold mining (ASGM) and pandemic-reinforced innovative technologies such as energy transition [9].

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In sub-Saharan Africa, Ghana is ranked as the leading gold producer, with an estimated 117.6 tons produced in 2021, followed closely by South Africa, with 100 tons [10]. Gold mining activities also occur predominantly in Northern and Southern Nigeria, with the schist belt in northwest and southwest Nigeria's Anka, Bin Yauri, Gwari-Kwaga, Gurmana, Malele, Maru, Okolom-Dogondaji, Tsohon Birnin, and Iperindo regions all connected, with significant gold deposits presence [11]. Gold mineralization in Nigeria is confined to a zone of quartz-carbonate veins, mainly calcite and hydrothermally altered gneisses, along with associated small-scale intrusions along a second-order, steeply dipping fault zone that roughly parallels the main Ifewara-Zungeru fault.

Gold exploration is predominant in Iperindo, Osun State, Nigeria, with prevalence in small-scale mining activities carried out by artisanal miners (mostly illegal). The increased illegal activities of these artisanal miners have raised concerns about the level of environmental pollution in Iperindo, thus prompting researchers to assess the levels of radionuclide (mainly ^{40}K, ^{238}U, and ^{232}Th) emissions in gold mining sites scattered within Iperindo [12–15]. Unfortunately, these artisanal miners are unaware of the health and environmental implications of mining. These unskilled miners use simple tools such as pans, chisels, hammers, and shovels for gold excavation, thereby exposing themselves and community dwellers to severe environmental problems linked with naturally occurring radioactive materials (NORMs). The tailings from these illegal gold mining operations constitute another significant source of pollution, as they are easily dispersed into the air, waterways, and landfills, further spreading NORMs.

The primary origins of NORMs have been documented to arise from natural or primordial sources [16]. NORMs emit ionizing radiation primarily in the form of alpha, beta, and gamma radiation. NORM contaminants can enter the food chain and affect the quality and safety of agricultural products and local water supplies [17–19]. Prolonged exposure to these contaminants can result in long-term health risks, including cancer, genetic mutations, and other radiation-related illnesses [20, 21]. The detrimental impacts of the mining process on the surrounding environment include ecological disruption; deterioration of the landscape; loss of biodiversity; contamination of soil, air, and water; ecological hazards; and potential harm to human health because of the presence of NORMs and heavy metal constituents in mining residues, inhalation of radioactive dust, and ingestion of contaminated water or food [22–25]. Bioaccumulation of NORMS in plants, crops, and aquatic organisms is another health hazard, as it can lead to increased radiation exposure in individuals consuming these products [26, 27].

Miners are potentially at risk of inhaling long-lived alpha-emitting radionuclides and radon, a carcinogenic gas, along with their daughter products, potentially impacting their respiratory tract. Notably, many radionuclides exhibit the characteristic of disintegrating their atomic nuclides, emitting penetrating gamma rays even at relatively low levels of exposure [28]. This combination of radiation exposure pathways and the specific risks associated with NORMs makes it imperative to address potential health hazards in gold mining areas. With a gram of gold selling at $65.20 globally [29] and ₦27,502.86 in Nigeria [30], there is no assurance that the activity of artisanal miners in several parts of Nigeria, including Iperindo, will slow down soon, thus motivating this study. Similarly, the most recent health risk assessment of NORMs at scattered mining sites within the Iperindo community, attributed to artisanal mining activities, was conducted three years ago [13, 31]. Thus, it is essential to reassess the scalability of environmental degradation and radiological exposures of artisanal and occupational miners and community dwellers to NORM in the Iperindo mining site and determine, if any, the associated health risk that calls for serious concern and immediate government intervention.

This study presents a novel investigation focused on re-assessing NORMs specific to Iperindo gold mining sites in Southwestern Nigeria. A significant novelty of this research lies in the meticulous analysis of soil samples collected from these mining sites by scrutinizing the activity concentrations of three prominent radionuclides: ^{238}U, ^{232}Th, and ^{40}K. These radionuclides are pivotal for radiological scalability due to their inherent radiological properties and potential health implications. This study further augments understanding of the environmental landscape by encompassing an array of radiological parameters, including radium equivalent, dose rates, annual effective dose rates, and alpha and gamma indices. These radiological parameters provide multifaceted insights into the potential health risks associated with artisanal mining in Iperindo. The results from this study will be compared with established international standards [32, 33] and data obtained from control locations outside the vicinity of Iperindo mining. This research is not a replication of existing studies, but a pioneering endeavor to explore the intricate interplay between artisanal gold mining, NORMs, and radiological risks. It offers a fresh perspective and lays a robust scientific foundation to inform policies and safeguard the well-being of the community and miners in Iperindo, Nigeria.

2 Materials and Method

2.1 Study Area

The study area of Iperindo is located in the Atakumosa-West and Oriade Local Government Areas of Osun State, Nigeria. The geographical coordinates of the study area, as shown in Fig. 1, are 7° 30′ 0″ North and 4° 49′ 0″ East. The study area is located in amphibolite-facies biotite granite-gneisses of Proterozoic age within the Ilesha schist belt [13, 14, 34], about 4 km east of the major crustal "break" known as the Ifewara-Zungeru fault. The choice of Iperindo for this study was based on the prevalence of small-scale gold mining activities by artisanal miners. Iperindo is one of the few areas in Southwestern Nigeria with primary gold deposits, and was previously assessed by the Nigerian Mining Corporation [15]. However, the area has become an informal, uncoordinated, and unmonitored mining site, resulting in intensified and unregulated artisanal mining activities within the community.

2.2 Sample Collection, Preparation, and Processing

The study area was stratified into four different parts, with three situated in the gold mining site and the fourth division used as a control and situated in a living area about 15 km from the mining site. Twenty soil samples were gathered randomly from within and outside the mining area and placed into appropriately labelled separate containers. Of the 20 soil samples, 15 were collected from three different locations in and around the gold mining site, whereas the remaining five samples, which were used as controls, were collected from the fourth division.

The collected samples were processed using International Atomic Energy Agency (IAEA) standard methods [35]. The soil and plant samples were all air-dried at room temperature for 24 h to remove traces of moisture and oven-dried at a constant temperature of 110 °C to obtain dry weights. Each soil sample was sealed hermetically in appropriately labelled plastic containers and stored for 28 days to enable secular equilibrium for ^{238}U and its short-lived progenies, after which gamma spectrometric analysis was carried out on the natural radionuclides. A sodium iodide (NaI) detector doped with thallium (Tl) was used to count the samples for 10 h.

2.3 Determination of Activity Concentration of Radionuclides

The radionuclides activity concentration in the soil samples was determined using a highly shielded and well-calibrated 3.0 cm by 3.0 cm co-axial NaI (Tl) detector enclosed in a 6-cm-thick lead shield to reduce background radiation. A computer-based multichannel analyzer (MCA) was used for data acquisition of the gamma spectra, and Genei 2000 software was used to analyze the data. The spectrometer was evaluated for linearity before calibration for energy using IAEA-provided gamma sources. The samples were counted using the IAEA standard method [33].

An empty container with the same geometry as the sample containers was used to determine the background gamma ray distribution. The gross count was subtracted from the background count to obtain the total net count. The statistical uncertainty was minimized in each sample by counting them

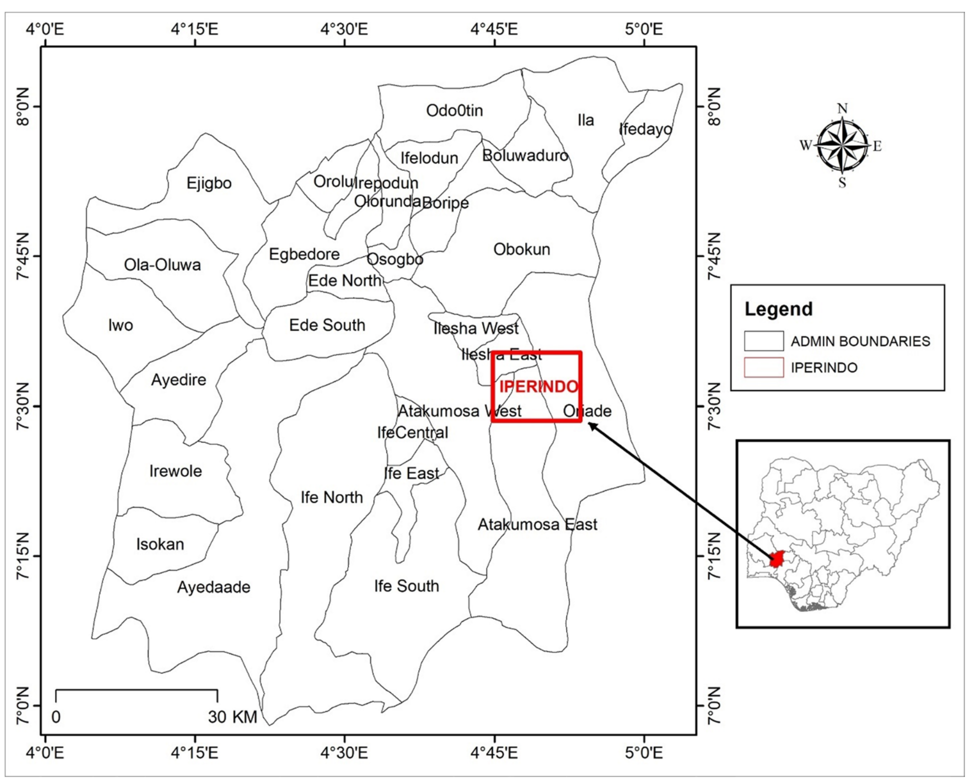

Fig. 1 Geological map of Osun state showing the study area

for 36,000 s. Activity concentrations of the samples were estimated in units of $Bqkg^{-1}$ using the total net counts of selected photo-peak efficiency, gamma intensity, and sample amount. Gamma energies of 1764.5 keV for ^{214}Bi, 2614.5 keV for ^{208}Tl, and the single 1460 keV for ^{40}K were used to determine the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil samples.

2.4 Determination of Radium Equivalent Concentration

The activity radium equivalent (R_{aeq}) concentration indicates the gamma radiation dose output from the natural radionuclide mixtures. In this study, the radium equivalent activity was determined based on the estimation of the activity concentrations of ^{238}U (A_U), ^{232}Th (A_{Th}), and ^{40}K (A_k) at 370 BqKg^{-1} ^{238}U, 259 BqKg^{-1} ^{232}Th, and 4810 BqKg^{-1} ^{40}K, respectively using [36, 37]:

$$R_{aeq} = A_U + 1.43A_{Th} + 0.077A_k \tag{1}$$

2.5 Determination of Hazard Index

The hazard index was categorized into the external hazard index (H_{ex}) and internal hazard index (H_{in}). The external hazard index is used to estimate the health risk linked to gamma radiation emission by different natural radionuclides which is estimated using [35, 36]:

$$H_{ex} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \tag{2}$$

The internal hazard index, on the other hand, is an indication of the dangers posed by radon and its progeny to the internal exposure of living tissues and cells and is estimated using [37, 38]:

$$H_{in} = \frac{A_U}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \tag{3}$$

2.6 Determination of Alpha and Gamma Index

Alpha index I_α is one of radiological parameters created to evaluate the environment's safety caused by excessive radiation exposure through inhaling soils used as building materials. The alpha index was determined using [39]:

$$I_\alpha = \frac{A_U}{200} \tag{4}$$

The gamma index, I_γ, however, evaluates the danger of gamma radiation resulting from natural radionuclides in the particular samples under investigation. For $I_\gamma \leq 1$, the annual effective dose fell within the upper limit of 1 mSv, indicating a lower soil radiological risk. This index is determined as follows [34]:

$$I_\gamma = \frac{A_U}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \tag{5}$$

2.7 Determination and Analysis of Dose Rate

The average absorbed dose rate, D, in air at 1m above ground level for naturally occurring radionuclides is determined by applying conversion factors to ^{238}U, ^{232}Th, and ^{40}K given by [30, 33]:

$$D\left(nGyh^{-1}\right) = 0.462A_U + 0.604A_{Th} + 0.042A_K \tag{6}$$

Estimating the annual effective dose rate (AEDR) of radionuclides for miners and people living within the mining site is imperative. By considering an outdoor occupancy factor (OF) of 0.2, a dose conversion factor (DCF) of 0.7 SvGy^{-1}, total absorbed dose rate (D), and time (T) of 8760 h per year, the annual effective dose rate for outdoors was obtained using [30, 40, 41]:

$$AEDR\left(\mu Svy^{-1}\right) = OF \times DCF \times D \times T \times 10^{-3} \tag{7}$$

2.8 Determination of Excess Lifetime Cancer Risk

This metric is known as excess lifetime cancer risk (ELCR) and was determined in this study from the AEDR, average duration of life (DL), estimated as 70 years in Nigeria, and the risk factor (RF) of 0.05 Sv^{-1} for the public, using [22, 33, 42]:

$$ELCR = AEDR \times DL \times RF \times 10^3 \tag{8}$$

2.9 Determination of Annual Gonadal Equivalent Dose

This study estimated the effect of NORMs on organs such as the gonads, bone surface cells, and active bone marrow of people living within the study area. The annual gonadal equivalent dose (AGED) was determined using the specific activities of ^{238}U, ^{232}Th, and ^{40} K, and their respective activity concentrations as follows [31]:

$$AGED\left(\mu Svy^{-1}\right) = 3.09A_U + 4.18A_{Th} + 0.314A_K \tag{9}$$

3 Results and Discussion

The gamma-ray measurements of the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in 20 soil samples from three gold mining locations and a control location in Iperindo, Southwestern Nigeria, are presented in Table 1.

3.1 Statistical Significance and Data Reproducibility of Radionuclides

The statistical significance of the data in Table 1, which presents the activity concentrations of radionuclides in soil samples collected from various locations in Iperindo, including gold mining sites and control locations, was assessed using descriptive statistics. In this analysis, the mean and standard deviations were employed to estimate the central tendency and extent of data dispersion for the activity concentrations of radionuclides at gold mining sites. The average mean and standard deviations activity concentration of radionuclides obtained from the gold mining sites is 61.55±3.71 $Bqkg^{-1}$ for ^{238}U, 72.65±4.45 $Bqkg^{-1}$ for ^{232}Th, and 1134.99±38.12 $Bqkg^{-1}$ for ^{40}K. In contrast, the average activity concentration obtained from the control site is 15.26±3.19 $Bqkg^{-1}$ for ^{238}U, 21.46±4.27 $Bqkg^{-1}$ for ^{232}Th, and 381.04±23.36 $Bqkg^{-1}$ for ^{40}K.

To assess the statistical significance and consistency of the data, the coefficients of variation (CV) were calculated for each radionuclide within each location. The average CV values across all radionuclides at the gold mining sites were approximately 22.44% for ^{238}U, 23.43% for ^{232}Th, and 20.92% for ^{40}K. For the control location, the CV values were approximately 25.36% for ^{238}U, 14.51% for ^{232}Th, and 22.86% for ^{40}K. The similarity in CV values across all three radionuclides within the gold mining sites and the control location indicated consistent variability in activity concentrations. This similarity in variability implies no significant statistical difference in the data spread between the radionuclides within the different locations (gold mining and control locations).

Furthermore, CV values were also considered for different locations within the study area to assess data reproducibility. The CV values ranged from 20.92 to 23.43% for the gold mining sites and 14.51 to 25.36% for the control locations. This CV value suggests moderate data reproducibility for all three studied radionuclides, as it falls within the typical range of 15–30% CV for moderate reproducibility. Thus, the moderate CV values indicate a reasonably consistent data reproducibility level, implying that similar results can be expected in repeated measurements of radionuclides within the different studied locations.

Table 1 Activity concentration of radionuclides in sampled soil from mining and control location in Iperindo

Sample code	^{238}U ($Bqkg^{-1}$)	^{232}Th ($Bqkg^{-1}$)	^{40}K ($Bqkg^{-1}$)
MSL-1	73.04 ± 16.07	79.30 ± 17.94	1303.10 ± 288.02
MSL-2	60.30 ± 10.68	70.52 ± 12.39	1165.02 ± 235.34
MSL-3	51.30 ± 14.17	68.12 ± 20.50	936.86 ± 191.56
Mean (mining site)	**61.55 ± 3.71**	**72.65 ± 4.45**	**1134.99 ± 38.12**
CSL (control site)	**15.26 ± 3.19**	**21.46 ± 4.27**	**381.04 ± 23.36**

In addition to the above analysis, the statistical significance of the findings is further supported by an analysis of variance (ANOVA) test. The F-statistic, along with its associated *p*-value, is a crucial indicator of the statistical significance of an analysis or comparison. This study obtained an F-statistic of 19.13, critical *F*-value of 4.26, and *p*-value of 0.000574. The F-statistic of 19.13, which significantly exceeds the critical *F*-value of 4.26, suggests a substantial difference among the groups compared in this study. However, the *p*-value associated with the F-statistic was further examined to determine whether the observed difference was statistically significant. Because the *p*-value of 0.000574 obtained in this study is considerably smaller than the conventional significance level of 0.05 (5%), this implies that the observed difference among the groups is highly unlikely to have occurred by random chance alone. Hence, there were no significant differences among the locations from which the radionuclide data were gathered for use in this study. This combination of statistical tests reinforces the robustness and reliability of the results obtained in this study, underscoring the significance of the observed differences in radionuclide activity concentrations among various locations in Iperindo.

3.2 Activity Concentration of Radionuclides in Soils

Figure 2 shows the graphical variation in the average activity concentration obtained for each location. From all the locations sampled, the singly occurring non-series ^{40}K was the highest and varied from 381.04 ± 23.36 $Bqkg^{-1}$ from the control site to 1303.10 ± 288.02 $Bqkg^{-1}$ at the first mining site. This was closely followed by the decay series of ^{232}Th and ^{238}U at values of 21.46 ± 4.27 to 79.30 ± 17.94 $Bqkg^{-1}$ and 15.26 ± 3.19 to 73.04 ± 16.07 $Bqkg^{-1}$ for the control locations and the first mining locations, respectively.

It is evident from the results that the activity concentration of radionuclides is higher in the gold mining areas of Iperindo than in the control locations outside the mining areas. A possible explanation for this highly significant radionuclide value could be related to the spread of radioactive dust across the mining site during gold mining. These unskilled artisanal miners' substandard tools and unprofessional conduct are primarily responsible for the significant increase in NORMs within mining sites. The geographical and geological formation of the Earth's crust has also been identified as a possible explanation for the high activity concentration of radionuclides observed in mining sites [13].

The average activity concentration of radionuclides obtained from the gold mining sites in Iperindo is alarmingly above the world permissible values of 33.0 $Bqkg^{-1}$ for ^{238}U, 45.0 $Bqkg^{-1}$ for ^{232}Th, and 420.0 $Bqkg^{-1}$ for ^{40}K [30]. In

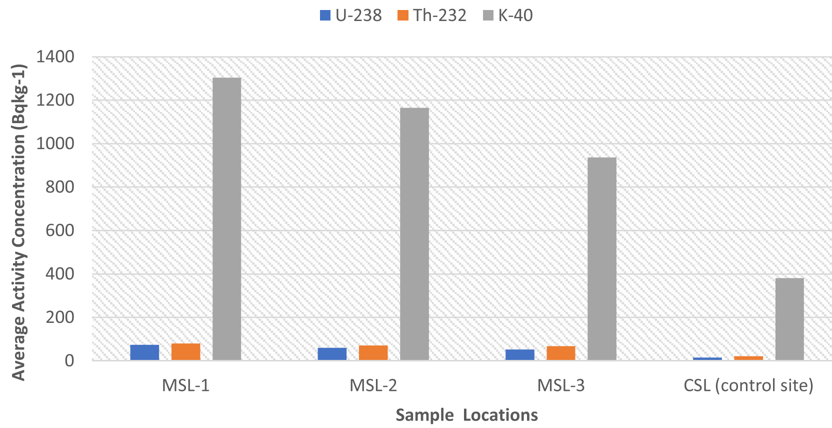

Fig. 2 Comparative analysis of average activity concentrations of radionuclides in the study area

contrast, the mean activity concentrations of radionuclides obtained from the control sites within the study area were well below the permissible world values. The recorded average activity concentration value of 61.55 $Bqkg^{-1}$ obtained for ^{238}U was 86.52% and 303.34%, respectively, which are significantly higher than the global permissible and control values, respectively. By contrast, the control value was 53.76% lower than the global permissible value. For ^{232}Th, the recorded average activity concentration value of 72.65 $Bqkg^{-1}$ is also distressingly higher than the global permissible and control values at 61.44% and 238.54%, respectively. However, the control value was 52.31% lower than the permissible values worldwide. The average activity concentration value of 1134.99 $Bqkg^{-1}$ obtained at ^{40}K was 170.24% and 197.87%, which is higher than the global permissible and control values, respectively, with a control value of 9.28% lower than the global permissible value. Figure 1 shows a graphical comparison of this situation.

The results obtained in this study are consistent with the average activity concentration values of 41.50 ± 4.60 $Bqkg^{-1}$ for ^{238}U, 39.70 ± 2.70 $Bqkg^{-1}$ for ^{232}Th, and 470.50 ± 12.20 420.0 $Bqkg^{-1}$ for ^{40}K reported by Refs. [13] for the same study area. Both studies agree that radionuclide activity concentrations in the gold mining area of Iperindo are above the permissible levels set by global standards. However, it is worth noting that the activity concentration reported in this study was conducted three years after the study conducted by [13]. The average activity concentrations of ^{238}U increased by 48.31%, ^{232}Th increased by an alarming 83%, and ^{40} K increased by 664.49%, respectively. The increase in radionuclide concentrations over the 3 years poses a significant threat to the health of residents of the Iperindo community.

Additionally, the significant increase in the concentration of ^{40}K is particularly worrisome, considering that K-40 is a vital component of nutrient-rich soil and is essential for promoting plant growth and human health through diet. High concentrations of K-40 are dangerous to human health because of the spontaneous emission of beta particles and gamma radiation. Studies have linked a high concentration of K-40 to stomach cancer [43] and an increased risk of lung cancer among smokers [44]. This prompted the authors to further investigate the soil-to-plant transfer factor to assess the radionuclide concentration level in crops cultivated on farmlands around gold mining sites in Iperindo. The outcomes of this investigation are presented in a different study.

A comparative analysis was performed between the average activity concentration values of the radionuclides obtained in this study and those obtained from other gold mining sites across Nigeria. The average activity concentration of ^{238}U in the present study was consistent with previous studies [20, 21, 31, 45], except for Orosun et al. [30], who reported values below global standards. All other studies showed values above the permissible levels. The average activity concentration of ^{232}Th in this study differed from that reported in Refs. [12, 27, 30]. The values in these references were below permissible levels, while they agree with the findings in Refs. [28, 29], which were above permissible levels. The average activity concentration of ^{40}K identified in the present study is consistent with the results of [20, 31, 45] and above global standards. However, this differs from the results of [21, 46], which are below the global standards. A graphical comparison between the average activity concentrations in this study and previous studies from gold mining sites across Nigeria is presented in Fig. 3.

3.3 Radiological Parameters and Associated Risks Assessment

Table 2 shows the results of various radiological parameters, including the radium equivalent, external and internal hazard risks, alpha and gamma indices, dose rate, annual effective dose rate, excess lifetime cancer risk, and annual gonadal dose rate. These radiological parameters and their associated risks were determined on the basis of the activity concentrations of the identified radionuclides at different gold mining and control locations in Iperindo, Nigeria. Table 3 compares the estimated radiological parameters obtained in the present study with those obtained in related studies from different gold mines across Nigeria and the world.

The radium equivalent is a significant radiological parameter to assess the potential radiation hazard of natural radionuclides in materials such as soil. In this study, the estimated radium equivalent values obtained for the gold mining locations in Iperindo varied from 220.85 to 286.78 Bqkg^{-1}, with an average value of 252.83 Bqkg^{-1}. Conversely, the control location had a lower radium equivalent value of 75.29 Bqkg^{-1}. These values indicate the radioactivity levels associated with the studied areas. The assessed radium equivalent results from gold mining and control locations are below the globally accepted threshold limit of 370 Bqkg^{-1} [30]. From a radiological safety perspective, this implies that the levels of radioactivity in the soil samples collected from both locations are within acceptable limits and do not pose immediate radiation hazards to individuals in the area. This study's accessed radium equivalent values were consistent with those of related gold mining studies in Nigeria [13, 21, 31]. This suggests that the radiological characteristics of the soil samples in the Iperindo gold mining locations align with what has been observed in other similar geological settings

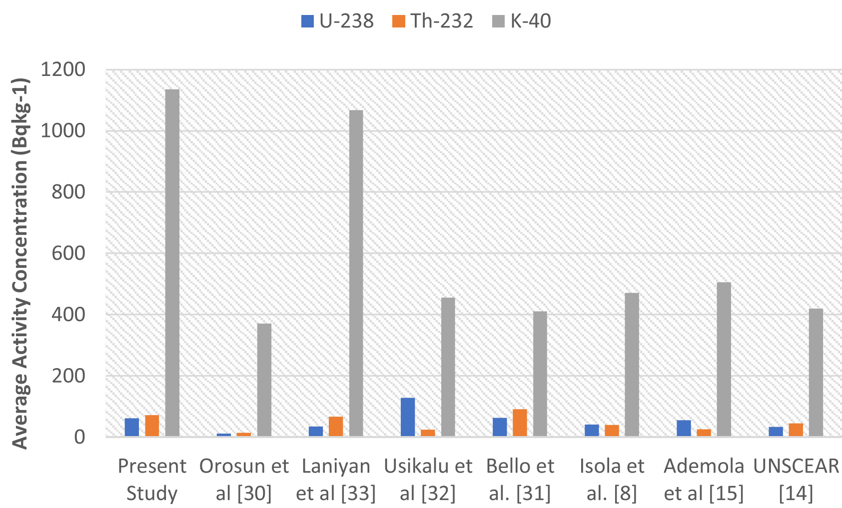

Fig. 3 Comparison of average radionuclide activity concentrations between the present study and previous gold mining site studies in Nigeria

Table 2 Estimated radiological parameters from sampled soil from the gold mining and control sites in Iperindo

Sample Code	Ra_{eq} (Bq/kg)	H_{ex} (Bq/kg)	H_{in} (Bq/kg)	I_α (Bq/kg)	I_γ (Bq/kg)	D (nGyh^{-1})	AEDR (μSv/y)	ELCR (×10^{-3})	AGED (μSv/y)
MSL-1	286.78	0.77	0.97	0.37	2.15	136.37	167.25	0.59	966.34
MSL-2	250.85	0.68	0.84	0.30	1.88	119.38	146.41	0.51	846.92
MSL-3	220.85	0.60	0.74	0.26	1.65	104.19	127.78	0.45	737.43
Mean (mining)	**252.83**	**0.68**	**0.85**	**0.31**	**1.89**	**119.98**	**147.15**	**0.52**	**850.23**
CSL (control)	75.29	0.20	0.24	0.08	0.57	36.02	44.17	0.15	256.50

Table 3 Comparative analysis of radiological parameters from this study in Iperindo and those obtained in similar studies

Reference	Ra_{eq} (Bqkg^{-1})	H_{ex}	H_{in}	I_α	I_γ	D (nGyh^{-1})	AEDR (μSvy^{-1})	ELCR (×10^{-3})	AGED (μSvy^{-1})
Present study	**252.83**	**0.68**	**0.85**	**0.31**	**1.89**	**119.98**	**147.15**	**0.52**	**850.23**
Itagunmodi gold mine [15]	132.14	0.36	0.51	NI	0.97	66.3	81.3	NI	439.73
Iperindo gold mine [8]	134.24	0.36	0.48	NI	NI	62.88	77.11	0.27	NI
Shanono & Bagwai gold mine [31]	224.04	0.61	0.78	0.31	0.86	100.89	130.00	0.71	NI
Ijero gold mine [30]	NI	NI	0.88	NI	1.41	89.70	110.00	0.38	NI
Moro gold mine [33]	NI	NI	NI	NI	1.18	74.18	90.00	0.32	NI
UNSCEAR [14]	370.00	1	1	1	1	59.00	70.00	0.29	300.00

"NI" values mean not investigated

in Nigeria. However, it should be noted that the average radium equivalent obtained in the present study increased significantly by 88.34% from the values reported by Isola et al. [13], who also conducted a radiological study in Iperindo gold mining sites. This increase over a relatively short time frame underscores the dynamic nature of radioactivity in the environment and may warrant further investigation into potential factors contributing to this rise.

The external hazard index in the gold mining locations of Iperindo ranged from 0.60 to 0.77 $Bqkg^{-1}$, with an average of 0.68 $Bqkg^{-1}$. This index is associated with environmental exposure to gamma radiation from radionuclides. Gamma radiation is highly penetrating and can penetrate the human body, potentially damaging living tissues and cells. The control location, in contrast, had a significantly lower external hazard index of 0.20 $Bqkg^{-1}$. The external hazard index measures the potential for external gamma radiation exposure to individuals in the studied area. The internal hazard index estimated for the gold mining locations ranged from 0.74 to 0.97 $Bqkg^{-1}$, with an average value of 0.85 $Bqkg^{-1}$. This index is associated with inhaling or ingesting radionuclides, such as radon and its decay products, which can emit alpha and beta radiation internally within the body. The control location had a lower internal hazard index of 0.24 $Bqkg^{-1}$. When individuals inhale or ingest radioactive particles, these particles can become lodged in tissues or organs, increasing the risk of radiation-induced health issues, including lung cancer.

It is important to note that for all the locations considered, the internal and external hazard indices were less than the permissible value of unity [34]. This suggests that, from a radiological safety perspective, the external and internal radiation exposure levels in these locations did not exceed the recommended safety limits. These results align with those reported in the literature by Refs. [13, 21, 31, 45]. A comparative analysis between the present study and Isola et al. [13] shows that over 3 years, the external and internal hazard indices in the Iperindo gold mining locations have increased significantly by 88.89% and 77.08%, respectively. This increase raises concerns about potential health risks associated with gamma radiation emissions and the inhalation or ingestion of radon progeny in the Iperindo community, particularly the possibility of respiratory tract diseases and other radiation-related health issues. These findings underscore the importance of monitoring and addressing radiological risks associated with gold mining activities in the area to protect the health of the community and miners.

The alpha and gamma indices are important radiological parameters for evaluating the potential radiation hazards associated with natural radionuclides in soil samples. For the gold mining locations in Iperindo, the estimated alpha index values ranged from 0.26 to 0.37 $Bqkg^{-1}$, with an average of 0.31 $Bqkg^{-1}$. The alpha index values obtained in the present study for gold mining and control locations are below the permissible limit of 1, thus indicating a safe environment for alpha radiation exposure. This indicates that the levels of alpha radiation in the environment were within safe limits, suggesting a low radiological risk associated with alpha radiation. The study's findings are consistent with the Shanono and Bagwai gold mine results in Kano for alpha index [21].

The gamma index values for the Iperindo gold mining locations ranged from 1.65 to 2.15 $Bqkg^{-1}$, with an average of 1.89 $Bqkg^{-1}$. Conversely, the control locations had lower alpha and gamma index values, with estimated values of 0.08 and 0.57 $Bqkg^{-1}$, respectively. The gamma index values obtained for gold mining exceeded the permissible limit of 1, indicating a higher radiological risk associated with gamma radiation in the soil of these areas. In contrast, the gamma index values for the control locations remained within the permissible limit of 1, signifying a lower radiological risk in those areas. Comparatively, the study's findings are consistent with the works of Ijero [45] and Moro [46] gold mines, with gamma index values of 1.41 and 1.18 $Bqkg^{-1}$, respectively, which were all above the threshold [29, 30]. The gamma index value estimated in the present study, however, differed entirely from values of 0.86 and 0.97 $Bqkg^{-1}$ reported, respectively, for Shanono and Bagwai [21] and Itagunmodi [31] gold mines, which were lower than the global threshold limit of 1.

The estimated dose rate for the gold mining areas ranged from 104.19 to 136.37 $nGyh^{-1}$, with an average dose rate of 119.98 $nGyh^{-1}$. This is in contrast to the lower dose rate of 36.02 $nGyh^{-1}$ obtained for the control locations. This substantial difference in dose rates implies that the risk of radiation exposure is much higher within the gold mining areas, with a remarkable 103.36% higher than the global permissible limit of 59 $nGyh^{-1}$ [30]. This further represents a notable 90.81% increase compared to the values reported by Isola et al. [13]. Moreover, the estimated AEDR due to external exposures in the gold mining areas ranged from 127.78 to 167.25 μSvy^{-1}, with an average value of 147.15 μSvy^{-1}. This is in contrast to the average AEDR value of 44.17 μSvy^{-1} estimated at the control locations. The estimated AEDR value at the control locations is below the permissible limit, while the gold mining areas are above the permissible limit [14]. A comparison between the average dose rate and AEDR values estimated in this study with those presented in related literature [15, 30, 31, 33] reveals that the radiation risk within the gold mining areas is notably higher, surpassing the globally accepted dose and exposure limits. This signifies a critical radiation hazard in these areas, emphasizing the urgent need for radiation safety measures and mitigation strategies to protect the health and well-being of individuals within the community.

The ELCR obtained in the study varied from 0.45×10^{-3} to 0.59×10^{-3} for the gold mining locations, with an estimated average value of 0.52×10^{-3}. Notably, this value is lower than

0.15×10^{-3} obtained from the control locations but higher than the global threshold limit of 0.29×10^{-3}[14]. Conversely, the ELCR value for the control locations is lower than the global threshold limit, signifying compliance with established safety standards. Therefore, the ELCR values obtained for the Iperindo gold mines suggest an elevated cancer risk associated with radiation exposure in these areas. The result obtained in the present study in the Iperindo gold mines is consistent with those reported for Moro [33], Ijero [30], Shanono and Bagwai [21], and Itagunmodi [31] gold mines. However, the result differs significantly from the value of 0.27×10^{-3} reported 3 years prior for the Iperindo gold mine by Isola et al. [8], which was below the global threshold limit.

Additionally, the estimated AGED value for the study varied from 737.43 to 966.34 μSvy^{-1}, with an average of 850.23 μSvy^{-1}. In contrast, the control location had an estimated lower AGED value of 256.50 μSvy^{-1}. Remarkably, the AGED values obtained for the gold mine and control locations are higher and lower than the global permissible limit of 300 Svy^{-1}, respectively. The study is, however, consistent with the reported value of 439.73 Svy^{-1} for Itagunmodi gold mines in Osun, Nigeria [31]. The AGED values in the Iperindo gold mines emphasize elevated radiation exposure levels in these areas, reinforcing the urgent need for comprehensive radiation safety measures and risk mitigation strategies to safeguard the health and well-being of the community and miners.

4 Conclusion

The scalability of natural radionuclides and its associated risks in soils from gold mining areas in Iperindo, Southwestern Nigeria, has been assessed in this study using a well-calibrated NaI (Tl) gamma-ray spectrometry. The average activity concentrations of radionuclides in soil samples from gold mining sites in Iperindo were 61.55±3.71 $Bqkg^{-1}$ for 238U, 72.65±4.45 $Bqkg^{-1}$ for 232Th, and 1134.99±38.12 $Bqkg^{-1}$ for 40K. In contrast, the control locations in Iperindo yielded concentrations of 15.26±3.19 $Bqkg^{-1}$ for 238U, 21.46±4.27 $Bqkg^{-1}$ for 232Th, and 381.04±23.36 $Bqkg^{-1}$ for 40K. Additionally, a CV value ranging from 14.51 to 25.36% implies moderate data reproducibility, suggesting that similar results can be expected in repeated measurements of the radionuclides within the different studied locations. The *F*-test results further affirmed the significance and consistency of our findings regarding radionuclide activity concentrations within different locations in Iperindo, in which a *p*-value of 0.000574 was obtained.

Further results obtained in the study revealed that the gold mining sites have a high concentration of ^{40}K compared to ^{238}U, ^{232}Th, and other published studies from gold mining fields across Nigeria. The activity concentration of radionuclides from the gold mining site is also above the world permissible level. It exhibited a significant increase compared to a study conducted 3 years ago by Isola et al. [8] in the same area. The estimates of the average radiological parameters assessed from Iperindo gold mines reveal that the radium equivalent, external and internal hazard risks, and alpha index are all significantly lower than the global threshold limits, while the gamma index, dose rate, annual effective dose rate, excess lifetime cancer risk, and the annual gonadal dose rate are all above the global threshold limits.

These radiological parameters have also increased by over 70% compared to results published three years ago by Isola et al. [8] for the same study area. From the accessed results, the artisanal gold mining activities in the Iperindo community pose serious radiological and health risks to the community's residents. Although estimated results from the control areas in Iperindo are below the global threshold limit, radionuclide concentrations and associated risk factors are more likely to increase over the years as gold mining activity continues.

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Data Availability Data will be available upon request.

Declarations

Competing Interests The authors declare no competing interests.

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