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Artisanal Gold Mining Activity in Northcentral Nigeria and Its Implications: Radiological Approach

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ABSTRACT

Artisanal gold mining is one of the anthropogenic activities identified by the United Nations Scientific Committee on the Effects of Atomic Radiation as potential source of exposure to naturally occurring radionuclides. 40 surface soil samples randomly collected from Gababiyu artisanal gold mining site, in Minna Metropolis (Nigeria), were assessed for their natural radioactivity using gamma spectrometric technique which employs a NaI (Tl) gamma-ray detector. The specific activities of ^{226}Ra, ^{232}Th and ^{40}K in the soil varied from 10.272.88± Bq/kg to 152.60±3.80 Bq/kg, 32.67±1.93 Bq/kg to 185.90±6.06 Bq/kg and 35.18±1.45 Bq/kg to 947.50±7.51 Bq/kg respectively, with mean values of 65.06±4.20 Bq/kg, 87.63±2.89 Bq/kg and 267.94±4.29 Bq/kg in sequence. Although ^{226}Ra and ^{232}Th recorded activity values slightly above the world average, they are still within the safety range prescribed by UNSCEAR. The computed average absorbed dose rate at 1 m above the ground was 94.16 nGy/h with a corresponding mean annual dose equivalent of 0.12 mSv/y. Furthermore, calculated average excess lifetime cancer risk was found to be 0.40×10^{-3}, which is slightly above the UNSCEAR safety limit. Pearson correlation statistics identified ^{226}Ra and ^{232}Th as principal radionuclides responsible for the computed radiation risk variables. Although the results of this investigation does not show any immediate radiological risk, continuous monitoring of the gold mining site is encouraged in order to keep the radiation effects as low as reasonably achievable.

KEYWORDS

Artisanal gold mining, Excess lifetime cancer risk, NORM, Northcentral Nigeria, NaI (Tl) gamma detector.

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INTRODUCTION

People's life and development requires natural resources which are randomly distributed in the earth crust **(Candeias *et al.*, 2018).** Mining and mineral extraction occurs wherever natural resources (metallic, non-metallic minerals and fossils) are located and at economically viable amount **(Ako *et al.*, 2014).** When the activities are properly done and in compliance with the regulations established by the government and other regulatory agencies, radioactive mineral extractions can be of great benefit to the population. Aside jobs creation, mining and mineral extraction activities are viable sources of economic development and foreign exchange earnings for any nation. One of the most precious and economically viable natural resources that has attracted continuous attention from miners and investors is the gold. On a large scale, gold-mining can be a promising means of economic development and foreign exchange earnings for any nation. Artisanal (small-scale) mining is any activity that encompasses small, medium, informal, legal and illegal mining that involves the use of rudimentary methods and processes to extract mineral resources **(Sabo *et al.*, 2018).**

Mining and mineral extraction processes have been found over time to incite depletion of the environment such as land degradation, de-vegetation, air and water pollutions and loss of aquatic organisms **(Ako *et al.*, 2014).** Additionally, these processes have been known to propagate and concentrate natural radioisotopes within the environment to such levels that may become detrimental to human health **(Kolo *et al.,* 2015, Kolo *et al.,* 2016).** Environmental impact of artisanal gold mining in developing countries particularly in West Africa has been well documented **(De Lacerda & Salomons, 2012; Hilson, 2002; Hollaway, 1993; Meech *et al.,* 1998; Mireku-Gyimah & Suglo, 1993).**

Nigeria is a gold-rich country. Gold deposits are found in most parts of northern Nigeria with an average deposit of 21.40 tons **(Okore, 2018).** Gold Mining in Nigeria resumed in the 1960s, but could not be developed as rapidly as expected due to the Civil war between 1967 and 1970. In the 1980s, however, there was a rebirth of this precious metal mining as a result of the efforts of the Nigerian Mining Corporation. Yet, poor attention from the government regarding this mineral resource exploitation, unemployment and extreme poverty has driven large number of socially and economically marginalized communities to adopt local mining activity as their main occupation **(Pure Earth., 2008).** Several gold-rich rural areas in Nigeria have been dominated by unskilled artisanal miners who are underequipped and have little appreciation for the environment **(Sabo *et al.*, 2018).** Most of these artisanal miners are totally ignorant of, or uninformed about the implications of mining activities on human health and the environment. Therefore, management of radionuclide enriched mine wastes has become a critical challenge in mining sites. **UNSCEAR (2000)** identified mining and mineral exploitation processes as one of the potential sources of exposure to naturally occurring radioactive materials (NORM) **(Faanu *et al.*, 2016).** Exposure to ionizing radiation emitted by NORM poses radiological risk to humans and the environment **(Alharbi, 2016).** The probability and nature of corresponding effects (somatic or genetic) induced in any human population depend on the radiation dose received **(NYSDH, 2007).**

Gababiyu in North-Central Nigeria has been known for artisanal gold mining activities for decades, with poor or no attention paid to radiation safety guidelines by the local miners. Gold mine wastes are dumped haphazardly all-round the mine by the local miners and thus become avenues for radiological contamination of the soil environment. The locals have constant and continuous access to the mining site as a result of their agricultural activities, which leads to their constant exposure to radiation. Consumption of food grown on this contaminated soils is an additional pathway for radiation exposure. Furthermore, soils from Gababiyu mining site have been used by the locals on regular basis, either for landfills or as aggregates of building materials, thereby enhancing their chances of constant radiation exposure.

Almost nothing is known about basic data and information on the radiological implications and associated radiological risk due to artisanal gold mining activities in Gababiyu mining site. We consider that research trials in this area will be useful to the industrial sector of Nigeria government. This study is therefore, aimed at assessing the radiological implications of artisanal gold mining activities in Gababiyu artisanal gold mine site. It is considered a pilot study, whose results will assist the Nigerian government and regulatory authorities in providing comprehensive radiological safety management protocols to keep radiation effects due to artisanal mining activities as low as reasonably achievable, considering economic and social factors.

MATERIALS AND METHOD

Sample Site

Gababiyu artisanal goldmine is located between longitude 6° 20’ 00″ to 6° 37’ 30″ E and latitude 9° 32’ 30″ to 9° 42’ 30″ N, in Chanchaga local government area, of Minna, Niger State, in North-Central Nigeria. It is characterized by two distinct seasons namely, rainy (from April/May through October) and dry (December – March), with the two seasons often separated by somewhat transitional periods in April and November. The mean annual rainfall is about 1284 mm, with temperature range of 27ºC to 33ºC. The site (Figure 1), which is characteristically grass-dominated, forming a mixture of the southern and northern Guinea Savanna ecological biomes, falls within the temperate humid zone that coincides with the tropical hinterland and Guinea Savanna zone of Nigeria. The site which is geologically surrounded by rugged terrain of granitic rocks, is part of Minna Sheet 164 of the Basement Complex Terrain of Nigeria **(Ahmed *et al*., 2019).**

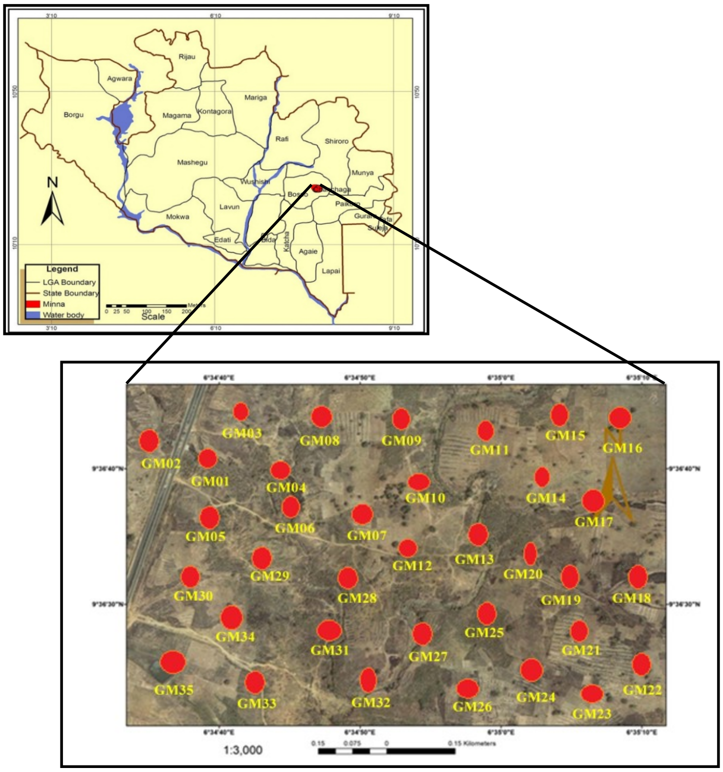


Fig. (1): *Location map of the study area and the sampling points.*

Sample Collection and Preparation

40 surface soil samples were randomly collected at 15 cm of the upper soil surface from Gababiyu artisanal goldmine for radiometric analysis. The samples were carefully collected at different points to adequately represent the entire mine site. 1.0±0.1 kg of the collected soil samples were neatly packed into well labelled polyethylene bags (GM01 to GM40) and conveyed to the laboratory for preparation.

In order to assure completely moisture free samples, each soil sample was air dried at room temperature for 96 hours in the Applied Nuclear Physics Laboratory, Federal University of Technology Minna. The dried samples were thoroughly pulverized and sieved using BSS 63 aperture (≈250 micron mesh size) to obtain uniformly homogenous sample matrix with improved surface area to volume ratio. 500±0.1 g of the sieved samples were packed in accurately labeled polyethylene bags and transported for analysis to the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria. Before analysis, each sample was packaged into radon-impermeable cylindrical plastic containers, selected based on the volume of the detector vessel (7.6 cm by 7.6 cm) geometry. Each container was triple sealed by smearing of the inner rim of container lid with Vaseline jelly, filling the lid assembly gap with candle wax to block the gaps between lid and container, and tight-sealing lid-container with masking adhesive tape. Sealed samples were stored for about 35 days to allow radon and its short-lived progenies attain secular radioactive equilibrium **(Girigisu *et al.*, 2014)** prior to gamma spectrometry analysis.

Sample Analysis

Gamma spectrometric analysis was carried out on the samples using a 7.62 cm×7.62 cm NaI (Tl) gamma detector crystal optically coupled to a photomultiplier tube (PMT). The assembly has a preamplifier incorporated into it and a 1 KV external source. The detector was enclosed in a 6 cm lead shield lined with cadmium and copper sheets to minimize the effects of background and scattered radiation. Data acquisition and gamma spectra analysis was performed using Maestro software (Canberra Nuclear Products). Calibration of the system for energy and efficiency were done prior to sample analysis using two calibration point sources: ^{137}Cs and ^{60}Co, with amplifier gain of 72% energy resolution for the 661.16 KeV of ^{137}Cs. Dependability of calibration and quality assurance of gamma spectrometry were checked using the IAEA gamma spectrometric reference materials RGU-1, RGTh-1 and RGK-1. Characteristic gamma energy lines used to compute the specific activities of primordial radionuclides are given in Table 1.

Table (1) : *Detected radionuclides and their gamma energy lines used for determination of activity.*

Nuclide of interest	Detected isotope	γ-ray energy (keV)
^{226}Ra	^{214}Bi	1764.0
^{232}Th	^{208}Tl	2614.5
^{40}K	^{40}K	1460.0

The system was set at a working energy range of 0–3000 keV to accommodate the energy range of interest in the study. Each sample was counted for a period of 29000 seconds (≈8 hours). The area of each energy peak in the spectrum was used to compute the activity concentrations in each sample by employing the equation **(Njinga *et al.*, 2015):**

$$A_i\ (\mathrm{Bq\ kg^{-1}}) = \frac{C_n}{I_{(\gamma)}\varepsilon M T} \qquad (1)$$

where, A_i is the activity concentration of a particular radionuclide in the sample, C_n is the net count rate (counts per second), $I_{(\gamma)}$ is the emission probability of a specific energy photo peak, $\varepsilon\varepsilon$ is the absolute efficiency of the detecting system, T is the time for collecting the sample spectrum, and M is the mass of the sample.

Radiological Parameters

From the activity concentrations obtained using Equation 1, the following assessment criteria were used to quantify exposure to radiation in the artisanal gold mining area.

Radium Equivalent Activity (Ra_{eq})

Radium Equivalent Activity (Ra_{eq}) is the weighted sum of hazards associated with ^{226}Ra, ^{232}Th and ^{40}K. This index presumes that 1, 0.7 and 13 Bq/kg of ^{226}Ra, ^{232}Th and ^{40}K, respectively, produce equal terrestrial gamma dose rates **(Beretka & Mathew, 1985; Kolo et al., 2019; UNSCEAR, 2000)**. **UNSCEAR (2000)** stipulates a threshold of 370 Bq/kg for Ra_{eq} (Suleiman *et al.*, 2018). Ra_{eq} was estimated using the equation **(Kolo *et al.*, 2019; Osimobi *et al.*, 2018):**

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \qquad (2)$$

where A_{Ra}, A_{Th} and A_K are the specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in the soil samples.

Gamma Radiation Dose (D_R)

The gamma radiation dose or absorbed dose (D_R) at 1 m above the ground was estimated using the equation **(Munyaradzi *et al.*, 2018; UNSCEAR, 2000):**

$$D_R = 0.462A_{Ra} + 0.604\,A_{Th} + 0.0417A_K \qquad (3)$$

where D_R is the gamma radiation dose in nGy/h and the coefficients (0.462, 0.604 and 0.0417 in nGy/h per Bq/kg) are the dose conversion factors for ^{226}Ra, ^{232}Th and ^{40}K, respectively, as contained in the **UNSCEAR (2008)** report.

Annual Effective Dose Equivalent (AEDE)

Annual Effective Dose Equivalent (AEDE) in mSv/y is estimated as the product of the gamma radiation dose, D (nGy/h), time in a year (8760 hours), dose conversion factor of 0.7 Sv/Gy and occupancy factor of 0.2 for outdoor exposure **(Taskin *et al.*, 2009; UNSCEAR, 2000).** AEDE was computed using the equation:

$$AEDE = D \times 8760 \times 0.7 \times 0.2 \times 10^{-6} \qquad (4)$$

ICRP (2007) provided AEDE threshold of 1 mSv/y for public exposure.

Annual Gonadal Dose Equivalent (AGDE)

The annual gonadal dose equivalent (AGDE) is a measure of the dose received by the gonads (gamete producing organs) of exposed population in a year **(Kolo *et al.*, 2015; Morsy *et al.*, 2012):**

$$AGDE(\mu Sv.y^{-1}) =$$
$$3.09A_{Ra} + 4.18A_{Th} + 0.314A_K \qquad (5)$$

where A_{Ra}, A_{Th} and A_K assume their respective definitions given before.

Activity Utilization Index (AUI)

Activity Utilization Index (AUI) is a parametric model used in determining NORM dose levels in the atmosphere from soil samples **(Osimobi *et al.*, 2018).** AUI was calculated from the specific activities of ^{226}Ra, ^{232}Th and ^{40}K in the sampled soils using the equation **(Osimobi *et al.*, 2018; Sivakumar *et al.*, 2014):**

$$AUI = \left(\frac{A_{Ra}}{50Bq/Kg}\right) f_{Ra} + \left(\frac{A_{Th}}{50Bq/Kg}\right) f_{Th} + \left(\frac{A_K}{500Bq/Kg}\right) f_K \qquad (6)$$

where f_{Ra}, f_{Th} and f_K having the numerical values of 0.462, 0.604 and 0.041, respectively, represent fragmentary supplements of ^{226}Ra, ^{232}Th and ^{40}K to the entire gamma dose **(Chandrasekaran *et al.*, 2014).**

External and Internal Hazard Indices

External hazard index (H_{ex}) is a parameter used for evaluating external exposure to gamma radiation in air. The maximum allowed value for H_{ex} is 1, which corresponds to the upper limit of Ra_{eq} (370 Bq/kg) **(Stranden, 1976; Suleiman *et al.*, 2018).** Internal hazard index (H_{in}), on the other hand, is a factor used to evaluate the hazardous effects of radon and its short lived progeny to the respiratory organs **(Suleiman *et al.*, 2018).** The threshold for H_{in} is also 1.

The external hazard index (H_{ex}) and internal hazard index (H_{in}) were estimated using the equations **(Berekta and Mathew, 1985; Osimobi *et al.*, 2018):**

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \quad (7)$$

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \quad (8)$$

Representative Gamma Index

Representative gamma index ($I_{\gamma r}$) is used to evaluate the conformity of soil to dose standards set for building materials **(Jibiri *et al.*, 2014; Kolo *et al.*, 2019).** It categorizes materials that may induce radiological risk if deployed for construction **(Osimobi *et al.*, 2018).** $I_{\gamma r}$ was computed from the equation **(Khater, et al., 2010; Osimobi et al., 2018)::**

$$I_{\gamma r} = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \quad (9)$$

$I_{\gamma r}$ must be ≤ 1 to satisfy the given dose criteria. This corresponds to an annual effective dose below 1 mSv **(Kolo *et al.*, 2019; Osimobi *et al.*, 2018).**

Excess lifetime Cancer Risk (ELCR)

Excess Lifetime Cancer Risk (ELCR) is a measure of the probability that a certain stochastic effect will occur in an individual exposed to low doses of ionizing radiation over a given period of time **(Turyahabwa et al., 2016; UNSCEAR, 2000).** The most common radiation induced health effects are incidence of cancers and genetic effects. ELCR was estimated using the equation **(Munyaradzi et al., 2018; Taskin et al., 2009): :**

$$ELCR = AEDE \times DL \times RF \quad (10)$$

where DL is the average duration of human life (estimated to be 70 years) and RF is risk factor (Sv^{-1}) or fatal cancer risk per sievert. For stochastic effects, which produce low background radiation, the ICRP 60 stipulates RF value of 0.05 for public exposure **(Munyaradzi *et al.*, 2018; Taskin *et al.*, 2009).**

RESULTS

Specific activities of primordial radionuclides in soil samples collected from Gababiyu artisanal goldmine along with the location coordinates are shown in Table 2. Activity concentrations of ^{226}Ra varied from 10.27±2.88 Bq/kg to 152.60±3.80 Bq/kg with an average value of 65.06±4.20 Bq/kg. Specific activity values for ^{232}Th ranged between 32.67±1.93 Bq/kg to 185.90±6.06 Bq/kg, with mean activity value of 87.63±2.90 Bq/kg. ^{40}K show much higher activity values than ^{226}Ra and ^{232}Th which of course should be expected owing to the natural abundance of ^{40}K in soils.

Activity concentration of ^{40}K varied from 35.18±1.45 Bq/kg to 947.50±7.51 Bq/kg, with mean value of 267.94±4.29 Bq/kg (Table 2). The average activity value for ^{40}K in the investigated mining site was lower than the world mean value of 400 Bq/kg.

Radiological Parameters

Computed Ra_{eq}, radiological doses and other radiation hazard indices are given in Table 3. Ra_{eq} varied from 96.67±4.56 to 396.18±13.87 $Bq.kg^{-1}$ with mean values of 210.86±8.66 $Bq.kg^{-1}$. This value was below the global upper limit of 370 $Bq.kg^{-1}$ **(Kolo *et al.*, 2012; UNSCEAR, 2000).** D_R at 1 m above the ground varied from 44.02 nGy/h to 173.46 nGy/h, with an average value of 94.16 nGy/h.

Table (2) : *Activity concentrations of NORM in soil samples collected from Gababiyu artisanal goldmine.*

Sample ID	Coordinates		Activity concentration (Bq/kg)		
	Longitude	Latitude	^{226}Ra	^{232}Th	^{40}K
GM01	06° 34’ 40.9”	09° 36’ 39.5”	10.27±2.88	60.12±0.31	183.84±8.58
GM02	06° 34’ 40.4”	09° 36’ 38.2”	129.1±3.40	96.92±3.07	236.02±1.56
GM03	06° 34’ 39.6”	09° 36’ 39.1”	19.18±2.80	48.21±0.94	144.85±5.47
GM04	06° 34’ 40.0”	09° 36’ 39.8”	89.13±6.75	38.06±4.72	137.82±1.14
GM05	06° 34’ 40.0”	09° 36’ 40.5”	41.44±3.08	80.80±0.28	732.34±6.44
GM06	06° 34’ 40.2”	09° 36’ 40.4”	17.50±2.24	78.76±1.53	277.74±7.94
GM07	06° 34’ 41.7”	09° 36’ 40.4”	152.60±3.80	124.72±1.34	166.84±3.00
GM08	06° 34’ 42.7”	09° 36’ 40.1”	81.07±2.84	91.57±2.20	281.65±6.38
GM09	06° 34’ 43.2”	09° 36’ 39.5”	38.48±3.00	66.33±1.34	247.06±6.86
GM10	06° 34’ 43.3”	09° 36’ 38.6”	120.19±4.99	185.90±6.06	135.41±2.90
GM11	06° 34’ 45.8”	09° 36’ 39.4”	61.45±4.68	59.88±2.08	189.57±2.63
GM12	06° 34’ 45.4”	09° 36’ 40.4”	75.64±3.36	96.41±1.42	228.51±2.57
GM13	06° 34’ 44.2”	09° 36’ 39.5”	25.05±0.92	63.62±0.20	233.34±8.85
GM14	06° 34’ 43.8”	09° 36’ 39.1”	84.95±4.52	83.75±1.02	184.69±5.79
GM15	06° 34’ 44.2”	09° 36’ 38.9”	28.33±1.08	32.67±1.93	281.65±9.49
GM16	06° 34’ 45.0”	09° 36’ 38.1”	95.68±8.47	66.80±7.67	174.34±1.24
GM17	06° 34’ 42.9”	09° 36’ 36.8”	89.90±3.32	79.62±0.39	291.20±3.49
GM18	06° 34’ 42.3”	09° 36’ 37.6”	33.52±2.60	60.43±2.01	82.48±3.00
GM19	06° 34’ 42.5”	09° 36’ 37.6”	51.06±3.80	73.41±1.61	232.26±5.68
GM20	06° 34’ 42.5”	09° 36’ 37.3”	41.36±5.43	109.23±1.85	297.96±6.01
GM21	06° 34’ 53.6”	09° 36’ 31.0”	92.40±7.79	110.45±6.88	333.66±1.00
GM22	06° 34’ 53.3”	09° 36’ 30.6”	88.66±3.76	75.77±0.83	260.69±0.97
GM23	06° 34’ 50.9”	09° 36’ 31.2”	41.71±4.00	52.49±1.10	35.18±1.45
GM24	06° 34’ 54.4”	09° 36’ 30.8”	22.22±1.68	68.34±1.42	135.46±6.06
GM25	06° 34’ 53.9”	09° 36’ 31.2”	108.42±4.43	98.45±5.23	157.34±0.72
GM26	06° 34’ 54.1”	09° 36’ 30.8”	41.40±4.44	83.00±2.24	209.90±5.63
GM27	06° 34’ 53.5”	09° 36’ 30.7”	97.32±5.51	92.01±5.62	162.05±1.20
GM28	06° 34’ 53.8”	09° 36’ 30.8”	36.39±3.20	45.85±4.76	153.26±0.47
GM29	06° 34’ 53.8”	09° 36’ 31.0”	102.91±7.95	132.90±8.85	232.20±1.56
GM30	06° 34’ 53.1”	09° 36’ 30.5”	42.03±3.76	100.46±0.24	130.10±6.92
GM31	06° 34’ 53.6”	09° 36’ 31.6”	34.52±2.00	68.10±0.98	168.77±6.76
GM32	06° 34’ 50.6”	09° 36’ 31.2”	13.83±6.63	99.75±0.24	405.86±6.97
GM33	06° 34’ 53.8”	09° 36’ 31.4”	99.79±7.79	122.64±3.26	322.55±1.06
GM34	06° 34’ 42.2”	09° 36’ 32.3”	22.58±0.76	61.18±0.39	829.41±7.83
GM35	06° 34’ 43.2”	09° 36’ 32.0”	116.79±2.88	123.07±2.56	93.90±0.21
GM36	06° 34’ 43.4”	09° 36’ 31.6”	75.60±5.03	137.18±4.95	408.27±7.99
GM37	06° 34’ 42.7”	09° 36’ 32.1”	83.61±7.47	83.08±9.24	91.06±0.39
GM38	06° 34’ 41.3”	09° 36’ 29.9”	49.07±4.24	165.69±6.68	947.50±7.51
GM39	06° 34’ 42.0”	09° 36’ 32.0”	109.58±5.23	87.41±5.15	155.62±1.02
GM40	06° 34’ 41.8”	09° 36’ 30.7”	37.56±5.47	100.30±3.07	745.27±6.97
Min.			10.27±2.88	32.67±1.93	35.18±1.45
Max.			152.60±3.80	185.90±6.06	947.50±7.51
Mean			65.06±4.20	87.63±2.89	267.94±4.29

Table (3) : *Radiological parameters characterizing the soil samples collected from Gababiyu artisanal goldmine.*

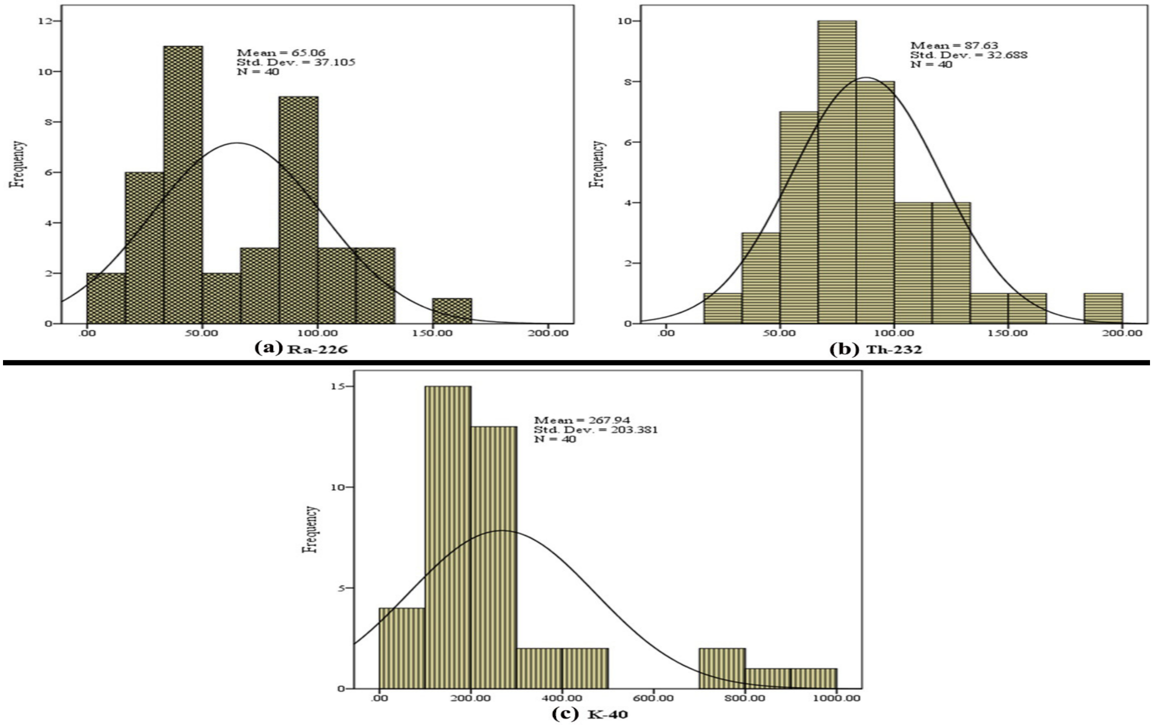
Sample ID	Ra_{eq} (Bq/Kg)	Radiological dose			Radiation hazard indices (≤1)				ELCR ($\times 10^{-3}$)
		D_R (nGy/h)	AEDE (mSv/y)	AGDE (µSv/y)	AUI	H_{ex}	H_{in}	$I_{\gamma r}$	
GM01	110.29±3.99	48.72	0.06	340.75	0.84	0.30	0.33	0.79	0.21
GM02	285.71±7.90	128.03	0.16	878.16	2.38	0.77	1.12	1.99	0.55
GM03	99.19±4.57	44.02	0.05	306.24	0.77	0.27	0.32	0.71	0.19
GM04	154.10±13.58	69.91	0.09	477.77	1.29	0.42	0.66	1.07	0.30
GM05	213.20±3.96	98.49	0.12	695.74	1.42	0.58	0.69	1.57	0.42
GM06	151.37±5.04	67.24	0.08	470.49	1.14	0.41	0.46	1.09	0.29
GM07	343.60±5.94	152.79	0.19	1045.24	2.93	0.93	1.34	2.38	0.66
GM08	233.56±6.47	104.51	0.13	721.73	1.88	0.63	0.85	1.64	0.45
GM09	152.24±5.43	68.14	0.08	473.74	1.18	0.41	0.52	1.08	0.29
GM10	396.18±13.87	173.46	0.21	1190.97	3.37	1.07	1.40	2.75	0.74
GM11	161.58±7.85	72.47	0.09	499.73	1.31	0.44	0.60	1.13	0.31
GM12	230.94±5.58	102.71	0.13	708.47	1.88	0.62	0.83	1.62	0.44
GM13	133.88±1.88	59.73	0.07	416.60	1.02	0.36	0.43	0.96	0.26
GM14	218.80±6.42	97.53	0.12	670.56	1.81	0.59	0.82	1.53	0.42
GM15	96.67±4.56	44.57	0.05	312.55	0.68	0.26	0.34	0.70	0.19
GM16	204.52±19.52	91.82	0.11	629.62	1.71	0.55	0.81	1.42	0.39
GM17	226.05±4.15	101.77	0.12	702.05	1.82	0.61	0.85	1.59	0.44
GM18	126.20±5.69	55.43	0.07	382.10	1.05	0.34	0.43	0.88	0.24
GM19	173.80±6.54	77.62	0.10	537.57	1.38	0.47	0.61	1.23	0.33
GM20	220.32±8.54	97.50	0.12	677.92	1.73	0.60	0.71	1.57	0.42
GM21	275.85±17.70	123.31	0.15	851.96	2.22	0.75	1.00	1.94	0.53
GM22	216.96±5.01	97.60	0.12	672.54	1.76	0.59	0.83	1.52	0.42
GM23	119.41±5.68	52.44	0.06	359.36	1.02	0.32	0.44	0.83	0.23
GM24	130.26±4.17	57.19	0.07	396.83	1.04	0.35	0.41	0.92	0.25
GM25	261.17±11.96	116.12	0.14	795.97	2.20	0.71	1.00	1.81	0.50
GM26	176.12±8.07	78.01	0.10	540.77	1.40	0.48	0.59	1.25	0.33
GM27	241.22±13.64	107.29	0.13	736.18	2.02	0.65	0.91	1.68	0.46
GM28	113.68±10.03	50.90	0.06	352.22	0.90	0.31	0.41	0.80	0.22
GM29	310.62±20.71	137.50	0.17	946.41	2.58	0.84	1.12	2.17	0.59
GM30	195.56±4.63	85.52	0.10	590.66	1.61	0.53	0.64	1.37	0.37
GM31	144.79±3.92	64.12	0.08	444.33	1.16	0.39	0.48	1.02	0.28
GM32	187.55±7.51	83.56	0.10	587.12	1.37	0.51	0.54	1.36	0.36
GM33	299.80±12.53	133.63	0.16	922.26	2.43	0.81	1.08	2.11	0.57
GM34	173.78±1.92	81.97	0.10	585.93	1.02	0.47	0.53	1.32	0.35
GM35	299.83±6.54	132.21	0.16	904.80	2.57	0.81	1.13	2.07	0.57
GM36	302.98±12.73	134.81	0.17	935.22	2.39	0.82	1.02	2.15	0.58
GM37	209.30±20.70	92.61	0.11	634.23	1.78	0.57	0.79	1.45	0.40
GM38	358.65±14.36	162.26	0.20	1141.72	2.53	0.97	1.10	2.62	0.70
GM39	246.42±12.67	109.91	0.13	752.82	2.08	0.67	0.96	1.71	0.47
GM40	238.18±10.39	109.01	0.13	769.34	1.62	0.64	0.75	1.75	0.47
Min.	96.67±4.56	44.02	0.05	306.24	0.68	0.26	0.32	0.70	0.19
Max.	396.18±13.87	173.46	0.21	1190.97	3.37	1.07	1.40	2.75	0.74
Mean	210.86±8.66	94.16	0.12	651.47	1.68	0.57	0.75	1.49	0.40

Calculated AEDE values ranged between 0.05 mSv/y and 0.21 mSv/y, with mean value of 0.12 mSv/y, which was lower than the 1 mSv/y threshold recommended by **ICRP (2007)** for public exposure. AGDE recorded values ranging from 306.24 µSv/y to 1190.97 µSv/y, with mean value of 651.47 µSv/y. Furthermore, the values computed for AUI ranged between 0.68 and 3.37, with a mean of 1.68. This satisfied the <2 threshold, corresponding to AEDE below 1 mSv/y for radiological safety **(Osimobi *et al.*, 2018; Sivakumar *et al.*, 2014).** Computed values for external hazard index H_{ex} and internal hazard index, H_{in} ranged from 0.26 to 1.07 and 0.32 to 1.40 respectively, with average values of 0.57 and 0.75 in sequence. Furthermore, calculated values for $I_{\gamma r}$ varied from 0.70 to 2.75, with about 30 of the investigated samples registering $I_{\gamma r}$ values above unity. The computed mean $I_{\gamma r}$ of 1.49 was slightly above the global screening value of unity for building materials **(Osimobi *et al.*, 2018; Sivakumar *et al.*, 2014).** Similarly, computed ELCR values for the artisanal gold mining site varied from 0.19×10^{-3} to 0.74×10^{-3}, with average value of 0.40×10^{-3}.

DISCUSSIONS

Results presented in Table 2 clearly showed spatial variations in activity concentrations which, according to **El-Mamney and Khater (2004)** and **Kolo et al. (2015),** may be a result of geochemical and physiochemical characteristics of the radionuclides. However, despite the variations in the activity values, there appeared to be an even distribution of primordial radionuclides across the mining site as depicted in the frequency distribution histograms shown in Figure 2.

Mean activity concentration of ^{226}Ra was 65.06±4.20 Bq/kg, while ^{232}Th recorded average specific activity of 87.63±2.90 Bq/kg. These values were found to be higher than their respective global average of 35 Bq/kg and 30 Bq/kg, respectively, as documented by **UNSCEAR (2000)** for normal soils. This therefore, points to the likelihood of radioactive pollution of Gababiyyu gold mining environment as a result of the constant and continuous mining activities performed by the locals.



(a) Ra-226 **(b)** Th-232 **(c)** K-40

Fig. (2): *Frequency distribution histograms of (a) ^{226}Ra, (b) ^{232}Th and (c) ^{40}K in the studied soil samples.*

Comparison of the data generated from this study with those of similar studies conducted in some parts of the world as presented in Table 4, showed some degree of agreement.

Table (4) : *Comparison of specific activities (Bq/kg) of primordial radionuclides in the present study with similar studies around the world.*

Location	^{226}Ra	^{232}Th	^{40}K	Reference
Nigeria	49.43	37.69	564.63	Suleiman et al. (2018)
Uganda	55.3	216	566.93	Turyahabwa et al. (2016)
China	12.64	15.89	746.84	Hu et al. (2016)
Ghana	65.1	71.8	1168.3	Faanu et al. (2016)
Nigeria	55.3	26.4	505.1	Ademola and Onyema (2014)
Iraq	77.33	9.36	426.31	Al-Gazaly et al. (2014)
India	138.24	83.15	343.2	Vinay Kumar Reddy et al. (2012)
Malaysia	178	841	104	Kuan et al. (2009)
Nigeria	65.06	87.63	267.94	Present study
World average	35	30	400	UNSCEAR (2000)

Activity ratios of primordial radioisotopes were further computed in order to give a clear insight into the level of radioactive contamination of the investigated site. The plots of computed radioactivity ratios are shown in Figure 3. Computed ^{232}Th:^{226}Ra varied from 0.43 t0 7.22, with a mean value of 1.87. This value for the investigated site was above the value for normal soils (1.2) reported by **Eisenbud and Gesell (1997)**, which showed relative abundance of ^{232}Th compared to ^{226}Ra in the site. Average values for ^{232}Th:^{40}K and ^{226}Ra:^{40}K ratios were 0.46 and 0.37, respectively. These values were lower than 1, showing that ^{40}K exhibits higher radioactivity compared to ^{226}Ra and ^{232}Th in the investigated mining site.

Gamma radiation dose D_R characterizing the studied soil samples from Gababiyu artisanal mining site is shown in Figure 4. Average D_R at 1 m above the ground was found to be 94.16 nGy/h. Although this value appears to be relatively above the global average of 57 nG/h documented by **UNSCEAR (2000),** it compares moderately with results of similar studies around the world **(Doyi *et al.*, 2013; Kamunda *et al.*, 2016; Kuan *et al.*, 2009; Turyahabwa *et al.*, 2016; Vinay Kumar Reddy *et al.*, 2012).**

Calculated H_{ex} for the studied samples varied between 0.27 and 1.07, with a mean value of 0.57. Although the average value was lower than the UNSCEAR established threshold of unity, one of the investigated samples (sample GM10) exceeded the threshold by about 7% as seen in Figure 5. This may however not constitute any immediate radiological threat that will require urgent attention.

A plot of the computed H_{in} for the studied soil samples is shown in Figure 6. Although the calculated mean H_{in} value of 0.75 was below the UNSCEAR threshold of unity, 8 of the samples exceeded this limit as can be seen in Figure 6. These include samples GM2, GM7, GM10, GM29, GM33, GM35, GM36 and GM38. This result points to the possibility of internal contamination of the local miners by radon and its byproducts after long time exposure. Radiation protection protocols must therefore be strictly adhered to by the miners at these locations for their radiation safety.

The variation in the representative gamma index $I_{\gamma r}$ obtained for the studied samples is shown in Figure 7. 32 samples which represent about 80% of the studied samples recorded $I_{\gamma r}$ values above the recommended UNSCEAR threshold. This shows that the investigated samples may induce radiation risk among the populace especially when used as aggregate of building material. Furthermore, strong positive correlation was found to exist between $I_{\gamma r}$ and ^{226}Ra (+0.72) and also with ^{232}Th (+0.93) as seen in Table 5. This showed that the rise in values of gamma index is principally due to ^{226}Ra and ^{232}Th contents in the studied samples. Thus, very serious precautionary measures must be taken in deploying soil from Gababiyu gold mining site for construction, from point of view of radiation protection.

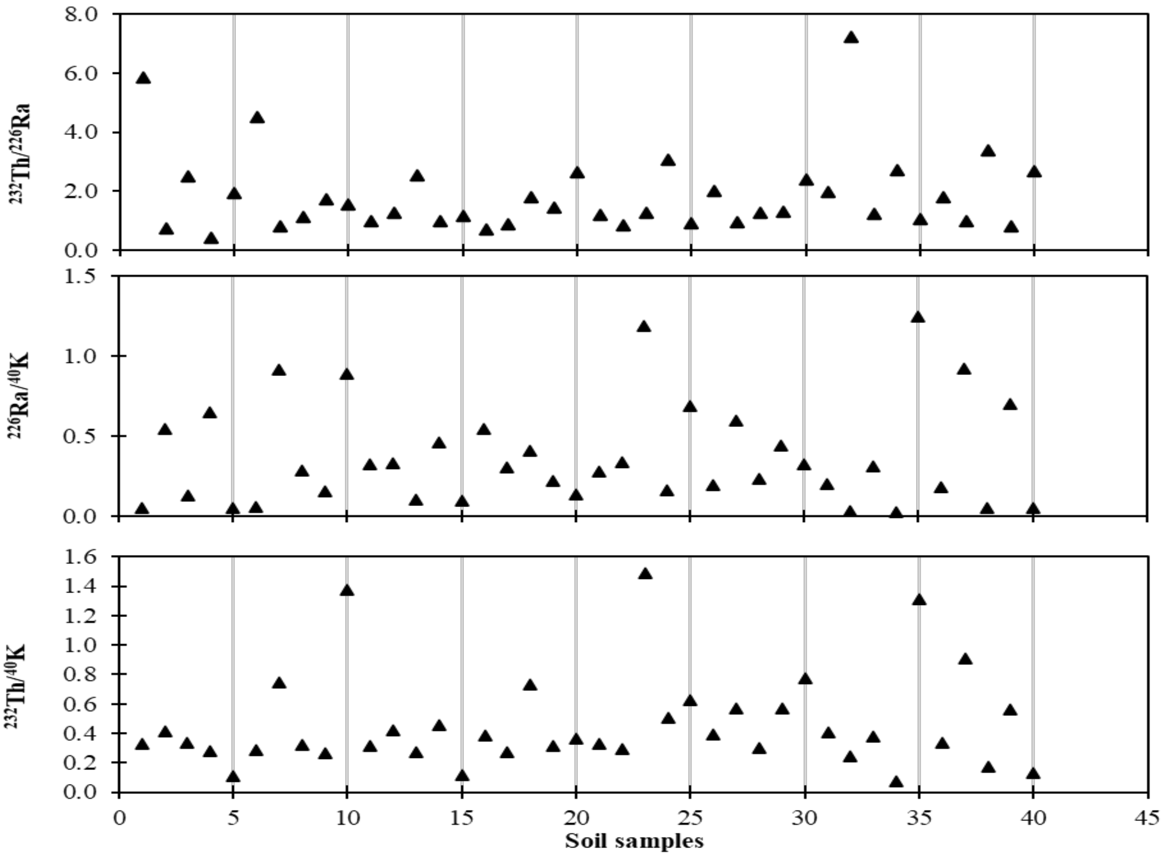


Fig. (3): *Activity ratios of ^{232}Th/^{226}Ra, ^{226}Ra/^{40}K and ^{232}Th/^{40}K in the studied soil samples.*

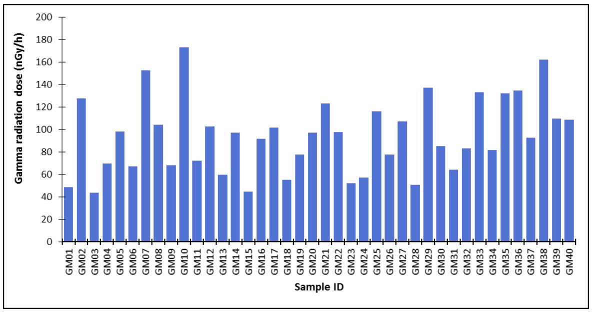


Fig. (4): *Gamma Radiation Dose characterizing the considered samples.*

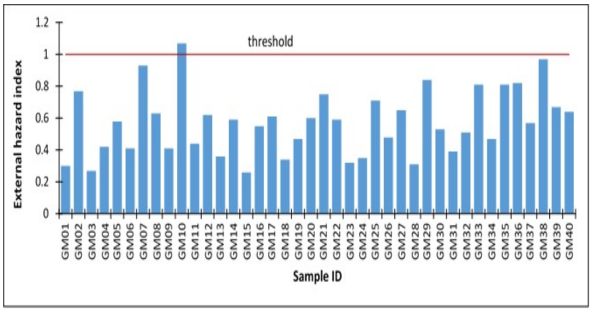


Fig. (5): *External Hazard Index values obtained for the considered samples.*

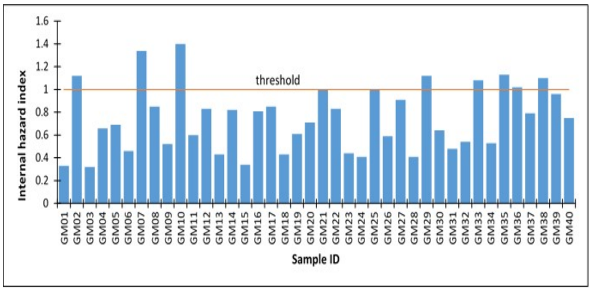


Fig. (6): *Internal Hazard Index values obtained for the considered samples.*

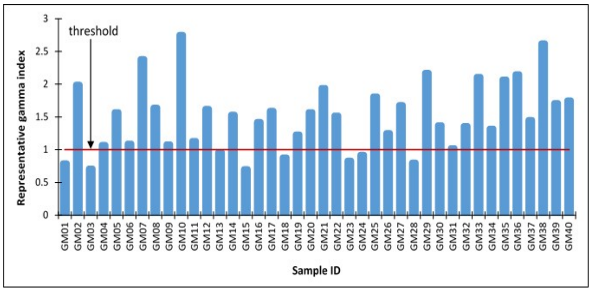


Fig. (7): *Representative Gamma Index characterizing the considered samples.*

Computed average for ELCR was 0.40×10^{-3}, which is higher than the global mean of 0.29×10^{-3} **(Munyaradzi *et al.*, 2018; Taskin *et al.*, 2009).** The results suggest that serious caution should be applied when using the soil from this gold mine as aggregates of building material or for agricultural purposes, in order to forestall likelihood of cancer incidence over long period of time.

Pearson's Correlation Analysis

To check the possibility of correlations and degree of dependency between primordial radionuclides and the computed radiological parameters, data obtained in this study were subjected to Pearson's correlation analysis. Computed linear correlation coefficients obtained at alpha testing level $p<0.05$ for samples (n=40), were classified as "very strong" ($r>0.75$), "strong" ($0.50<r<0.75$), "weak" ($0.36<r<0.49$) and "very weak" ($r<0.36$), respectively. Results of the correlation analysis are presented in Table 5.

The results showed strong positive association between ^{226}Ra and ^{232}Th (r = 0.50), very weak negative relationship between ^{226}Ra and ^{40}K (r = -0.25) and very weak relationship between ^{232}Th and ^{40}K (r = 0.26). This showed that ^{226}Ra and ^{232}Th may have a common natural origin and existence, different from that of ^{40}K. Very strong relationship was also noticed among all computed radiological variables ($r>0.75$). Additionally, ^{226}Ra and ^{232}Th correlated very strongly ($r>0.75$) with all computed radiological parameters (Table 5). This indicated that ^{226}Ra and ^{232}Th are the principal radionuclides responsible for gamma radiation emission in Gadabiyyu gold mining site.

Table (5) : *Comparison of specific activities (Bq/kg) of primordial radionuclides in the present study with similar studies around the world.*

Variables	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	D_R	AEDE	AGDE	AUI	H_{ex}	H_{in}	I_γ	ELCR
^{226}Ra	1.00											
^{232}Th	0.50	1.00										
^{40}K	-0.25	0.26	1.00									
Ra_{eq}	0.75	0.92	0.25	1.00								
D_R	0.75	0.92	0.28	1.00	1.00							
AEDE	0.75	0.92	0.28	1.00	1.00	1.00						
AGDE	0.73	0.92	0.31	1.00	1.00	1.00	1.00					
AUI	0.84	0.89	0.05	0.98	0.97	0.97	0.97	1.00				
H_{ex}	0.75	0.92	0.25	1.00	1.00	1.00	1.00	0.98	1.00			
H_{in}	0.89	0.83	0.09	0.97	0.97	0.97	0.96	0.99	0.97	1.00		
I_γ	0.72	0.93	0.30	1.00	1.00	1.00	1.00	0.97	1.00	0.96	1.00	
ELCR	0.75	0.91	0.28	1.00	1.00	1.00	1.00	0.97	1.00	0.97	1.00	1.00

CONCLUSIONS

Surface soil samples from artisanal gold mining environment in Gababiyu were assessed for their radiological contents using gamma spectrometry technique. Average specific activity values for ^{226}Ra, ^{232}Th and ^{40}K were 65.06 Bq/kg, 87.63 Bq/kg and 267.94 Bq/kg, respectively. These values, except for ^{40}K, were above the global mean values recommended by the United Nations Scientific Committee on Effects of Atomic Radiation. This gives an indication of possible radioactive pollution as a result of the local gold mining activities.

Average gamma dose rate was found to be slightly higher than the recommended global average. Some samples also showed slightly enhanced values of internal hazard index, which points to the possibility of internal contamination of the local miners by radon and its byproducts. Similarly, almost 80% of the studied samples recorded $I_{\gamma r}$ values above the recommended UNSCEAR threshold. This give an indication of the likelihood of occurrence of radiation incidences after long time exposure. Mean Excess Lifetime Cancer Risk of 0.40×10^{-3} may suggest that serious caution should be applied when using soil from Gababiyu artisanal gold mine as aggregates of building material or for agricultural purposes, in order to forestall likelihood of cancer incidence over long period of time. There is therefore the need for constant and continuous radiological monitoring of Gababiyu artisanal gold mine so as to keep any foreseeable radiation effects as low as reasonably achievable (ALARA), within the framework of social and economic provisions.

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