Journal of Radiation and Nuclear Applications
An International Journal

http://dx.doi.org/10.18576/jrna/110108

Comparative Analysis of Radiological Hazards Indices from Residual Radioactivity around Mika Uranium Mining Site in North-Eastern Nigeria.

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Received: 30 Aug. 2025, Revised: 20 Oct. 2025, Accepted: 30 Nov. 2025
Published online: 1 Jan. 2026

Abstract: Uncontrolled mining activities can increase the background radiation to members of the public by facilitating the release of natural radioactivity from the host materials to the environment as a result of the extraction of mineral ores, resulting in undue radiation hazards in the long run. This study evaluated the comparative analysis of Radiological Hazards indices from Residual Radioactivity to the residents around Mika Uranium mining site in North Eastern Nigeria, by performing analytical evaluation of radiological hazard indices parameters and evaluating the Offsite Dose and excess cancer risk using the RESRAD Offsite computer code from residual radioactivity concentrations of ^{238}U, ^{232}Th and ^{40}K in soil samples around Mika Uranium Mining site in Taraba State, North Eastern, Nigeria. The representative soil samples were collected using systematic random sampling techniques. The soil samples collected were analyzed for radioactivity concentrations of ^{238}U, ^{232}Th, and ^{40}K using a Sodium Iodide NaI (Tl) detector at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, Nigeria. Comparing these results with international recommended values, the mean activity concentration of ^{40}K (457.44 Bq/kg) is higher than the global average of 420 Bq/kg reported by UNSCEAR (2000), while the mean ^{238}U (15.68 Bq/kg) and ^{232}Th (12.53 Bq/kg) fall below the worldwide average values of 33 Bq/kg and 45 Bq/kg respectively. The mean absorbed dose rate (33.89 nGy/h) and Ra_{eq} (69.22 Bq/kg) are within safe global limits. The external hazard index (0.186) is far below unity, indicating a negligible external gamma hazard. The mean AEDE (0.042 mSv/y) is much lower than the 1.0 mSv/y global safety limit. The mean ELCR (0.145×10^{-3}) is within the safe band but indicates a slight elevation in potential cancer risk. The result of simulation using the RESRAD Offsite computer code shows that the highest total offsite dose is 4.99e-03mSv/yr after 70 years. Although the total dose is below the EPA dose limit of 0.1mSv/yr for inhalation, the dose has remained stable after 70 years and remains stable due to the long half-lives of NORM radionuclides. The doses recorded were all lower than the EPA dose limit of 0.1mSv/yr, indicating that the inhalation doses emanating from residual radioactivity from the Mika uranium mining site considered in this study have less impact on offsite residents in the long run. However, the danger of radiation exposure and its impacts must be understood by the population living near the mining sites, as no radiation exposure is safe since accumulation of low exposure dose can result in stochastic effects.

Keyword: Activity Concentration; Uranium Mining, Residual Radioactivity, Radiological Hazards, Radiation Exposure.

1 Introduction

Due to the nature of the daughter radioactive products produced by gaseous decay, mining operations have had a negative effect on people and the environment, even at low concentrations, facilitating the release of radioactive elements from the host material and posing some undue risk to human health [1-3]. Humans are exposed to both external and internal radiation from naturally occurring radionuclides, which can be found in the air we breathe due to aerosol contamination, the food we eat due to radionuclide fallout and transfer factors from soil to plants, and the water we drink from contaminated sources that have caused public health issues [4-6]. The largest contributors to radiation exposure are Radon and Thoron (^{222}Rn and ^{220}Th), which are both alpha emitters and are also the decay products of ^{238}U and ^{232}Th commonly found in rocks and soils. These decay products released might contaminate the air and deliver radiation dose to the public residing around the vicinity of uranium mining sites and the environs, mainly through the inhalation pathway, resulting in radiological hazards [7]. Contaminant reaches an

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individual or population via several routes of exposure or exposure pathways, mainly the external and internal exposure pathways. Inhalation, ingestion, or wound exposure are the three most common pathways of internal exposure[8]. Inhalation of contaminated air with radioactive particle dust or aerosols constitutes inhalation exposure. Offsite dwellers residing away from the mining vicinity are at risk from breathing in radioactively polluted air due to a variety of internal and environmental factors. Additionally, several ventilation channels allow external pollutants to penetrate the internal environment, making internal receptors vulnerable.

[5]. The present study aims at performing comparative evaluation of Radiological Hazards indices including Gamma Absorbed Dose Rate (D)**,** Radium Equivalent Activity (Ra_{eq})**,** External Hazard Index (H_{ex})**,** Annual Effective Dose Equivalent (AEDE)**,** and Excess Lifetime Cancer Risk (ELCR) thereby providing a comprehensive assessment of the radiological impact of activity concentrations of ^{238}U, ^{232}Th and ^{40}K in soil around Mika uranium mining site, as well as evaluating the Offsite Dose and excess cancer risk to the public over the duration of seventy (70) years using the RESRAD Offsite computer code residual radioactivity concentrations of ^{238}U, ^{232}Th and ^{40}K in soil samples. The study will employ the average activity concentration level of ^{238}U, ^{232}Th, and ^{40}K in soil obtained in the Mika Uranium mining site as part of the input parameter for analysis alongside other ICRP standard parameters as embedded in the code. Such mining activities are potential sources of radiation and radioactivity, contaminating the environment and exposing people to radiation. Current ICRP references are established on the rational postulation that no radiation exposure dose is harmless, even the least radiation dose has the potential to cause stochastic effects such as cancer. However, in addition to maintaining below the dose limitations, the underlying objective was to maintain all such exposure levels "As Low As Reasonably Achievable" (ALARA) [9-13].

2 Materials and Methods

2.1 Study Area

Taraba is one of the six states that make up the North-Eastern geopolitical zone of Nigeria, and shares political borders with Bauchi and Gombe States to the North, Adamawa State to the East, and Benue, Nasarawa, and Plateau States to the West. Its southern boundary is shared with Cameroon, with Jalingo as the state capital. The state covers an area of 54,472sqm and lies at a latitude of 8° 00' North and a longitude of 10° 30' East. It has a population of 2,294,800 (2006 census), 3,066,834 according to the 2016 estimate, and a population density of 42. Mika is located at latitude 8˚58′34.5″N and longitude 11˚37′34.81″E in Taraba State's Yorro Local Government Area (LGA) in Northeastern Nigeria, as shown in Figure 1. Yorro's landscape is characterized by a surging and mountainous landscape, with around a quarter of the land suitable for agriculture. Figure 1 shows a geographical map of the Mika uranium mining site in Yorro LGA of Taraba State, North-Eastern Nigeria.

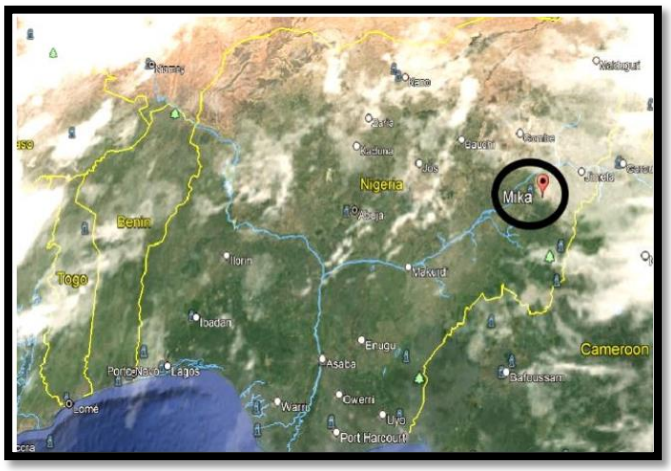

Fig. 1: Mika uranium mining site, Yorro LGA, Taraba State.

2.2 Sample and Sampling Technique

A total of ten soil samples were obtained from the study area at 500 meters apart using systematic sampling. To avoid cross-contamination during transit, soil samples were collected using a shovel at a depth of about 15cm and placed in a sealed, labeled polythene bag. To eliminate moisture, open-air drying at room temperature for seven days was used, and stone samples were ground into powder form with a mortar and pestle and sieved with a wire mesh with holes of thickness 0.5mm to achieve uniformity of sample size. Before going to the lab for examination, about 400g of mass were held in polythene bags for 28 days to achieve secular equilibrium between ^{238}U, ^{232}Th, and ^{40}K and their progeny. Table 1 shows the sample points as well as their coordinates and sample identification code.

Table 1: Geographical Coordinates of Mika Uranium Mining site alongside sample codes.

Mining Sites	Soil Sample	Elevation (Meters)	Geographical Coordinates	
			Latitude	Longitude
Mika Uranium Mining site, Yorro LGA, Taraba State (GH)	MK1	569	09º00′32″.57	11º39′02″.50
	MK2	569	09º00′33″.89	11º39′03″.85
	MK3	569	09º00′37″.16	11º39′01″.12
	MK4	569	09º00′30″.81	11º39′00″.52
	MK5	575	09º00′30″.34	11º38′59″.23
	MK6	536	09º00′29″.65	11º38′57″.46
	MK7	536	09º00′29″.73	11º38′54″.81
	MK8	569	09º00′30″.70	11º38′52″.80
	MK9	575	09º00′31″.58	11º38′52″.20
	MK10	532	09º00′33″.01	11º38′50″.68

2.3 Analysis of Radiological Hazard Indices

The data on radioactivity concentration levels of ^{238}U, ^{232}Th, and ^{40}K from soil samples obtained around Mika Uranium Mining site in North Eastern Nigeria were analyzed to determine the radiological hazard indices including Gamma Absorbed Dose Rate (D), Radium Equivalent Activity (Ra_{eq}), External Hazard Index (H_{ex}), Annual Effective Dose Equivalent (AEDE) and Excess Life Cancer Risk (ELCR) respectively. Radiological exposure doses and cancer risk resulting from residual radioactivity of ^{238}U, ^{232}Th, and ^{40}K to Off-site dwellers around the environs were also evaluated using RESRAD computer codes. The Methodology employed is stated below:-

2.3.1 Measurement of Gamma Absorbed Dose Rate

Gamma Absorbed Dose Rate (D) was determined from the activity concentration and by applying the conversion factors of 0.462, 0.604, and 0.0417 for ^{238}U, ^{232}Th, and ^{40}K, respectively, as expressed by UNSCEAR (2000a) as:

$$\mathbf{D}\ (\mathbf{nGy}.\boldsymbol{hr}^{-1}) = \mathbf{0.462A_U + 0.604A_{Th} + 0.0417A_K} \quad \textbf{(1)}$$

2.3.2 Measurement of Radium Equivalent Activity

Radium Equivalent Activity (Ra_{eq}) was determined using the weighted sum of activity concentrations of ^{238}U, ^{232}Th, and ^{40}K as expressed by ICRP (2007) as:

$$\boldsymbol{Ra_{eq}(Bq.kg^{-1}) = A_U + 1.43A_{Th} + 0.077A_K} \quad \textbf{(2)}$$

Where A_U, A_{Th}, and A_K are the specific activities of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1}, respectively.

2.3.3 Measurement of External Hazard Index

External Hazard Index (H_{ex}) was evaluated to limit the activity concentration (A) of ^{238}U, ^{232}Th, and ^{40}K to ensure that a permissible dose rate of less than 1 mSv/y, as expressed by UNSCEAR (2000), as:

$$\mathbf{H_{ex} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1} \quad \textbf{(3)}$$

Where A_U, A_{Th}, and A_K are the specific activities of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1}, respectively.

2.3.4 Measurement of Annual Effective Dose Rate

Annual Effective Dose Rate (AEDR) was evaluated using the absorbed dose rate (D) data obtained and a conversion factor value of 0.7 SvGy^{-1} of absorbed dose in air to the effective dose an adult receives, as expressed by UNSCEAR (2000b):

$$\mathbf{AEDR}(\boldsymbol{mSv.y^{-1}}) = \mathbf{D \times 8760 \times 0.2 \times 0.7 \times 10^{-6}} \quad \textbf{(4)}$$

2.3.5 Measurement of Excessive Life Cancer Risk

Excess Life Cancer Risk (ELCR) is determined by the product of the determined AEDR with Duration of Life (DL), 70 years for children and 50 years for adults, and low dose background radiation Risk Factor (RF) of 5% for public exposure considered to produce stochastic effect as expressed in ICRP (1997) as:

$$\mathbf{ELCR = AEDR \times RF \times DL} \quad \textbf{(5)}$$

2.4 *RESRAD-Offsite Computer Code*

RESRAD Offsite estimates radiological exposure dose and excess cancer risk to receptors within and outside the primary contamination boundary. The sources of polluted exposure can be outdoor the boundary of the prime contamination and could be entirely within the boundary. Some exposure scenes can be onsite, offsite, and even straddle the site boundary [9]. The main contamination, being the source of all exposure examined by the code, is presumed to be within a cover of soil. The code shows how contaminants spread from the primary contamination to groundwater, the air, and outward release. When appropriate, it simulates the buildup of pollutants at such locations in order to mimic the flow of pollutants from the original contamination to the receptors.

Any influence of pollutants from the environment is also modeled. Direct exposure from soil contamination, inhalation of particulates, inhalation of short-lived radon progeny, ingestion of plant food (i.e., vegetables, grains, and fruits), ingestion of meat, ingestion of milk, ingestion of aquatic foods, ingestion of water, and (incidental) ingestion of soil are all considered in RESRAD-Offsite. Its computational algorithm analyzes the concentration, dose, and risk numerically throughout the period. To simulate radiological dose using RESRAD Offsite, the offsite scenario assumes the public is within the vicinity of a uranium mining. The exposure pathway considered is inhalation. The code uses a Gaussian plume model, where the radionuclide concentration and plume remain constant over time [9].

2.4.1 Atmospheric Dispersion Model (ADM)

Atmospheric dispersion is important to study the dispersion models to estimate the off-site radiological consequences. Prediction of the dispersion of radioactive materials into the environment is very important because it can assist in planning for emergency preparedness and evacuation [10]. It is important to define the atmospheric conditions of the release location because these conditions help to predict the atmospheric dispersion [11]. When the radioactive materials are released to the atmosphere, they can

contaminate the environment and the public through various pathways. The models are used to mimic the atmospheric dispersion; the most commonly used one is the straight-line steady-state Gaussian model [12]. A dispersal model is a kind of mathematical equation that represents the discharge and dispersion of air contaminants in the atmosphere. There are several types of air dispersion models used in atmospheric dispersion modeling. These models can be classified into four categories, namely Gaussian, Numerical, statistical or empirical, and physical. The Gaussian Plume Model (GPM) is most widely used to predict dispersal from the continuous release, also used for estimating the impact of nonreactive pollutants [13].

2.4.2 Governing Equations of RESRAD-OFFSITE

RESRAD-OFFSITE uses a Gaussian plume model derived from a three-dimensional (3-D) equation for atmospheric diffusion to evaluate radionuclide concentration. The 3-D diffusion equation for atmospheric diffusion is given as:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial x}\left[C_x \left(\frac{\partial X}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[C_y \left(\frac{\partial X}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[C_z \left(\frac{\partial X}{\partial z}\right)\right] \quad \textbf{(6)}$$

where,:

x, y, and z = downwind, cross-wind, and vertical directions, and C_x, C_y, C_z = diffusivity in x-, y-, and z-directions.

The Gaussian plume model is expressed by the equation:

$$\mathbf{Q(x,y,z)} = \frac{Q}{2\pi\sigma_y(x)\sigma_z u}\exp\left\{-\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2\right\} \times \left(\exp\left\{-\frac{1}{2}\left[\frac{z-H}{\sigma_z}\right]^2\right\} + \exp\left\{-\frac{1}{2}\left[\frac{z+H}{\sigma_z}\right]^2\right\}\right)\exp\left[\frac{\lambda x}{u}\right] \mathbf{DF}\,(x) \quad \textbf{(7)}$$

However, if the σ_z Exceeds the inversion height (L), the following relation is used:

$$\boldsymbol{P(x,y,z)} = \frac{R}{2\pi\sigma_y L u}\exp\left\{-\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2\right\}\exp\left[-\frac{\lambda x}{u}\right] \mathbf{PF}\,(x) \quad \textbf{(8)}$$

where:
P = time-integrated atmospheric concentration (Ci-s)/ (m^3),
R = source term (Ci),
H = effective release height (m),
λ = decay constant (s–1),
x = downwind distance (m),
y = crosswind distance (m),
z = vertical axis distance (m),
σ_y = standard deviation (SD) of integrated concentration distribution in the crosswind direction (m),
σ_z = standard deviation (SD) of the integrated concentration distribution in the vertical direction (m),
u = mean wind speed at the effective release height,
L = inversion layer height (m),
PF(x) = plume depletion factor (PDF).

3 Results and Discussion

3.1 Activity Concentration of ^{238}U, ^{232}Th and ^{40}K in Soil Samples

The activity concentration of ^{238}U, ^{232}Th, and ^{40}K in soil samples obtained from the Mika Uranium Mining site in the study area is presented in Table 2.

Table 2: Activity Concentration of ^{238}U, ^{232}Th, and ^{40}K from soil samples.

Soil Sample	K-40 (Bq/Kg)	U-238 (Bq/Kg)	Th-232 (Bq/Kg)
MK1	569.96±28.64	34.96±3.46	13.83±3.80
MK2	471.83±15.09	20.15±1.90	16.19±1.24
MK3	616.09±31.74	2.17±2.10	7.35±0.47
MK4	348.83±38.33	17.43±2.89	7.77±0.93
MK5	375.81±36.14	9.42±1.98	16.53±2.30
MK6	430.44±28.34	9.19±2.70	10.24±0.64
MK7	136.61±14.80	8.36±1.80	13.59±1.57
MK8	658.04±24.62	14.61±2.49	20.51±2.92
MK9	649.14±35.13	22.08±1.64	9.92±3.85
MK10	317.59±33.01	18.45±3.54	9.35±0.97
Average	**457.44**	**15.68**	**12.53**
UNSCEAR	**420**	33	45
AC Ratio	**1..09**	**0.48**	**0.28**

Table 2 presents the results of activity concentration levels in soil samples collected from the Mika Uranium mining site, Taraba State. The results of the soil samples collected from the Mika Uranium mining site in Yorro, Taraba State, revealed notable variations in the activity concentrations of naturally occurring radionuclides. Potassium-40 (^{40}K) showed the highest activity concentration across the samples, with values ranging from 136.61 Bq/kg (MK-7) to 658.05 Bq/kg (MK-8), and a mean concentration of 457.44 Bq/kg. This dominance of ^{40}K is consistent with global observations in soil samples, where potassium is naturally abundant due to its geochemical properties. For ^{238}U, the activity concentration varied widely between 2.17 Bq/kg (MK-3) and 34.96 Bq/kg (MK-1), with a mean of 15.68 Bq/kg. Meanwhile, ^{232}Th concentrations ranged from 7.35 Bq/kg (MK-3) to 20.51 Bq/kg (MK-8), with an average of 12.53 Bq/kg. Comparing these results with international recommended values, the mean activity concentration of ^{40}K (457.44 Bq/kg) is higher than the global average of 420 Bq/kg reported by UNSCEAR (2000), while the mean ^{238}U (15.68 Bq/kg) and ^{232}Th (12.53 Bq/kg) fall below the worldwide average values of 33 Bq/kg and 45 Bq/kg

respectively. The relatively elevated concentration of ^{40}K in this mining environment could be attributed to geological factors and mineral composition of the host rocks, while the lower levels of ^{238}U and ^{232}Th indicate minimal buildup of uranium and thorium decay series radionuclides in the soils. These findings highlight the need for continuous monitoring, as uranium mining activities could enhance the mobilization of these radionuclides into the environment, with potential radiological and ecological implications.

3.2 Radiological Hazard Indices

The calculated radiological hazard indices, including Gamma Absorbed Dose Rate (D), Radium Equivalent Activity (Ra_{eq}), External Hazard Index (Hex), Annual Effective Dose Equivalent (AEDE), and Excess Lifetime Cancer Risk (ELCR), were obtained using equations 1 to 5 and are presented in Table 3.

Table 3: Calculated radiological hazard parameters from the Mika uranium mining site.

Soil Sample	D (nGy/h)	R_{eq} (Bq/kg)	H_{ex}	AEDE (mSv/y)	ELCR ($x10^{-3}$)
MK1	48.27399	99.07039	0.26639	0.059203	0.207211
MK2	38.76595	80.15644	0.215078	0.047543	0.166399
MK3	31.13089	60.34964	0.162315	0.038179	0.133626
MK4	27.29104	55.64771	0.149625	0.03347	0.117144
MK5	30.00873	62.52707	0.16742	0.036803	0.128809
MK6	28.3798	57.3042	0.153862	0.034805	0.121817
MK7	17.7658	38.74351	0.103456	0.021788	0.076258
MK8	46.57893	95.26628	0.255487	0.057124	0.199935
MK9	43.26338	86.57047	0.232943	0.053058	0.185704
MK10	27.41705	56.57942	0.152006	0.033624	0.117685
Mean	33.88756	69.22151	0.185858	0.04156	0.145459
World Av.	84	370	1	0.52	0.29 X 10^{-3}

Table 3 presents the calculated radiological hazard parameters of the soil sample of the Mika uranium mining site, Taraba State. The absorbed dose rate ranged from 17.77 to 48.27 nGy/h, with a mean of 33.89 nGy/h. This mean value is below the world average of 84 nGy/h recommended by UNSCEAR (2000). Hence, the radiation dose contribution from soils in Mika is low and does not pose a significant external hazard at present.

Ra_{eq} values varied between 38.74 and 99.07 Bq/kg, with a mean of 69.22 Bq/kg. This is far below the safety threshold of 370 Bq/kg (OECD, 1979), meaning that the soils from this mining site do not present harmful gamma radiation risks and remain safe for agricultural or residential use. Hex values ranged from 0.103 to 0.266, with a mean of 0.186. All values are well below the safety limit of 1.0, confirming that exposure to external radiation from Mika soils is within acceptable limits and poses negligible health risk to the local population. The AEDE ranged from 0.022 to 0.059 mSv/y, with a mean of 0.042 mSv/y. This is significantly lower than the recommended public exposure limit of 1.0 mSv/y (ICRP, 2007). Thus, long-term exposure to soils in Mika does not exceed safe annual dose limits and is radiologically safe for residents. The ELCR values ranged from 0.076×10^{-3} to 0.207×10^{-3}, with a mean of 0.145×10^{-3}. This average value is below the global reference of 0.29×10^{-3} (UNSCEAR, 2000). While the risk remains within the acceptable band, it still implies that prolonged exposure to soil radionuclides could contribute slightly to lifetime cancer risk, especially among those spending extended time in mining zones. In summary, the mean absorbed dose rate (33.89 nGy/h) and Ra_{eq} (69.22 Bq/kg) are within safe global limits. The external hazard index (0.186) is far below unity, indicating a negligible external gamma hazard. The mean AEDE (0.042 mSv/y) is much lower than the 1.0 mSv/y global safety limit. The mean ELCR (0.145×10^{-3}) is within the safe band but indicates a slight elevation in potential cancer risk.

3.3 RESRAD OFFSITE

The result of the simulation of radiological hazard indices from the Mika uranium mining site using RESRAD offsite from the determined mean activity concentration of ^{238}U, ^{232}Th, and ^{40}K is presented in Figure 2 below.

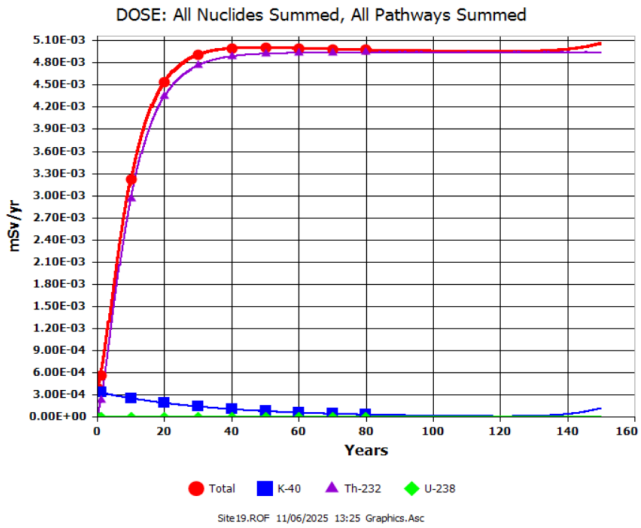

Fig. 2: Result of RESRAD Off-site dose assessment from the Mika Uranium mining site.

The exposure pathway considered for this analysis is the inhalation of gaseous decay products of NORMs over a period of 70 years, which is considered to be the average lifespan of a child according to equation 5. However, there is no contribution of inhalation dose from ^{40}K as it is less harmful for internal exposure and more harmful for external exposure because of the nature of its decay process, ^{40}K emits 89% beta and 11% gamma. Since dose contribution from ^{238}U and ^{232}Th is due to gaseous decay of daughter products, with a higher inhalation dose from ^{232}Th than ^{238}U, the inhalation of gaseous decay products of ^{238}U and

^{232}Th over 70 years is the exposure pathway for this investigation. From Figure 2, the highest total offsite dose is 4.99e-03mSv/yr after 70 years. Although the total dose is below the EPA dose limit of 0.1mSv/yr for inhalation, as suggested by [15], the dose still remained stable after 70 years and remains stable due to long half-lives of NORM radionuclides. These results show that it is safe for off-site residents to reside within a vicinity of the Mika uranium mining site. However, the modern ICRP recommendations had stated that accumulation of low levels of exposure from radiation has the tendency of resulting to stochastic effects in the end [6].

4 Discussions

Findings from this study have shown that the order of activity concentration in soil samples was: ^{40}K>^{232}Th > ^{238}U. Even though ^{40}K constitutes the highest total mean activity concentration of 457Bq/kg in soil, findings from this research have shown that the public is more prone to ^{238}U and ^{232}Th than ^{40}K. This is because ^{238}U and ^{232}Th undergo alpha decay, which are hazardous when inhaled even at low concentrations, and the accumulation could result in stochastic consequences. This finding is in line with previous researchers such as [16], from beryllium and gold mining sites in Ilorin, Nigeria, and [17], from gold mining sites in Itagunmodi, Nigeria, but different from that of [18], from Olode mining sites in Osun State.

Findings from this study have also revealed that, the total offsite doses due to inhalation after 70years from Mika uranium mining site is below the EPA dose limit of 0.1mSv/yr for inhalation as suggested by [15], which shows that the inhalation doses emanating from residual radioactivity from Mika uranium mining site considered in this study has less impact on offsite residents in the short long than in the long run. These findings are well comparable with those of [19], who reported a public dose of 7.43E-02mSv/yr from the Mujuni River in Tanzania using the RESRAD Offsite computer code, which is much higher than those reported in this study but still lower than the recommended limit. Also, in line with [20], who reported an off-site dose of 3.15E-02mSv/yr at 30 years from Wonderfonteinspruit in South Africa using the RESRAD OFFSITE code.

5 Conclusions

In this study, a comparative analysis of radiological hazard indices around the Mika uranium mining site was performed using analytical evaluation and RESRAD offsite computer code from residual radioactivity due to uranium mining activities to the public. The absorbed dose rate ranged from 17.77 to 48.27 nGy/h, with a mean of 33.89 nGy/h, which falls below the world average of 84 nGy/h recommended by UNSCEAR (2000). Ra_{eq} values varied between 38.74 and 99.07 Bq/kg, with a mean of 69.22 Bq/kg, which is far below the safety threshold of 370 Bq/kg. Hex values ranged from 0.103 to 0.266, with a mean of 0.186, which falls below the safety limit of 1.0. The AEDE ranged from 0.022 to 0.059 mSv/y, with a mean of 0.042 mSv/y, which is significantly lower than the recommended public exposure limit of 1.0 mSv/y (ICRP, 2007). The ELCR values ranged from 0.076×10^{-3} to 0.207×10^{-3}, with a mean of 0.145×10^{-3}. This average value is below the global reference of 0.29×10^{-3} (UNSCEAR, 2000). The results of the assessments using the inhalation pathway from the Mika Uranium mining site fall below the EPA dose limit of 0.1mSv/yr for inhalation as suggested by [15]. This value acts as a barrier between deterministic and stochastic effects, preventing deterministic impacts while minimizing the likelihood of stochastic effects. If the dose is greater than 0.1mSv/yr, public protection measures must be implemented. Although the ICRP affirms that there is no safe level of radiation exposure, however, the lowest exposure has a tendency to yield stochastic effects. Estimating radiation exposure dose is very critical in protecting the population from undue radiation exposure, which can vary subject to human and natural activities [21]. Therefore, it is suggested that all exposure be kept as low as reasonably achievable while upholding the dose limit. The dangers of radiation exposure and the impacts that could produce severe effects must be understood by populations living near mining sites. Effective protection, routine assessment, and a setback of at least 1000 meters for residential areas will be required to reduce the magnitude of exposure based on the radiation protection principle of maximizing distance, thereby minimizing radiation exposure.

Footnotes

Funding: This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests: All authors have declared that there are no financial relationships with any organizations that might have an interest in the submitted work and no other relationships or activities that could appear to have influenced the submitted work.

Ethical Approval: Ethical Requirement of Research Ethics Board approval for this project was formally waived by the institution.

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