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Analytical Evaluation of Inhalation Dose from Residual Radioactivity to Offsite Residents in Nigeria using ICRP Age Dependent Dose Coefficients.

Soja Reuben Joseph[1,] Nasiru-Deen Adebayo Bello[1] Umar Ibrahim[2] Nuraddeen Nasiru Garba[2] Muhammad Bello Gusau[1,] and Abdullahi A Mundi[3]*

[1] Nigerian Nuclear Regulatory Authority (NNRA), Abuja, Nigeria.
[2] Department of Physics, Nasarawa State University Keffi, Nigeria.
[3]Department of Physics, Ahmadu Bello University, Zaria, Nigeria.

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Abstract: One of the primary means by which people are exposed to radionuclides with prolonged half-lives such as ^{238}U, ^{232}Th and ^{40}K is mining, which involves physically removing minerals from the earth's surface. This study performed analytical evaluation of inhalation dose from residual radioactivity arising from mining activities to offsite residents using ICRP age dependent dose coefficients for five different age groups; 1 Year, 5 Years, 10 Years, 15 Years and Adult age groups respectively. In order to estimate age-dependent inhalation dose using analytical technique, data on measured activity concentration of NORMs radionuclides, comprising of ^{238}U, ^{232}Th and ^{40}K in soil samples obtained from selected mining areas were extracted from previous literatures along with their methods of analysis. Sixteen (16) mining sites, randomly selected across Five (5) Geopolitical zones of North East, North West, North Central, South West and South Eastern Nigeria respectively. The highest inhalation dose was recorded in Gura top mining site in Jos Plateau state, North Central geographical region with annual inhalation dose of 6.06E-02 mSv/yr, 9.51E-02 mSv/yr, 1.10E-01 mSv/yr, 1.40E-01 mSv/yr and 1.46E-01 mSv/yr while the lowest inhalation dose was recorded in Itagunmodi mining site in Osun, South West region with annual inhalation doses of 5.01E-03 mSv/yr, 7.36E-03 mSv/yr, 8.36E-03 mSv/yr, 1.05E-02 mSv/yr and 1.07E-02 mSv/yr for all age groups considered in this study. The higher inhalation dose are reported from ^{238}U and ^{232}Th than ^{40}K due to gaseous decay of radon and thoron which are harmful when inhaled and deposited in the human respiratory tract system. All the inhalation doses reported falls below the United State Environmental Protection Agency (US-EPA) recommended dose limit of 0.1mSv/yr from release of aerosol, and International Commission on Radiological Protection (ICRP) dose limit of 1 mSv/yr for the public, demonstrating that the short-term effects of inhaling radiation from mining sites on offsite dwellers are minimal. However, it is important to note that the ICRP are based on the thoughtful assumptions that there is no safe level of radiation exposure since the accumulation of small doses of radiation can have unpredictable effects. The offsite dwellers living within the vicinity of the mining site need to be conscious of the dangers of radiation exposure and its repercussions. To minimize the severity of exposure in accordance to the “As Low As Reasonable Achievable” principle and also to ensure strict adherence to radiation protection, routine assessment of exposure dose from mining activities to both onsite and offsite dwellers is recommended.

Keywords: Mining, Activity Concentration, Inhalation, Dose Coefficients, Inhalation rate, Exposure.

1 Introduction

One of the main causes of radiation exposure from long-lived naturally occurring radioactive materials (NORMs) is mining activities, which have resulted in significant public exposure doses that violates radiation protection standards [1]. Such radionuclides mainly consist of Uranium (^{238}U), thorium (^{232}Th) and Potassium (^{40}K) decay series. ^{238}U and ^{232}Th are primordial radionuclides and are present in all raw Materials in variable concentrations, and constitutes the main sources of natural background radiation to the surrounding environment [2]. Uranium (^{238}U), Thorium (^{232}Th) and their decay products (^{226}Ra, ^{212}Pb, etc.) and Potassium element (^{40}K) are the natural radionuclides witnessed as inborn soil contents with well-known impact to the radiation exposure and emission of gamma ray as well as successive inhalation of airborne decay products of

*Corresponding author e-mail: sojareuben@gmail.com

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Thoron and radon and ingestion via the food chain. Such radionuclides have low activity concentrations in raw materials, but human activities like mining can cause them to rise above background levels, thereby increasing the radiological risk and possibly exposing the public to unjustified radiation exposure. Different route and pathways through which humans can get exposed to such radiation includes external irradiation, skin contamination, inhalation of dust in the form of aerosol particles, in-advertent ingestion, and inhalation of radon, thoron, and their progeny via the decay products of ^{238}U and ^{232}Th [3]. Some guidelines and recommendations have been issued by notable international organizations such as the International Commission for Radiological Protection (ICRP), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Atomic Energy Agency (IAEA) among others, thereby ensuring that the radiation exposure to the public resulting from mining activities is less than the recommended ICRP dose limit of 1mSv/yr, and that such exposure is kept "as low as reasonably achievable" (ALARA), in addition to staying below the dose boundary thereby guarantees public and environmental protection [4, 5, 6 & 7]. Modern ICRP recommendations are based on the considerate assumption that there is no safe level of radiation exposure, and that even the smallest amount of exposure has a probability of resulting to stochastic effects including cancer among others. However, the basic principle of keeping all exposure levels "as low as reasonably achievable" (ALARA), in addition to staying below the dosage limits, was recommended as one of the measure of ensuring strict adherence to radiation protection principles. Thus, evaluation of the extent of such exposure is key for maintaining the recommended public dose limit. For proper regulatory guidance, it is crucial to carry out dose evaluation arising from several pathways in order to identify the predominant route of exposure. One method of conducting such an evaluation could be to use the ICRP age dependent dose coefficients to assess the tissue's sensitivity to radiation at different stages of development. This study performed analytical evaluation of inhalation dose from residual radioactivity of ^{238}U, ^{232}Th and ^{40}K arising from mining activities to offsite residents using ICRP age dependent dose coefficients for five different age groups; 1 year, 5 years, 10 years, 15 years and Adult age groups respectively thereby determining the sensitivity of tissue to radiation at various stages of development. Several studies has been performed on determination and activity concentration and public dose from mining activities by various authors [8, 9, 10, 11, 12 & 13]. However, there is little or no studies performed on analytical evaluation of public dose resulting from inhalation of radon and thoron decay products of ^{238}U and ^{232}Th due to mining activities by dwellers around the vicinity of mining site using ICRP age dependent dose coefficients, hence the need for this study.

2 Methodologies

2.1 Description of Study Area

The study areas comprises of sixteen mining sites randomly selected across five Geographical locations in Nigeria namely, North-East, North-West, North-Central, South-West and South-Eastern Geographical regions alongside their respective coordinates from each mining sites as presented in Table 1, while the geographical map showing the mining locations is also presented in Figure 1.

Table1. Geographical Information of some selected mining sites Across Nigeria

Geographical Region	Mining site/State	Geographical Coordinates Latitude	Longitude	Reference
	Raycon/Adamawa	09˚ 08 ' 36 " N	12˚ 19 ' 09 " E	[9]
North East	NRC/Adamawa	09˚ 21 ' 42 " N	12˚ 11 ' 32 " E	[9]
	AG Vision/ Adamawa	09˚ 56 ' 19 " N	12˚ 37 ' 46 " E	[9]
	Arufu/Taraba	7˚ 50 '59 " N	9˚ 5 ' 00 "E	[15]
North Central	Okobo/Kogi	07˚ 21 ' 14 " N	07˚ 37 ' 31 " E	[16]
	Gura Top/ Plateau	09˚ 49 ' 51 " N	08˚ 54 ' 48"E	[20]
	Central Nasarawa	08˚ 32 '59 " N	08˚ 05 ' 19 " E	[23]
North West	Shanono & Bagwai/Kano	12˚ 09 ' 00 " N	08˚ 08 ' 00 " E	[11]
	Wurno/Sokoto	13˚ 17 ' 30 " N	05˚ 25 ' 39 " E	[14]
	Anka/Zamfara	12˚ 06 ' 30 " N	5˚ 56 ' 00 " E	[18]
South West	Itagunmodi/Osun	7˚ 31 ' 00 " N	4˚ 39 ' 00 " E	[19]
	Iwajowa/Oyo	07˚ 30 ' 00 " N	03˚ 02 ' 24 " E	[17]
	Oke-Ogun/ Oyo	8˚ 39 ' 00 " N	3˚ 46 ' 00 " E	[24]
	Ijero/Ekiti	7˚ 46 ' 00 " N	5˚ 5 '00 " E	[15]
South East	Umuahia/Abia	5˚ 51 ' 66 " N	7˚ 41 ' 39 " E	[21]
	Mbara-Ozu/ Anambra	6˚ 00' 52'' N	7˚ 00' 54'' E	[22]

Fig.1: Geographical Map showing the selected mining locations Across Nigeria.

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2.2 Measurement of Activity Concentration

The present study employs data on measured activity concentration of ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K alongside methods of analysis obtained from prior literatures. The mean activity concentration of ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K obtained from representatives soil samples across sixteen mining sites randomly selected from five Geographical locations in Nigeria were computed and recorded with appropriate citation. Details of the mining sites randomly selected from each geographical region alongside their process of analysis and determination of the radionuclides analyzed from each respective mining sites are tabulated and presented in Table 2.

Table 2: Method of Analysis for ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K Radionuclides

Region	Mining site/State	Method of Analysis	Radionuclides	Reference
North East	Raycon/Adamawa	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[9]
	NRC/Adamawa	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[9]
	AG Vision/ Adamawa	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[9]
North Central	Arufu/Taraba	HPLC-ICPMS**	^{238}U, ^{232}Th and ^{40}K	[15]
	Okobo/Kogi	HPGe ***	^{238}U, ^{232}Th and ^{40}K	[16]
	Gura Top/ Plateau	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[20]
	Central Nasarawa	Na(TI) ∗	^{226}Ra, ^{232}Th and ^{40}K	[23]
North West	Shanono & Bagwai/Kano	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[11]
	Wurno/Sokoto	Na(TI) ∗	^{226}Ra, ^{232}Th and ^{40}K	[14]
	Anka/Zamfara	Na(TI) ∗	^{226}Ra, ^{232}Th and ^{40}K	[18]
South West	Itagunmodi/Osun	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[19]
	Iwajowa/Oyo	Na(TI) r∗	^{226}Ra, ^{232}Th and ^{40}K	[17]
	Oke-Ogun/ Oyo	Na(TI) ∗	^{226}Ra, ^{232}Th and ^{40}K	[24]
	Ijero/Ekiti	HPLC-ICPMS**	^{238}U, ^{232}Th and ^{40}K	[15]
South East	Umuahia/Abia	Na(TI) ∗	^{238}U, ^{232}Th and ^{40}K	[21]
	Mbara-Ozu/ Anambra	HPGe ***	^{238}U, ^{232}Th and ^{40}K	[22]

∗Gamma spectroscopy using sodium iodide with thallium (Na (TI)) Detector.
**High-Performance Liquid Chromatography with Inductive Coupled Plasma Mass Spectrometry
*** High purity germanium (HPGe) Detector.

2.3 Methodology for Dose Assessment

Depending on whether the radiation source is external or internal to the body, radiation exposure dose can be classified as either internal or external exposure dose. Internal dose results from inhalation of contaminated airborne as well as ingestion of contaminated food, water, or any other items containing radioactive materials. External dose is caused by direct gamma radiation or through contact with any materials containing radiation sources. However, one method of estimating external and internal exposure dose using analytical methods is by applying the ICRP dose coefficient for the specific radionuclide of interest along with other computational parameters [25].

2.4 Determination of Age Dependent Effective Dose Coefficients

For radionuclides of importance, the ICRP established dose coefficients for evaluating equivalent and effective doses from inhalation. The inhalation dose can be estimated using the activity aerodynamic diameter (AMAD), absorption type, and absorption fraction (fi). Absorption types for the human respiratory tract model are identified by particulates as fast (F), moderate (M), and slow (S) rate of solubilization, which is only applicable to inhalation dose calculation. Materials that are quickly absorbed into body fluids are deposited through fast absorption from the respiratory tract, while slow absorption deposits substances that are insoluble in the respiratory tract, moderate absorption deposits substances that have intermediate rates of absorption into bodily fluids [26]. To estimate the inhalation dose, multiply the activity concentration of radionuclides inhaled by the appropriate dose coefficient, as well as other computational exposure parameters such as inhalation rate and time or duration of exposure. The time of exposure used in this study is the standard ICRP exposure time for all age groups. The study assumed that offsite dwellers resides within the vicinity of the mining sites although their livelihood. Table 3 presents the age-dependent effective dose coefficient values for Inhalation of ^{238}U, ^{232}Th and ^{40}K obtained from ICRP Publication 119, as well as inhalation rate [27].

Table 3: Age-dependent Effective Dose Coefficients for Inhalation and inhalation rate.

Nuclides	$T_{1/2}$ (Yrs)	Age Dependent Effective Dose Coefficient for Inhalation (Sv/Bq) extracted from ICRP 119 [26].						
		Type	fi	1 Year	5 Years	10 Years	15 Years	Adult
^{238}U	4.468×10^{9}	F	0.02	1.3×10^{-6}	8.2×10^{-7}	7.3×10^{-7}	7.4×10^{-7}	5.0×10^{-7}
		M	0.02	9.4×10^{-6}	5.9×10^{-6}	4.0×10^{-6}	3.4×10^{-6}	2.9×10^{-6}
		S	0.002	2.5×10^{-5}	1.6×10^{-5}	1.0×10^{-5}	8.7×10^{-6}	8.0×10^{-6}
^{226}	1.60 ×	F	0.6	9.4×10^{-7}	5.5×10^{-7}	7.2×10^{-7}	1.3×10^{-6}	3.6×10^{-7}
		M	0.2	1.1 ×	7.0 ×	4.9 ×	4.5 ×	3.5 ×

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Ra	10^{3}			10^{-5}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
		S	0.02	2.9×10^{-5}	1.9×10^{-5}	1.2×10^{-5}	1.0×10^{-5}	9.5×10^{-6}
^{232}Th	1.405×10^{1}	F	0.0005	2.2×10^{-4}	1.6×10^{-4}	1.3×10^{-4}	1.2×10^{-4}	1.1×10^{-4}
		M	0.0005	8.1×10^{-5}	6.3×10^{-5}	5.0×10^{-5}	4.7×10^{-5}	4.5×10^{-5}
		S	0.0005	5.0×10^{-5}	3.7×10^{-5}	2.6×10^{-5}	2.5×10^{-5}	2.5×10^{-5}
^{40}K	1.28×10^{9}	F	1.0	1.7×10^{-8}	7.5×10^{-9}	4.5×10^{-9}	2.5×10^{-9}	2.1×10^{-9}
Age-Dependent Inhalation rate extracted from ICRP recommendations as citied by [27].								
Unit	Inhalation rate of 1 m^3/h = 24 m^3/d = 1225 g/hr							
m^3/d	-	-	-	5.1	10.2	15.2	20.3	22.2
m^3/hr	-	-	-	0.2125	0.43	0.63	0.85	0.925
g/hr	-	-	-	260	515.23	775.12	1035.14	1331.13

2.5 Governing Equation for Estimating Inhalation Dose and Total Effective Dose

The internal dose is the amount of radiation absorbed by the body because of radioactive materials entering through various pathways mainly through inhalation or ingestion. Such radioactive material accumulates in particular organs or tissues inside the body, delivering a radiation dose. The inhalation dose is mainly attributed to aerosols containing radioactive particles mainly radon and thoron gases, which are inhaled and deposited in the respiratory tract system. The annual effective dose from inhalation $\mathbf{D_{Internal(Inh)}}$ measured in millisievert per year (mSv/yr) can be estimated using equation 1 as:-

$$\mathbf{D_{Internal(Inh)}(mSv/yr)} = \mathbf{AC_R} \times \mathbf{Inh_R} \times \mathbf{Exp_t} \times \mathbf{DC_{Inh}} \quad (1)$$

where

$\mathbf{AC_R}$ = Measured Activity Concentration of inhaled radionuclide R in air (Bq/g)

$\mathbf{Inh_R}$ = Inhalation rate by an individual decay products ($1\ m^3/h$ or $1225\ g/hr$)

$\mathbf{Exp_t}$ = Exposure time to contamninated air (hr/yr)

$\mathbf{DC_{Inh}}$ = Inhalation Dose Coefficient in Sv/Bq

The ICRP's recommended dose limit should not be exceeded in terms of overall radiation exposure to the public. The total effective dose (mSv/yr) is the sum of radiation doses from all possible exposure pathways, such external exposure resulting from direct gamma radiation and internal exposure resulting from radionuclides inhalation and ingestion can be estimated using equation 2 expressed as:

$$\mathbf{D_{Total}(mSv/yr)} = \mathbf{D_{Ext.}} + \mathbf{D_{Int(Inh)}} + \mathbf{D_{Int(Ing)}}, \quad (2)$$

where:

D_{Total} = *Total Effective Dose (mSv/yr)*

$\mathbf{D_{Ext.}}$ = *Annual external dose from direct gamma radiation (mSv/yr)*

$\mathbf{D_{Int(Inh)}}$ = *Annual internal dose due to inhalation pathway (mSv/yr)*

$\mathbf{D_{Int(Ing)}}$ = *Annual internal dose due to ingestion pathway (mSv/yr)*

2.6 Summary of Scenario Description for Inhalation Dose

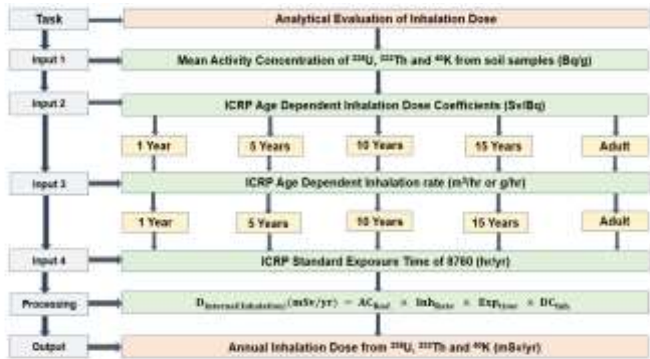

Fig. 2: Summary of Scenario Description.

2.7 Activity Concentration

Data on measured activity concentration of ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K obtained from representatives soil samples across sixteen mining sites randomly selected from five Geographical locations in Nigeria were estimated from previous studies. The average activity concentration obtained from soil samples from the selected mining locations across are tabularized in Table 4.

Table 4: Measured Activity Concentration of ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K in Bq/kg.

Region	Mining site/ State	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Reference
North East	Raycon/ Adamawa	108.72 ± 0.17	85.21 ± 1.06	859.72 ± 2.71	[9]
	NRC/ Adamawa	113.75 ± 1.24	97.04 ± 0.92	397.38 ± 0.85	[9]
	AGV/ Adamawa	87.24 ± 0.23	76.11 ± 0.46	328.02 ± 0.76	[9]
	Arufu/ Taraba	78 ± 3.00	31 ± 1.00	341 ± 19.00	[15]
North Central	Okobo/ Kogi	32.66 ± 2.12	54.00 ± 1.50	158.78 ± 3.14	[16]
	Gura Top/ Plateau	46.47 ± 5.19	396.17 ± 7.69	161.96 ± 7.56	[20]
	Central	32.52 ±	56.23 ±	403.963	[23]

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	Nasarawa	4.65	2.30	± 7.29	
North West	Shanono & Bagwai/ Kano	62.73 ± 0.21	90.66 ± 0.16	411.27 ± 0.36	[11]
	Wurno/ Sokoto	58.34 ± 0.65	53.76 ± 0.96	679.70 ± 4.32	[14]
	Anka/ Zamfara	41.60 ± 11.06	151.15 ± 21.09	380.34 ± 116.41	[18]
South West	Itagunmodi /Osun	53 ± 1.20	26 ± 2.70	505 ± 7.10	[19]
	Iwajowa/ Oyo	3.16 ± 1.91	56.70 ± 8.78	381. 69 ± 12.53	[17]
	Oke-Ogun/ Oyo	71.27 ± 10.25	35.21 ± 17.70	774.77 ± 63.65	[24]
	Ijero/Ekiti	78 ± 3.00	31 ± 1.00	341 ± 19.00	[15]
South East	Umuahia / Abia	76.31 ± 2.21	47.15 ± 2.16	173 ± 4.07	[21]
	Mbara-Ozu/ Anambra	33.15 ± 1.01	77.31 ± 0.76	100.22 ± 2.04	[22]

3 Results and Discussion

3.1 Age Dependent Inhalation Dose

The result of Inhalation dose obtained from the measured activity concentration of ^{238}U, ^{232}Th and ^{40}K from representatives soil samples across sixteen mining sites using ICRP age dependent dose coefficients as well as inhalation rate for 1 year, 5 years, 10 years, 15 years and Adult age groups are presented in Figures , 3, 4, 5, 6 and 7 respectively.

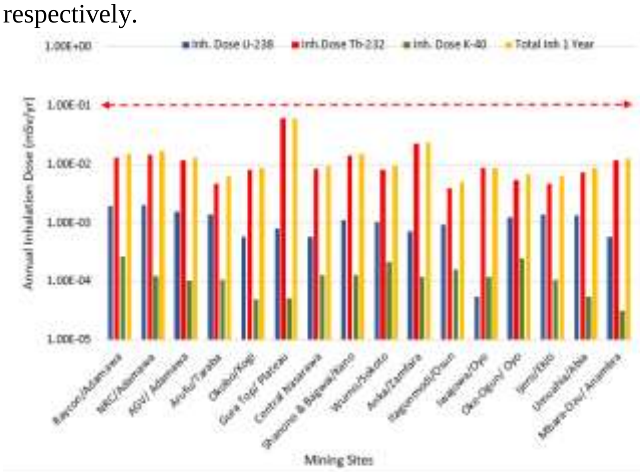

Fig.3. Inhalation Dose using ICRP Age Dependent for 1 Year Old**.**

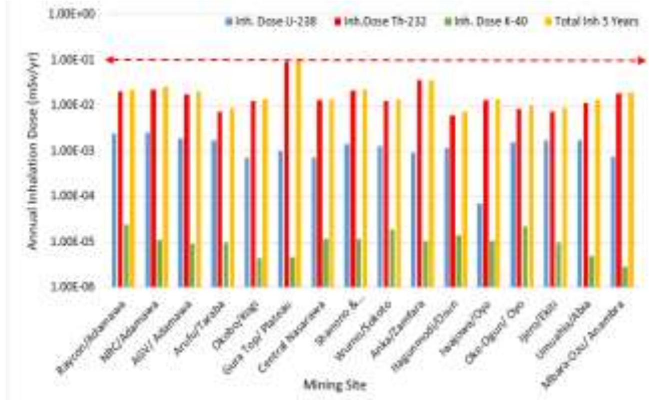

Fig. 4: Inhalation Dose using ICRP Age Dependent for 5 years Old**.**

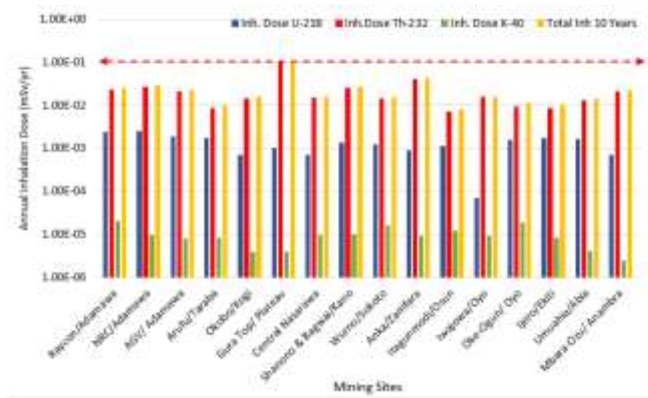

Fig. 5: Inhalation Dose using ICRP Age Dependent for 10 years Old.

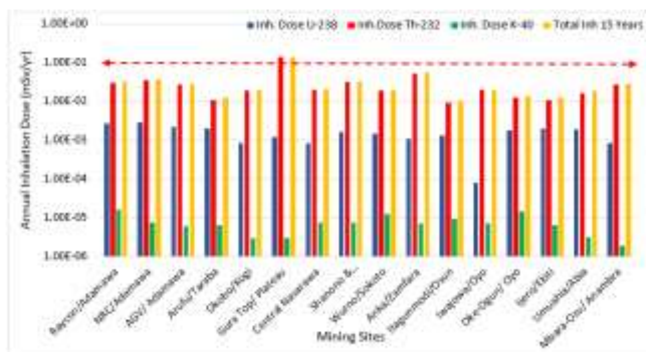

Fig. 6: Inhalation Dose using ICRP Age Dependent for 15 years Old.

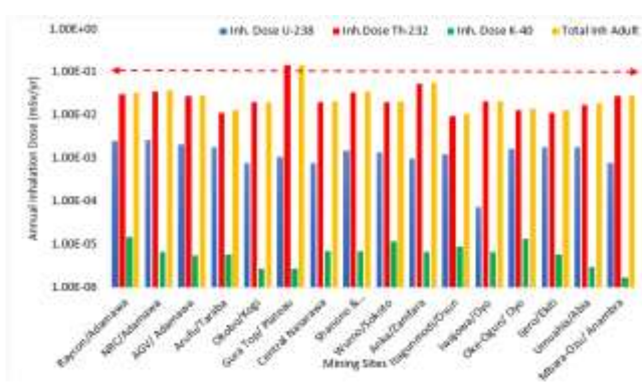

Fig. 7: Inhalation Dose using ICRP Age Dependent for Adult.

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From Figure 3, the highest inhalation dose for 1 year old is 6.06E-02 associated with Gura Top mining sites in Jos, Plateau State. The contribution of inhalation dose from ^{238}U, ^{232}Th and ^{40}K are 8.13E-04, 5.97E-02 and 5.13E-05. Higher inhalation dose is associated from ^{232}Th and ^{238}U while lower inhalation dose is reported in ^{40}K. The lowest inhalation dose is 5.01E-03mSv/yr associated with Itagunmodi mining site in Osun state. The contribution of inhalation dose associated with ^{238}U, ^{232}Th and ^{40}K are 9.27E-04, 3.92E-03 and 1.60E-04 respectively with ^{40}K contributing the lowest inhalation dose.

From Figure 4. The highest inhalation dose for 5 years old was reported at Gura Top mining site in Jos Plateau state with the total dose of 9.51E-02 mSv/yr while the lowest inhalation dose of 7.36E-03 mSv/yr was recorded in Itagunmodi mining site in Osun state. The contribution of inhalation dose from ^{238}U, ^{232}Th and ^{40}K to the highest inhalation dose are 1.03E-03 mSv/yr, 9.40E-02 mSv/yr and 4.58E-06 mSv/yr. the highest inhalation dose recorded from Gura Top mining site was due to high activity concentration recorded from the site and abundant mining activities ongoing in the region.

From Figure 5. The highest inhalation dose for 10 years old was reported at Gura Top mining site in Jos Plateau state with the total dose of 1.10E-01 mSv/yr followed by Anka mining site with total inhalation dose of 4.26E-02 mSv/yr while the lowest inhalation dose of 8.36E-03 mSv/yr was recorded in Itagunmodi mining site in Osun state. The individual contribution of ^{238}U, ^{232}Th and ^{40}K to the highest dose in Gura Top are 1.03E-03 mSv/yr, 1.09E-01 mSv/yr and 4.02E-06 mSv/yr with ^{238}U and ^{232}Th contributed to the highest inhalation dose due to gaseous decay product of radon and thoron, which are harmful when inhaled, however, contribution of ^{40}K to inhalation dose is negligible.

Figure 6 shows the highest inhalation dose for 15 years old was reported at Gura Top mining site in Jos Plateau state with the total dose of 1.40E-01 mSv/yr followed by Anka mining site with total inhalation dose of 5.40E-02 mSv/yr followed by NRC mining site in Adamawa which reported the third highest inhalation dose of 3.68E-02 mSv/yr with shanono and Bagwai reported the fourth inhalation dose of 3.33E-02 mSv/yr.

The order of inhalation dose from various mining sites are Shanono/Bagwai<NRC Adamawa<Anka<Gura Top representing 3.33E-02 mSv/yr < 3.68 E-02 mSv/yr<5.40E-02 mSv/yr<1.40E-01 mSv/yr. The lowest inhalation dose of 1.05E-02 mSv/yr was recorded in Itagunmodi mining site in Osun state followed by Arufu/Taraba and Ijero in Ekiti State with inhalation dose of 1.28E-02 mSv/yr each then Oke-Ogun mining site in Oyo with inhalation dose of 1.41E-02 mSv/yr with the other Arufu<Ijero<Itagunmodi< Oke-Ogun.

The contribution of ^{238}U and ^{232}Th to inhalation dose are higher than that of ^{40}K due to gaseous decay of radon and thoron from ^{238}U and ^{232}Th. Since, ^{40}K undergoes beta and gamma decays, beta emitters are harmful when inhaled or ingested. From Figure 7, the peak inhalation dose for Adult age group was reported at Gura Top mining site in Jos Plateau state with the total dose of 1.46E-01 mSv/yr, followed by Anka mining site with total inhalation dose of 5.61E-02 mSv/yr, followed by NRC and Raycon mining site in Adamawa which reported the third highest inhalation dose of 3.81E-02 and 3.36E-02 mSv/yr. Shanono and Bagwai reported the fourth inhalation dose of 3.45E-02 mSv/yr.

The sequence of inhalation dose from various mining sites are Shanono/Bagwai<Raycon<NRC Adamawa <Anka<Gura Top representing. Due to the gaseous radon and thoron decay from ^{238}U and ^{232}Th, their contribution to the inhalation exposure is greater than that of ^{40}K. The beta and gamma decays of ^{40}K make beta emitters hazardous when inhale in or ingest. The inhalation dose from each mining site is less than United State Environmental Protection Agency (US-EPA) recommended limit of 0.1mSv/yr from release in aerosol, and International Commission on radiological Protection (ICRP) dose limit of 1 mSv/yr for the public [28].

Also from Figures 3 to 7, the inhalation dose were evaluated using ICRP dose coefficients for ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K radionuclides alongside inhalation rate as well as exposure time. the evaluation were made with the assumption that the offsite resident dwells around the vicinity of the mining site, as a result a standard exposure time of 8760 hours per year were used for the evaluation.

The inhalation dose is mainly attributed to aerosols containing radioactive particles mainly radon and thoron gases, which are inhaled and deposited in the respiratory tract system. The inhalation dose reported from the measured activity concentration of ^{238}U and ^{232}Th are higher than the one reported from activity concentration of ^{40}K, mainly because of gaseous decay of ^{238}U and ^{232}Th (radon and thoron) which are harmful when inhaled.

Low inhalation dose reported for ^{40}K because it decays by emitting 89% beta emitter and 11 % gamma emitter, thus

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contribution of inhalation rate is negligible when compared to radon and thoron which are alpha emitters and are harmful when inhaled. Betta emitters are harmful when inhaled or ingested, as retention of the radionuclide inside the human body is dependent on biological clearance and physical half-life.

The long half-life associated with such radionuclides constitutes a great concern. The order of inhalation dose associated with ^{238}U, ^{232}Th and ^{40}K from each mining sites for all age groups considered in this study (1 Year old, 5 Years old, 10 Years old, 15 Years old and Adult) are ^{232}Th >^{238}U> ^{40}K in the order of daughter decay products of alpha, alpha, and betta/gamma for ^{238}U, ^{232}Th and ^{40}K.

3.2 Mining Site Specific Total Inhalation Dose

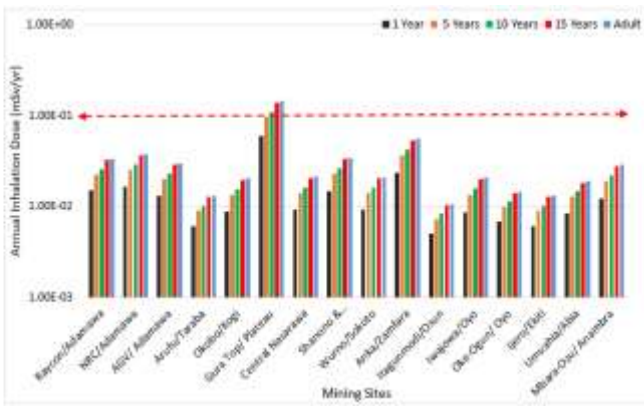

Fig. 8: Age Dependent total Inhalation Dose from Each Mining Site.

Figure 8 shows the age dependent inhalation dose from each mining sites considered in this study. The inhalation dose increases with increase in age for all the mining sites due to variation in values of the activity concentration of ^{238}U, ^{232}Th and ^{40}K radionuclides alongside age dependent dose coefficients and inhalation dose for various age groups. The inhalation dose coefficient associated with each radionuclide of interest (^{238}U, ^{232}Th and ^{40}K) as well as inhalation rate for 1 Year old is lower than that of 5 Years, 10 Years, 15 Years and Adult age groups in the order 1 Year<5 Years<10 Years<15 Years<Adult. This variation has greatly impact the computational results for the same activity concentration used. The highest inhalation dose for all age groups was recorded in Gura Top Mining site with the inhalation dose of 6.06E-02 mSv/yr, 9.51E-02 mSv/yr, 1.10E-01 mSv/yr, 1.40E-01 mSv/yr and 1.46E-01 mSv/yr for 1 Year old, 5 Years old, 10 Years old, 15 Years old and Adult age groups respectively.

The higher inhalation dose is attributed due to many human activities such as mining which give rise to elevated radiation level above the background level resulting from inadvertent inhalation of radon and radioactive aerosols. Such might have tendency of resulting to stochastic effects in the end. The order of inhalation dose by age groups recorded in Gura top mining sites are Adult>15 Years>10 Years>5 Years>1year old respectively. The lowest inhalation dose for all age groups was recorded in Itagunmodi mining site with the inhalation dose of 5.01E-03 mSv/yr, 7.36E-03 mSv/yr, 8.36E-03 mSv/yr, 1.05E-02 mSv/yr and 1.07E-02 mSv/yr for 1 Year old, 5 Years old, 10 Years old, 15 Years old and Adult age groups respectively. The lower inhalation dose is attributed due to less mining activities. The order of inhalation dose by age groups recorded in Itagunmodi mining site are Adult>15 Years>10 Years>5 Years>1year old respectively. Analysis by region shows the highest inhalation dose occurs in Gura Top in Jos, North Central followed by Anka in Zamfara, North West, NRC mining site in Adamawa, North East, and Mbara-Ozu mining site in Anambra, South East and Iwajowa mining site in Oyo, South Western region. The order of the highest inhalation dose by geographical region are North Central>North West>North East>South East>South West respectively.

4 Conclusions

Environmental hazards related to Naturally Occurring Radioactive Materials (NORMs) commonly contaminate the environment and put the public at risk of radiation exposure, due to the health hazards associated with exposure to such materials following airborne inhalation of radon and thoron decay products. Mining, which requires physically removing minerals from the earth's surface, is one of the main ways that people are exposed to these radionuclides with extended half-lives. This study evaluates the inhalation dose from residual radioactivity arising from mining activities to offsite resident using analytical techniques by applying the ICRP age dependent dose coefficients for five categories of age groups namely 1 Year old, 5 Years old, 10 Years old, 15 Years old and Adult age groups as well as age dependent inhalation rate. A standard exposure time were assumed all through the analysis. The coverage of the present study comprises of some selected mining location across the five geographical regions of Nigeria.

The highest inhalation dose was recorded in Gura top mining site in Jos Plateau state located in North Central geographical region with annual inhalation dose of 6.06E-02 mSv/yr, 9.51E-02 mSv/yr, 1.10E-01 mSv/yr, 1.40E-01 mSv/yr and 1.46E-01 mSv/yr while the lowest inhalation dose was recorded in Itagunmodi mining site with the inhalation dose of 5.01E-03 mSv/yr, 7.36E-03 mSv/yr, 8.36E-03 mSv/yr, 1.05E-02 mSv/yr and 1.07E-02 mSv/yr for all age groups considered in this study.

Inhalation dose results from all mining sites considered in this study are all below the US-EPA dose limit of 0.1mSv/yr for inhalation [28], and ICRP dose limit of 1 mSv/yr for the public, 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 the

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recommended values, public protection measures need to be implemented. The variation in the inhalation dose across each mining site is because of many or few mining activities ongoing in the region which contributed in the elevating the radiation level above the normal background radiation level. The higher inhalation dose are reported in ^{238}U and ^{232}Th due to gaseous decay of radon and thoron which are inhaled and deposited in the respiratory tract system. Low inhalation dose reported for ^{40}K because it decays by emitting 89% beta emitter and 11 % gamma emitter, thus contribution of inhalation rate is negligible when compared to radon and thoron which are alpha emitters and are harmful when inhaled. While beta emitters are detrimental when inhaled or ingested, the retention of radionuclide inside the human body is dependent on biological clearance and physical half-life. The present study only focuses on evaluation of inhalation dose using ICRP age dependent dose coefficients; however, it is recommended that evaluation of ingestion dose and TEDE be performed in a similar manner.

Footnotes

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