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The influence of gold mining on radioactivity of mining sites soil in Tanzania

Erasto Focus[1]*, Mwemezi J. Rwiza[1], Najat K. Mohammed[2], Firmi P. Banzi[3]

1 The Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania
2 Dar es Salaam Institute of Technology (DIT), Dar es Salaam, Tanzania
3 Tanzania Atomic Energy Commission (TAEC), Arusha, Tanzania

*Corresponding author E.mail: focuse@nm-aist.ac.tz

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Abstract
The activity of ^{226}Ra, ^{232}Th and ^{40}K in soil samples were measured by gamma spectrometry using high-purity germanium detector. The study involved 40 samples from four divisions: 10 samples each were drawn from the control area (CTR), washing area 1 (W1), washing area 2 (W2) and the mining pits (MP). Radium and Thorium were measured in highest value (80.44 and 94.62) Bq/kg, respectively at MP-9 while the lowest levels (1.56 and 0.96) Bq/kg, respectively were detected at MP-2. At W1, ^{40}K (max. 887.5 Bq/kg) recorded the highest mean level while ^{232}Th (mean=16.7 Bq/kg) had the lowest level. For W2, ^{40}K (max. 1535.7 Bq/kg) recorded highest level and ^{232}Th (mean = 8.1 Bq/kg) recorded the lowest (10.7 Bq/kg). Results further show that mean activity levels of ^{226}Ra, ^{232}Th and ^{40}K from mining area were 42.5, 35.5 and 652.4Bq/kg, respectively. In comparison, the respective average activity for ^{40}K, ^{226}Ra, and ^{232}Th recoded 118.4, 14.5 and 9.7 Bq/kg, respectively in control area. For the sake of assessing the suitability of building materials, hazard indices were calculated and their results were less than unity indicating that, building materials are safe. The annual gonadal equivalent dose, representative gamma index, alpha index revealed values of 484.8 µSv/y, 1.1 and 0.2, respectively. The average annual effective dose was 85.5 mSv which is about 8% greater than the world average. Results show that mining activities in Rwamagasa might be posing radiological hazard to people. Therefore, measures on radioactive materials to the miners and the surrounding community are recommended.

Keywords
Radionuclides in mining sites; Tanzania mining pollution; Rwamagasa small scale gold miners; Radiological hazard indices; gamma spectroscopy

Introduction

Natural radiations are the main sources of radiation exposure (UNSCEAR, 2000). The natural radiation exposure is also known to originate from two main sources, namely, terrestrial and cosmogenic radionuclides that result to human external and internal radiation exposure (Lecomte et al., 2019). Natural Radionuclides are constituents of the earth's environment; with variable levels from

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one environmental location to another. Though, the geochemical cycles and biochemical balance of radionuclide elements in the environment are continuously being changed by anthropogenic activities (Liu et al., 2020).

Furthermore, different studies have shown that, human activities such as mining processes, oil and gas extraction may result in situations where increments of radioactivity levels from materials that contain natural radionuclides can become significant enough to warrant regulatory control (UNSCEAR, 2000; IAEA, 2005). As a result, the need for environmental intensive care and safety from radionuclides is one of the urgency areas of studies. Radionuclides can accumulate to aerosols; pollute soil, water and food as pathways to human. In the human body, radionuclides can bio-accumulate in different organs causing risks to the human health. Long time exposure to radioactive materials have been reported to cause human health problem including haemorrhage, premature aging and death with reduced lifespan, leukemia, anaemia, cancer risks and other cardiovascular complications (Knoll, 2000). Cancer risk resulting from low doses of ionizing radiation remain the focus of a long-standing controversy in radiation protection (Korblein and Hoffmann, 2006).

Furthermore, gold mining activities are linked with elevated concentrations of radioactivity mainly from radium (^{226}Ra) , potassium (^{40}K), thorium (^{232}Th) and their daughters (Stucchi et al., 2012; UNSCEAR, 2020). For example, different authors (Malanca et al., 1993; Ntihabose, 2010; Kamunda et al., 2016) have reported elevated concentrations of ^{226}Ra, ^{232}Th and ^{40}K above the world average in gold mines samples from South Africa, Brazil and Rwanda, while higher level of radioactivity has also been reported in soil around the Mkuju uranium deposit in Tanzania (Mohammed and Mazunga, 2013). Literature shows also that tailings from gold mines contain significant concentration levels of ^{226}Ra, ^{232}Th and ^{40}K higher than the normal soil (IAEA, 2007; Esiole et al., 2019). This implies that, gold mining wastes that are not properly monitored could result to be substantial sources of exposure to the naturally occurring radionuclides to the people dwelling in the vicinity and within the gold mining sites.

Tanzania has been practicing gold mining for more than 100 years (Stucchi et al., 2012) with Large Scale Gold Mines (LSGM) and Artisanal and small scale Gold Mines (ASGM) activities. Over the past decades, the ASGM sector in Tanzania has been progressively significant for poverty lessening nationwide. Tanzania's mostly informal ASGM sector started to propagate in the 1980s. The decline in production in other industries, inadequate market for agricultural products, droughts, and many other livelihood factors have been identified and associated with the rise in the number of persons working in ASGM in the 1980s and 1990s (UNEP, 2012). It is reported elsewhere that termination of national-owned mines in the 1980s and those owned by individuals and private sectors in the early 1960s resulted to semi-skilled individuals engaging in ASGM (Jønsson and Fold, 2009). Nevertheless, the different ASGM activities performed in various regions of the nation play a substantial role together as a straight source of employment adding jobs and incomes to the rural economy and national revenue (Mwaipopo et al., 2004). Recently, the government has started transforming the ASGM into a formal sector. This has led to outbreak of many ASGM in the country especially in the Lake Victoria Gold Field (LVGF) that is also associated with environmental degradations including radionuclide. The current study was conducted at Rwamagasa ASGM centre in the LVGF where there are different economic activities that are likely to expose people to radioactive materials from mining activities. There are families living within the mining area, local guest houses, agricultural activities and many other livelihood activities within the Rwamagasa small scale gold mine. Soil from the area is also used for house construction which may accelerate the exposure due to radon gas. Furthermore, on regular basis children are playing with the soil, expecting and mothers with newborns are involved in gold recovery with bare hands and using poor technology during gold recovery processes.

Majority of miners at Rwamagasa ASGM are

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overworking throughout the week for about 13 hours a day without any protective gears. Dusts from rocks, hips of soil and crashing machines are directly inhaled by the workers and people surrounding the area through wind. In an effort to enhance protection and control radiations from radionuclides exposure, this paper measured the natural specific activity, and estimated the radiation hazard indices namely radium equivalent activity, annual effective dose, absorbed dose rate, external hazard index and internal hazard index, and representative gamma index. Also, annual gonadal equivalent dose and alpha index were estimated.

Materials and methods

Study area

This study was conducted at Rwamagasa small scale gold mine shown in Figure 1. Rwamagasa lies within latitudes 3.1166°S and longitude 32.0417°E in Geita region, Tanzania in the Lake Victoria Gold Field (LVGF). The study area is estimated to have about 4000 ASGM (Kivyiro, 2017).

Sample collection and preparation

Forty (40) soil samples were investigated. The sampled area was subdivided into four categories;

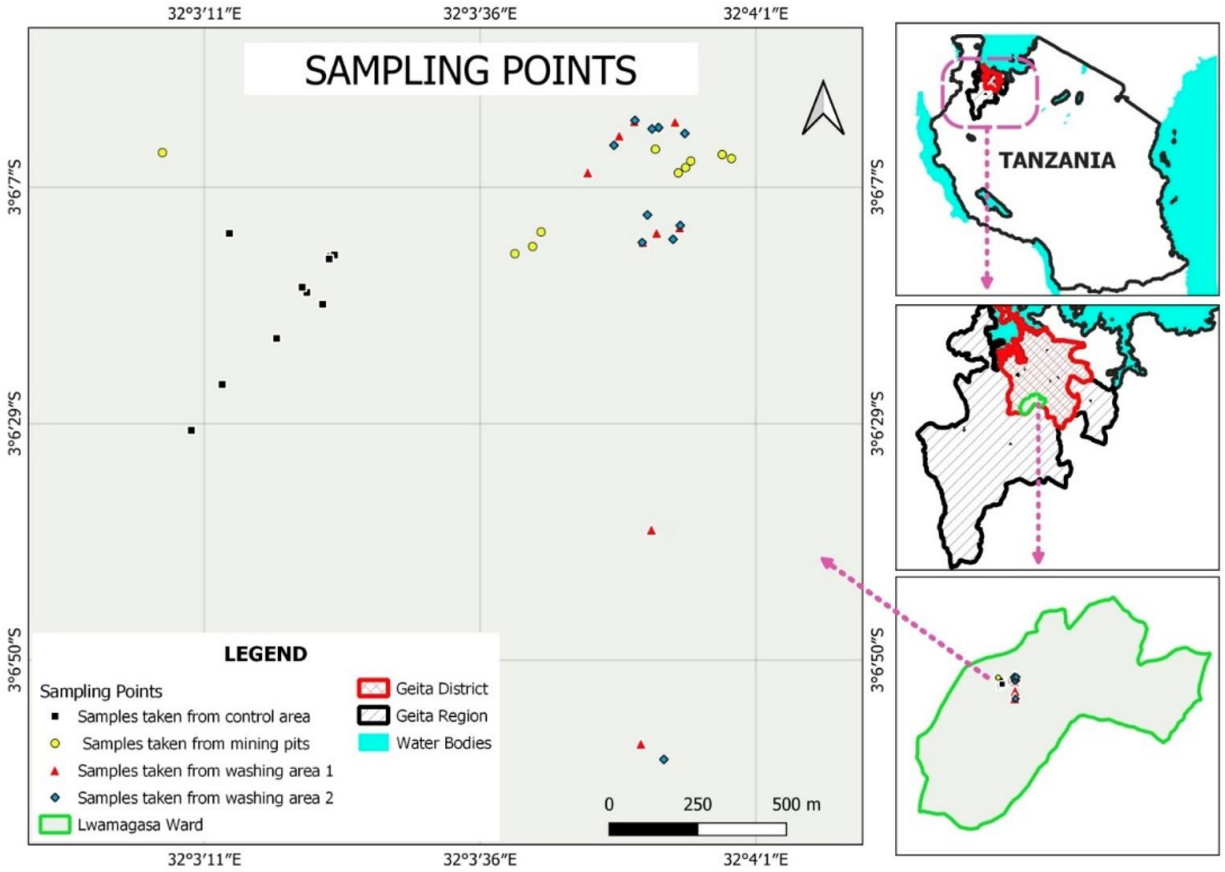

Figure 1. *Top right showing a map of Tanzania, middle right shows the Geita district and the bottom right shows sampling points as enlarged at the left side.*

MP referring to mining pits comprised of 10 soil samples taken from the mining pits, W1 is washing area 1 out of which 10 soil samples were taken from washing area 1. In W1, the soil is washed for the first stage after being crashed in crashing machines characterized by high dust concentration. W2 is washing area 2 which contained 10 soil samples taken from the washing area 2. In W2 the soil from W1 is re-washed to identify soil which might contain gold.

(Focus et al., 2021) reported high level of mercury (3.72 mg/kg) and other trace elements at W2. CTR

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referred to control area with 10 soil samples taken about 4 km from the un-mined area where residents live. About 1 kg of a sample was put in each clean and labeled polythene bag and transported to the Nelson Mandela African Institute of Science and Technology (NM-AIST) laboratory for storage and preparation. After preparation, the samples were shifted to the Tanzania Atomic Energy Commission (TAEC) laboratory for analysis. For future referencing needs, the global positioning system receiver was used to geo-reference all sampling points. The sampling codes and coordinates are presented in Table 2.

Soil samples were firstly ruptured into reduced aggregates, air dried at room temperature for 10 days followed by thoroughly drying at a temperature of 50°C in a drying cabinet to hasten the drying process without loss of radionuclides from the samples (Avwiri et al., 2013). The dry soil samples were then ground with a mortar and pestle, sieved through a steel 2 mm sieve, packed in sealed canisters, and kept for no less than 28 days to attain secular equilibrium needed for gamma ray spectrometry analysis (Habib et al., 2018).

Radioactivity analysis

The samples were analyzed using a lead-shielded coaxial high-purity germanium detector (HPGe), with serial number 57-P51572A. The detector cavity was sheltered with three liners of lead, cadmium and copper of 100 mm, 3 mm and 30 mm thick, respectively to prevent background radiation in the counting surroundings. The system has high relative efficiency of about 51% and a resolution at *Full Width Half Maximum* (FWHM) of about 7.2% at energy of 0.662 MeV (^{137}Cs) which is adequate to resolve the gamma ray energies of interest. The gamma-ray energy calibration was conducted every day using multi-nuclide sources of ^{137}Cs, ^{133}Ba, ^{57}Co, ^{109}Cd, ^{60}Co, ^{22}Na, and ^{54}Mn. The efficiency standardization was performed using in situ object counting-system of Genie 2000 software (Fatima et al., 2007). The activity concentrations of the radionuclides in the samples were determined from corresponding gamma ray lines emanating from the decay products. The gamma line of 1460.8 keV was used to determine ^{40}K. The weighted mean activity levels from gamma lines of 583.1 keV (^{212}Pb), 2614.5 keV of ^{208}Tl and 911.1 keV (^{228}Ac) were used to determine ^{232}Th. The gamma lines of 609.3 keV (^{214}Bi), 1764 KeV of ^{214}Bi, 295.2 keV (^{214}Pb), and 186.1 keV (^{226}Ra) were used to determine ^{226}Ra.

The International Atomic Energy Agency (IAEA) soil 375 was used as a standard reference material to assess the accuracy and precision of the results. The standard was counted for the similar time as used for the samples (10 hours); its activity at different energies was determined and equated with the certified value after modification of the decay based on the date of December 31st, 1991 provided in the data sheet. The experimental concentration values were in line with the suggested values within 10% accuracy as shown in Table 1.

Activity determination

The activity concentrations of the samples were determined using the net area under the photo peaks using Equation [1].

$$A = \frac{N_c}{\gamma_p \times T \times \eta(E) \times m_s} \qquad [1]$$

where A is the activity concentration of the radionuclide in the sample in Bq/kg, m_s is the mass of the sample in kg, η (E) is the detector efficiency at the specific γ-ray energy, T is the counting time, is the absolute transition probability of the specific γ-ray, and N_c is the net count rate under the corresponding peak.

Public exposure dose from gamma rays

The mean dose rates absorbed in air from gamma emission were estimated using equation 2 (UNSCEAR, 1993). The calculation is based only on ^{226}Ra, ^{232}Th and ^{40}K assuming that concentrations of other elements such as ^{90}Sr, ^{137}Cs and the decay series of ^{235}U can be neglected due to insignificant concentration contributions to the

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whole environmental background doses (Kocher and Sjoreen, 1985). This dose tells the exposure due to emissions and not the amount received in the human body.

$$D = 0.043A_k + 0.662A_{Th} + 0.427A_{Ra} \quad [2]$$

where D is the dose rate (nGy h^{-1}) at 1m above the ground due to ^{226}Ra, ^{232}Th and ^{40}K in the soil samples, A_K, A_{Th} and A_{Ra} are the activity levels of ^{40}K, ^{232}Th and ^{226}Ra in Bq/kg, respectively.
The dose conversion coefficient (0.7 Sv Gy^{-1}) was used in the estimation of the annual effective dose due to the natural radionuclides. Also the occupancy of 0.2 for outdoor (average of 4.8 hours spent in the area every day for a year) as suggested by UNSCEAR(UNSCEAR, 2000) was used. The effective dose rate was estimated using equation 3 (Jibiri and Adewuyi, 2008). This dose indicates the amount of radiation that affects negatively the human body.

$$E_{eff} = T * O_f * Q * D * X \quad [3]$$

where E_{eff} is the effective dose rate in mSv y^{-1}, T is the time in seconds in a year, O_f is the occupancy term which fixes the mean time spent outside in the area, Q is the proportion of the effective and absorbed dose rate in air, X is the factor converting units to the micro from nano scales and D is the absorbed dose rate in air in nGy h^{-1}.

Radium equivalent dose

For assessment of the associated risk due to gamma radiation exposures to people linked with interactions with soil from the mining site, radium equivalent level was estimated. This provides a particular index which defines the gamma yield from diverse mixture of ^{226}Ra, ^{232}Th and ^{40}K in the samples. Radium equivalent activity (Ra_{eq}) is given by equation 4 (Isinkaye et al., 2018).

$$Ra_{eq} = 0.077A_k + 1.43T_h + A_{Ra} \quad [4]$$

where A_K, A_{Th} and A_{Ra}, are the activity concentration of ^{40}K, ^{232}Th and ^{226}Ra, respectively.

The internal Hazard Index

For the determination of the internal hazards due to soil which when accidentally ingested or other soil pica actions such as geophagia complications, equation [5] (UNSCEAR, 2020) was used.

$$H_{in} = \frac{C_k}{4810} + \frac{C_{Th}}{259} + \frac{C_{Ra}}{185} \leq 1 \quad [5]$$

where H_{in} is the internal hazard index and C_K, C_{Th} and C_{Ra} are the activity concentration of ^{40}K, ^{232}Th and ^{226}Ra, respectively.

The external Hazard Index

The hazard due to the natural gamma radiations contacted externally by the human body was estimated using Equation 6 (UNSCEAR, 2020). For the safety purpose, this value has to be kept less than unity.

$$H_{ext} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \quad [6]$$

where: A_{Ra}, A_{Th} and A_K are radioactivity concentrations (Bq/Kg) of radium, thorium and potassium, respectively from the sample.

Representative gamma index

Equation 7 is used to derive the gamma activity value index (Iγ) for pinpointing if soil is safe for building materials such as bricks (Avwiri and Agbalagba, 2007; Ademola and Obed, 2012).

$$I_\gamma = \frac{A_k}{1500} + \frac{A_{Th}}{100} + \frac{A_{Ra}}{150} \quad [7]$$

Annual gonadal equivalent dose

Referring to UNSCEAR (1982), the gonads, the bone surface cells and the active bone marrow are reflected as the organs of attention in radiation protection. Thus the Annual Gonadal Equivalent Dose (AGED mSv y^{-1}) for the residents of Rwamagasa due to the specific activities of ^{40}K, ^{226}Ra and ^{232}Th was estimated using Equation [8] (Arafa, 2004).

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$$AGED = 0.314A_K + 3.09A_{Ra} + 4.18A_{Th} \quad [8]$$

where A_K, A_{Ra} and A_{Th} and are the activity concentration of ^{40}K, ^{226}Ra and ^{232}Th, respectively

Alpha index (Iα)

This index is necessary to calculate alpha radiation contact resulted from inhalation of radiation from building materials such as soil. This index was estimated using equation 9 (Tufail et al., 2007).

$$I_\alpha = \frac{A_{Ra}}{200} \quad [9]$$

where as is the ^{226}Ra activity concentration (Bq / kg) in the soil.

Results

The agreement between the recommended and experimental concentration values of radioactivity are presented in Table 1.

Table 1. *The experimental activity values (Bq/kg ± SD) and the standard reference values.*

Radionuclide	Energy (keV)	Certified reference value	Experimental activity concentration	Accuracy (%)
^{226}Ra	186.1	20.0±0.9	20.53±0.6	3.0
^{40}K	1460.8	423.40±0.2	499.89±2.2	0.4
^{214}Pb	295.2	19.96±0.8	19.54±0.7	3.6
	351.92	19.96±0.5	21.01±1.2	5.7
^{214}Bi	1764	19.96±0.4	19.98±0.9	4.5
	2477.7	19.96±0.9	20.34±1.3	6.4
^{208}TI	860.4	20.46±0.3	21.19±1.0	4.7
	2614.5	20.46±0.6	22.44±1.8	8.0
^{228}Ac	338.5	20.46±0.3	20.52±1.6	7.8
	911	20.46±0.5	21.32±0.8	3.7
	968.5	20.46±0.5	22.69±1.1	4.8

*SD=Standard Deviation

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The sampled points were geo-referenced using the Global Positioning System (GPS) for future referencing with coordinates presented in Table 2.

Table 2. *Sampling codes with their co-ordinate locations.*

Sample code	Latitude	Longitude	Sample code	Latitude	Longitude
CTR-1	S03º06.490′	E032º03.160′	W1-1	S03º06.181′	E032º03.904′
CTR-2	S03º06.280′	E032º03.336′	W1-2	S03º06.189′	E032º03.869′
CTR-3	S03º06.225′	E032º03.372′	W1-3	S03º06.203′	E032º03.848′
CTR-4	S03º06.223′	E032º03.378′	W1-4	S03º06.027′	E032º03.870′
CTR-5	S03º06.229′	E032º03.370′	W1-5	S03º06.641′	E032º03.861′
CTR-6	S03º06.272′	E032º03.329′	W1-6	S03º06.019′	E032º03.835′
CTR-7	S03º06.298′	E032º03.360′	W1-7	S03º06.041′	E032º03.812′
CTR-8	S03º06.190′	E032º03.218′	W1-8	S03º06.097′	E032º03.764′
CTR-9	S03º06.420′	E032º03.207′	W1-9	S03º06.967′	E032º03.845′
CTR-10	S03º06.350′	E032º03.290′	W1-10	S03º06.020′	E032º03.897′
MP-1	S03º06.067′	E032º03.116′	W2-1	S03º06.178′	E032º03.9045′
MP-2	S03º06.076′	E032º03.983′	W2-2	S03º06.199′	E032º03.894′
MP-3	S03º06.070′	E032º03.969′	W2-3	S03º06.162′	E032º03.855′
MP-4	S03º06.062′	E032º03.867′	W2-4	S03º06.204′	E032º03.847′
MP-5	S03º06.080′	E032º03.921′	W2-5	S03º06.029′	E032º03.872′
MP-6	S03º06.090′	E032º03.913′	W2-6	S03º06.031′	E032º03.862′
MP-7	S03º06.098′	E032º03.902′	W2-7	S03º06.018′	E032º03.836′
MP-8	S03º06.188′	E032º03.693′	W2-8	S03º06.056′	E032º03.804′
MP-9	S03º06.221′	E032º03.653′	W2-9	S03º06.991′	E032º03.880′
MP-10	S03º06.210′	E032º03.680′	W2-10	S03º06.038′	E032º03.912′

The results of the average activity levels of ^{226}Ra, ^{232}Th and ^{40}K from different sampling categories are presented in Table 3.

Table 3. *Average activity concentrations for ^{226}Ra, ^{232}Th and ^{40}K in the samples for different sampling categories (Bqkg^{-1}* ± SD)

Category	^{226}Ra	^{232}Th	^{40}K
Mining pits (MP) (N=10)	66.29 ± 25.8	69.77 ± 27.3	624.82 ± 190.8
Washing area 1 (W1) (N=10)	29.16 ± 4.9	16.69 ± 5.3	639.40 ± 105.37
Washing area 2 (W2) (N=10)	32.33 ± 12.5	19.98 ± 8.1	692.86 ± 324.7
Average (A)	42.59	35.48	652.36
Control (CTR) (N=10)	14.45 ± 4.9	9.67 ± 5.9	236.84 ± 82.5

SD=Standard Deviation; N=Number of Samples

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Table 4 shows the activity concentrations from different sampling categories.

Table 4. *Activity levels of ^{226}Ra, ^{232}Th and ^{40}K for all points from different sampling categories.*

Category - Sample ID		Average (Bq/kg)			
^{226}Ra		^{232}Th	^{40}K		
Control	CTR-1	22.23	13.38	282.2	SD=Standard Deviation
	CTR-2	12.32	6.40	26.8	
	CTR-3	14.56	9.97	221.9	
	CTR-4	9.29	20.21	256.6	
	CTR-5	8.79	6.17	234.7	
	CTR-6	12.25	3.61	320.9	
	CTR-7	10.19	5.90	254.7	
	CTR-8	15.27	4.97	306.4	
	CTR-9	17.97	5.73	265.5	
	CTR-10	21.67	20.35	198.7	
Mean ± SD		**14.45** ± 4.90	**9.67** ± 5.90	**236.8** ± 82.5	
Mining pits	MP-1	95.00	96.2	598.3	
	MP-2	1.56	0.96	597.4	
	MP-3	57.20	70.8	809.8	
	MP-4	73.24	80.5	463.5	
	MP-5	54.72	74.94	564.7	
	MP-6	83.14	78.60	1070.7	
	MP-7	64.74	54.34	480.2	
	MP-8	74.60	82.02	514.2	
	MP-9	80.44	94.62	461.9	
	MP-10	78.24	64.68	687.4	
Mean ± SD		**66.29 ± 25.8**	**69.77 ± 27.30**	**624.8 ± 190.8**	
Washing area 1	W1-1	32.54	12.70	887.5	
	W1-2	34.74	28.08	582.2	
	W1-3	33.32	21.36	564.0	
	W1-4	21.48	8.86	714.4	
	W1-5	29.66	16.98	554.0	
	W1-6	30.16	15.00	539.4	
	W1-7	21.48	13.30	704.6	
	W1-8	24.74	18.92	625.9	
	W1-9	32.74	16.74	626.7	
	W1-10	30.74	14.94	595.4	
Mean ± SD		**29.16 ± 4.9**	**16.69 ± 5.30**	**639.4 ± 105.4**	
Washing area 2	W2-1	56.68	35.00	543.6	
	W2-2	22.46	32.84	717.0	
	W2-3	52.36	16.90	672.0	
	W2-4	28.04	21.22	641.0	
	W2-5	19.26	11.04	1535.7	
	W2-6	23.22	10.68	285.5	
	W2-7	30.10	19.62	585.9	
	W2-8	34.40	19.38	646.8	
	W2-9	29.32	17.64	771.3	
	W2-10	27.48	15.48	529.7	
Mean ± SD		**32.33 ± 12.5**	**19.98 ± 8.10**	**692.9 ± 324.7**	

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Using Equation [2], the absorbed dose rates were estimated and presented in Figure 2 (a).We assumed that the contribution from other naturally occurring radionuclides and cosmic radiation at the locations were insignificant as reported elsewhere (Lecomte et al., 2019). Based on Equation [3], the annual effective dose was estimated and their averages are presented in Figure 2 (a); Figure 2 (b) and 2 (c) present other calculated radiation indices.

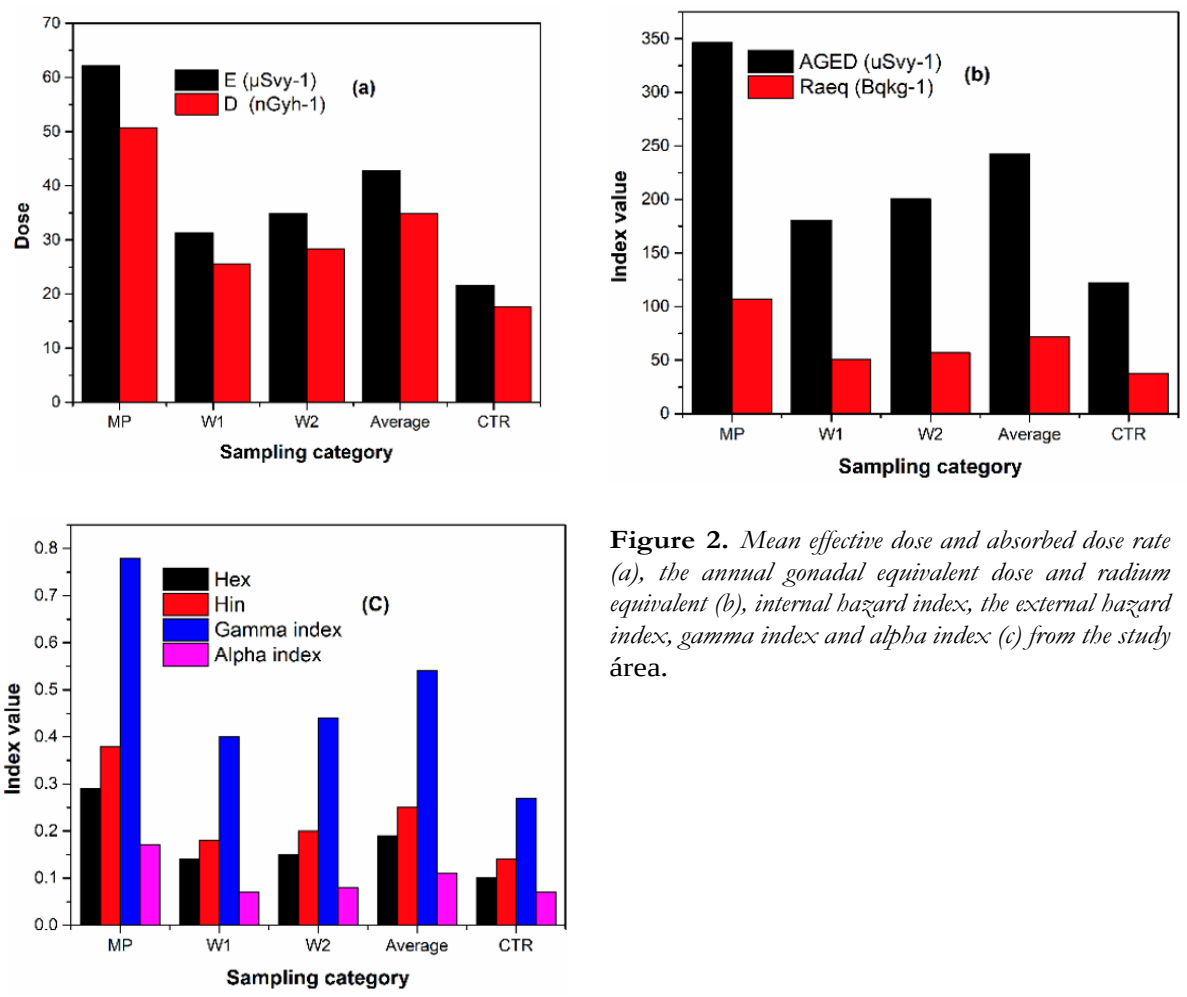

Figure 2. *Mean effective dose and absorbed dose rate (a), the annual gonadal equivalent dose and radium equivalent (b), internal hazard index, the external hazard index, gamma index and alpha index (c) from the study* área.

Discussion

Table 4 shows that the highest activity concentration of ^{226}Ra was detected in the mining pits category in location MP-1 (95 Bq/kg) and the highest activity concentration of ^{232}Th with almost same magnitude was detected in same mining pit (96.2 Bq/kg). This observation might be due to the chemistry of radium, thorium and uranium that, as ^{232}Th disintegrates, it gives radiation and produce decay daughters that include ^{228}Th and ^{228}Ra (Sarin et al., 1990). Also the geographical location of the area might be contributing to these higher levels as wind blows towards MP-1 (present study, field measurement). As shown in Table 3, the average activity concentration of ^{226}Ra in the mining site was 42.59 Bq/kg while in the living (control) area the concentrations of ^{226}Ra was 14.45 Bq/kg. For ^{232}Th, the average activity concentrations were 35.48 Bq/kg and 9.67 Bq/kg in the mining and control areas, respectively. The mean activity level of ^{40}K in the mining area was 652.36 Bq/

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kg while in the living area it was 236.84 Bq/kg. The concentrations of radionuclides are mostly greater in the mining area (categories MP, W1 and W2) than in CTR category. This observation may confirm the findings reported in literature that mining activities if not well controlled elevates the radioactivity levels in the environment (Ademola and Obed, 2012; Innocent et al., 2013; Aliyu et al., 2015; Kamunda et al., 2016; UNSCEAR, 2020). Also, researchers observed that, dust is not suppressed by water, the fact that might lead to this increment of radionuclides in mining area. The activity levels of ^{226}Ra and ^{40}K in the mining area categories (MP, W1 and W2) (Table 3) were upper than the world recommended values of 35 Bq/kg and 420 Bq/kg, respectively whereas the concentration of ^{232}Th was lesser than the world mean value of 45 Bq/kg(Esiole et al., 2019) but 25% higher than a CTR value which alerts the need for radiation protection and control strategies. In the CTR category, all the values calculated were lower than the world recommended levels (Ademola and Obed, 2012).

The mean absorbed dose rate in the mining locations MP, W1 and W2 (Figure 2) were 101.36; 50.99; and 56.83 nGyh^{-1}, respectively. The overall average absorbed dose rate in the mining categories was 69.73 nGy h^{-1} while in the control was 22.76 nGy h^{-1}. The absorbed dose rate estimated for the mining area is greater than the world suggested mean value of 60 nGy h^{-1} (UNSCEAR, 2000). The average annual effective doses in the sampled categories MP, W1and W2 were respectively, 124.30, 62.54 and 69.69 mSvy^{-1} with the total average in the mining site of 85.51 mSvy^{-1}. The mean annual effective dose in the CTR category was 27.90 mSvy^{-1}. The Ra_{eq} presented in Figure 2 shows that the mean values estimated in the mining locations MP, W1, and W2 and in the CTR category were lower compared the recommended world tolerable value of 370 Bq/kg (UNSCEAR, 1982). However, the MP category has the incremental value of 60% greater than the control area. This observation informs a need of control strategies.

The calculated mean value of Hex (0.5) in the study area was lower than unity as suggested. The mean values of Iγ estimated were above unity in category MP and below the standard of unity in categories W1, W2 and CTR and the total average values in the mining area were above the criterion of unity which is not safe for the public. The results for the alpha index estimated indicate all values below unity. The average value of AGED in the mining area for categories MP, W1, W2 are 692.65, 360.64, and 400.98 mSvy^{-1}, respectively, values about 5, 3 and 3 times, respectively greater than results from the CTR category, which indicate the influence of mining actives to the radionuclides increments. The overall mean value of AGED in mining area was 484.76 mSvy^{-1} which is greater than the world recommended average of 298 µSvy^{-1} (Al-Jundi et al., 2005) but about 3.5 times higher than the CTR value.

A study conducted by Munyao et al. (2020) from sand samples along Ekalakala River in Kenya reported low average levels of ^{226}Ra 14.3±3.8Bq/kg and ^{232}Th 17.3±4.2Bq/kg ranging between 11.5-26.2 Bq/kg and 9.7-24.0 Bq/kg for ^{232}Th and ^{226}Ra, respectively while ^{40}K had concentration of 1300±300 Bq/kg a value higher about 3 times the world average. In comparison, both studies by (Ademola and Obed, 2012; Kamunda et al., 2016) and results from the current study (Table 3 and 4) suggest that mining activities contribute elevated concentration of radionuclides to the natural environment. However, higher value of ^{40}K can also be associated to the geology of the area and probably the use of potassium enriched fertilizers by farmers around the study area. Further relationship of the results obtained in the present study with published results from similar studies in other areas of the country and around the world is presented in Figure 3.

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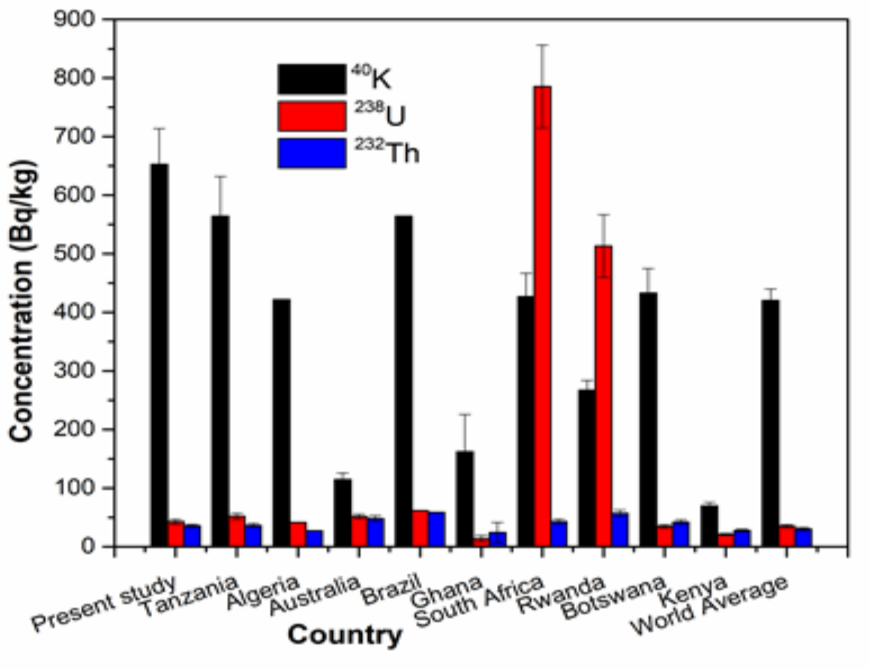

Figure 3. *Comparison of the findings in the present study with other published results elsewhere.*

Lower activity concentrations were reported by several authours (Ademola and Ademonehin, 2010; Ademola and Obed, 2012; Innocent et al., 2013) in Nigeria; in Algeria (Amrani and Tahtat, 2001) and Faanu et al. (2011) in Ghana for ^{226}Ra, ^{232}Th and ^{40}K compared to this study. Also, lower concentrations were reported in Kenya (Osoro et al., 2011). The concentration of ^{40}K obtained in Brazil (Malanca et al., 1993), in Australia (Beretka and Mathew, 1985), South Africa (Kamunda et al., 2016) and Rwanda (Ntihabose, 2010) were lower than values from the current study. The mean activity levels of ^{226}Ra, and ^{232}Th estimated in this study is lower than that reported in Tanzania by (Mohammed and Mazunga, 2013), Australia (Mathew, 1985), Brazil (Malanca et al., 1993), South Africa (Kamunda et al., 2016) and Rwanda (Ntihabose, 2010). Higher level of ^{226}Ra reported by Mohammed compared to what is reported in this study is due to the fact that Mohammed reported radioactivity concentrations from uranium deposit at Mkuju. The mean activity of ^{40}K; ^{226}Ra and ^{232}Th obtained in this study are higher about 1.5 times, 1.2 times and 1.18 times than the world recommended values.

Conclusions

The activity of ^{226}Ra, ^{232}Th and ^{40}K in forty soil samples from Rwamagasa small scale gold mine have been measured using HPGe gamma ray spectrometry. The results indicated that the concentration of natural radionuclides was not uniform in the sample stations. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in samples from the mining area were higher (42.59, 35.48 and 652.36) Bq/kg, respectively compared to the control area having respectively 14.45, 9.67 and 236.84 Bq/kg. The results indicated that the mining activities contribute to higher level of radionuclides. The estimated mean activity levels of ^{226}Ra, ^{232}Th and ^{40}K in the mining area are greater than the recommended world values. The activity levels of ^{226}Ra, ^{232}Th and ^{40}K and the effective dose in the normal living (control) area is lower than the world recommended average. The average annual effective dose (85.51 mSv y^{-1}) obtained from the current study is about 18% greater compared to the world permissible average (UNSCEAR, 2000). It is clear noted from the results that, mining activities in Rwamagasa might be contributing

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significantly to radiological hazard to the public. Therefore, measures on radioactive materials to the miners and the surrounding community are recommended.

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