International Journal of Environmental Protection and Policy
2022; 10(3): 48-58
http://www.sciencepublishinggroup.com/j/ijepp
doi: 10.11648/j.ijepp.20221003.12
ISSN: 2330-7528 (Print); ISSN: 2330-7536 (Online)

Risk Assessment of Natural Radionuclides and Radon Gas in the Artisanal and Small-Scale Gold Mine of Buhemba, Tanzania

Erasto Focus[1, *], Msafiri Jackson[2], Charles Simon[2], Emmanuel Njale[3], Anna Kanyanemu[4], Yohana Siyajali Anatory[5], Makoye Mhozya[5], Pamela Semiono[6]

[1]Department of Physics, Mwalimu Nyerere University of Agriculture and Technology (MJNUAT), Mara, Tanzania

[2]Department of Environmental Engineering, Mwalimu Nyerere University of Agriculture and Technology (MJNUAT), Mara, Tanzania

[3]Department of Chemistry, Mwalimu Nyerere University of Agriculture and Technology (MJNUAT), Mara, Tanzania

[4]Department of Agriculture, Mwalimu Nyerere University of Agriculture and Technology (MJNUAT), Mara, Tanzania

[5]Department of Veterinary Sciences, Mwalimu Nyerere University of Agriculture and Technology (MJNUAT), Mara, Tanzania

[6]Department of Physical and Environmental Sciences, The Open University of Tanzania (OUT), Dar es Salaam, Tanzania

Email address:

rassymuta@gmail.com (E. Focus), msafiri.jackson@mjnuat.ac.tz (M. Jackson), njaleemmanueli@gmail.com (E. Njale), yohana.anatory@mjnuat.ac.tz (Y. S. Anatory), makoyemhozya86@gmail.com (M. Mhozya), rsemiono@yahoo.com (P. Semiono)

[*]Corresponding author

To cite this article:

Erasto Focus, Msafiri Jackson, Charles Simon, Emmanuel Njale, Anna Kanyanemu, Yohana Siyajali Anatory, Makoye Mhozya, Pamela Semiono. Risk Assessment of Natural Radionuclides and Radon Gas in the Artisanal and Small-Scale Gold Mine of Buhemba, Tanzania. *International Journal of Environmental Protection and Policy*. Vol. 10, No. 3, 2022, pp. 48-58. doi: 10.11648/j.ijepp.20221003.12

Received: May 4, 2022; **Accepted**: May 18, 2022; **Published**: May 31, 2022

Abstract: Currently, the mining industry in Tanzania faces significant challenges including the presence of radionuclides in the working environment. In this work, different indices were applied to assess the health risk of people living and working in the study area. The radiation hazards in the studied mining areas are compared with the recommended local and international guidelines. The health risk and mitigation measures due to radioactive elements exposure to mine workers and people dwelling in the mines is established. The hyper pure germanium detector (HPGe) was used for radioactivity analysis. The radon gas levels were measured using the Alpha Guard radon monitor. The results on radioactivity; mean effective dose; annual gonadal equivalent and absorbed dose; radium equivalent; internal and external hazard indices; alpha and gamma indices; and the radon gas revealed high values in mining areas compared to the control area. However, some of the levels of radionuclides along with their hazard indices are lower than the recommended international limits. The mitigation measures which include dust suppression using water spray and the use protection gears such as masks and gloves are recommended. The present study recommends follow up and further studies in the ASGM subsector.

Keywords: Radionuclides, Mining Pollution, Buhemba Small Scale Gold Miners, Radiological Hazard Indices, Risk Assessment, Risk Characterization, Gamma Spectroscopy

1. Introduction

Natural background radiation is the most significant source of radiation exposure to people all over the world especially to areas where human activities such as mining are being conducted [17]. The principal source of external exposure is gamma and alpha emitting radionuclides primarily ^{40}K and the ^{238}U and ^{232}Th families, which are found in in the soil, water, and air [36]. The decay series of ^{238}U give a radon (^{222}Rn) gas which has a negative health impact when inhaled. Two of ^{222}Rn daughter (^{214}Po, and ^{218}Po) are alpha emitters. ^{222}Rn is the most significant natural source of radiation that exposes members of the public [35]. As a result, ^{40}K, $^{238}U/^{226}Ra$, ^{232}Th, and ^{222}Rn are of relevance in terms of radiation protection, and their studies have gained a lot of attention around the world. Several studies have been undertaken in the last two decades to quantify radionuclides in soil that can be connected to the absorbed dose rate in air [3, 5, 6, 21, 23, 26, 32, 38, 39], among others. These findings provide a more comprehensive assessment of background exposure levels in various countries.

Furthermore, natural radionuclides have an impact on people due to their existence in many environmental matrices [16]. Some natural radionuclides, including ^{226}Ra, ^{232}Th, and ^{40}K, are found in rock constituent minerals and contribute to ionizing radiation exposure of living organisms on the Earth's surface [5]. Due to human exposure to gamma-rays, the environmental distribution of radionuclides has apparent radiological consequences [32], and specifically the assessment of radiation hazard emanating directly or indirectly from natural sources, especially soil. As a result, assessing gamma radiation dosage from soil or other natural sources is critical [35]. The amount of these dose rates is proportional to the number of natural radionuclides in the soil and the area is considered a health risk, when the incremental dose becomes significant than the background values [35].

The current study assesses occupational health risks using data collected from Buhemba Artisanal and Small-Scale Gold Mine (BASGM) in Tanzania as the main case study area.

Mining has been connected to a rise in radioactive elements that were previously at natural background levels prior to mining activity [35]. This rise is becoming increasingly important for environmental and human health protection, particularly in the Artisanal and Small-Scale Gold mines (ASGM) sub-sector. This could be due to a lack of information and inadequate awareness; inappropriate mining techniques; a lack of capital; unsupportive policies, rules, and regulations; and inadequate knowledge on proper mine waste management by the ASGM operators and laborer's [22, 27, 28].

The most frequently reported source of high radioactivity in the industrial and mining areas are the naturally occurring radionuclides such as ^{40}K, ^{232}Th, and ^{238}U [9, 18, 30]. These natural radionuclides contribute a significant amount of ionizing radiation to the earth's atmosphere. ^{232}Th and ^{238}U account for around 83% of total human exposure, with the primordial radioisotope ^{40}K accounting for almost 16% of total exposure and artificial radionuclide sources accounting for the remaining 1% [4]. Natural radionuclides from the environment are typically absorbed by the human body through different pathways, including inhalation, ingestion, and skin contact [9, 18, 37]. It has been estimated that, the ingestion route accounts for around one-eighth of total exposures from natural radioactive sources [36]. In addition, inhalation (especially for ^{222}Rn gas exposure) and dermal contact pathways continue to contribute significantly to global human exposure doses, particularly in mining areas [13, 16].

Mining activities especially in the ASGM sub-sector have been reported to increase the level of natural radionuclides [13, 35]. This results to the need for regulatory control for environmental intensive care and radiation safety. Radiation protection and control are two of the most pressing areas of research. Radionuclides can accumulate in aerosols, causing damage to land, water, and food before reaching the human body. Radionuclides can build up in a variety of organs in the human body, creating a health risk. Humans' exposure to incremental dose from the natural radionuclides have been associated to cancer risks, haemorrhage, early aging and mortality, leukemia, shorter lifespan, anemia, and cardiovascular difficulties [19]. In the field of radiation protection, the danger of cancer from low doses of ionizing radiation has been the topic of a long-running controversy [21].

Gold mining has been linked to significant quantities of radiation, mostly from the isotopes ^{238}U, ^{40}K, and ^{232}Th, as well as their offspring [36]. Different authors [17, 24, 29] have reported elevated concentrations of ^{226}Ra, ^{232}Th, and ^{40}K above the background/ control and world average values in gold mine samples from South Africa, Rwanda, and Brazil, respectively. These results are supported by the findings reported at Rwamagasa ASGM in Geita region, Tanzania [9]. Gold mine tailings have further been reported to have higher quantities of ^{226}Ra, ^{232}Th, and ^{40}K than ordinary soil [13]. This suggests that unmonitored gold mining wastes could be a significant source of natural radionuclide exposure for people living near or within gold mining sites.

Significant levels of radionuclides were reported by [25] from Zamfara State in Nigeria. [25] found that the average activity levels of ^{40}K, ^{232}Th, ^{238}U, and ^{226}Ra in soil, rocks, and sediments samples in Bq/Kg were 380.34 ± 116.41, 151.15 ± 21.09, 41.60 ± 11.06, and 37.94 ± 6.01, correspondingly, reporting higher values in rock samples. The external and internal hazard indices of 1.53 and 1.35, respectively was reported. The external and internal hazard indices values were greater than unity suggesting a high level of risk. The mean radium equivalent was 499.18 Bq/kg, and the radioactivity level index was 3.24. The reported gamma dose rate was 221 ± 35 nGy/h, and the radioactivity level index was 3.24. The annual effective dose equivalents for indoor and outdoor were 985.39 Sv/y and 271.03 Sv/y, respectively. The estimated values were above the allowed limits and the world mean values [36]. [25] concluded that the ASGM played a substantial role in the heightened levels of radionuclides, putting people working and living in the mining region at occupational health risk.

2. Material and Methods

2.1. Study Area

This research was carried out at Buhemba ASGM in Tanzania's Mara region (Figure 1). Mara is in the Lake Victoria Goldfields (LVGF); a gold-rich region of Tanzania [9]. As a result, the study location was chosen for its lengthy history of mineral extraction by both ASGM and LSGM in East Africa's gold-rich countries. The study locations may give valuable data on radioactivity levels and distribution, allowing researchers to assess the long-term effects of ASGM on the ecosystem and human health in the area.

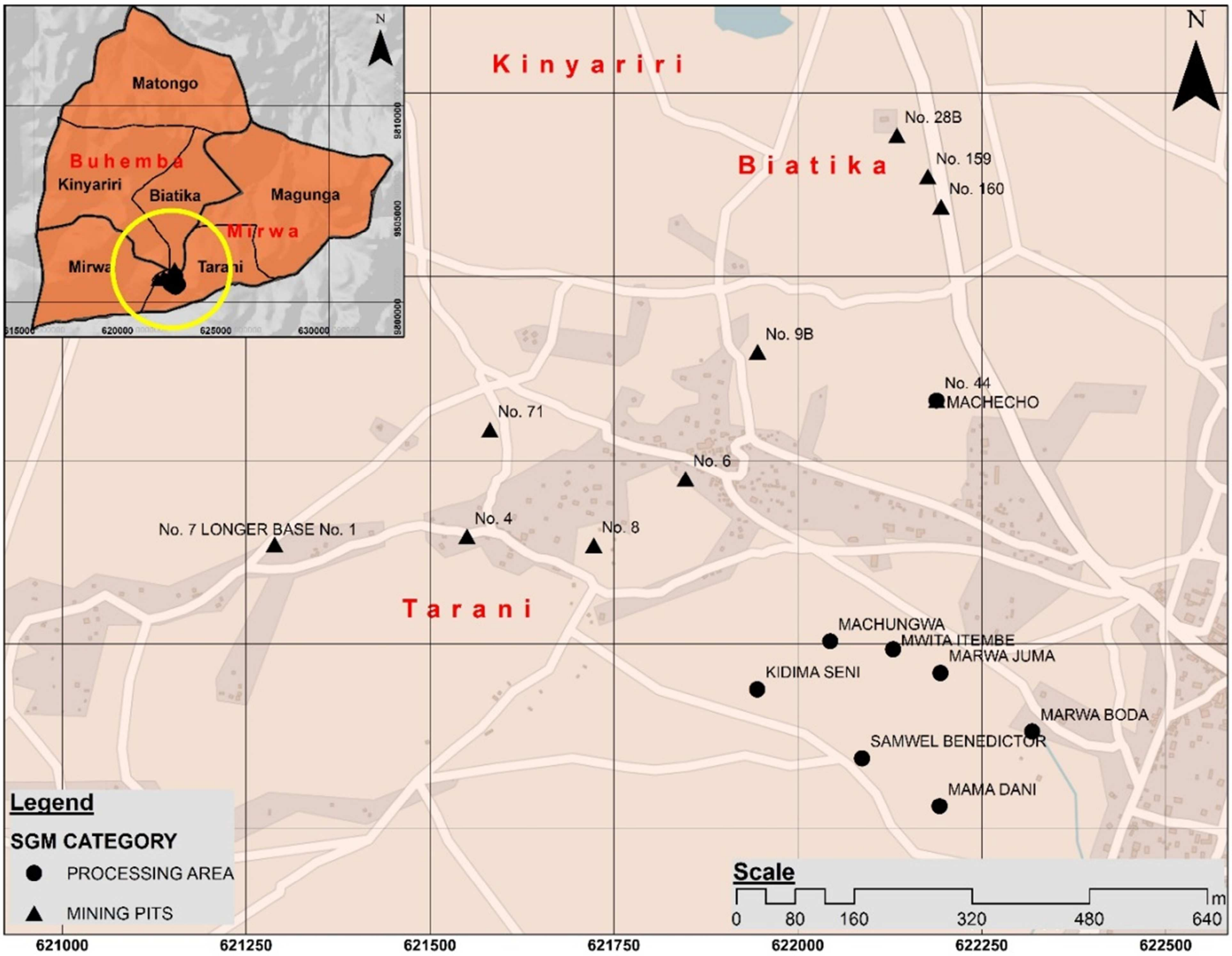

Figure 1. *The map of Buhemba small-scale gold mine area showing mining pits where samples were collected.*

2.2. Radon Measurements

The levels of radon were measured in 12 mining pits at the BASGM. Also, five measurements were taken from five offices at Mwalimu J. K Nyerere University as a control area (about 30 km from BASGM). At each sampling point, radon detection device (Alpha Guard, Genitron 1998) was set to measure the radon concentrations, temperature, pressure, and relative humidity after every ten minutes cycle for six hours. The instrument was placed at least 1 meter from any obstacle to allow easy air flow into the device. The hourly and overall means were recorded.

The intake (I) of activity of the radon daughter for a subject exposure to 1 WLM was estimated using equation (1) [36].

$$I = C_{Rn}\left({}^{Bq}/_{m^3}\right) \times P(h) \times R\left({}^{m^3}/_{h}\right) \quad (1)$$

where, C_{Rn}, *P,* and *R,* are the Radon concentration, exposure period and Breathing rate, respectively. The exposure period is estimated to be 170 hours and the breathing rate for the underground workers is estimated by [36] to be 1.3 m^3/h.

The inhaled dose (D) due to radon gas was estimated using Equation 2 [36].

$$D(msv/y) = C_{Rn} \times Df \times P(h) \times F \times T\,(h) \quad (2)$$

where C_{Rn}, *Df, P, F* and *T,* are Radon concentration, Dose conversion factor, Occupancy factor, Equilibrium factor and Occupancy time, respectively. The dose conversion factor of 9×10^{-6} Sv $(Bqhm^3)^{-1}$, the occupancy factor of 0.8, the equilibrium factor of 0.4 and the exposure time adjusted to one year (in hours) of 2000 hours for workers were adapted from [36].

2.3. Soil Radioactivity

2.3.1. Sample Collection and Preparation

Thirty soil samples were considered for radioactivity. Twenty-five samples were taken from the mining pits, another five samples were taken from the control area about 30 km from the mined area. To speed up the drying process, soil samples were first fractured into reduced aggregates, then thoroughly dried at a temperature of 50°C [5]. After that, the dry samples were crushed with a mortar and pestle, sieved through a steel 2 mm sieve, stored in sealed canisters, and held for at least 28 days to achieve secular equilibrium for gamma ray spectrometry analysis [11].

2.3.2. Radioactivity Analysis

A lead-shielded coaxial high-purity germanium detector (HPGe, serial number 57-P51572A, ORTEC, USA) was used to assess radioactivity levels. To prevent background radiation in the counting environment, three liners of Pb, Cd, and Cu, each 100 mm, 3 mm, and 30 mm thick, respectively were used as the shielding materials. At an energy of 0.662 MeV (^{137}Cs), the system has a relative efficiency of about 51% and a resolution of about 7.2% at Full-Width Half Maximum (FWHM), which is sufficient to resolve the gamma-ray energies of interest. Before the measurement process, multi-nuclide sources of ^{137}Cs, ^{133}Ba, ^{57}Co, ^{109}Cd, ^{60}Co, ^{22}Na, and ^{54}Mn were used to calibrate the gamma-ray energy. The Genie 2000 software's in-situ object counting technology was used to standardize efficiency [8]. The associated gamma-ray lines originating from the decay products were used to determine the activity concentrations of the radionuclides in the samples. ^{40}K was calculated using the 1460.8 keV gamma line. ^{232}Th was calculated using the weighted mean activity levels of gamma lines of 583.1 keV (^{212}Pb), 2614.5 keV (^{208}Tl), and 911.1 keV (^{228}Ac). ^{226}Ra was determined using gamma lines of 609.3 keV (^{214}Bi), 1764 keV (^{214}Bi), 295.2 keV (^{214}Pb), and 186.1 keV (^{226}Ra).

2.3.3. Activity Determination

Equation (3) [36] was used to compute the activity (*A*) in Bq/kg of the samples based on the net area under the photo peaks.

$$A = \frac{N_c}{\gamma_p \times T \times \eta(E) \times m_s} \quad (3)$$

where m_s is the mass of the sample in kg, η (E) is the efficiency of the detector, T is the counting time, γ_p is the absolute transition probability, and N_c is the net count rate.

2.3.4. Exposure from Gamma Rays

Equation 4 [34] was used to estimate the average dose *D* (nGy/h). The estimation was based solely on the levels of ^{226}Ra, ^{232}Th, and ^{40}K, presuming that levels of other additional radioactive elements such as ^{90}Sr, ^{137}Cs, and the decay series of ^{235}U could be ignored due to small concentration contributions to the overall background dosages [20].

$$D = 0.043A_k + 0.662A_{Th} + 0.427A_{Ra} \quad (4)$$

where A_K, A_{Th} and A_{Ra} are the activity levels of ^{40}K, ^{232}Th and ^{226}Ra in Bq/kg, respectively.

2.3.5. Radium Equivalent Dose

The radium equivalent level was estimated to evaluate the risk of gamma radiation exposure to persons associated with interactions with soil from the mining site. Equation 5 [15] was used to estimate the radium equivalent activity.

$$Ra_{eq} = 0.077A_k + 1.43T_h + A_{Ra} \quad (5)$$

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

2.3.6. The Internal Hazard Index

Equation (6) [36] was used to estimate the internal risks (H_{in}) due to unintentionally consumed soil.

$$H_{in} = \frac{C_k}{4810} + \frac{C_{Th}}{259} + \frac{C_{Ra}}{185} \leq 1 \quad (6)$$

where C_K, C_{Th} and C_{Ra} are the activity levels of ^{40}K, ^{232}Th and ^{226}Ra, respectively.

2.3.7. The External Hazard Index

Equation 7 was used to estimate the risk of natural gamma radiations contacting the human body externally [36]. This value must be kept lower than unity for safety reasons.

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

where A_{Ra}, A_{Th} and A_K are radioactivity levels in Bq/kg of radium-226, thorium-232, and potassium-40, respectively.

2.3.8. Representative Gamma Index

The gamma activity value index (I_γ) was estimated using Equation 8 [1]. This value is used to determine if soil is suitable for building materials such as bricks. The building materials are safe if the value is less than unity.

$$I_\gamma = \frac{A_k}{1500} + \frac{A_{Th}}{100} + \frac{A_{Ra}}{150} \quad (8)$$

2.3.9. Annual Gonadal Equivalent Dose

Some human organs are reported to be very sensitive to radiations. Organs such as gonads, bone surface cells, breasts, and active bone marrow are reported to be the organs of attention in radiation protection [36]. Equation (9) was used to calculate the annual gonadal equivalent dose (AGED mSv/y) for mine workers at BASGM.

$$AGED = 0.314A_K + 3.09A_{Ra} + 4.18A_{Th} \quad (9)$$

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

2.4. Risk Characterization

Risk characterization gives a wider view of the existing problem, instead of just reporting the results of exposure and the dose-response analysis, further, its synthesis on the potential hazards that address the need and interest of decision makers regarding the problem.

Among other mathematical models used to evaluate risk, also, different factors were considered. Factors such as population, routes of exposure, people's behaviors, time of exposure, frequency of exposure, age groups, concentrations and doses all contribute to risk.

The lifetime cancer risk due to soil exposure (LCR_{soil}) was estimated using equation 10. Equation 11 was used to estimate the annual effective dose to the lungs (EDL) due to inhalation of radon gas and its daughters. To calculate the lifetime cancer risk due to radon inhalation (LCR_{radon}), equation 12 was used. The number of lung cancer cases per year per million people (LCC) was estimated using equation 13.

$$LCR_{soil} = AEDE \times LE \times RF \tag{10}$$

$$EDL = D_{inh}(Rn) \times W_R \times W_T \tag{11}$$

$$LCR_{radon} = D_{inh}(Rn) \times LE \times RF \tag{12}$$

$$LCC = D_{inh}(Rn) \times 18 \times 10^{-6} \tag{13}$$

Where, LE is the life expectance taken to be 65 years, RF is the fatal risk factor per sievert (0.05), W_R is the radiation-weighting factor (20 for α-particles), W_T is the tissue weighting factor (0.12 for the lungs), AEDE is annual effective dose equivalent estimated using equation 14 [14].

$$AEDE = D(nGyhr^{-1}) \times 8760(hry^{-1}) \times 0.8 \times 0.7(SvGy^{-1}) \times 10^{-6} \tag{14}$$

The risk due to radionuclides exposure is gauged by referring to the incremental dose, where, the incremental dose, is the dose above the background, which in our case are the levels and dose of the control area.

2.5. Risk Management

Cost benefit analysis is a decision-making process that analyse mitigation measures alternatives and select course of action in terms of proper mix of mitigation measures. Decision making process involve three steps: assess the threat to health as a function of exposure to the agent, measure the value of reducing mortality or morbidity rates as a function of control levels, estimate the cost of implementing each level of control. The analysis consist of 6 steps which are: identification of all non-trivial effect, separate these effect into benefits and costs, quantify the value of each benefit and cost, assign to each benefit and cost value a monetary value, consider future costs and benefits (put them on a common basis), sum costs and benefits to ascertain which one is greater, opponents of cost-benefit analysis urge that one cannot put monetary value to life, yet the cost-benefit analysis remain an important tool for risk managers in making rational decision.

2.6. Limitations of the Study

Samples acquired from human subjects would be extremely useful in a study including exposure and human health risk. Risk assessments based on blood and other human samples would yield more accurate results than those based solely on environmental samples. Another limitation in this study is that element concentrations in soils were determined and utilized as the foundation for risk analysis. High quantities of radioactivity in soils, on the other hand, do not always imply that those levels are directly causing harm to human. The current study suggests that more research be done in this area, specifically on organ damage.

3. Results and Discussion

3.1. Radon from Buhemba ASGM

The radon concentrations from randomly selected mining pits and intake computed values and annual doses to which the mine workers are exposed, are presented in Table 1.

Table 1. *Mean radon concentrations (Bq/m³), Intake (Bq) and Dose (mS/y) and other Environmental Parameters.*

Pit number	Location		Levels (Bq/m³)	Intake (Bq)	Dose (mS/y)	Temperature (°C)	Pressure (Mbar)	Humidity (%)
4	S-1.79875°	E34.09281°	74 ± 11	6541.6 ± 972	0.43	28	864	28
7	S-1.79885°	E34.09046°	72 ± 11	6364.8 ± 972	0.42	28	864	28
9A	S-1.79886°	E34.09436°	121 ± 27	10696.4 ± 2386	0.70	26	862	26
9B	S-1.79648°	E34.09636°	140 ± 29	12376 ± 2563	0.80	27	861	21
9C	S-1.79804°	E34.09548°	121 ± 27	10696.4 ± 2386	0.70	26	862	99
14	S-1.79432°	E34.09844°	69 ± 8	6099.6 ± 707	0.40	25	860	96
28B	S-1.79381°	E34.09806°	76 ± 12	6718.4 ± 1060.8	0.44	24	863	99
44	S-1.79708°	E34.09855°	161 ± 21	14232.4 ± 1856.4	0.93	26	860	99
52	S-1.79708°	E34.09855°	148 ± 46	13083.2 ± 4066.4	0.90	31	863	96
71	S-1.79744°	E34.09309°	66 ± 11	5834.4 ± 972.4	0.38	24	864	98
156	S-1.79708°	E34.09855°	215 ± 24	19006 ± 2121.6	1.23	26	860	80
176	S-1.79708°	E34.09855°	698 ± 54	61703.2 ± 4773.6	4.02	27	858	93
Average			163.42 ± 23	14445.98 ± 2070	0.95	26.5	861.75	71.9
Minimum			66 ±11	5834.4 ± 707	0.38	24	858	21
Maximum			698 ± 54	61703.2 ± 4773.6	4.02	31	864	99
C-1	S-1.79743°	E33.97378°	30 ± 4	2448 ± 326	0.1728	30	918	67
C-2	S-1.79758°	E33.97393°	62 ± 7	5059.2 ± 571	0.3571	27	919	72
C-3	S-1.79792°	E33.97317°	28 ± 3	2284.8 ± 245	0.1613	26	920	73
C-4	S-1.79787°	E33.97399°	41 ± 4	3345.6 ± 326	0.2362	27	919	73
C-5	S-1.79798°	E33.97346°	59 ± 5	4814.4 ± 408	0.3398	27	920	71
Average			44 ± 4.6	3590.4 ± 375	0.2534	27.4	919.2	71.2
Minimum			28 ± 3	2284.8 ± 245	0.1613	26	918	67
Maximum			62 ± 7	5059.2 ± 571	0.3571	30	920	73

The international limits for radon according to the [14] and [37] are 200 Bq/m³ and 100 Bq/m³, respectively. It is clearly seen from Table 1 that the average indoor radon concentrations from the selected mining pits is 163.42 ± 23

Bq/m^3, with the highest value (698 ± 54 Bq/m^3) observed in pit number 176. The results further show that 58% of the pits have concentrations higher than the permissible amount of 100 Bq/m^3 [37]. The results (Table 1) further reveal that, the average radon level at BASGM mining pits is 163.42 ± 23 Bq/m^3 which is 4 times higher than in the control area average (C-AVR) value of (44 ± 4.6 Bq/m^3) (Figure 2).

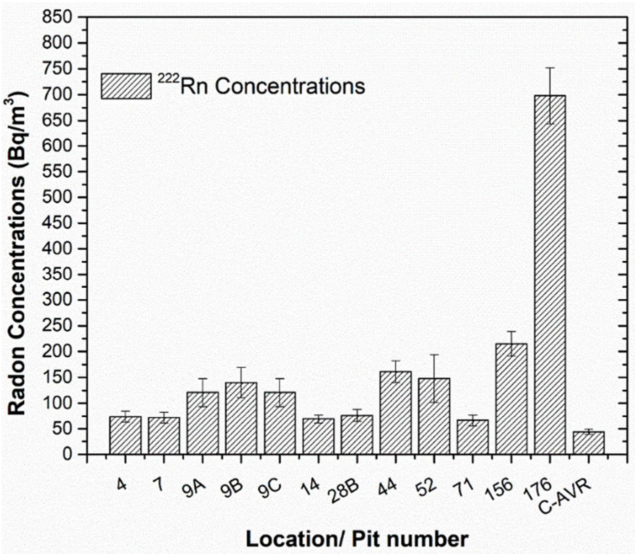

Figure 2. Radon gas concentration measured in different underground mining pits at BASGM compared to the average levels (C-AVR) measured at MJNUAT as a control.

Radon concentrations in the pits ranged from 66 ± 11 to 698 ± 54 Bq/ m^3, compared to 28 ± 3 to 62 ± 7 Bq/ m^3 in the control area. In the mining pits, the yearly effective dose ranged from 0.38 to 4.02 mSv, with a mean value of 0.95 mSv. These dose values from pits were greater than the control results (Figure 3), which ranged from 0.16 to 0.36 mSv with an average of 0.25 mSv. The intakes followed the same pattern as the dose results. The acceptable average yearly effective dose from inhalation of radon and its decay products is 1.26 mSv [36]. Therefore, these findings inform the need for radiation protection and control measures at BASGM.

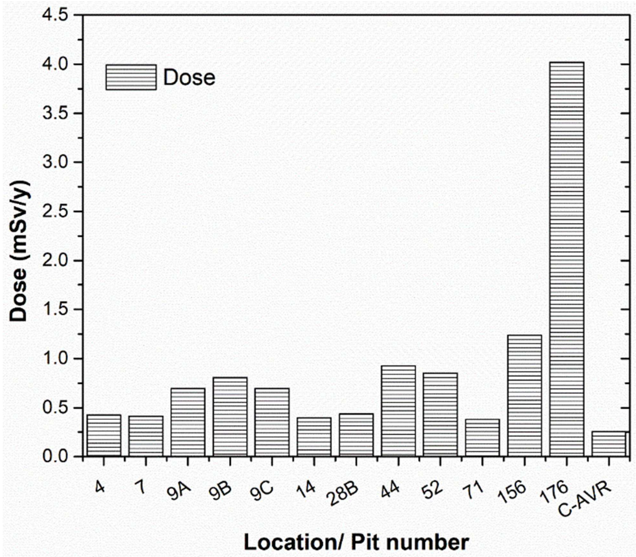

Figure 3. The estimated annual doses inhaled due to radon gas in different mining pits at Buhemba mines compared to the dose estimated from the control area (C-AVR) at MJNUAT.

It is also noted that two mining pits (number 156 and 176) have dose values higher than the acceptable value of 200 Bq/m^3 [14]. Higher levels of radon in the mining pits might be due to poor ventilation (present study field observation). These results highlight the need for the responsible authorities to oversee the improvement of ventilation systems for the cited mining pits, while frequently monitoring the performance of ventilation systems in all the mining pits.

3.2. Soil Radioactivity

3.2.1. Radionuclide's Concentrations

The detailed information of geo-references, activity concentrations, minimum and maximum values of soil radionuclides from different sampling points are presented in Table 2. The average activity levels of ^{226}Ra, ^{232}Th and ^{40}K are presented in Figure 4.

Table 2. Levels of Radioactivity from the Control and Mining Pit Areas.

Coordinates		Sample ID	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
S-1.79752°	E33.97281°	C-1	3.98 ± 0.69	1.09 ± 0.10	206.03 ± 15.62
S-1.79830°	E33.97334°	C-2	4.23 ± 0.36	2.13 ± 0.23	199.12 ± 14.71
S-1.79981°	E33.97432°	C-3	3.89 ± 0.42	1.50 ± 0.11	205 ± 15.23
S-1.79780°	E33.98121°	C-4	4.32 ± 0.59	3.08 ± 0.29	212 ± 16.07
S-1.79642°	E33.98240°	C-5	2.16 ± 0.19	1.08 ± 0.12	215 ± 17.76
S-1.80063°	E34.09636°	BHB00059	4.35±0.94	2.67±0.8	205.01±14.18
S-1.80004°	E34.09802°	BHB0067	2.21±0.8	ND	18.59±7.96
S-1.79708°	E34.09855°	BHB00084	7.07±1.14	3.61±0.62	335.63±20.13
S-1.80224°	E34.09818°	MIR	2.99±0.94	2.05±0.84	116.21±11.5
S-1.80148°	E34.09766°	MIM	6.29±0.99	3.33±0.7	108.62±10.0
S-1.80121°	E34.09986°	MR1R	3.94±0.72	2.56±0.64	104.66±10.46
S-1.80039°	E34.09811°	MRJIR	2.84±0.65	1.67±0.68	325.67±19.21
S-1.79978°	E34.09732°	P09	2.62±0.61	ND	41.21±7.08
S-1.79875°	E34.09281°	P4	7.37±0.85	16.53±1.18	85.94±9.79

Coordinates		**Sample ID**	**^{226}Ra (Bq/kg)**	**^{232}Th (Bq/kg)**	**^{40}K (Bq/kg)**
S-1.80029°	E34.09619°	P4A	10.89±1.3	6.86±0.74	87.44±8.53
S-1.79804°	E34.09548°	P6	2.9±0.63	17.56±1.2	187±13.27
S-1.79885°	E34.09046°	P7A	6.17±0.83	9.94±1.02	370.4±22.07
S-1.79886°	E34.09281°	P8	3.12±0.62	4.5±0.69	22.71±6.26
S-1.80115°	E34.09972°	P14A	5.89±0.85	7.33±0.82	87.37±9.07
S-1.80014°	E34.09802°	P28B	7.03±0.82	5.54±0.78	306.15±18.61
S-1.79708°	E34.09855°	P44	10.03±1.06	5.14±0.8	86.23±9.6
S-1.79709°	E34.09857°	P52	4.48±0.78	4.16±0.71	383.29±22.53
S-1.79744°	E34.09309°	P71	7.6±1.0	20.44±1.34	143.01±11.63
S-1.79648°	E34.09636°	P71A	3.23±0.74	5.52±1.35	193.62±14.46
S-1.79432°	E34.09844°	P139	9.13±1.35	6.78±0.77	99.31±9.3
S-1.79469°	E34.09860°	P140	10.63±1.3	6.95±0.88	375.14±21.11
S-1.79708°	E34.09855°	P156	8.53±1.52	5.48±0.92	445.06±25.8
S-1.79381°	E34.09806°	P158	8.09±1.13	8.73±0.85	158.08±12.56
S-1.79708°	E34.09855°	P176	7.97±1.31	6.55±0.74	275.55±16.81
S-1.80148°	E34.09818°	S1R	4.19±0.97	2.08±0.72	122.08±11.13

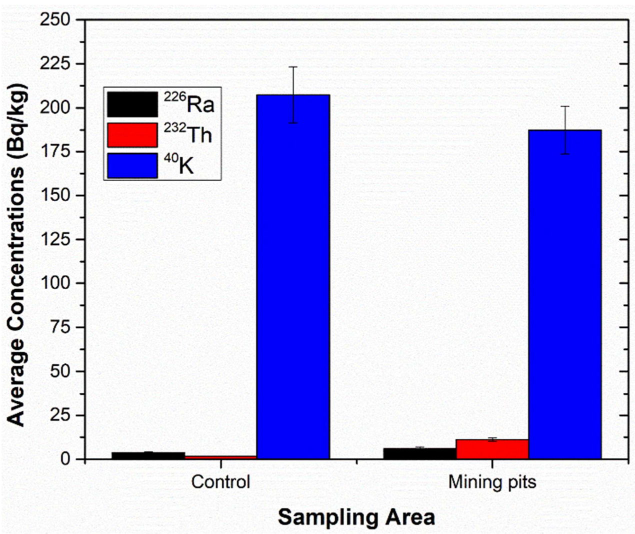

Figure 4. *Average Concentrations of Radionuclides from the Control and Mining Pits.*

Results in Figure 4 shows that, higher levels of ^{238}U and ^{232}Th were detected in the mining pits compared to the control samples. This observation might be due to the fact that, ^{238}U and ^{232}Th are expected in the phosphate rocks, therefore, probably the area has the uranium-and thorium-rich rocks [26]. Furthermore, it is noted in Table 2 that, the highest activity concentration of ^{226}Ra was detected in P4A (10.89 ± 1.3 Bq/kg) and the highest activity of ^{232}Th (20.44 ± 1.3 Bq/kg) was revealed in P71. This observation might be due to the chemistry of ^{226}Ra, ^{232}Th, and ^{238}U that, as ^{232}Th disintegrates, gives radiation and produce decay daughters that include ^{228}Th and ^{228}Ra [1] as P4A and P71 were adjacent and about 5 meters from each other. As shown in Table 2 and Figure 4, the average activity concentration of ^{226}Ra in the mining pits was 5.98 ± 0.94 Bq/kg while in the control area the concentration of ^{226}Ra was 3.72 ± 0.45 Bq/kg. For ^{232}Th, the average activity concentrations were 11.17 ± 0.93 Bq/kg and 1.78 ± 0.17 Bq/kg in mining pits and control areas, respectively. The mean activity of ^{40}K in the mining pits was 187.36 ± 13.72 Bq/kg while the control area revealed a value of 207.43 ± 15.88 Bq/kg. High value of ^{40}K revealed in the control area might be due to potassium fertilizer used in agricultural activities, since some agricultural activities were undertaken in the control areas in the recent past.

The observed higher levels of radioactivity for ^{232}Th and ^{226}Ra in mining pits than in the control area may confirm the findings reported in the literature that mining activities, if not well controlled, elevates the radioactivity levels in the environment [1, 2, 36]). These high levels of radionuclides might be detrimental to workers and the public at BASGM. Also, in the present study, field observation discovered that soil was not wetted during its handling including transportation from pits to processing areas, this might add up the risk, as the soil is being packed and transported from the pit areas to the processing areas. This observation might lead to an increase of radioactivity levels in the mining area [10]. Furthermore, the blasting of rocks and transportation of mined soil, might contribute to the higher level of radionuclides in the pits compared to the control area. Although the activity levels of ^{226}Ra, ^{232}Th, and ^{40}K in in the mining pits were lower compared to the world recommended values of 35 Bq/kg, 45 Bq/kg and 420 Bq/kg, respectively; the values from the mining pits are higher compared to those in the control areas. Figure 4 indicates that, the average values of ^{226}Ra, and ^{232}Th from the mining pits, are 2 and 10 times higher than the control values. The observed high levels of radionuclides in the mining pit samples, might be a result of not watering mine rock piles and excavated soils. The vulnerable groups such as children, women, and aged people at BASGM, might be at a high risk of these radiations. The fast-growing cells and cell divisions for children and the most sensitive parts to radiations for women (breasts) are reported to be affected more [7, 33]. Therefore, workers of Buhemba Mines and women and children in and the surrounding community may be subjected to higher cancer risks.

3.2.2. Radiological Hazard Assessment

Using Equation (8), the Doses (Ds) were estimated using activities of ^{40}K, ^{232}Th, and ^{238}U and presented in Figure 5. It has been assumed that, the contribution from other naturally occurring radionuclides and cosmic radiation at the locations are insignificant as reported elsewhere [2]. Figure 5 also present other calculated radiation indices.

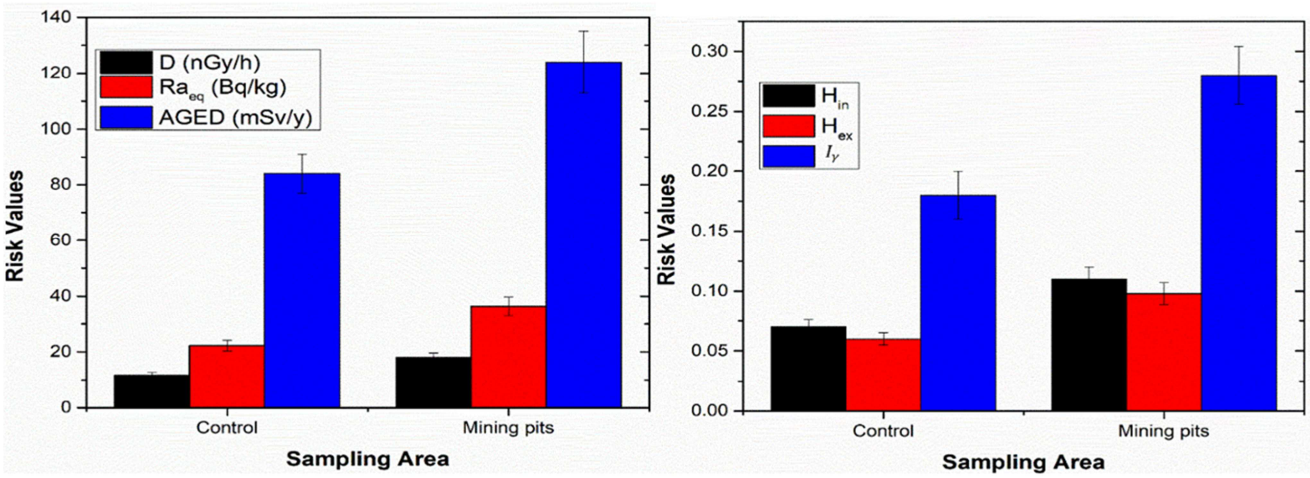

Figure 5. *Mean absorbed dose rate, the annual gonadal equivalent dose and radium equivalent, internal hazard index, the external hazard index, gamma index and alpha index from the study area.*

The average hazard index in the mining pits Ds, Ra_{eq}, H_{in}, H_{ex}, I_γ, and the AGED were at 18.01 ± 1.61 nGy/h, 36.39 ± 3.34 Bq/kg, 0.11 ± 0.01, 0.1 ± 0.01, 0.28 ± 0.03, and 124.02 ± 11.14 mSv/y, correspondingly (Figure 5); were higher than values obtained in the control samples at 11. 68 ± 0.99 nGy/h, 22.23 ± 1.92 Bq/kg, 0.07 ± 0.01, 0.06 ± 0.02, 0.18 ± 0.02, and 84.04 ± 7.09 mSv/y in that order. Although the estimated Buhemba mines risk values were lower than the world suggested mean values [3], the results suggest the health risk due to the incremental values obtained when comparing the results from the control area as the background levels to the estimated levels from the mining pits. These incremental values might be hazardous to the public and mining workers, and others who resides close to the BASGM. Higher values in the mining pits might affect more men adults who work long hours in the mining pits during materials excavation and transportation at BASGM. The gonads, which are very sensitive organs in men, are reported to be more affected by radiations [4]. In order to reduce the risks associated with the mining activities at BASGM, public and occupational health education ought to be given to mining chain actors as well as the general public in the area.

The estimated radiological hazards from BASGM prove the need for the responsible radiation protection and regulatory bodies of Tanzania to work close with the workers and the public at BASGM in providing adequate education on public, environmental and workplace education. This is due to the fact that prolonged exposure to incremental levels even in small quantities may result to health effects [5]. Also, radiation protection education is important because radioactivity is site specific in a sense that miners might reach rocks with higher levels of radionuclides than the obtained from the present study. This will help in the pushing of the need for the Tanzanian government and world of attaining the Sustainable Development Goals (SDGs).

3.3. Risk Characterization

Risk characterization has different dimensions to consider. It has also to be noted that risk is additive, therefore, a broad consideration is required during the process of risk characterization. The process can be performed using different mathematical models but also various factors that might lead to risk should also be evaluated.

At BASGM, different factors that might contribute to occupational risk were determined. Buhemba ASGM has a population of about 500 workers and about 1200 people living in the vicinity of the project (information given by mine leaders). In risk characterization with a radiation point of view, exposure to high number of people is regarded as high risk. Also, different routes of exposure to radionuclides at the study area suggest high risk to workers. It is evidenced that three routes (inhalation, ingestion, and dermal contact) all contribute to the radionuclide exposure to workers. Not only that but also the living behaviors of residents in the study area question their occupational safety. Different social economic activities taking place within the area and people residing near and within the mining site might accelerate the high risk due to radionuclides. In radiation protection, time and the frequency of exposure play a big role in accelerating or reducing the risk. At BASGM, it was noted that people work long hours and throughout a week. This accelerates the risk due to radionuclides. Radiations act differently from age groups. Children are more vulnerable to radiations than adults. Therefore, children who happen to come across with radioactive materials at BASGM are expected to be at higher risk. Also, the concentration levels of radioactivity and the doses estimated tell the level of risk due to radionuclides.

The high concentration levels and doses estimated from the mining area than that from the control area (taken as baseline in this work) inform higher risk due to radionuclides to people at BASGM.

The results for the risk characterization for soil exposure and radon gas are presented in Table 3. The average estimated lifetime cancer risk of 0.32 from the excess gamma radiation from the mining pits' soil is higher than the allowable world value of 0.0029 [35]. This should inform the ASGM workers at the study area to minimize the time for their stay in the mining pits. Also, all other workers for example soil washers and those working in the crushing areas are reminded to use protections and reduce the period of their stay at working areas.

The average EDL estimated due to radon gas is 2.28 mSv/y a less value compared to the world average (3mSv/y). The lung cancer cases per year per million persons (LCC) due to inhalation of radon gas and its daughters was found to be 1.7×10^{-5}. The LCC average per million persons per year is less than the recommended average value of 3.6×10^{-5} [14].

Table 3. *Risk characterization values of soil and radon gas.*

Item	AEDE (mSv)	LCR	LCC	EDL (mSv/y)
Soil	0.10	0.32		
Radon		3.45	1.7×10^{-5}	2.28

3.4. Mitigation Measures

Considering the established risks which cumulatively exceed the acceptable risks, a number of mitigations measures are being put forward for the purpose of reducing the risks. Crashing and milling areas should be located far from residential areas for the purpose of reducing the level of inhaled particulate, the number of people exposed to radioactive materials. The crashing and milling processes should be located downwind with the reference to the mining area. The land use plan of the Buhemba should be developed with consideration of dominant wind direction, with a purpose reducing additional risks for the general population of the area. The use protective gears such as gloves and masks should be emphasized. Engineering pollution control facilities which include fabric filters, Electrostatic Precipitators (ESP), and cyclones should be locally designed, fabricated, and installed; with a purpose of controlling air pollution, and enabling the recycling of dusts. Proper design and operation of ventilation systems in the mining pits, crushing, and milling facilities; should be instituted. Also, sufficient ventilation in residential houses in the vicinity of the mines should be emphasized through awareness campaigns. To reduce the level of dust emission, the use of wet milling methods is encouraged. Water from the mining pits which is normally pumped out and lost, should be recycled, and used to spray off dusts but also in the wet processes. After a day work, miners, and other workers such as gold extractors using water and mercury, should be required to change clothes when leaving the working place. This should be done through awareness campaigns. Considering the established constituent of soil in the area, people should not use waste rocks and tailings in building constructions.

4. Conclusions

Natural radionuclides in the study area were spatially distributed. Samples from the mining area had higher levels compared to samples from the control area. the estimated hazard index values are greater compared to that from the control samples and some even higher than the world permissible levels [35]. Results show also that the mining activities contribute to higher level of radionuclides. Other than the world and other international permissible limits, the incremental value of radionuclides level, dose and index revealed in the mining area against those from the control area suggest occupational health risk measures at Buhemba ASGM.

5. Recommendations

Considering results obtained in the present study, some among other recommendations are presented. Follow up studies are suggested to be done on season variations. Also, future and follow up studies may consider a re-calculation (using own data) of the occupancy factor based on gender, age, and people's habits in the study area and not relying on international estimates in calculating different risk indices. Moreover, establishment of national radioactivity baselines, and dose limits in soil, water and food basing on Tanzania backgrounds is highly recommended. Not only that but also, we suggest other follow up and further studies to use samples from human subjects. Moreover, more studies are recommended to be done in other ASGM centers to get the complete mapping throughout the region and other areas in Tanzania.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Funding

The present research was kindly supported by the Tanzania Commission for Science and Technology (COSTECH), project funding No. FA. 403/489/79.

Acknowledgements

Appreciation extends to the Tanzania Commission for Science and Technology (COSTECH) for funding. Also, the

Tanzania Atomic Energy Commission (TAEC) is appreciated for technical assistance in Hyper pure Gamma Germanium Detector (HPGe) laboratory techniques. The authors are also thankful to the Buhemba mine management for co-operation and permission to perform research within their region.

References

[1] Ademola, A., & Obed, R. (2012). Gamma radioactivity levels and their corresponding external exposure of soil samples from tantalite mining areas in Oke-Ogun, South-Western Nigeria. *Radioprotection*, 47 (2), 243-252. https://doi.org/10.1051/radiopro/2012003

[2] Aliyu, A. S., Ibrahim, U., Akpa, C. T., Garba, N. N., & Ramli, A. T. (2015). Health and ecological hazards due to natural radioactivity in soil from mining areas of Nasarawa State, Nigeria. *Isotopes in Environmental and Health Studies*, 51 (3), 448-468. https://doi.org/10.1080/10256016.2015.1026339

[3] Amrani, D., & Tahtat, M. (2001). Natural radioactivity in Algerian building materials. *Applied Radiation and Isotopes* 54 (2001), 687-689. https://doi.org/doi.org/10.1016/S0969-8043(00)00304-3

[4] Asaduzzaman, K., Khandaker, M. U., Amin, Y. M., & Mahat, R. (2015). Uptake and distribution of natural radioactivity in rice from soil in north and west part of peninsular Malaysia for the estimation of ingestion dose to man. *Annals of Nuclear Energy*, 76 (2015), 85-93. https://doi.org/10.1016/j.anucene.2014.09.036

[5] Avwiri, G. O., Jafaru, E., & Ononugbo, E. (2013). Radiometric assay of hazard indices and excess lifetime cancer due to natural radioactivity in soil profile in Ogba/Egbema Ndoni local government area of rivers state Nigeria. *Academic Research International*, 4 (5), 54-65.

[6] Bjørklund, G., Christophersen, O. A., Chirumbolo, S., Selinus, O., & Aaseth, J. (2017). Recent aspects of uranium toxicology in medical geology. *Environ Res*, 156, 526-533. https://doi.org/10.1016/j.envres.2017.04.010

[7] Brusin, J. H. (2007). Radiation protection. *Radiologic technology*, 78 (5), 378-392.

[8] Fatima, I., Zaidi, J. H., Arif, M., & Tahir, S. N. (2007). Measurement of natural radioactivity in bottled drinking water in Pakistan and consequent dose estimates. *Radiat Prot Dosimetry*, 123 (2), 234-240. https://doi.org/10.1093/rpd/ncl093

[9] Focus, E., Mwemezi, J. R., Najat, K. M., & Firmi, P. B. (2021). The Influence of Gold Mining on Radioactivity of Mining Sites Soil in Tanzania. *EQA-International Journal of Environmental Quality*, 46 (2021), 46-59. https://doi.org/10.6092/issn.2281-4485/13288

[10] Ghose, M., & Majee, S. (2001). Air pollution caused by opencast mining and its abatement measures in India. *Journal of Environmental Management*, 63 (2), 193-202.

[11] Habib, M. A., Basuki, T., Miyashita, S., Bekelesi, W., Nakashima, S., Techato, K., Khan, R., Majlis, A. B. K., & Phoungthong, K. (2018). Assessment of natural radioactivity in coals and coal combustion residues from a coal-based thermoelectric plant in Bangladesh: implications for radiological health hazards. *Environ Monit Assess*, 191 (1), 27. https://doi.org/10.1007/s10661-018-7160-y

[12] Howell, S., & Shalet, S. (1998). Gonadal damage from chemotherapy and radiotherapy. *Endocrinology and metabolism clinics of North America*, 27 (4), 927-943.

[13] IAEA. (2005). *Measurements of radionuclides in food and the environment-A Guidebook.* (GC (50/4). (Annual Report 2005, Issue 295). International Atomic Energy Agency. https://www.iaea.org/publications/reports/annual-report-2005

[14] ICRP. (2019). *Radiological protection from naturally occurring radioactive material (NORM) in industrial processes* (115). (ICRP Publication Issue 4). ICRP. https://www.icrp.org/publication.asp?id=ICRP%20Publication%20142

[15] Isinkaye, M. O., Jibiri, N. N., Bamidele, S. I., & Najam, L. A. (2018). Evaluation of radiological hazards due to natural radioactivity in bituminous soils from tar-sand belt of southwest Nigeria using HpGe-Detector. *International Journal of Radiation Research*, 16 (3), 1-12.

[16] Joel, E. S., De, D. K., Omeje, M., Adewoyin, O., Olawole, O. C., Akinwumi, A., Erubami, S., & Adeyemi, G. A. (2020). Assessment of background radionuclides and gamma dose rate distribution in Urban-setting and its radiological significance. *Scientific African*, 8. https://doi.org/10.1016/j.sciaf.2020.e00377

[17] Kamunda, C., Mathuthu, M., & Madhuku, M. (2016). An Assessment of Radiological Hazards from Gold Mine Tailings in the Province of Gauteng in South Africa. *International Journal of Environmental Research and Public Health*, 13 (1), 1-7. https://doi.org/10.3390/ijerph13010138

[18] Kamunda, C., Mathuthu, M., & Madhuku, M. (2017). Determination of Radon in mine dwellings of gauteng province of South Africa using AlphaGUARD radon professional monitor. *J Environ Toxicol Stud*, 1 (1), 1-4. https://doi.org/10.16966/2576-6430.107

[19] Knoll, G. F. (2010). *Radiation detection and measurement*. John Wiley & Sons.

[20] Kocher, D. C., & Sjoreen, A. L. (1985). Dose-Rate Conversion Factors for External Exposure to Photon Emitters in Soil. *Hedfh Physics* 48 (2), 193-205.

[21] Korblein, A., & Hoffmann, W. (2006). Background radiation and cancer mortality in Bavaria: an ecological analysis. *Archives of Environmental and Occupational Health*, 61 (3), 109-114. https://doi.org/10.3200/AEOH.61.3.109-114

[22] Lissu, T., & Mark, C. (2008). *How Tanzania is Failing to benefit from Gold Mining* (2). (A golden oportunity?, Issue 2008). CCT. https://curtisresearch.org/a-golden-opportunity-how-tanzania-is-failing-to-benefit-from-gold-mining/

[23] Madzunya, D., Dudu, V. P., Mathuthu, M., & Manjoro, M. (2020). Radiological health risk assessment of drinking water and soil dust from Gauteng and North West Provinces, in South Africa. *Heliyon*, 6 (2), 1-7. https://doi.org/10.1016/j.heliyon.2020.e03392

[24] Malanca, A., Pessina, V., & Dailara, G. (1993). Radionuclide Content of Building Matrials and gamma ray dose rates in Dwellings of Rio Grande Do Notre, Brazil. *Radiation Protection Dosimetry*, 48 (2), 199-203. https://doi.org/10.1093/oxfordjournals.rpd.a081865

[25] MbetAmos, A., Ibrahim, U., Shekwonyadu, I., Emmanuel, O. J., Samson, Y., & Godwin, B. E. (2020). Determination of natural radioactivity levels and radiological hazards in environmental samples from artisanal mining sites of Anka, North-West Nigeria. *Scientific African*, 10 (2020), 1-11. https://doi.org/10.1016/j.sciaf.2020.e00561

[26] Mohammed, N., K., & Mazunga, M. S. (2013). Natural Radioactivity in Soil and Water from Likuyu Village in the Neighborhood of Mkuju Uranium Deposit. *International Journal of Analytical Chemistry*, 2013 (2013), 1-4. https://doi.org/10.1155/2013/501856

[27] Mutagwaba, W., John Bosco Tindyebwa, J., Makanta, V., Kaballega, D., & Maeda, G. (2018). *Artisanal and small-scale mining in Tanzania – Evidence to inform an 'action dialogue'* (8). (Artisanal and small-scale mining in Ta nzania, Issue 2018). MTL. http://mtlconsulting-tz.com/

[28] Mwaipopo, R., Mutagwaba, W., & Nyange, D. (2004). *Increasing the Contribution of Artisanal and Small-Scale Mining to Poverty Reduction in Tanzania* (Based on an analysis of mining livelihood in Misungwi and Geita districts, Mwanza region, Issue 2004). https://www.researchgate.net/publication/242636212_Increasing_the_contribution_of_artisanal_and_small-scale_mining_to_poverty_reduction_in_Tanzania_Basedon_an_analysis_of_mining_livelihoods_in_Misungwi_and_Geita_Districts Mwanza_region.

[29] Ntihabose, L. (2010). Assessment of Heavy Metal Flaxes and Radiation Exposure due to NORM in the Extraction and Processing of Coltan Ores in Selected Areas of Rwanda [Msc. Physics, University of Nairobi,]. Kenya. https://inis.iaea.org/collection/NCLCollectionStore/_Public/50/007/50007338.pdf

[30] Osoro, M. K., Rathore, I. V. S., Mangala, M. J., & Mustapha, A. O. (2011). Radioactivity in surface soils around the proposed sites for titanium mining project in Kenya. *Journal of Environmental Protection*, 2 (2011), 460-464. https://doi.org/10.4236/jep.2011.24053

[31] Sarin, M. M., Krishnaswami, S., Somayajulu, L. K., & Moorer, W. S. (1990). Chemistry of uranium, thorium, and radium isotopes in the Ganga Brahmaputra river system: Weathering processes and fluxes to the Bay of Bengal. *Gecchimica ef Ccmmxhimifa Acta* 54 (1990), 1313-1387. https://doi.org/10.1016/0016-7037(90)90163-F

[32] Singh, J., Singh, H., Singh, S., Bajwa, B. S., & Sonkawade, R. G. (2009). Comparative study of natural radioactivity levels in soil samples from the Upper Siwaliks and Punjab, India using gamma-ray spectrometry. *J Environ Radioact*, 100 (1), 94-98. https://doi.org/10.1016/j.jenvrad.2008.09.011

[33] Tomà, P., Bartoloni, A., Salerno, S., Granata, C., Cannatà, V., Magistrelli, A., & Arthurs, O. J. (2019). Protecting sensitive patient groups from imaging using ionizing radiation: effects during pregnancy, in fetal life and childhood. *La radiologia medica*, 124 (8), 736-744.

[34] UNSCEAR. (1993). *Sources, effects and risks of ionizing radiation* (1993 report to General Assembly, Issue United Nations). United Nations. https://www.unscear.org/unscear/en/publications/1993.html

[35] UNSCEAR. (2000). *effects and risks of ionizing radiation* (1). (United Nations Scientific Committee on the effects of Atomic Radiation. Exposures from natural sources, Issue United Nations). United Nations. https://www.unscear.org/unscear/en/publications/2000_1.html

[36] UNSCEAR. (2020). *Sourses and effects of ionizing radiations* (Annex B). (Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: implications of information published since the UNSCEAR 2013 Report, Issue UNSCEAR). United nations. https://www.unscear.org/unscear/en/publications/2020b.html

[37] WHO. (2009). *WHO handbook on indoor radon* (615). (A public health perspective, Issue WHO). World Health Organization. http://apps.who.int/iris/bitstream/handle/10665/44149/9789241547673_eng.pdf?sequence=1

[38] Wollin, K. M., Damm, G., Foth, H., Freyberger, A., Gebel, T., Mangerich, A., Gundert-Remy, U., Partosch, F., Röhl, C., Schupp, T., & Hengstler, J. G. (2020). Critical evaluation of human health risks due to hydraulic fracturing in natural gas and petroleum production. *Arch Toxicol*, 94 (4), 967-1016. https://doi.org/10.1007/s00204-020-02758-7

[39] Xinwei, L., Lingqing, W., Xiaodan, J., Leipeng, Y., & Gelian, D. (2006). Specific activity and hazards of Archeozoic-Cambrian rock samples collected from the Weibei area of Shaanxi, China. *Radiat Prot Dosimetry*, 118 (3), 352-359. https://doi.org/10.1093/rpd/nci339