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Evaluation of Radioactivity Concentration and Radiological Impact for a Closed Open Pit Gold Mine

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Abstract: Evaluating radioactivity concentration and radiological impacts in soil, water and air is essential for both operating and closed gold mines, as geological settings, mining, industrial and agricultural activities can increase the natural occurring radioactivity level. The assessment is critical since the presence of radioactive elements can pose significant health risks and social problems. While most studies focus on active mining operations, this study targets the radioactivity concentration and radiological impact due to exposure of radionuclides of 232Th, 226Ra, and 40K for the closed open pit gold mine located in Nzega, Tanzania. In this study, gamma spectrometry was used for radioactivity evaluation and radiological impact assessment. The results indicated that, the activity concentration levels of 232Th radionuclides range from 17.4±2.4 to 133±13 Bq/kg, with an average value of 42.1±4.4 Bq/kg. The activity levels of 226Ra radionuclides range from 13.1±1.6 to 308±28 Bq/kg, with an average value of 82.8±7.9 Bq/kg, and the activity levels of and 40K radionuclides range from 101±15 to 1,119±103, with an average value of 461±45 Bq/kg. These activity concentrations were found to be above those mean values reported by UNSCEAR 2000 of 30, 35, and 400 Bq/kg for 232Th, 226Ra, and 40K, respectively, for natural radionuclides in soils. The radiological parameters calculated from the activity concentration were below the acceptable limit. The mean annual effective dose of 0.5 mSv/Year was below the ICRP recommended limit of 1.0 mSv/Year for members of general public. The average value of radium equivalent activity was 178.4 Bq/kg. The estimated average values of Hex (0.4) and Hin (0.7) in the study area were both below the desirable limit of 1. However, the radiological parameters at Re-handle were above the public limit and this requires mitigation measures. It can be concluded that no risk may threat the residents around study area except for Re-handle area which we recommends continued monitoring of radiation levels to ensure they remain within safe limits, and restricted access to this area is necessary to safeguard public health and environmental integrity.

Keywords: Terrestrial radiation, external radiation exposure, gamma ray spectrometer, Closed Gold Mine.

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Évaluation de la Concentration en Radioactivité et de l'Impact Radiologique d'une Mine d'Or à Ciel Ouvert Fermée

Résumé: L'évaluation de la concentration en radioactivité et des impacts radiologiques dans le sol, l'eau et l'air est essentielle tant pour les mines d'or en exploitation que pour celles fermées, car les contextes géologiques, les activités minières, industrielles et agricoles peuvent augmenter le niveau de radioactivité naturelle. Cette évaluation est cruciale, car la contamination du sol, de l'eau et de l'air par des produits chimiques toxiques, y compris des éléments radioactifs, peut représenter des risques significatifs pour la santé et engendrer des problèmes sociaux. Alors que la plupart des études se concentrent sur les exploitations minières actives, cette étude cible la concentration en radioactivité et l'impact radiologique liés à l'exposition aux radionucléides 232Th, 226Ra et 40K provenant d'une mine d'or à ciel ouvert fermée située à Nzega, en Tanzanie. Dans cette étude, la spectrométrie gamma a été utilisée pour évaluer la radioactivité et l'impact radiologique. Les résultats indiquent que les niveaux de concentration en activité des radionucléides 232Th varient de 17,4 ± 2,4 à 133 ± 13 Bq/kg, avec une valeur moyenne de 42,1 ± 4,4 Bq/kg. Les niveaux d'activité des radionucléides 226Ra varient de 13,1 ± 1,6 à 308 ± 28 Bq/kg, avec une valeur moyenne de 82,8 ± 7,9 Bq/kg. Enfin, les niveaux d'activité des radionucléides 40K varient de 101 ± 15 à 1 119 ± 103 Bq/kg, avec une valeur moyenne de 461 ± 45 Bq/kg. Ces concentrations en activité se sont révélées supérieures aux valeurs moyennes rapportées par l'UNSCEAR 2000, à savoir 30, 35 et 400 Bq/kg pour 232Th, 226Ra et 40K respectivement, dans les radionucléides naturels présents dans les sols. Les paramètres radiologiques calculés à partir des concentrations en activité se situaient en dessous des limites acceptables. La dose efficace annuelle moyenne de 0,5 mSv/an était inférieure à la limite recommandée par la CIPR de 1,0 mSv/an pour les membres du public général. La valeur moyenne de l'activité équivalente en radium était de 178,4 Bq/kg. Les valeurs moyennes estimées pour Hex (0,4) et Hin (0,7) dans la zone d'étude étaient toutes deux inférieures à la limite désirable de 1. Cependant, les paramètres radiologiques au niveau du site de re-traitement étaient au-dessus de la limite publique, ce qui nécessite des mesures d'atténuation.

Mots-clés: Radiation terrestre, exposition externe aux rayonnements, spectromètre gamma, mine d'or fermée.

1. INTRODUCTION

Evaluating the radioactivity concentration and radiological impact of soil, water and air in operating or closed gold mines is crucial because mining activities and geological conditions can elevate the levels of naturally occurring radioactive materials (NORMs) [23, 34]. Moreover, many mining sites have been abandoned or closed without implementing environmental protection measures [33, 4, 26]. Environmental protection measures are crucial for ensuring sustainable post-mining land use. This importance is highlighted by numerous studies that emphasize the negative impacts that abandoned mining operations can have on surrounding communities [1, 20, 17]. Contamination from such sites have resulted in soil, water, and air being contaminated with toxic chemicals and radioactive materials, leading to severe health risks and social problems for local communities [8, 25].

Therefore, the impact of abandoned mines has prompted countries to establish regulations aimed at ensuring safe and sustainable mine closures [24]. While sustainable mining practices cannot be achieved if pollutants, including elevated amount of radionuclides, are left behind at mining sites [22], the critical assessments of radioactivity levels and potential exposure doses to mining staff and the public, as well as other contaminants at each stage of gold mining activities become very essential [10, 11, 18]. Moreover, assessing radioactivity levels in gold mines is particularly important because uranium resources, often present as by-products of gold mining, can significantly elevate radiation levels. For instance, the quartz pebble conglomerates of the Witwatersrand Basin in South Africa produce uranium as a by-product of gold mining [14, 22]. NORMs present in many natural resources like gold, copper, aluminum, oil, and gas, when disturbed by human activities such as mining, agriculture, and industry, can expose the public and environment to radiation [27, 22]. Given the long half-lives of radionuclides like ^{238}U, ^{232}Th, and ^{40}K (ranging from 700 million to 14 billion years), their environmental impact before and

after mine closure cannot be ignored, as they pose significant health risks [35, 28]. Thus, it is vital to monitor radioactivity levels at each stage of mining, including at abandoned or closed sites, to mitigate the potential health effects on the public and environment [37, 35].

In many countries, particularly in Sub-Sahara Africa, there are limited studies on the activity concentration and dose estimates for mining staff and the public in non-radioactive mining activities [22]. Most research focuses on active mines, with less attention given to abandoned or closed mines [23, 7, 6]. Research in South Africa and Spain has identified elevated levels of natural radionuclides in tailing dams, soils, and rocks, with some areas exceeding recommended regulatory limits [22]. Factors such as the presence of organic matter in the soil and the migration of contaminants were found to be influential [29]. Conversely, a study in Sudan's traditional gold mining area found the radiological impact to be generally insignificant, although some locations exhibited values above recommended levels [16, 5]. The assessment of radiological impact for the closed Golden Pride Project Gold mine site has not been done.

Therefore, in this study, the activity concentration of Thorium-232 (^{232}Th),Radium-226 (^{226}Ra) and Potasium-40 (^{40}K) in the soil and rock samples at Golden Pride Project Gold mine site, Tanzania have been determined by gamma-ray spectrometry with HPGe detector to estimates the radioactivity level and radiological impact to public.

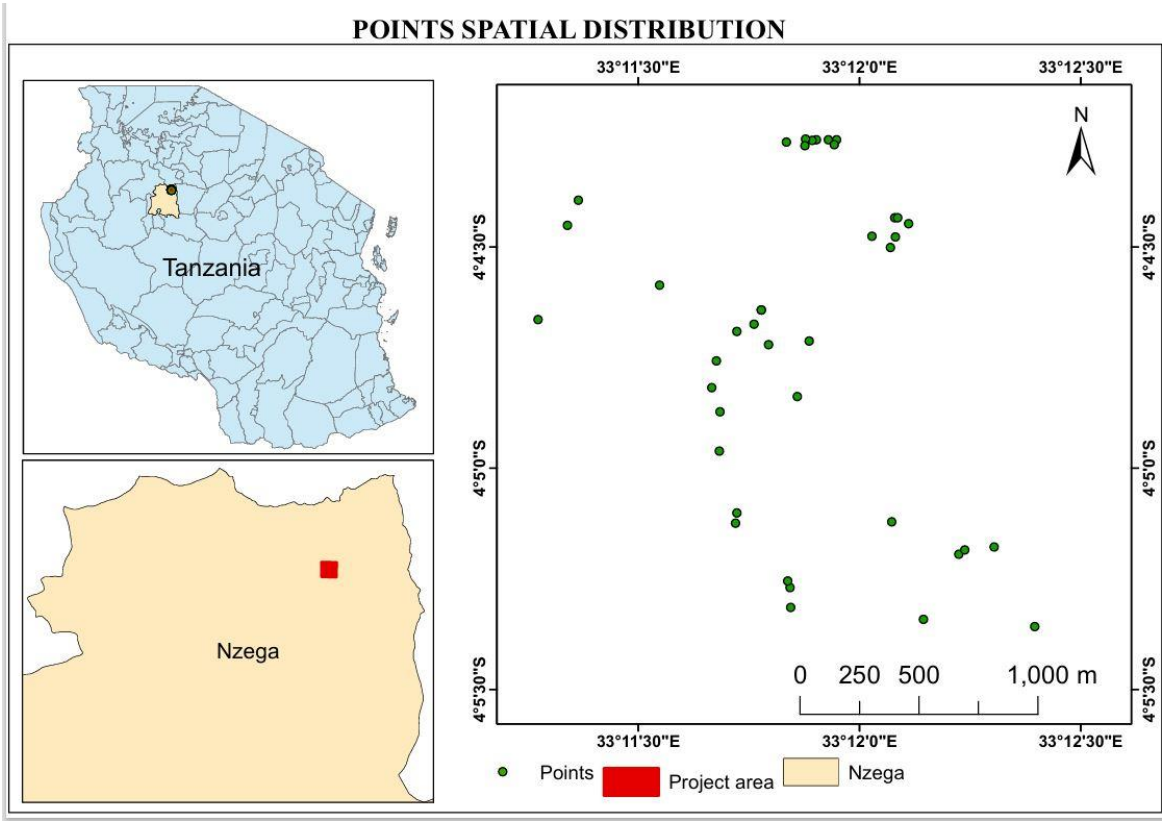
2. MATERIALS AND METHODS

2.1. The Study Area

The Resolute Tanzania Limited also known as Golden Pride Project is a closed gold mine (Figure 1) located in Nzega District, part of the Tabora Region in north central Tanzania, approximately 18 km north of the township of Nzega and 200 km south of the regional center of Mwanza. Construction of Golden Pride Project, the first modern gold

mine in Tanzania, began in October 1997 and was completed twelve months later with an initial mine life of seven years [39]. The mine was designed for modern open pit mining methods and the plant capacity was 2.6 Mt/a of an ore. A significant increase in ore reserves was announced during 2001, and as a result a staged upgrade to treat in an excess of 2.6 Mt of ore was undertaken. In 2002 the nominal design capacity of the plant was extended from 1.6 Mt/a to approximately 2.6 Mt/a. Expansions have included installation of a ball mill and pebble crushing circuit, additional leach tanks and tailings thickener, additional waste rock dumps and Tailings Storage Facility (TSF), a new stand-by power station and upgrading of the existing powerline feeding the mine from the Lusu sub-station. The mine life was later extended for another seven years, and was later closed in late 2013 [39, 21]. After closure of the mine, the site is currently owned by the University of Dar es Salaam for research and training purposes.

Figure 1.Sample Collection Points for The Closed Golden Pride Project Mine Site



2.2. Sample Collection and Preparation

Soil and waste rock samples were collected from the abandoned mine site from 10th to 20th February, 2022. Samples locations were determined using Global Positioning System (Table 1). Information related to site history, its proximity to the community and accessibility and safety issues were considered during selection of the appropriate sampling locations. Forty (40) samples were collected using nitrile gloves and stainless-steel trowel. True surface samples (waste rock and soil) were randomly collected at the surface above the depth of 15 cm for each mining locations. Samples were collected from various locations including the Stockpile of the plant, Re-handle area, Tailings Storage Facility, Waste rock dump, Main pit and Pit two. The samples were dried in an oven at a temperature of 108±10 °C in order to remove any available moisture, after cooling they were crushed using a jaw crusher, followed by milling to reduce particle sizes to less than 2 mm. The material was sieved to ensure uniformity, with larger particles reprocessed, and then homogenized by manual mixing [12, 19]. Samples of 1 Kg were packed into pre labeled plastic bags and transported for analysis at Tanzania Atomic Energy Commission (TAEC) Northern Zone Laboratory in Arusha.

Table 1. Collected Samples and their Corresponding Locations at Golden Pride Project Gold mine site

Sample ID	Sample Location	Longitudes	Latitude
1A	Stock pile of plant	S 04 04 15.5	E 33 11 56.9
1B	Stock pile of plant	S 04 04 15.5	E 33 11 54.2
2A	Stock pile of plant	S 04 04 15.6	E 33 11 53.6
2B	Stock pile of plant	S 04 04 15.4	E 33 11 52.7
2C	Stock pile of plant	S 04 04 15.8	E 33 11 50.1
3A	Stock pile of plant	S 04 04 15.5	E 33 11 55.8
3B	Stock pile of plant	S 04 04 16.2	E 33 11 56.6
3C	Stock pile of plant	S 04 04 16.3	E 33 11 52.6
4A	Re-handle	S 04 04 26.1	E 33 12 04.8
4B	Re-handle	S 04 04 26.1	E 33 12 05.2
5A	Re-handle	S 04 04 26.9	E 33 12 06.7
5B	Re-handle	S 04 04 28.7	E 33 12 04.9
5C	Re-handle	S 04 04 30.1	E 33 12 04.2
7A	Re-handle	S 04 04 28.6	E 33 12 01.7
8A	Tailing Storage Facility	S 04 04 23.7	E 33 11 21.9
9A	Tailing Storage Facility	S 04 04 27.1	E 33 11 20.4

Sample ID	Sample Location	Longitudes	Latitude
9B	Tailing Storage Facility	S 04 04 39.9	E 33 11 16.4
9C	Tailing Storage Facility	S 04 04 35.2	E 33 11 32.9
10A	Waste Damp	S 04 04 42.8	E 33 11 53.2
10B	Waste Damp	S 04 04 50.3	E 33 11 51.6
11A	Waste Damp	S 04 04 40.5	E 33 11 45.7
11B	Waste Damp	S 04 04 41.5	E 33 11 45.7
11C	Waste Damp	S 04 04 43.3	E 33 11 47.7
12A	Waste Damp	S 04 04 38.6	E 33 11 46.7
12B	Waste Damp	S 04 04 38.6	E 33 11 42.2
13A	Waste Damp	S 04 04 45.5	E 33 11 40.6
13B	Waste Damp	S 04 04 49.1	E 33 11 40.0
13C	Waste Damp	S 04 04 52.4	E 33 11 41.1
14A	Main Pit	S 04 04 57.7	E 33 11 41.0
14B	Main Pit	S 04 05 06.1	E 33 11 43.4
14C	Main Pit	S 04 05 07.5	E 33 11 43.2
15A	Main Pit	S 04 05 16.2	E 33 11 50.6
15B	Main Pit	S 04 05 18.9	E 33 11 50.7
15C	Main Pit	S 04 05 15.3	E 33 11 50.3
16A	Main Pit	S 04 05 11.7	E 33 12 13.5
16B	Main Pit	S 04 05 20.5	E 33 12 08.7
17A	Main Pit	S 04 05 11.1	E 33 12 14.3
17B	Main Pit	S 04 05 10.7	E 33 12 18.3
17C	Pit Two	S 04 05 07.3	E 33 12 04.4
18B	Pit Two	S 04 05 21.5	E 33 12 23.8

2.3. Laboratory Preparation and Experimental Analysis

In the laboratory, forty (40) samples were packed in stainless steel canisters. The packed canisters were properly sealed to prevent the escape of radiogenic gases and were kept for 30 days in order to attain radioactive secular equilibrium between the ^{222}Rn and ^{226}Ra and their progeny. Then, the measurement was performed 24 hours for each sample using High Purity Gemanium (HPGe) coaxial detector system with model number GEM40-83-SMP and serial number of 57-P51572A manufactured by ORTEC-USA. This equipment is coupled with Gamma vision software for data acquisition and analysis. Energy and efficiency calibration was performed by using multi-nuclide standard source CBSS2 containing ^{137}Cs, ^{60}Co, ^{241}Am,^{133}Ba, ^{57}Co, ^{109}Cd, ^{22}Na, and ^{54}Mn. The activity concentrations of radionuclides was determined in 40 soil samples collected from Stockpile of plant (08 samples), Re-handle

(06), Tailing Storage Facility (04), Waste Damp (10), Main Pit (10) and Pit Two (02 samples).The radioactivity concentration,and radiological impacts was calculated from the following Equations:

2.3.1. Activity Concentration (A)

Computation of the radionuclides concentration levels depend on the detected activity concentration. The activity concentration levels for ^{232}Th, ^{226}Ra, and ^{40}K which are the dominant radionuclides of our interest were calculated from data obtained from the gamma ray spectrometry system. The activity concentration of individual radionuclides was calculated using Equation (1).

$$A\left(\frac{Bq}{kg}\right) = \frac{N}{\epsilon_\gamma P_\gamma T_s M} \quad \text{(1)}$$

where A is the specific activity in Bq/kg of each radionuclide in the sample, N is the net peak count rate of the resulting photo-peak, ϵ_γ is the detector efficiency of the specific gamma-ray, P_γ is the gamma emission probability of the corresponding gamma energy, T_s is the counting time of the sample and M is the sample mass in kg. The total uncertainties were estimated from various uncertainties sources according to Equation (2). The equal counting time for both background and sample was chosen to minimize the uncertainty in the net counts as shown in Equation 2.

$$\Delta A = \sqrt{\left(\frac{\Delta N}{N}\right)^2 + \left(\frac{\Delta \epsilon_\gamma}{\epsilon_\gamma}\right)^2 + \left(\frac{\Delta P_\gamma}{P_\gamma}\right)^2 + \left(\frac{\Delta T_s}{T_s}\right)^2 + \left(\frac{\Delta M}{M}\right)^2} \quad \text{(2)}$$

Where ΔA is the total uncertainty of the sample measured and ΔN,$\Delta \epsilon_\gamma$,ΔP_γ , ΔM, and ΔT_s are the uncertainties of the net count rate, efficiency, gamma emission probability, sample weight, and counting time respectively [12].

2.3.2. Radiological Impact Measurement

2.3.2.1. Absorbed Dose Rate (D)

The Absorbed dose is the amount of energy deposited by radiation per unit mass of the material being irradiated. Its SI unit is (Gy) which has units of (j/kg). Therefore, the radioactivity concentration of the radionuclides ^{232}Th, ^{226}Ra, and ^{40}K obtained from Table 1, were used to calculate the absorbed dose rate. The absorbed dose rate in air due to the ^{232}Th, ^{226}Ra, and ^{40}K radionuclides is calculated using the conversion factors (CF) in Equation (3) with assumption that, other radionuclides such as ^{137}Cs.^{90}Sr and ^{235}U, are negligible since they contribute very little to the total dose from environmental background [34, 9].

$$D = \sum_i (\mathrm{A}\, i\, X\, CFi) \quad \text{(3)}$$

Where D ,is the absorbed dose rate in nGy/h at 1m above the ground, A is the radioactivity level of radionuclide i in Bq/kg and CF is the conversion factor for radionuclide i in (nGy/h per Bq/kg). The conversion factors of external gamma dose rate for ^{232}Th, ^{226}Ra, and ^{40}K are 0.604 nGy/h per Bq/kg, 0.462 nGy/h per Bq/kg and 0.0417 nGy/h per Bq/kg respectively (UNSCEAR 2000).

2.3.2.2. Annual Effective Dose Rate (E)

The absorbed dose rate(D) does not directly indicate radiological risk; rather, the annual effective dose equivalent from outdoor terrestrial gamma radiation is used for this purpose. The annual effective dose from the absorbed dose rate was calculated using Equation (4):

$$E = D\, X\, TXFX0.2 \quad \text{(4)}$$

Where E, is the annual effective dose rate in mSv/yr, D is the absorbed dose rate in nSv/h, T is the time conversion factor (hours in a year) 8760/year and F is the conversion coefficient

from absorbed dose in air to effective dose for adults: 0.7 Sv/Gy. The value, 0.2 is the assumption that, people spend 20% of their time outdoors [35, 15, 32].

2.3.2.3. Radium Equivalent Activity (Ra_{eq})

The Radium Equivalent Activity (Ra_{eq}) is a single quantity used to compare the radiological hazards of materials (e.g. construction materials) containing ^{232}Th, ^{226}Ra, and ^{40}K by representing a weighted sum of their activities. It helps simplify the varying concentrations of these radionuclides in soil and provides a way to assess the total radiation risk they pose. The Ra_{eq} formula is based on the assumption that specific amounts of each radionuclide (i.e. 249 Bq/kg of ^{232}Th, 370 Bq/kg of ^{226}Ra, and4810 Bq/kg of ^{40}K) contribute equally to the gamma radiation dose, and it is used as a guideline to ensure that public exposure to natural radiation from soil remains within safe limits of 1.5mGy per year and it was calculated using Equation (5) [30].

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

Where A_{Th} ,A_{Ra} , $A_k$are the activity concentrations in Bq/kg of ^{232}Th, ^{226}Ra, and ^{40}K and Ra_{eq} is therefore a single index or number to describe the gamma output from different mixtures of radionuclides in a material.

2.3.2.4. Radiation Hazard Indices

The External Hazard Index (Hex) is a parameter used to ensure that radiation exposure from natural radionuclides in samples does not exceed the safety limit of 1 mSv·y^{-1}. If the Hex value is less than one ($H_{ex} \leq 1$) the radiation hazard is considered negligible. However, if the value exceeds one, appropriate measures must be taken to reduce exposure (UNSCEAR 2000). The External Hazard Index (Hex) was calculated using Equation (6):

$$H_{ex} = \frac{1}{185}A_{Ra} + \frac{1}{256}A_{Th} + \frac{1}{4810}A_k \quad (6)$$

Radon and its short-lived products are also hazardous to the internal organs. So internal exposure to radon and its short-lived products is quantified by internal hazard index. The Internal Hazard Index (H_{in}) was calculated using Equation (7):

$$H_{in} = \frac{1}{185}A_{Ra} + \frac{1}{256}A_{Th} + \frac{1}{4810}A_k \quad \text{(7)}$$

If the value of ($H_{in} \leq 1$) is less than one, then the radiation hazard is negligible. Otherwise if the value exceeds one, appropriate measures must be taken to reduce exposure.

3. RESULTS AND DISCUSSIONS

3.1. Radioactivity Concentration

The activity concentration(Bq/kg) of ^{232}Th, ^{226}Ra, and ^{40}K in the soil and rock samples collected from the Closed Golden Pride Gold Mine have been determined by gamma-ray spectrometry with HPGe detector to estimates the radioactivity level and radiological impact to public. During computation (Equation 1), the radioactivity concentration (Bq/kg) for ^{232}Th, ^{226}Ra, and ^{40}K and their corresponding mean concentration values were first determined and the results are shown in Table 2.

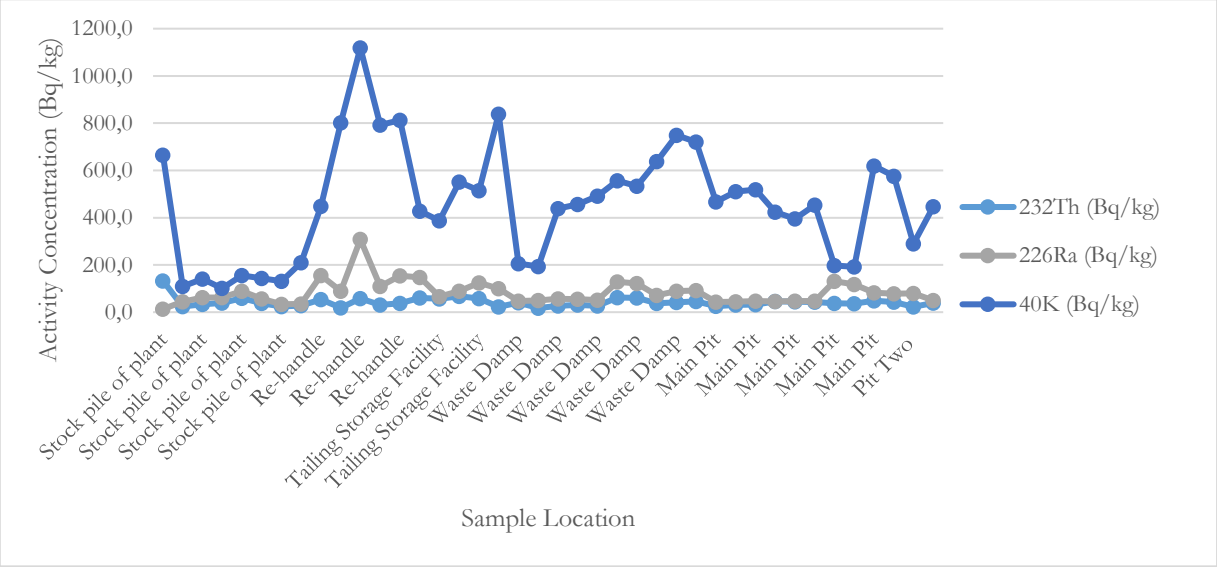
Table 2. Radioactivity Concentration of ^{232}Th, ^{226}Ra, and ^{40}K in the Soil Samples.

Sample ID	Sample Location	Longitudes	Latitude	^{232}Th (Bq/kg)	^{226}Ra (Bq/kg)	^{40}K (Bq/kg)
1A	Stock pile of plant	S 04 04 15.5	E 33 11 56.9	133±13	13.1±1.6	665±62
1B	Stock pile of plant	S 04 04 15.5	E 33 11 54.2	23.6±2.3	44.2±4.2	110±12
2A	Stock pile of plant	S 04 04 15.6	E 33 11 53.6	33.2±3.8	62.4±6.0	141±15
2B	Stock pile of plant	S 04 04 15.4	E 33 11 52.7	38.5±3.9	62.5±6.2	101±15
2C	Stock pile of plant	S 04 04 15.8	E 33 11 50.1	59.3±5.6	89.1±8.4	155±19
3A	Stock pile of plant	S 04 04 15.5	E 33 11 55.8	37.5±3.8	56.5±5.4	143±15
3B	Stock pile of plant	S 04 04 16.2	E 33 11 56.6	23.8±2.5	34.1±3.8	131±17
3C	Stock pile of plant	S 04 04 16.3	E 33 11 52.6	27.8±3.4	35.5±3.5	210±21
4A	Re-handle	S 04 04 26.1	E 33 12 04.8	53.9±5.0	155±14	448±42
4B	Re-handle	S 04 04 26.1	E 33 12 05.2	18.9±2.3	88.6±8.4	802±77
5A	Re-handle	S 04 04 26.9	E 33 12 06.7	58.4±5.6	308±28	1,119±103

Sample ID	Sample Location	Longitudes	Latitude	^{232}Th (Bq/kg)	^{226}Ra (Bq/kg)	^{40}K (Bq/kg)
5B	Re-handle	S 04 04 28.7	E 33 12 04.9	30.9±3.2	109±10	793±75
5C	Re-handle	S 04 04 30.1	E 33 12 04.2	37.7±4.3	154±15	813±83
7A	Re-handle	S 04 04 28.6	E 33 12 01.7	61.1±5.9	148±14	428±44
8A	Tailing Storage Facility	S 04 04 23.7	E 33 11 21.9	56.2±5.5	65.9±6.7	387±40
9A	Tailing Storage Facility	S 04 04 27.1	E 33 11 20.4	67.9±8.8	88.7±8.7	551±55
9B	Tailing Storage Facility	S 04 04 39.9	E 33 11 16.4	57.5±5.4	125±12	515±49
9C	Tailing Storage Facility	S 04 04 35.2	E 33 11 32.9	22.6±2.4	99.8±9.2	838±78
10A	Waste Damp	S 04 04 42.8	E 33 11 53.2	41.0±4.1	47.7±4.8	205±23
10B	Waste Damp	S 04 04 50.3	E 33 11 51.6	17.4±2.4	49.4±4.7	193±18
11A	Waste Damp	S 04 04 40.5	E 33 11 45.7	27.0±2.6	56.0±5.1	439±40
11B	Waste Damp	S 04 04 41.5	E 33 11 45.7	31.1±5.4	55.8±5.4	456±46
11C	Waste Damp	S 04 04 43.3	E 33 11 47.7	26.2±2.6	51.8±4.9	492±46
12A	Waste Damp	S 04 04 38.6	E 33 11 46.7	61.5±5.8	128±12	557±53
12B	Waste Damp	S 04 04 38.6	E 33 11 42.2	61.1±6.8	121±11	534±50
13A	Waste Damp	S 04 04 45.5	E 33 11 40.6	38.3±3.8	71.4±6.6	638±62
13B	Waste Damp	S 04 04 49.1	E 33 11 40.0	41.2±4.0	88.7±8.3	749±70
13C	Waste Damp	S 04 04 52.4	E 33 11 41.1	45.3±4.8	91.3±9.0	720±73
14A	Main Pit	S 04 04 57.7	E 33 11 41.0	26.1±2.6	43.7±4.3	467±44
14B	Main Pit	S 04 05 06.1	E 33 11 43.4	30.8±3.0	43.8±4.2	511±48
14C	Main Pit	S 04 05 07.5	E 33 11 43.2	31.9±3.7	47.2±4.4	519±48
15A	Main Pit	S 04 05 16.2	E 33 11 50.6	46.4±4.4	45.1±4.5	424±41
15B	Main Pit	S 04 05 18.9	E 33 11 50.7	44.7±4.4	47.2±4.7	395±41
15C	Main Pit	S 04 05 15.3	E 33 11 50.3	43.1±4.3	46.8±4.5	453±45
16A	Main Pit	S 04 05 11.7	E 33 12 13.5	37.6±4.3	131±13	197±21
16B	Main Pit	S 04 05 20.5	E 33 12 08.7	36.2±3.6	118±11	192±22
17A	Main Pit	S 04 05 11.1	E 33 12 14.3	48.6±4.6	82.5±7.7	619±58
17B	Main Pit	S 04 05 10.7	E 33 12 18.3	43.6±4.3	77.9±7.4	576±56
17C	Pit Two	S 04 05 07.3	E 33 12 04.4	22.7±2.3	79.9±7.5	290±28
18B	Pit Two	S 04 05 21.5	E 33 12 23.8	38.7±3.7	50.0±4.8	447±43
	Mean			**42.1±4.4**	**82.8±7.9**	**461±45**
	UNSCEAR			**30**	**35**	**400**

As seen in Table 2, the activity concentration of each radionuclide ^{232}Th, ^{226}Ra, and ^{40}K and their corresponding mean values were obtained. The activity concentration of ^{40}K were observed to be higher than that of ^{232}Th and ^{226}Ra and are higher for the Re-handle location than other analyzed locations. Figure 2 shows the distribution of the ^{232}Th, ^{226}Ra, and ^{40}K in the soil samples and their corresponding locations.

Figure 2. Radioactivity Concentration for ^{232}Th, ^{226}Ra, and ^{40}K in the Soil Samples.



Activity concentration of ^{40}K were observed to be higher than that of ^{232}Th and ^{226}Ra because of the geology of the material at re-handle area. Its geology is characterized by Archaean greenstone belt geology, with gold mineralization hosted in mafic volcanic rocks and sedimentary units within shear zones and fault zones [21]. The higher radioactivity are associated with igneous rock such as granite and lower radioactivity are associated with sedimentary rocks which is sometimes not always true as some shales and phosphate rocks have high concentration of radionuclides [34]. The results shows that the activity levels of ^{40}K radionuclides range from 101±15 to 1,119±103 Bq/kg, with a mean value of 461±45 Bq/kg. The activity levels of ^{232}Th radionuclides range from 17.4±2.4 to 133±13 Bq/kg, with a mean value of 42.1±4.4 Bq/kg, and the activity levels of ^{226}Ra radionuclides range from 13.1±1.6 to 308±28 Bq/kg, with an average value of 82.8±7.9 Bq/kg. These findings indicate that the mean activity concentration of ^{232}Th, ^{226}Ra, and ^{40}K exceeded the recommended mean values of 30, 35, and 400 Bq/kg for ^{232}Th, ^{226}Ra, and ^{40}K respectively, this indicates that the closed mine site has higher activity level due to mining activities [35]. The results show that the average values of activity concentration of ^{232}Th, ^{226}Ra and ^{40}K do not exceed 1,000 Bq/kg for the ^{238}U and ^{232}Th series and 10,000Bq/kg for ^{40}K and, therefore, are not considered subject to regulatory control [13].

3.2. Radiological Risk

The activity concentration (Bq/kg) of radionuclides ^{232}Th, ^{226}Ra, and ^{40}K were then used to compute (Equation 3) the absorbed dose rate of the three radionuclides (^{232}Th, ^{226}Ra, and ^{40}K) as shown in Table 3 Column 2.

3.2.1. Absorbed Dose Rate(D)

The average absorbed dose rate calculated as seen in Table 3 was 82.9nGy/h which is above the world average of 60 nGy/h [36]. This suggests a greater potential exposure to radiation for public and the environment, specifically in Re-handle, Waste dump, and some parts of Stock pile.

3.2.2. Annual Effective Dose Equivalent(E)

The annual effective dose rate was then calculated (Equation 4) and the results are shown in Table 3, Column 3. The calculated annual effective dose rate were compared with the ICRP recommended annual effective dose of 1.0 mSv/Year. The results shows that the annual effective dose range between 0.2 to 1.4 mSv/Year, with mean annual effective dose of 0.5 mSv/Year below the ICRP recommended limit of 1.0 mSv/Year. However the annual effective dose of 1.4 mSv/Year at Re-handle was above the ICRP recommendation.

Moreover, Radium Equivalent Activity (Ra_{eq}), External Hazard Index (Hex) and Internal Hazard Index (H_{in}) were computed using Equations 5, 6 and 7 and results in Table 3.

3.2.3. Radium Equivalent Activity (Ra_{eq})

The Ra_{eq} within the study area is presented in Table 3, where Column 3 indicates that, the range between 78.2 to 477.7 Bq/kg. The soil at Re-handle which is measuring 477.7 Bq/kg, exceeds the suggested maximum permissible value of 350 Bq/kg, making this material unsuitable for construction [35].

3.2.4. Radiation Hazard Indices

The estimated average values of Hex (0.4) and Hin (0.7) in the study area were both below 1, which is the desirable limit [35]. This indicates that, the materials in the mining site can be used as building materials except the materials from the Re-handle which exceed 1, (Figure 3).

Table 3. Absorbed Dose Rate (D),The annual effective dose rate (E) Radium Equivalent Activity (Raeq), External Hazard Index (Hex) and Internal Hazard Index (Hin)

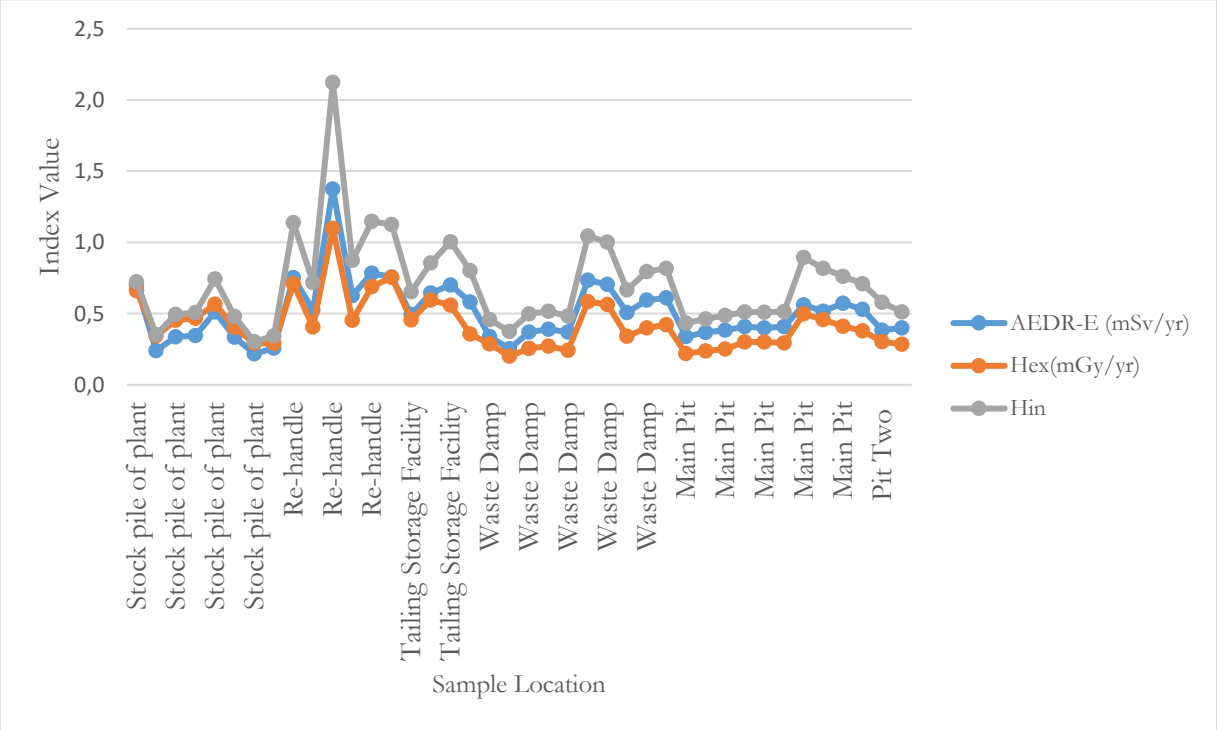
Sample Location+A1:F26	Absorbed Dose Rate-D (nGy/hr)	AEDR-E (mSv/yr)	Raeq (Bq/kg)	Hex(mGy/yr)	Hin
Stock pile of plant	114.1	0.7	254.5	0.7	0.7
Stock pile of plant	39.2	0.2	86.4	0.3	0.4
Stock pile of plant	54.8	0.3	120.7	0.5	0.5
Stock pile of plant	56.3	0.3	125.3	0.5	0.5
Stock pile of plant	83.4	0.5	185.8	0.6	0.7
Stock pile of plant	54.7	0.3	121.1	0.4	0.5
Stock pile of plant	35.6	0.2	78.2	0.3	0.3
Stock pile of plant	42.0	0.3	91.4	0.3	0.3
Re-handle	122.7	0.8	266.6	0.7	1.1
Re-handle	85.8	0.5	177.4	0.4	0.7
Re-handle	224.4	1.4	477.7	1.1	2.1
Re-handle	102.1	0.6	214.2	0.5	0.9
Re-handle	127.7	0.8	270.5	0.7	1.1
Re-handle	123.3	0.8	268.3	0.8	1.1
Tailing Storage Facility	80.5	0.5	176.1	0.5	0.7
Tailing Storage Facility	105.0	0.6	228.2	0.6	0.9
Tailing Storage Facility	114.2	0.7	246.9	0.6	1.0
Tailing Storage Facility	94.7	0.6	196.6	0.4	0.8
Waste Damp	55.3	0.3	122.1	0.3	0.5
Waste Damp	41.4	0.3	89.1	0.2	0.4

Sample Location+A1:F26	Absorbed Dose Rate-D (nGy/hr)	AEDR-E (mSv/yr)	Raeq (Bq/kg)	Hex(mGy/yr)	Hin
Waste Damp	60.5	0.4	128.4	0.3	0.5
Waste Damp	63.5	0.4	135.4	0.3	0.5
Waste Damp	60.3	0.4	127.2	0.2	0.5
Waste Damp	119.7	0.7	258.8	0.6	1.0
Waste Damp	114.9	0.7	249.5	0.6	1.0
Waste Damp	82.7	0.5	175.3	0.3	0.7
Waste Damp	97.1	0.6	205.3	0.4	0.8
Waste Damp	99.5	0.6	211.5	0.4	0.8
Main Pit	55.4	0.3	117.0	0.2	0.4
Main Pit	60.1	0.4	127.2	0.2	0.5
Main Pit	62.7	0.4	132.8	0.3	0.5
Main Pit	66.5	0.4	144.1	0.3	0.5
Main Pit	65.3	0.4	141.5	0.3	0.5
Main Pit	66.5	0.4	143.3	0.3	0.5
Main Pit	91.7	0.6	199.9	0.5	0.9
Main Pit	84.3	0.5	184.6	0.5	0.8
Main Pit	93.3	0.6	199.7	0.4	0.8
Main Pit	86.3	0.5	184.6	0.4	0.7
Pit Two	62.7	0.4	134.7	0.3	0.6
Pit Two	65.1	0.4	139.8	0.3	0.5
Mean	**82.9**	**0.5**	**178.4**	**0.4**	**0.7**

Generally, these results indicated that there are elevated levels of radiation exposure from Re-handle area, exceeding the ICRP recommended limits. It is then important to take appropriate measures to mitigate these exposures and ensure that radiation levels are within safe limits for human health. These measures includes soil remediation using techniques such

as soil washing, excavation and stabilization to reduce the activity level. Moreover, monitoring programs in this area are required.

Figure 3. Radium Equivalent Activity (Raeq), External Hazard Index (Hex) and Internal Hazard Index (Hin) from the study area.



The Table 3, shows the annual effective dose for sample at Re-Handle location from the soil, exceeding the ICRP recommended limits. Exceeding permissible levels in soil poses significant environmental and public health risks [2, 3].

Figure 3 shows, Radium Equivalent Activity (Raeq), External Hazard Index (Hex) and Internal Hazard Index (Hin) from the Re-Handle area to be above the limit of 1 [35]. The study recommends continued monitoring of radiation levels in the area to ensure they remain within safe limits.

4. CONCLUSIONS

This study was conducted at the Golden Pride Project closed open pit gold mine located in Nzega, Tanzania, to evaluate the activity concentration of ^{232}Th, ^{226}Ra, and ^{40}K in the soil and rock samples. The radioactivity evaluation was performed using gamma spectrometry with HPGe detector and the radiological impact was calculated using dose conversion factor. The aim is to determine the radiation exposure levels and to propose the mitigation measures from the radionuclides. Based on the results, the following conclusions can be reached.

The activity concentration levels of ^{232}Th radionuclides range from 17.4±2.4 to 133±13Bq/kg, with an average value of 42.1±4.4 Bq/kg. The activity levels of ^{226}Ra, radionuclides range from 13.1±1.6 to 308±28 Bq/kg, with an average value of 82.8±7.9 Bq/kg, and the activity levels of and ^{40}K radionuclides range from 101±15 to 1,119±103, with an average value of 461±45 Bq/kg. These findings indicate that the activity concentration of ^{232}Th, ^{226}Ra, and ^{40}K exceeded the recommended mean values of 30, 35, and 400 Bq/kg for ^{232}Th, ^{226}Ra, and ^{40}K respectively as given by the United Nations Scientific Committee on the Effects of Atomic Radiation.

The mean annual effective dose of 0.5 mSv/Year below the ICRP recommended limit of 1.0 mSv/Year. However the annual effective dose of 1.4 mSv/Year at Re-handle was above the ICRP recommendation. It is important to take appropriate measures to mitigate these exposures and ensure that radiation levels are within safe limits for human health.

It can be concluded that no risk may threat the residents around study area except for Re-handle area which we recommends continued monitoring of radiation levels in the area to ensure they remain within safe limits. Remediation techniques such as soil washing, excavation, and stabilization are proposed to reduce the activity levels of the radionuclides. Additionally, implementing a comprehensive monitoring program, restricting access, and raising awareness in the affected area are essential steps.

Furthermore, the study advocates for further investigation into the levels of radioactivity in water, vegetation, and the migration patterns of radionuclides, with a focus on assessing their impacts on nearby agricultural farms. Given that the concentrations of ^{232}Th, ^{226}Ra, and ^{40}K exceed the permissible limits of 30, 35, and 400 Bq/kg respectively, ongoing monitoring and remediation efforts, including restricted access to the area, are deemed necessary to safeguard public health and environmental integrity.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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