



Natural Radioactivity and Radiological Dose Assessment of Rocks from Mbeere South, Kenya

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Abstract

Natural radioactivity in rocks and building materials is a major contributor to outdoor gamma radiation exposure. This study determined the activity concentrations of ^{238}U (estimated via ^{226}Ra assuming secular equilibrium), ^{232}Th and ^{40}K and assessed radiological hazard indices in 30 purposively sampled rocks from Mbeere South, Embu County, Kenya using high-resolution HPGe gamma-ray spectrometry. Mean activity concentrations were $19.02 \pm 14.00 \text{ Bq}\cdot\text{kg}^{-1}$, $38.66 \pm 34.43 \text{ Bq}\cdot\text{kg}^{-1}$ and $634.88 \pm 302.94 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{238}U , ^{232}Th and ^{40}K , respectively ($^{40}\text{K} > ^{232}\text{Th} > ^{238}\text{U}$). ^{238}U was below the world average of $35 \text{ Bq}\cdot\text{kg}^{-1}$, while ^{232}Th and ^{40}K were 28.9% and 58.7% above world averages of 30 and $400 \text{ Bq}\cdot\text{kg}^{-1}$. Mean radium equivalent activity (R_{eq}), absorbed dose rate (D) and outdoor annual effective dose (AED_{out}) were $123.19 \pm 73.10 \text{ Bq}\cdot\text{kg}^{-1}$, $58.61 \pm 33.21 \text{ nGy}\cdot\text{h}^{-1}$ and $0.0719 \pm 0.0407 \text{ mSv}\cdot\text{y}^{-1}$, respectively. All R_{eq} values were below the $370 \text{ Bq}\cdot\text{kg}^{-1}$ screening limit, and mean D and AED_{out} were comparable to world averages of $59 \text{ nGy}\cdot\text{h}^{-1}$ and $0.07 \text{ mSv}\cdot\text{y}^{-1}$. These values were 53% - 91% lower than high-background areas in Kenya, Nigeria, Saudi Arabia and Brazil, and comparable to Jaintiapur, Bangladesh. The results indicate low external gamma hazard; suitability with respect to indoor radon was not assessed.

Subject Areas

Nuclear Physics

Keywords

Natural Radioactivity, Radium Equivalent, Absorbed Dose, Annual Effective Dose, Mbeere South

1. Introduction

Natural radioactivity arises from the spontaneous disintegration of unstable

atomic nuclei occurring naturally in the environment. The principal naturally occurring radionuclides contributing to terrestrial radiation are uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) [1]. These radionuclides are widely distributed in rocks, soils, water bodies, and construction materials, making them important contributors to human exposure to ionizing radiation. Their activity concentrations are strongly influenced by lithology, mineral composition, geochemical processes, and weathering history. Since these radionuclides are ubiquitous in the Earth's crust, exposure to natural radiation is unavoidable and constitutes the largest component of the radiation dose received by the general population [2].

Human exposure to natural radiation occurs through both external and internal pathways. Because rocks are widely used as construction materials, elevated concentrations of naturally occurring radionuclides may contribute to indoor external gamma exposure and internal exposure through radon inhalation. External exposure results primarily from gamma radiation emitted by radionuclides present in rocks, soils, and building materials. Internal exposure occurs when radioactive substances enter the body through inhalation, ingestion, or absorption. Among the naturally occurring radionuclides, radon (^{222}Rn), a decay product of ^{238}U , is of particular concern because it can accumulate in enclosed environments and significantly increase the risk of lung cancer. Long-term exposure to elevated levels of ionizing radiation has been associated with various adverse health effects, including genetic mutations, tissue damage, and an increased probability of cancer development [3]-[5]. Consequently, assessment of environmental radioactivity is essential for evaluating potential radiological risks to both humans and ecosystems.

Terrestrial radiation originates primarily from the decay series of uranium and thorium and from the naturally occurring isotope potassium-40. The activity concentrations of these radionuclides in geological materials are influenced by lithology, mineral composition, weathering processes, and tectonic history. Igneous rocks, particularly granites and pegmatites, generally contain elevated concentrations of uranium and thorium, while sedimentary rocks often exhibit lower activity levels. Potassium-bearing minerals, particularly K-feldspars and micas commonly contribute to elevated ^{40}K activity concentrations in crystalline rocks. Because rocks constitute the parent material from which soils and many construction materials are derived, the determination of radionuclide concentrations in rocks provides important information regarding environmental radiation exposure and the suitability of geological materials for human use [6].

Assessment of natural radioactivity in geological materials has gained increasing attention worldwide due to concerns regarding environmental safety and public health. According to United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) the worldwide average activity concentrations in rocks are approximately $35 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{238}U , $30 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{232}Th , and $400 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{40}K [7]. These reference values are widely used for evaluating the radiological

significance of measured radionuclide concentrations. In addition to activity concentrations, several radiological hazard indices, including radium equivalent activity (Ra_{eq}), absorbed dose rate (D) and annual effective dose (AED) are commonly employed to assess the potential health implications of exposure to natural radioactivity.

Numerous studies conducted in different regions of the world have demonstrated substantial variability in natural radioactivity levels. Elevated background radiation has been reported in areas such as Ramsar in Iran and Kerala in India due to the presence of uranium- and thorium-rich geological formations [8] [9]. Similar investigations have been carried out across Africa, where natural radioactivity levels are strongly influenced by local geology. Studies conducted in South Africa, Nigeria, and Angola have reported varying concentrations of naturally occurring radionuclides associated with granitic rocks, mineral deposits, and industrial activities [10]-[12]. These studies have highlighted the importance of site-specific assessments in establishing baseline radiation levels and identifying areas that may require continuous monitoring.

In Kenya, investigations of natural radioactivity have been conducted in several geological settings, including the Ruri Hills region and areas associated with mineral exploitation [13]. Elevated concentrations of thorium and uranium have been reported in some locations, emphasizing the influence of geological formations on radionuclide distribution. The increasing demand for mineral resources and construction materials further underscores the need for detailed radiological characterization of geological materials [14]. Such information is essential for environmental management, radiation protection, and sustainable utilization of natural resources.

Mbeere South Constituency, located in Embu County, Kenya, is characterized by diverse lithological formations, active quarrying with widespread use of local rocks as building materials and mineral occurrences, including coltan-bearing rocks particularly within Kiambeere Ward. Coltan deposits are frequently associated with accessory minerals containing uranium and thorium, which may contribute to elevated natural radioactivity levels. Despite the increased exploration of coltan and other mineral resources in Mbeere South, limited information is available on the activity concentrations of naturally occurring radionuclides and the associated radiological hazards in rocks from the region. Consequently, the radiological characteristics and potential health implications of these geological materials remain poorly understood, highlighting the need for a comprehensive radiological assessment.

Accordingly, this study quantified the activity concentrations of ^{238}U , ^{232}Th , and ^{40}K in rock samples collected from selected areas in Mbeere South using high-resolution HPGe gamma-ray spectrometry. In addition, radiological hazard indices were evaluated to assess potential health risks associated with exposure to natural radioactivity in the area. The findings provide baseline radiological data for Mbeere South, improve understanding of radionuclide distribution in Kenyan ge-

ological formations, and provide information useful for environmental radiation monitoring, mineral resource management, and radiation protection.

2. Materials and Methods

2.1. Study Area

The study was conducted in Mbeere South Constituency, Embu County in Kenya located between latitudes $0^{\circ}50.40'S$ and $0^{\circ}37.80'S$, and longitudes $37^{\circ}35.40'E$ and $37^{\circ}48.0'E$ occupying an area of approximately 1312 km^2 . The constituency is comprised of five wards namely, from Mwea, Makima, Mbeti South, Mavuria, and Kiambeere wards. According to the 2019 Kenya Population and Housing Census, Mbeere South had a population of 163,476 residents [15]. The constituency has a predominantly rural economy supported by agriculture, livestock keeping, trade, and natural resource exploitation including artisanal mineral extraction. The climate is largely semi-arid. Mbeere South, like much of Embu County, has a diverse geological composition that comprises the Precambrian Mozambique belt, which is part of the basement rocks dominated by gneisses, schists, granites, and pegmatites, together with localized sedimentary deposits [16] [17]. These lithological characteristics make the area suitable for investigating the distribution of naturally occurring radionuclides and evaluating associated radiological hazards. The map of the sampling sites is shown in **Figure 1** [18].

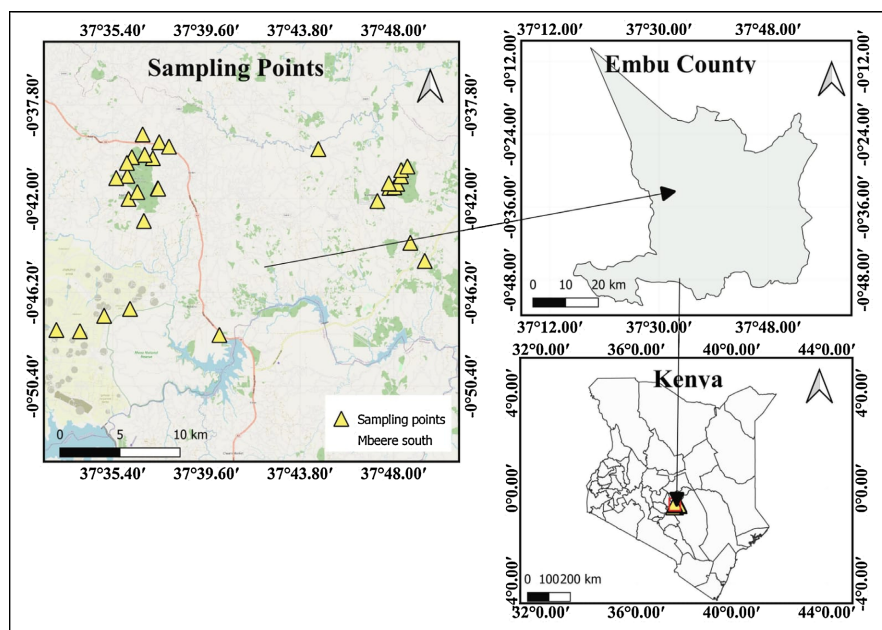


Figure 1. Location of Mbeere South and sampling sites in Embu County, Kenya.

2.2. Study Design

This study employed an experimental and observational research design to determine the activity concentrations of naturally occurring radionuclides in rock samples collected from Mbeere South, Kenya. Field investigations involved in situ ra-

diation measurements using a portable radiation survey meter, while laboratory analyses were performed using high-resolution HPGe gamma-ray spectrometry.

2.3. Sample Collection and Preparation

In-situ ambient dose rate screening was conducted at potential sites using a calibrated portable BR-9B XR1 Geiger-Müller (GM) detector (background $\sim 0.10 \mu\text{Sv}\cdot\text{h}^{-1}$). Screening was used to guide selection and ensure inclusion of a range of lithologies and exposure conditions. Sampling was purposive, not random, based on accessibility, active quarrying status, and lithological variation observed after GM screening. Thirty rock samples were purposively selected with rock samples preferentially collected from sites showing relatively elevated or representative radiation levels, as well as from different geological settings, including quarries, seasonal riverbeds, hillsides, and mineralized zones in Mbeere South. The samples were collected from the five wards as follows: four samples from Mwea, one sample from Makima, thirteen samples from Mbeti South, three samples from Mavuria, and nine samples from Kiambeere. Results are therefore limited to the sampled sites and are not extrapolated to the entire Mbeere South constituency. The geographical coordinates of each quarry were recorded using a handheld GPS.

Approximately 0.5 - 1.0 kg of fresh representative rock was collected from each selected site. The samples were immediately placed in clean, well-labelled polyethylene bags. Each sample was assigned a unique identification code (001-030) corresponding to its sampling location and carefully packaged to prevent cross-contamination and loss of material during transportation to Chuka University. At Chuka University Science Laboratory, the samples were pulverized into a fine homogeneous powder using hardened steel hammers, with cleaning between samples to avoid cross-contamination.

The pulverized powders were transported to the Institute of Nuclear Science and Technology [INST], University of Nairobi, oven-dried at 80°C for 8 h to constant mass, sieved through 1 mm mesh to obtain uniform particle size, homogenized, weighed, and packed into 500 g (500 ml) Marinelli beakers to ensure identical counting geometry. Beakers were hermetically sealed and stored for 30 days to allow ^{226}Ra and its short-lived progeny (^{214}Pb , ^{214}Bi) and ^{232}Th series to attain secular equilibrium before measurement on HPGe [19] [20].

2.4. Gamma-Ray Spectrometry

The activity concentrations of ^{226}Ra (as a proxy for ^{238}U under secular equilibrium), ^{232}Th and ^{40}K in the 30 purposively selected rock samples from Mbeere South, screened with a handheld GM counter, were determined by high-resolution gamma-ray spectrometry at the Institute of Nuclear Science and Technology (INST), University of Nairobi. The system is equipped with a p-type coaxial High Purity Germanium detector (Baltic Scientific Instruments, Latvia) model GCW-30180 housed within a cylindrical multilayer graded shield and supported by a low-background lead shield to minimize external background radiation. The de-

tector was operated at 3500 V bias, with energy resolution (FWHM) of 1.91 keV at 1332.5 keV of ^{60}Co and relative efficiency 27.8% [21].

To attain secular equilibrium between ^{226}Ra and its short-lived progeny, and between ^{232}Th and its daughters, sealed 500 ml Marinelli beakers containing 500 g of pulverized rock were stored for 30 days prior to counting. Each sample was counted for 36,000 s.

Energy and efficiency calibrations were carried out using certified mixed radionuclide standard BB-3591 covering 60 - 3500 keV containing ^{137}Cs , ^{241}Am , ^{60}Co , ^{88}Y , ^{57}Co , ^{113}Sn and ^{139}Ce , traceable to international standards. Spectral acquisition was via SpectraLine-GP software. Background correction was performed by counting an empty Marinelli beaker filled with deionized water under identical geometry for 12 h and subtracting the background spectrum.

^{232}Th was evaluated from weighted mean of ^{212}Pb (238.6 keV) and ^{228}Ac (911.1 keV), ^{226}Ra (proxy for ^{238}U) from ^{214}Pb (351.9 keV) and ^{214}Bi (609.3 keV), and ^{40}K directly from 1460.8 keV [22].

Quality assurance was confirmed by concurrent analysis of Certified Reference Material IAEA-447 Natural and Anthropogenic Radionuclides in Moss-Soil with certified values: $25.1 \pm 2.0 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{226}Ra , $22.2 \pm 0.8 \text{ Bq}\cdot\text{kg}^{-1}$ ^{238}U , $21.8 \pm 0.8 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{234}U , with information $550 \pm 18 \text{ Bq}\cdot\text{kg}^{-1}$ for values ^{40}K , $37.3 \pm 2.0 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{232}Th , $37.3 \pm 1.5 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{212}Pb , $37.3 \pm 2.0 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{228}Ac . Measured vs certified recoveries were 96.2% for ^{238}U (as ^{226}Ra), 98.5% for ^{232}Th and 102.3% for ^{40}K within acceptance 90% - 110%.

The Minimum Detectable Activity (MDA) was $1.18 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{238}U (as ^{226}Ra), $0.85 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{232}Th , $12.4 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{40}K . Uncertainties combined counting statistics and calibration, reported as $\pm 1\sigma$. Assessment is external gamma screening only; radon exhalation was not assessed.

3. Data Analysis and Radiological Hazard Assessment

Activity concentrations were calculated using Spectraline GP (GCW-30180) software based on net peak areas corrected for efficiency and background. The activity concentration (A) of each radionuclide in $\text{Bq}\cdot\text{kg}^{-1}$ in the studied samples was computed using Equation (1) [19].

$$A = \frac{\text{cps} \times 1000}{\varepsilon_{\gamma} \times I_{\gamma} \times m} \quad (1)$$

where A represents activity concentration of the sample in $\text{Bq}\cdot\text{kg}^{-1}$, cps is the net counts per second (sample count rate minus background count rate), ε_{γ} is the counting efficiency of the gamma energy, I_{γ} stands for absolute intensity of the gamma ray and m is the sample's net mass in grams.

To evaluate the potential health risks associated with natural radioactivity in rocks, several radiological hazard indices were calculated.

3.1. Calculation of Radium Equivalent Activity Concentration

The radium equivalent activity (Ra_{eq}) was calculated to assess the combined radi-

ological hazard arising from ^{226}Ra , ^{232}Th and ^{40}K . The activity concentration of ^{226}Ra was assumed to be equal to that of ^{238}U under secular equilibrium. It was determined using Equation (2) [20] [21].

$$\text{Ra}_{\text{eq}} = C_{\text{Ra}} + 1.43C_{\text{Th}} + 0.077C_{\text{K}} \quad (2)$$

where C_{Ra} , C_{Th} , and C_{K} are the activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K in $\text{Bq}\cdot\text{kg}^{-1}$ respectively. The recommended safety limit of Ra_{eq} is $370 \text{ Bq}\cdot\text{kg}^{-1}$ [7].

3.2. Absorbed Dose Rate

The absorbed dose rate (D) in air was calculated from the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K to assess external gamma radiation exposure from the rock samples, assuming secular equilibrium between ^{238}U and ^{226}Ra following 30 days of sample storage. It was determined using the Equation (3) [23].

$$D = 0.462C_{\text{Ra}} + 0.604C_{\text{Th}} + 0.0417C_{\text{K}} \quad (3)$$

where C_{Ra} , C_{Th} and C_{K} are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in $\text{Bq}\cdot\text{kg}^{-1}$ respectively. The worldwide average outdoor absorbed dose rate is approximately $59 \text{ nGy}\cdot\text{h}^{-1}$, and values significantly higher than this may indicate elevated natural background radiation levels [7].

3.3. Outdoor Annual Effective Dose

The outdoor annual effective dose (AED_{out}) was estimated to evaluate the potential radiological health risk to members of the public from external gamma radiation emitted by natural radionuclides in the samples. The absorbed dose rate in air was converted to outdoor annual effective dose using the Equation (4) [24].

$$\text{AED}_{\text{out}} = D \times \text{DCF} \times T \times O_f \times 10^{-6} \quad (4)$$

where AED_{out} is the outdoor annual effective dose, D is the absorbed dose rate calculated in Equation 3, According to UNSCEAR 2000, the DCF (dose conversion factor) and O_f (outdoor occupancy factor) values are 0.7 Sv/Gy and 0.2 , respectively, T is the time factor ($8760 \text{ hours per year}$). An outdoor occupancy factor, $O_f = 0.2$ was adopted in accordance with UNSCEAR recommendations, assuming that humans spend 20% of their time outdoors. The annual effective dose equivalent should not exceed $1 \text{ mSv}\cdot\text{y}^{-1}$ for safety purposes [7]. Values exceeding this level may indicate increased radiological exposure to the population and thus require further assessment. All radiological hazard indices were evaluated against internationally recommended reference limits to assess the suitability of the investigated rocks for use as building materials.

4. Results and Discussion

4.1. Activity Concentrations

The activity concentrations of the primordial radionuclides ^{238}U , ^{232}Th and ^{40}K in 30 rock samples from selected sites in Mbeere South are presented in **Table 1** while the variations in the concentrations of the naturally occurring radionuclides

Table 1. Activity concentrations of ^{238}U , ^{232}Th and ^{40}K in rock samples.

Sample ID	Latitude	Longitude	^{238}U (Bq·kg ⁻¹)	^{232}Th (Bq·kg ⁻¹)	^{40}K (Bq·kg ⁻¹)
001	-0.683410	37.809611	27.87 ± 2.53	38.65 ± 3.33	407.21 ± 28.17
002	-0.746494	37.823190	14.07 ± 1.98	24.06 ± 2.61	852.03 ± 39.96
003	-0.732929	37.812444	19.92 ± 2.24	48.09 ± 3.69	422.98 ± 28.83
004	-0.691957	37.796815	4.84 ± 1.17	6.42 ± 1.50	296.55 ± 24.57
005	-0.691508	37.800468	52.68 ± 3.67	57.91 ± 4.60	820.29 ± 40.62
006	-0.688825	37.802630	18.52 ± 2.25	37.21 ± 3.37	76.63 ± 13.43
007	-0.666667	37.805426	12.40 ± 1.86	15.63 ± 2.33	681.62 ± 38.00
008	-0.678616	37.805580	7.70 ± 1.48	9.63 ± 1.79	269.70 ± 24.57
009	-0.675346	37.810277	7.10 ± 1.36	6.64 ± 1.63	436.33 ± 29.15
010	-0.688524	37.796317	54.59 ± 3.87	100.30 ± 5.72	684.59 ± 38.65
011	-0.701725	37.788025	14.48 ± 2.14	55.98 ± 4.21	902.14 ± 43.57
012	-0.801840	37.669708	28.47 ± 2.93	55.16 ± 4.27	335.39 ± 27.84
013	-0.782357	37.602883	16.70 ± 2.19	28.83 ± 3.07	548.59 ± 35.38
014	-0.787470	37.583526	35.92 ± 2.78	122.14 ± 5.61	293.53 ± 90.41
015	-0.799020	37.565421	31.47 ± 3.31	107.58 ± 6.04	1023.07 ± 46.19
016	-0.798059	37.547962	5.60 ± 1.21	6.12 ± 1.47	332.44 ± 24.90
017	-0.716620	37.613240	23.30 ± 2.54	32.12 ± 3.14	873.27 ± 43.90
018	-0.700159	37.601768	28.18 ± 2.77	67.63 ± 4.92	1223.44 ± 50.12
019	-0.695018	37.608379	40.93 ± 3.17	21.50 ± 2.52	743.63 ± 37.34
020	-0.692195	37.623628	8.54 ± 1.34	7.23 ± 1.53	510.66 ± 30.14
021	-0.692448	37.623909	18.61 ± 2.37	74.80 ± 4.59	986.31 ± 43.90
022	-0.666667	37.619957	6.27 ± 1.31	7.94 ± 1.65	790.10 ± 38.33
023	-0.657807	37.624699	3.91 ± 1.32	5.34 ± 1.61	474.15 ± 34.72
024	-0.667197	37.613844	3.81 ± 1.27	5.12 ± 1.63	432.94 ± 34.40
025	-0.669098	37.604252	4.18 ± 1.21	5.63 ± 1.66	485.69 ± 32.43
026	-0.682896	37.600908	26.11 ± 2.90	76.37 ± 5.29	1138.68 ± 49.79
027	-0.684563	37.592560	16.64 ± 2.43	27.10 ± 2.61	1057.67 ± 47.83
028	-0.672974	37.633876	10.60 ± 1.85	18.56 ± 2.63	453.37 ± 31.78
029	-0.661122	37.692005	23.83 ± 2.67	85.32 ± 5.13	1058.88 ± 46.84
030	-0.657562	37.612309	3.23 ± 1.13	4.82 ± 1.58	434.43 ± 33.74
MEAN ± SD			19.02 ± 14.00	38.66 ± 34.43	634.88 ± 302.94
WORLD AVERAGE			35	30	400

are represented graphically as shown in **Figure 2**. The values ranged from 3.23 ± 1.13 to 54.59 ± 3.87 Bq·kg⁻¹ for ²³⁸U, 4.82 ± 1.58 to 122.14 ± 5.61 Bq·kg⁻¹ for ²³²Th and 76.63 ± 13.43 to 1223.44 ± 50.12 Bq·kg⁻¹ for ⁴⁰K. The mean activity concentrations were 19.02 ± 14.00 Bq·kg⁻¹ for ²³⁸U, 38.66 ± 34.43 Bq·kg⁻¹ for ²³²Th and 634.88 ± 302.94 Bq·kg⁻¹ for ⁴⁰K.

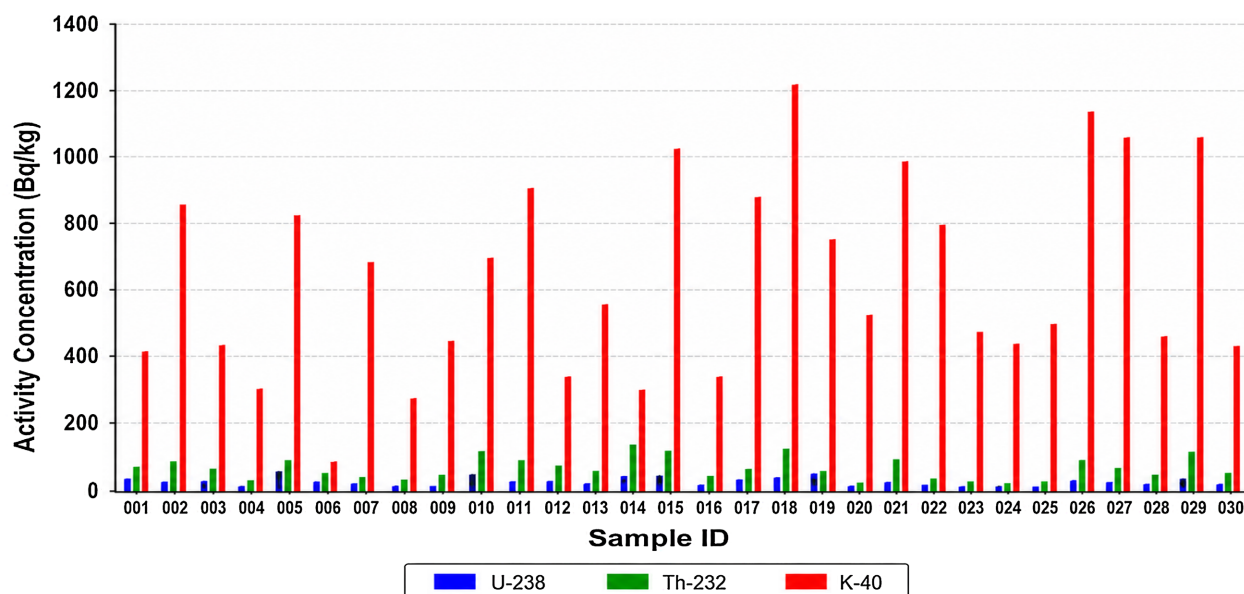


Figure 2. Activity concentrations of U-238, Th-232 and K-40 in the investigated samples.

The mean of ²³⁸U was 45.7% below the world average of 35 Bq·kg⁻¹ for rocks [UNSCEAR 2000]. Only 3 samples (005, 010, and 019) exceeded the world average, indicating generally low uranium content in Mbeere South basement. The relatively high value at 010 (54.59 Bq·kg⁻¹) may be consistent with localized enrichment in felsic intrusives, as uranium tends to concentrate in late-stage magmatic differentiates. These are presented as hypotheses based on regional geology.

The mean of ²³²Th was 28.9% above the world average of 30 Bq·kg⁻¹, indicating a slight thorium enrichment in the study area. The large standard deviation (SD) (34.43) shows high heterogeneity. Elevated values > 70 Bq·kg⁻¹ at 010 (100.30 Bq·kg⁻¹), 014 (122.14 Bq·kg⁻¹), 015 (107.58 Bq·kg⁻¹), 021 (74.80 Bq·kg⁻¹), 026 (76.37 Bq·kg⁻¹) and 029 (85.32 Bq·kg⁻¹) are hypothetically consistent with the reported occurrence of accessory minerals such as monazite and zircon in gneissic rocks of the Mozambique Belt. Thorium is immobile and concentrates in resistate minerals, which could explain these hotspots. Samples with <10 Bq·kg⁻¹ (004, 008, 009, 016, 020, 022, 025 and 030) may reflect quartzitic lithologies depleted in heavy minerals.

The mean of ⁴⁰K was 58.7% above the world average of 400 Bq·kg⁻¹. Potassium is the dominant contributor to total activity in Mbeere South. 70% of samples exceeded 400 Bq·kg⁻¹. The highest values at 018 (1223.44 Bq·kg⁻¹), 026 (1138.68 Bq·kg⁻¹), 029 (1058.88 Bq·kg⁻¹), 027 (1057.67 Bq·kg⁻¹), 015 (1023.07 Bq·kg⁻¹) and 021 (986.31 Bq·kg⁻¹) are consistent with K-feldspar-rich lithologies such as gra-

nitic gneisses and pegmatites, which are commonly mapped in Mbeere South. The very low value at 006 ($76.63 \text{ Bq}\cdot\text{kg}^{-1}$) suggests a mafic enclave or quartz vein. Again, these lithological links are hypothetical and based on the geology of the Embu area [17].

The order of mean activity is $^{40}\text{K} > ^{232}\text{Th} > ^{238}\text{U}$, which is typical for crustal rocks where potassium is a major rock-forming element. The low $^{238}\text{U}/^{232}\text{Th}$ ratio (mean 0.49) suggests thorium preferential enrichment, a common feature in weathered basement terrains. The mean activity concentrations obtained in this study were compared with mean activity concentrations from other regions of the world as shown in Table 2.

Table 2. Comparison of mean activity concentrations of ^{238}U , ^{232}Th and ^{40}K in rocks from Mbeere South with selected studies from other regions.

Region/Country	^{238}U ($\text{Bq}\cdot\text{kg}^{-1}$)	^{232}Th ($\text{Bq}\cdot\text{kg}^{-1}$)	^{40}K ($\text{Bq}\cdot\text{kg}^{-1}$)	References
Mbeere South, Kenya	19.02 ± 14.00	38.66 ± 34.43	634.88 ± 302.94	This study
Kerio Valley, Kenya	94.47 ± 31	65.0 ± 23	1003.9 ± 217	[25]
Northern Uganda	57.1 ± 5.4	122.3 ± 11.2	914.2 ± 30.2	[26]
Oyo, Nigeria	355.95 ± 3.91	709.17 ± 13.94	1102.02 ± 22.05	[27]
Anka, Nigeria	63.29 ± 13.87	226.67 ± 28.05	832.59 ± 241.53	[28]
Aja, Saudi Arabia	103.80 ± 78.96	477.2 ± 354.7	780.6 ± 570.5	[29]
Jaintiapur, Bangladesh	25 ± 2	37 ± 4	884 ± 41	[30]
San Paulo, Brazil	72.87 ± 71.65	113.42 ± 102.88	1127.54 ± 329.46	[31]
World Average	35	30	400	[7]

The mean activity concentration of ^{238}U was 79.9% lower than Kerio Valley. Kerio Valley is underlain by alkaline syenites and granites with zircon and apatite that concentrate uranium. Mbeere South, though also in the Mozambique Belt, is dominated at sampled sites by quartzo-feldspathic migmatites where uranium U has been depleted by weathering and leaching, explaining the low values in samples 024 ($3.81 \text{ Bq}\cdot\text{kg}^{-1}$) and 030 ($3.23 \text{ Bq}\cdot\text{kg}^{-1}$). It is 66.7% lower than Northern Uganda $57.1 \pm 5.4 \text{ Bq}\cdot\text{kg}^{-1}$, 94.7% lower than Oyo, Nigeria $355.95 \pm 3.91 \text{ Bq}\cdot\text{kg}^{-1}$, 70.0% lower than Anka, Nigeria $63.29 \pm 13.87 \text{ Bq}\cdot\text{kg}^{-1}$, and 81.7% lower than Aja, Saudi Arabia $103.80 \pm 78.96 \text{ Bq}\cdot\text{kg}^{-1}$. Oyo and Aja are documented High Natural Background Radiation Areas developed on uraniferous charnockites and peraluminous granites respectively [27] [29]. The fact that Mbeere South is 70% - 95% lower confirms the absence of such highly differentiated U-rich granites in the sampled sites.

The only comparable value is Jaintiapur, Bangladesh $25 \pm 2 \text{ Bq}\cdot\text{kg}^{-1}$. Mbeere South is 23.9% lower than Jaintiapur, while Jaintiapur is only 31.4% higher than Mbeere. Jaintiapur is a sedimentary basin with sandstones and shales [30]. The similarity suggests Mbeere South accessible outcrops behave radiologically more like a low-U sedimentary terrain than a typical Kenyan basement granite. It is 73.9% lower than San Paulo, Brazil $72.87 \pm 71.65 \text{ Bq}\cdot\text{kg}^{-1}$, which is developed on

alkaline intrusives [31].

The mean activity concentration of ^{232}Th is 40.5% lower than Kerio Valley $65.0 \pm 23 \text{ Bq}\cdot\text{kg}^{-1}$, 68.4% lower than Northern Uganda $122.3 \pm 11.2 \text{ Bq}\cdot\text{kg}^{-1}$, 94.6% lower than Oyo $709.17 \pm 13.94 \text{ Bq}\cdot\text{kg}^{-1}$, 82.9% lower than Anka $226.67 \pm 28.05 \text{ Bq}\cdot\text{kg}^{-1}$, and 91.9% lower than Aja $477.2 \pm 354.7 \text{ Bq}\cdot\text{kg}^{-1}$. The extremely high Th in Oyo, Anka and Aja is attributed to monazite and thorite-bearing granites [27]-[29]. The 82% - 94% lower values in Mbeere South suggest limited monazite content in the sampled gneisses.

Importantly, Mbeere South is 4.5% higher than Jaintiapur $37 \pm 4 \text{ Bq}\cdot\text{kg}^{-1}$ and essentially comparable to it. Jaintiapur is 4.3% lower than Mbeere. This again groups Mbeere South with low-Th sedimentary terrains. It is 65.9% lower than San Paulo $113.42 \pm 102.88 \text{ Bq}\cdot\text{kg}^{-1}$. The large SD in Mbeere (± 34.43) is due to two high samples 014 ($122.14 \text{ Bq}\cdot\text{kg}^{-1}$) and 015 ($107.58 \text{ Bq}\cdot\text{kg}^{-1}$) which hypothetically reflect local concentration of resistate Th-bearing minerals like zircon, versus low samples 030 ($4.82 \text{ Bq}\cdot\text{kg}^{-1}$) and 023 $5.34 \text{ Bq}\cdot\text{kg}^{-1}$ in quartz veins.

The mean activity concentration of ^{40}K is 36.8% lower than Kerio $1003.9 \pm 217 \text{ Bq}\cdot\text{kg}^{-1}$, 30.6% lower than Northern Uganda $914.2 \pm 30.2 \text{ Bq}\cdot\text{kg}^{-1}$, 42.4% lower than Oyo $1102.02 \pm 22.05 \text{ Bq}\cdot\text{kg}^{-1}$, 23.8% lower than Anka $832.59 \pm 241.53 \text{ Bq}\cdot\text{kg}^{-1}$, 18.7% lower than Aja $780.6 \pm 570.5 \text{ Bq}\cdot\text{kg}^{-1}$, 28.2% lower than Jaintiapur $884 \pm 41 \text{ Bq}\cdot\text{kg}^{-1}$ and 43.7% lower than San Paulo $1127.54 \pm 329.46 \text{ Bq}\cdot\text{kg}^{-1}$.

Although elevated versus world average, Mbeere K is 18% - 43% lower than the compared basement areas. The elevation is hypothetically attributed to K-feldspar and microcline in the Mozambique Belt gneisses, observed as very high values in 018 ($1223.44 \text{ Bq}\cdot\text{kg}^{-1}$), 026 ($1138.68 \text{ Bq}\cdot\text{kg}^{-1}$) and 015 ($1023.07 \text{ Bq}\cdot\text{kg}^{-1}$). The low value 006 ($76.63 \text{ Bq}\cdot\text{kg}^{-1}$) likely represents a mafic band. High K is common in basement terrains and contributes less to dose than U and Th due to its lower dose conversion factor.

4.2. Radiological Hazard Indices

The radiological hazard indices calculated from activity concentrations are presented in Table 3 while the variations in the radium equivalent activity, absorbed dose rate and annual effective dose values among the investigated sample are represented graphically in Figure 3. Radium equivalent activity (R_{eq}) ranged from 36.85 - 264.09 $\text{Bq}\cdot\text{kg}^{-1}$ with a mean of $123.19 \pm 73.10 \text{ Bq}\cdot\text{kg}^{-1}$. The absorbed dose rate (D) ranged from 18.48 ± 1.47 to $122.18 \pm 4.19 \text{ nGy}\cdot\text{h}^{-1}$ with a mean of $58.61 \pm 33.21 \text{ nGy}\cdot\text{h}^{-1}$, while outdoor annual effective dose (AED_{out}) ranged from 0.0227 - 0.1498 $\text{mSv}\cdot\text{y}^{-1}$ with a mean of $0.0719 \pm 0.0407 \text{ mSv}\cdot\text{y}^{-1}$.

R_{eq} values for all the 30 samples are below the screening limit of $370 \text{ Bq}\cdot\text{kg}^{-1}$. The mean is 66.7% below the limit. The maximum value from sample 015 (264.09 ± 9.91) $\text{Bq}\cdot\text{kg}^{-1}$ is still 28.6% below limit, while minimum sample 004 (36.85 ± 3.09) $\text{Bq}\cdot\text{kg}^{-1}$ is 90.0% below limit. High values 015 (264.09 ± 9.91), 010 (250.73 ± 9.53), 029 (227.37 ± 8.60), 026 (233.00 ± 8.96) and 018 (219.10 ± 8.49) hypothetically reflect local enrichment of Th-bearing resistate minerals in granitic gneiss,

Table 3. Radium equivalent activity, absorbed dose rate and outdoor annual effective dose.

Sample	Ra _{eq} (Bq·kg ⁻¹)	D (nGy·h ⁻¹)	AED _{out} (mSv·y ⁻¹)
001	114.49 ± 5.81	53.20 ± 2.61	0.0652 ± 0.0032
002	114.08 ± 5.23	56.56 ± 2.47	0.0694 ± 0.0030
003	121.26 ± 6.15	55.89 ± 2.74	0.0685 ± 0.0034
004	36.85 ± 3.09	18.48 ± 1.47	0.0227 ± 0.0018
005	198.65 ± 8.16	93.52 ± 3.67	0.1147 ± 0.0045
006	77.63 ± 5.42	34.23 ± 2.35	0.0420 ± 0.0029
007	87.24 ± 4.81	43.59 ± 2.29	0.0535 ± 0.0028
008	42.24 ± 3.51	20.62 ± 1.64	0.0253 ± 0.0020
009	50.19 ± 3.51	25.49 ± 1.69	0.0313 ± 0.0021
010	250.73 ± 9.53	114.35 ± 4.21	0.1402 ± 0.0052
011	164.00 ± 7.22	78.12 ± 3.28	0.0958 ± 0.0040
012	133.17 ± 7.10	60.46 ± 3.14	0.0741 ± 0.0039
013	100.17 ± 5.61	48.00 ± 2.58	0.0589 ± 0.0032
014	233.18 ± 10.98	102.61 ± 5.23	0.1258 ± 0.0064
015	264.09 ± 9.91	122.18 ± 4.40	0.1498 ± 0.0054
016	39.95 ± 3.09	20.15 ± 1.48	0.0247 ± 0.0018
017	136.47 ± 6.17	66.58 ± 2.89	0.0817 ± 0.0035
018	219.10 ± 8.49	104.89 ± 3.85	0.1286 ± 0.0047
019	128.93 ± 5.59	62.91 ± 2.62	0.0772 ± 0.0032
020	58.20 ± 3.46	29.61 ± 1.68	0.0363 ± 0.0021
021	201.52 ± 7.75	94.91 ± 3.50	0.1164 ± 0.0043
022	78.46 ± 4.00	40.64 ± 1.98	0.0498 ± 0.0024
023	48.06 ± 3.77	24.80 ± 1.85	0.0304 ± 0.0023
024	44.47 ± 3.75	22.91 ± 1.84	0.0281 ± 0.0023
025	49.63 ± 3.65	25.58 ± 1.77	0.0314 ± 0.0022
026	223.00 ± 8.96	105.67 ± 4.04	0.1296 ± 0.0050
027	136.83 ± 5.78	68.16 ± 2.78	0.0836 ± 0.0034
028	72.05 ± 4.85	35.01 ± 2.24	0.0429 ± 0.0027
029	227.37 ± 8.60	106.70 ± 3.86	0.1309 ± 0.0047
030	43.57 ± 3.62	22.52 ± 1.78	0.0276 ± 0.0022
Mean ± SD	123.19 ± 73.10	58.61 ± 33.21	0.0719 ± 0.0407
Range	36.85 - 264.09	18.48 - 122.18	0.0227 - 0.1498
World Average/Limit	370 (limit)	59 (average)	0.07 (average)

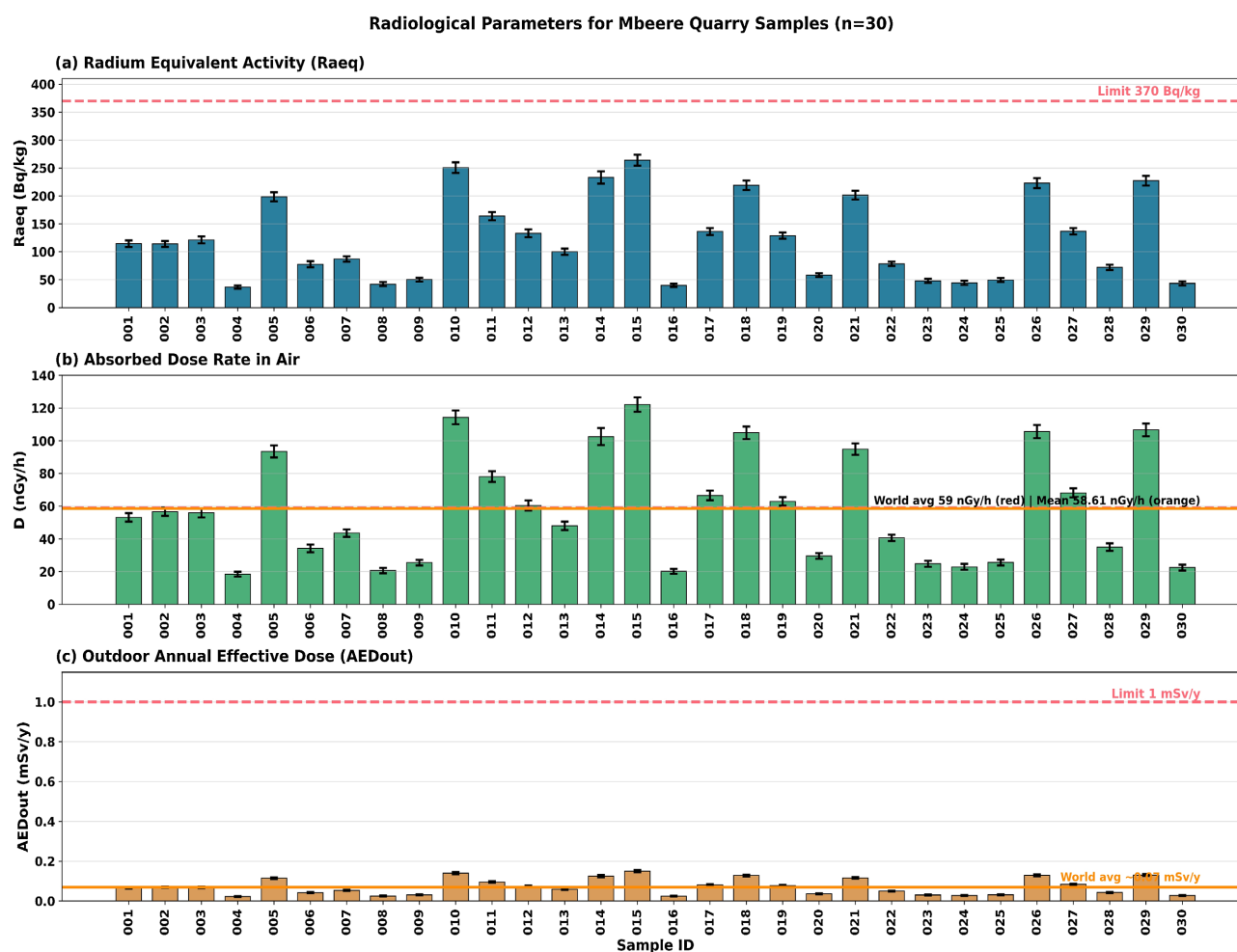


Figure 3. Variation of radium equivalent activity, absorbed dose and annual effective dose among the samples.

while low values 004 ($36.85 \text{ Bq}\cdot\text{kg}^{-1}$), 016 ($39.95 \pm 3.09 \text{ Bq}\cdot\text{kg}^{-1}$), 030 ($43.57 \pm 3.62 \text{ Bq}\cdot\text{kg}^{-1}$), 024 ($44.47 \pm 3.75 \text{ Bq}\cdot\text{kg}^{-1}$) and 023 ($48.06 \pm 3.77 \text{ Bq}\cdot\text{kg}^{-1}$) hypothetically reflect quartzitic bands. The high SD of ± 73.10 indicates high heterogeneity within the Mozambique Belt lithology.

The mean D is 0.66% below world average of $59 \text{ nGy}\cdot\text{h}^{-1}$. 12 of the 30 samples exceed world average. The highest D was in sample 015 ($122.18 \pm 4.40 \text{ nGy}\cdot\text{h}^{-1}$) is 107.1% above the world average, 010 ($114.35 \pm 4.21 \text{ nGy}\cdot\text{h}^{-1}$) is 93.8% above, 029 ($106.70 \pm 3.86 \text{ nGy}\cdot\text{h}^{-1}$) is 80.8% above. The lowest D is 004 ($18.48 \pm 1.47 \text{ nGy}\cdot\text{h}^{-1}$) is 68.7% below world average. This pattern follows Ra_{eq} , driven by ^{232}Th contribution (D factor 0.604).

The mean AED_{out} is 2.7% higher than world average $0.07 \text{ mSv}\cdot\text{y}^{-1}$. This is an outdoor external gamma value only. The highest AED_{out} value 015 ($0.1498 \pm 0.0054 \text{ mSv}\cdot\text{y}^{-1}$) is 114% above world average, while the lowest 004 ($0.0227 \pm 0.0018 \text{ mSv}\cdot\text{y}^{-1}$) is 67.6% below.

From an external gamma screening perspective, the 30 purposively sampled rocks show low radiological hazard. Mean Ra_{eq} is well below $370 \text{ Bq}\cdot\text{kg}^{-1}$, mean D is at world average and mean AED_{out} is close to the world average. The rocks sam-

pled may be considered suitable for use as building materials for external gamma. Suitability with respect to indoor radon exhalation cannot be concluded because radon was not assessed.

The mean radiological hazard indices from the present study are compared with values reported in Kenya and other parts of the world as presented in **Table 4**.

Table 4. Comparison of mean radiological parameters in the present study with values reported in other regions of the world.

Region/Country	Ra_{eq} (Bq·kg ⁻¹)	D (nGy·h ⁻¹)	AED_{out} (mSv·y ⁻¹)	Reference
Mbeere South, Kenya	123.19	58.61	0.0719	This study
Kerio, Kenya	264.7	124.78	0.153	[25]
Northern Uganda	302.3	138.34	0.170	[26]
Oyo, Nigeria	1453.9	638.55	0.783	[27]
Anka, Nigeria	451.54	200.91	0.246	[28]
Aja, Saudi Arabia	846.7	368.84	0.452	[29]
Jaintiapur, Bangladesh	146.0	70.72	0.087	[30]
São Paulo, Brazil	321.9	149.15	0.183	[31]
World Average/Safety Limit	370	59	0.07	[7]

Mbeere South samples are 53.5% lower in Ra_{eq} , 53.0% lower in D , and 53.0% lower in AED_{out} than those from Kerio Valley. Both are in basement complex, but Kerio values are more than double Mbeere South, hypothetically attributed to higher ⁴⁰K and ²³²Th in Kerio phonolites. This shows significant heterogeneity within Kenya and that Mbeere South's sampled outcrops are not a High Natural Background Radiation Area (HNBRA). Mbeere South is 59.2% lower in Ra_{eq} , 57.6% lower in D , 57.7% lower in AED_{out} than Northern Uganda. Northern Uganda granite has been reported with ²³²Th up to 122.3 Bq·kg⁻¹ vs Mbeere's mean of 38.66 Bq·kg⁻¹. The lower Th in Mbeere South hypothetically suggests less monazite enrichment. Mbeere South is 91.5% lower in Ra_{eq} , 90.8% lower in D , 90.8% lower in AED_{out} . Oyo exceeds Ra_{eq} limit by 293%, while Mbeere is 66.7% below. Mbeere South is 72.7% lower in Ra_{eq} , 70.8% lower in D , 70.8% lower in AED_{out} . Anka exceeds Ra_{eq} limit by 22%. This confirms Mbeere South's sampled sites are low-background compared to Nigerian pegmatite/granite terrains.

Mbeere South is 85.4% lower in Ra_{eq} , 84.1% lower in D , 84.1% lower in AED_{out} than Aja. Aja is 129% above Ra_{eq} limit. Mbeere South is 15.6% lower in Ra_{eq} , 17.1% lower in D , 17.4% lower in AED_{out} . Both are low-background sedimentary-influenced signatures despite Mbeere being basement, hypothetically due to quartzitic dilution. Mbeere South samples are 61.7% lower in Ra_{eq} , 60.7% lower in D , 60.7% lower in AED_{out} than those from São Paulo, Brazil.

The 30 purposively selected rock samples from Mbeere South are 53% - 91% lower than High Natural Background Radiation Areas in Kenya, Uganda, Nigeria

and Saudi Arabia. They are below the $370 \text{ Bq}\cdot\text{kg}^{-1}$ external gamma screening limit. Suitability of the rocks as building materials is concluded for external gamma screening only, as indoor radon exhalation was not assessed.

5. Conclusions

This study assessed the natural radioactivity and associated radiological hazards as an external gamma-screening assessment only for 30 purposively selected rock samples from selected sites in Mbeere South Constituency screened with a handheld GM counter. Selection was based on accessibility and elevated count rate, therefore results are limited to sampled areas. Mean activity concentrations were $19.02 \pm 14.00 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{238}U , $38.66 \pm 34.43 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{232}Th and $634.88 \pm 302.94 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{40}K . ^{232}Th and ^{40}K exceed world averages of 30 and 400 $\text{Bq}\cdot\text{kg}^{-1}$ by 28.9% and 58.7% respectively, while ^{238}U is 45.7% below global average of 35 $\text{Bq}\cdot\text{kg}^{-1}$. The activity pattern $^{40}\text{K} > ^{232}\text{Th} > ^{238}\text{U}$ hypothetically reflects felsic gneissic lithology, with ^{40}K being dominant contributor to natural radioactivity, but lithological links remain hypotheses as thin-section analysis was not performed.

The mean radiological hazard indices were $123.19 \pm 73.10 \text{ Bq}\cdot\text{kg}^{-1}$ for Ra_{eq} , $58.61 \pm 33.21 \text{ nGy}\cdot\text{h}^{-1}$ for D and $0.0719 \pm 0.0407 \text{ mSv}\cdot\text{y}^{-1}$ for AED_{out} , with ranges of 36.85 - 264.09 $\text{Bq}\cdot\text{kg}^{-1}$, 18.48 - 122.18 $\text{nGy}\cdot\text{h}^{-1}$ and 0.0227 - 0.1498 $\text{mSv}\cdot\text{y}^{-1}$, respectively. All samples recorded Ra_{eq} below the construction screening limit of 370 $\text{Bq}\cdot\text{kg}^{-1}$ [7], with mean 66.7% below limit. Mean D is 0.66% below world average 59 $\text{nGy}\cdot\text{h}^{-1}$ and mean AED_{out} is 2.7% above world average 0.07 $\text{mSv}\cdot\text{y}^{-1}$ [7], essentially at world average. No comparison is made with the 1 $\text{mSv}\cdot\text{y}^{-1}$ public dose limit as it excludes natural background and radon. Spatial variability is hypothetically attributed to lithological heterogeneity, with relatively higher values in granitic gneiss zones and lower values in quartzitic zones.

Compared to other regions, Mbeere South exhibits significantly lower radioactivity than high background areas such as Kerio Valley, Kenya, Oyo and Anka, Nigeria, Aja, Saudi Arabia and São Paulo, Brazil, being 53% - 91% lower in Ra_{eq} and 51% - 90% lower in dose rate. Specifically, Mbeere South is 53.5% lower than Kerio 264.7 $\text{Bq}\cdot\text{kg}^{-1}$, 59.2% lower than Northern Uganda 302.3 $\text{Bq}\cdot\text{kg}^{-1}$, 91.5% lower than Oyo 1453.9 $\text{Bq}\cdot\text{kg}^{-1}$, 72.7% lower than Anka 451.54 $\text{Bq}\cdot\text{kg}^{-1}$ and 85.4% lower than Aja 846.7 $\text{Bq}\cdot\text{kg}^{-1}$. Values are comparable only to low-background terrains such as Jaintiapur, Bangladesh (146.0 $\text{Bq}\cdot\text{kg}^{-1}$), being only 15.6% lower, confirming sampled quarries as low natural background radiation areas for external gamma.

It is concluded that rocks from the 30 purposively sampled rocks in Mbeere South pose insignificant external gamma radiological health risk and are radiologically suitable for use as construction materials from an external gamma perspective, subject to radon assessment. Suitability with respect to indoor radon cannot be concluded as radon exhalation was not assessed. Periodic monitoring and radon assessment are, however, recommended to establish baseline data for future anthropogenic modifications.

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Author Contributions

Conceptualization, J.N.W. and W.N.; methodology, J.N.W.; software, J.N.W.; validation, J.N.W., W.N. and M.M.; formal analysis, J.N.W.; investigation, J.N.W.; resources, W.N.; data curation, J.N.W.; writing—original draft preparation, J.N.W.; writing—review and editing, W.N. and M.M.; visualization, J.N.W.; supervision, W.N. and M.M.; project administration, W.N.; funding acquisition, not applicable. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Alotaibi, M.F., Alharbi, K.N., Alosime, E.M., Alhawali, L.H., Albarqi, M.M. and Alsulami, R.A. (2024) Natural Radioactivity in Soil and Water of Saudi Arabia: A Mixed-Studies Review. *Journal of Radiation Research and Applied Sciences*, **17**, Article 100897. <https://doi.org/10.1016/j.jrras.2024.100897>
- [2] Bathoum, D., Semghouli, S. and Choukri, A. (2025) Cosmic Radiation Exposure Calculation for Domestic Flights Departs from Fez. 2025 11th International Conference on Optimization and Applications (ICOA), Kenitra, 16-17 October 2025, 1-5. <https://doi.org/10.1109/icoa66896.2025.11236883>
- [3] Wen, H. (2024) Research Progress on the Impact of Nuclear Radiation in Food on Human Health. *Highlights in Science, Engineering and Technology*, **91**, 105-117. <https://doi.org/10.54097/19r9am21>
- [4] Talapko, J., Talapko, D., Katalinić, D., Kotris, I., Erić, I., Belić, D., *et al.* (2024) Health Effects of Ionizing Radiation on the Human Body. *Medicina*, **60**, Article 653. <https://doi.org/10.3390/medicina60040653>
- [5] Raham, A. and Al-Attabi, H. (2023) Estimating the Risk of Exposure to Internal and External Radiation Resulting from Portland Cement. *Journal of Wasit for Science and Medicine*, **16**, 88-96. <https://doi.org/10.31185/jwsm.560>
- [6] Jha, S.K., Patra, A.C., Verma, G.P., Iyer, I.S. and Aswal, D.K. (2024) Natural Radiation and Environment. In: *Handbook on Radiation Environment, Volume 1*, Springer, 27-72. https://doi.org/10.1007/978-981-97-2795-7_2
- [7] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2000) Sources and Effects of Ionizing Radiation. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. Volume I: Sources. United Nations.

- [8] Monfared, A.S., Jalali, F., Sedaghat, S., Mansoorizade, E., Jarrahi, A.M., Hajiahmadi, M., *et al.* (2006) High Natural Background Radiation Areas in Ramsar, Iran: Can Inhabitants Feel Safe? *International Journal of Low Radiation*, **3**, 171-177.
<https://doi.org/10.1504/ijlr.2006.012016>
- [9] Thomas, J.R., Sreejith, M.V., Aravind, U.K., Sahu, S.K., Shetty, P.G., Swarnakar, M., *et al.* (2022) Outdoor and Indoor Natural Background Gamma Radiation across Kerala, India. *Environmental Science: Atmospheres*, **2**, 65-72.
<https://doi.org/10.1039/d1ea00033k>
- [10] Mbatha, N.B. (2007) Radiometric Study of Beach Sand Deposits along the Coast of Western Cape Province, South Africa. PhD Thesis, University of the Western Cape.
- [11] Isinkaye, O.M., Jibiri, N.N. and Olomide, A.A. (2015) Radiological Health Assessment of Natural Radioactivity in the Vicinity of Obajana Cement Factory, North Central Nigeria. *Journal of Medical Physics*, **40**, 52-59.
<https://doi.org/10.4103/0971-6203.152256>
- [12] Salupeto-Dembo, J., Szabó-Krausz, Z., Völgyesi, P., Kis, Z. and Szabó, C. (2020) External Radiation Exposure of the Angolan Population Living in Adobe Houses. *Journal of Radioanalytical and Nuclear Chemistry*, **323**, 353-364.
<https://doi.org/10.1007/s10967-019-06920-z>
- [13] Achola, S.O., Patel, J.P., Mustapha, A.O. and Angeyo, H.K. (2012) Natural Radioactivity and External Dose in the High Background Radiation Area of Lambwe East, South Western Kenya. *Radiation Protection Dosimetry*, **152**, 423-428.
<https://doi.org/10.1093/rpd/ncs047>
- [14] Atibu, E.K., Arpagaus, P., Mulaji, C.K., Mpiana, P.T., Poté, J., Loizeau, J., *et al.* (2022) High Environmental Radioactivity in Artisanal and Small-Scale Gold Mining in Eastern Democratic Republic of the Congo. *Minerals*, **12**, Article 1278.
<https://doi.org/10.3390/min12101278>
- [15] Kenya National Bureau of Statistics (2019) 2019 Kenya Population and Housing Census Volume I: Population by County and Sub-County. Kenya National Bureau of Statistics.
- [16] Key, R.M., Charsley, T.J., Hackman, B.D., Wilkinson, A.F. and Rundle, C.C. (1989) The Geology of the Mozambique Belt and Adjacent Areas of Kenya. British Geological Survey.
- [17] Githenya, L.K. (2020) Geology and Economic Mineralization of the Neoproterozoic Mozambique Belt Rocks of the Mwitika-Makongo Area, Kitui County, South Eastern Kenya. Master's Thesis, South Eastern Kenya University.
- [18] State Department for Physical Planning (2026) Embu County National Spatial Plan Guidelines. Ministry of Lands, Public Works, Housing and Urban Development, Government of Kenya.
- [19] Bangou, C., Otoo, F. and Darko, E.O. (2021) Performance Testing and Comparative Study of Natural Radioactivity in Soil Samples Using High Purity Germanium (HPGe) Detector. *MethodsX*, **8**, Article 101397.
<https://doi.org/10.1016/j.mex.2021.101397>
- [20] Barros, L.F. and Pecequilo, B.R.S. (2013) Evaluation of Ra, Th, K and Radium Equivalent Activity in Sand Samples from Camburi Beach, Vitoria, Espirito Santos, Brazil. *International Nuclear Atlantic Conference (INAC 2013)*, Recife, 24-29 November 2013. Brazilian Association of Nuclear Energy.
- [21] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2021) Sources, Effects and Risks of Ionizing Radiation: UNSCEAR 2020/2021 Report. United Nations.

- [22] United Nations Scientific Committee on the Effects of Atomic Radiation (2000) Sources and Effects of Ionizing Radiation: UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. United Nations.
- [23] Guérin, G., Christophe, C., Philippe, A., Murray, A.S., Thomsen, K.J., Tribolo, C., *et al.* (2017) Absorbed Dose, Equivalent Dose, Measured Dose Rates, and Implications for OSL Age Estimates: Introducing the Average Dose Model. *Quaternary Geochronology*, **41**, 163-173. <https://doi.org/10.1016/j.quageo.2017.04.002>
- [24] Pintilie-Nicolov, V., Georgescu, P.L., Iticescu, C., Moraru, D.I. and Pintilie, A.G. (2021) The Assessment of the Annual Effective Dose Due to Ingestion of Radionuclides from Drinking Water Consumption: Calculation Methods. *Journal of Radioanalytical and Nuclear Chemistry*, **327**, 49-58. <https://doi.org/10.1007/s10967-020-07438-5>
- [25] Agora, J.O. and Hashim, N.O. (2015) Assessment of Radioactivity Levels and Risks Due to Different Rock Types from the KERIO Valley 'High Background Radiation Area (HBRA)' of Kenya. *International Journal of Mathematics and Physical Sciences Research*, **3**, 40-47.
- [26] Olanya, A., Okello, D., Oruru, B. and Kisolo, A. (2022) The Primordial Radionuclides Activity Concentrations and Associated Minerals in Rocks from Selected Quarries in Northern Uganda. *International Journal of Sciences: Basic and Applied Research*, **66**, 45-65.
- [27] Ajetunmobi, A.E., Biere, P., Alausa, S.K., Coker, J.O., David, T.W., Talabi, A.T., *et al.* (2022) Measurement of Activity Concentrations of Rock Samples from Rocks-Surrounded Town in Igbeti, Oyo State, Nigeria. *Scientia Africana*, **21**, 183-194. <https://doi.org/10.4314/sa.v21i1.16>
- [28] Akpanowo, M., Umaru, I., Iyakwari, S., Joshua, E.O., Yusuf, S. and Ekong, G.B. (2020) Determination of Natural Radioactivity Levels and Radiological Hazards in Environmental Samples from Artisanal Mining Sites of Anka, North-West Nigeria. *Scientific African*, **10**, e00561. <https://doi.org/10.1016/j.sciaf.2020.e00561>
- [29] Kinsara, A.A., Shabana, E.I. and Qutub, M.M.T. (2014) Natural Radioactivity in Some Building Materials Originating from a High Background Radiation Area. *International Journal for Innovation Education and Research*, **2**, 70-78. <https://doi.org/10.31686/ijer.vol2.iss6.195>
- [30] Dina, N.T., Das, S.C., Kabir, M.Z., Rasul, M.G., Deebea, F., Rajib, M., *et al.* (2022) Natural Radioactivity and Its Radiological Implications from Soils and Rocks in Jaintiapur Area, North-East Bangladesh. *Journal of Radioanalytical and Nuclear Chemistry*, **331**, 4457-4468. <https://doi.org/10.1007/s10967-022-08562-0>
- [31] Moura, C.L., Artur, A.C., Bonotto, D.M., Guedes, S. and Martinelli, C.D. (2011) Natural Radioactivity and Radon Exhalation Rate in Brazilian Igneous Rocks. *Applied Radiation and Isotopes*, **69**, 1094-1099. <https://doi.org/10.1016/j.apradiso.2011.03.004>