Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Assessing the environmental hazard of natural radioactivity in coal, coal waste and soil at Nkandabbwe Coalfield in Sinazeze

Phillimon SHABA

pshaba@nisir.org.zm

National Institute for Scientific and Industrial Research https://orcid.org/0009-0001-7177-2433

Patrick HAYUMBU

Copperbelt University

Alick B. MUVUNDIKA

National Institute for Scientific and Industrial Research

Research Article

Keywords: Naturally occurring radioactive materials (NORM), Coal mining, Radiological hazard assessment, External gamma radiation, Technologically enhanced naturally occurring radioactive material (TENORM), Occupational radiation exposure

Posted Date: June 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9957434/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Assessing the environmental hazard of natural radioactivity in coal, coal waste and soil at Nkandabbwe Coalfield in Sinazeze

Phillimon Shaba[1,2], Alick B. Muvundika[1], Patrick Hayumbu[2]

[1]National Institute for Scientific and Industrial Research, (NISIR), Kenneth Kaunda International Airport Road, P.O Box 310158, 15302 Chelston, Lusaka, Zambia

[2]Copperbelt University, School of Mathematics and Natural Sciences, Department of Chemistry, Riverside, Kitwe, Zambia

Corresponding Author: Phillimon Shaba, National Institute for Scientific and Industrial Research, Kenneth Kaunda International Airport Road, P.O Box 310158, 15302 Chelston, Lusaka, Zambia Email: pshaba@nisir.org.zm, https://orcid.org/0009-0001-7177-2433

Highlights

1. Radium-226 and thorium-232 exceeded UNSCEAR world averages in all matrices
2. Coal waste absorbed dose rate marginally exceeded the 60 nGy/h benchmark
3. External gamma radiation contributed over 99.7% of total occupational dose
4. All radiological hazard indices remained below international safety limits
5. Radium-226 and thorium-232 were the principal drivers of radiological risk

Abstract

Coal mining is a recognised source of technologically enhanced naturally occurring radioactive material (TENORM) exposure, yet baseline radiological data from sub-Saharan African coal mining environments remain scarce. This study quantified the activity concentrations of radium-226, thorium-232, and potassium-40 in coal, soil, and coal waste from an active mining area, and evaluated associated radiological hazards to workers and surrounding communities. Gamma-ray spectrometry was employed to determine radionuclide activity concentrations across all matrices. Hazard parameters including radium equivalent activity, external and internal hazard indices, and absorbed dose rate were computed using internationally established formulae. Effective dose contributions from external gamma radiation, inhalation, and ingestion pathways were assessed, and Pearson correlation analysis examined relationships among radionuclides and derived hazard indices.

Mean radium-226 concentrations of 47 Bq/kg in coal and 88 Bq/kg in coal waste, together with thorium-232 concentrations of 37 Bq/kg in coal and 72 Bq/kg in coal waste, exceeded United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) world averages of 35 and 30 Bq/kg, confirming a TENORM scenario. External gamma radiation dominated total effective dose at 99.7%, yielding 0.972 mSv/year, while inhalation and ingestion contributions were negligible. Although hazard indices remained below internationally accepted thresholds, the absorbed dose rate in coal waste (85 nGy/h) exceeded the global benchmark of 60 nGy/h. Radium-226 and thorium-232 were strongly inter-correlated ($r = 0.76$) and drove hazard indices, whereas potassium-40 behaved independently with weak negative correlations.

Although no immediate radiological threat was identified, elevated radionuclide concentrations in coal waste and marginal dose rate exceedance underscore the need for continuous gamma monitoring, structured waste containment, and integrated environmental surveillance incorporating radon measurement and toxic element analysis to ensure long-term protection of workers and surrounding communities.

Key Words: *Naturally occurring radioactive materials (NORM); Coal mining; Radiological hazard assessment; External gamma radiation; Technologically enhanced naturally occurring radioactive material (TENORM); Occupational radiation exposure*

1. Introduction

Coal remains one of the most widely used energy minerals due to its accessibility and abundance in nature. It contains naturally occurring radionuclides, including primordial isotopes such as ^{238}U, ^{235}U, ^{232}Th, and ^{40}K, as well as their common decay products. These include uranium progeny (^{230}Th, ^{226}Ra, ^{222}Rn and its daughters ^{210}Pb and ^{210}Po) and thorium progeny (^{228}Ra and ^{228}Th) [1]. Because naturally occurring radioactive materials (NORM) such as coal are abundant in the environment, living organisms are continuously exposed to natural radiation from these radionuclides. Coal mining for industrial purposes is known to enhance the activity of these radionuclides, producing technologically enhanced naturally occurring radioactive materials (TENORM).

Mining operations involve the removal of large volumes of overburden (topsoil and waste rock) above coal seams, while coal washing generates considerable waste (tailings) with enhanced radioactivity. Tailings are typically dumped around the mine license area, where they may be wind-blown or leach into soil during the wet season. Acid mine drainage and tailings leachates can mobilize radionuclides and heavy elements into surface and groundwater systems, posing environmental risks.

Coal and fly ash from Maamba Collieries have been reported to contain ^{226}Ra and ^{232}Th with mean values of 46 ± 8 and 56 ± 9 Bq/kg, respectively, nearly two and a half times higher than the world average for coal and comparable to lignite or brown coal [2]. In contrast, Collum Coal Mine, in operation since the 1960s, has no publicly available baseline radiological data. The absence of NORM/TENORM monitoring suggests that workers may be poorly monitored for radiological hazards, alongside other occupational risks such as respirable crystalline silica (RCS), toxic gases, and heavy metals. Overexposure to mine dust and fine particulates poses occupational health risks to workers, environmental health risks to surrounding communities, and ecological risks to biota.

Recent studies have highlighted the radiological risks associated with coal mining and the presence of natural radioactivity in coal [3,4]. While coal commonly contains uranium, thorium, their decay products, and ^{40}K, the environmental impact of these radionuclides is influenced by regional geology, heavy metals, and sulfur content [5]. A 2020 study identified increased respiratory disease incidence in coal mining communities in China, underscoring the health risks of coal mining [6].

The purpose of this study was to estimate the extent of radioactivity pollution within and around Collum Coal Mine and to assess radiological risks to workers and nearby communities. Although some environmental radioactivity studies have been conducted at Maamba Collieries

and Konkola Copper Mines [2,7], no radiological data exist for Collum Coal Mine. Given that overexposure to natural radionuclides and mine dust can cause serious health problems and environmental pollution, this study addresses a critical gap in Zambia's coal mining sector.

2. Material and Method

The study investigated contamination of coal, soil, and coal waste by naturally occurring radionuclides. The geographical area, sampling procedures, and sample preparation methods are described in detail in the following sections.

2.1 Geographical Area

Sinazeze town is located in Sinazongwe District, Southern Province of Zambia, at latitude 17° 8′ 44″ South and longitude 27° 24′ 18″ East. Figure 1 presents a map of the Collum Coal Mining Industries Limited colliery, where coal, soil, and coal waste samples were collected. The mine is an underground coal operation situated approximately 300 km from Lusaka and about 45 km northeast of Maamba Town, in the Sinazeze area of Sinazongwe District. Access to the mine is via a 5 km gravel road branching off the Maamba–Batoka Road (D775). The general topography of the mine area is gently undulating, with elevations ranging between 620 and 680 metres above mean sea level (AMSL). The precise coordinates of the site are 17.15515332° South and 27.36820936° East.

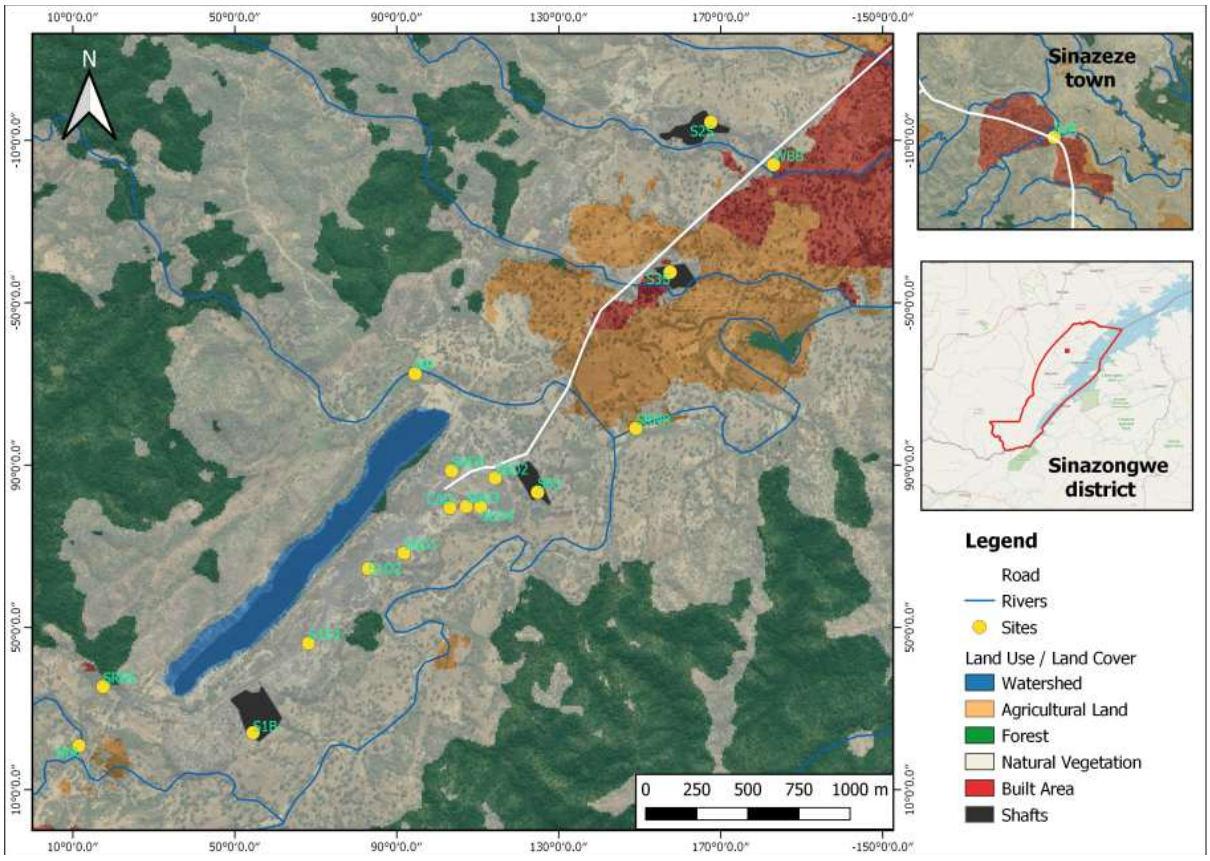


Figure 1: Sampling locations at Collum coal mine **Source:** Researcher's field work

2.1.1 Geology

Figure 2 illustrates the south-eastern part of Zambia, highlighting the three coal-bearing sub-basins of the Mid-Zambezi Valley. The Collum Coal Mine lies within the Nkandabbwe Coalfields area, which outcrops extensively along the north-western margin and occurs within the Kanzinze Basin. Geologically, the mine is located adjacent to the Maamba Coal Deposit, while other known coal occurrences are confined exclusively to the Lower Gwembe Formation. This formation comprises a series of fault-controlled basins that make up the Mid-Zambezi Rift Valley.

The Maamba Coal Deposit itself occurs within the Kanzinze Basin, but coal seams have also been discovered in adjacent basins such as the Sinakumbe Group the oldest sedimentary succession in the area. The Sinakumbe Group outcrops extensively along the north-western margin of the Nkandabbwe Coalfields and extends into a small portion of the Siankondobo Coalfields. The position of the coal seam is within the Gwembe Formation of the Lower Karoo [8].

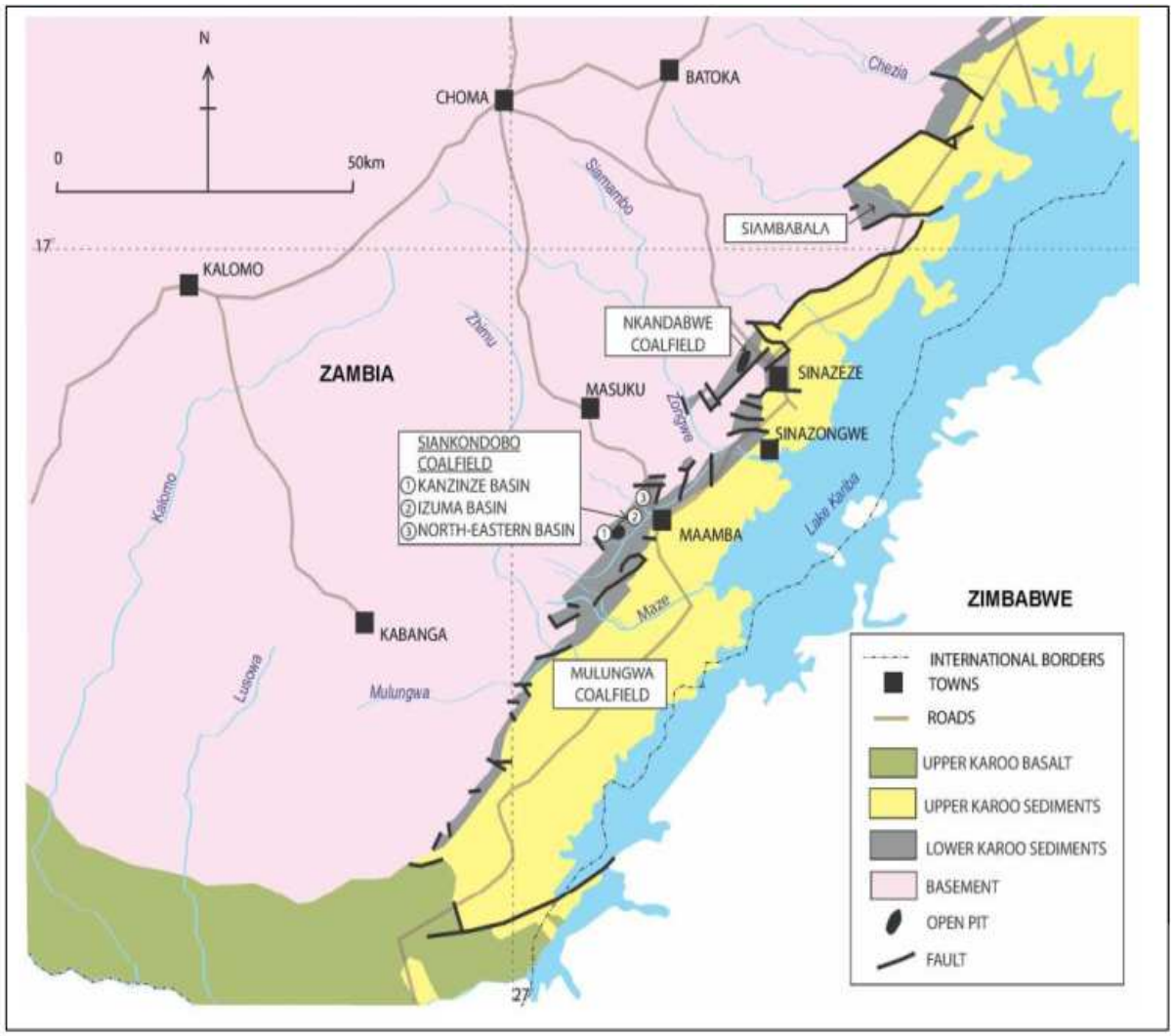


Figure 2: Geological map of South-Eastern Zambia highlighting the three coal-bearing sub-basins in the Mid-Zambezi Valley and showing the study town, Sinazeze.
Source: Nyambe and Dixon, 2000

2.2 Field investigation and Sample Transportation

Physical features such as mine shafts, discharge points, altered landscapes, legacy coal ash, human settlements, and polluted land were considered indicators of potential environmental impacts. For specific site surveys, soil samples were collected from within and around the mine. Fine coal was obtained from four shafts, while legacy coal ash was sampled from dumps near shafts 1 and 6. Surface dose rates were measured at one meter above ground level using a Thermo Scientific RAD-Eye Personal Radiation Meter. Coordinates for each sampling location were recorded with a Garmin eTrex 10 Global Positioning System (GPS).

The collected samples were packed in separate Ziplock bags, clearly labeled, placed in plastic boxes, and transported to the laboratory for analysis.

2.3 Sampling and Sample Preparation

A total of 19 samples representing different matrices were collected from the sampling area and stored separately. These included four coal samples from shafts 1, 2, 3, and 6; eight coal ash samples from dumps near shafts 1 and 6; and seven soil samples collected at a depth of 16 cm using a soil auger. All solid samples were sealed in uniquely labeled 1 kg Ziplock bags and transported to the laboratory for analysis.

Coal, coal waste, and soil samples were sun-dried for 10 days in aluminum trays and subsequently oven-dried to a constant temperature of 105 °C. Soil samples were sieved using an ASTM sieve with an aperture size of 3.15 mm to remove stones and organic matter, then ground to a particle size of 75 µm [9]. Processed samples were weighed into 50 g portions, placed in sample containers, and sealed tightly. The sealed samples were stored for four weeks to attain secular equilibrium [9–12].

2.3.1 Sample Counting and Analysis using the Gamma Spectrometer

Coal, coal waste and soil samples were analysed at the National Institute for Scientific and Industrial Research's Nuclear Analytical Laboratory. Gamma-ray spectrometry with a Hyper Purity Germanium detector (HPGe) was used for this analysis: The detector is identified as a: Model: GX 5021 Canberra extended range GX with a relative efficiency of: 50%, a full width at half maximum (FWHM) for a ^{60}Co gamma energy transition at 1332 keV of: 2.1 keV, a counting time of: 50,021 seconds (to minimize photopeak fitting errors). Detector calibration was done using a multi-gamma certified cocktail standard (^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{60}Co, ^{65}Zn and ^{88}Y) in the same geometry as the studied samples. The spectra were analysed using Genie 2000 software. The activity concentration of ^{40}K was determined from its 1460 keV gamma line, while the activity concentration of ^{226}Ra was determined based on the average activity concentrations of ^{214}Pb at 352 keV and ^{214}Bi at 609 keV gamma lines. The activity concentration of ^{232}Th was determined based on the average activity concentrations of ^{212}Bi at 727.17 keV and ^{228}Ac at 911.21 keV gamma lines. Background spectra were collected and subtracted from spectra collected of the samples. The activity concentration of individual radionuclides in samples were calculated using the following equation;

$$A = \frac{N_{net}}{I*\gamma*\varepsilon*m*t} \qquad \text{Equation 1}$$

where *A:* calculated gamma activity concentration (Bq/kg),
N_{net}: net peak area count, subtract background of the sample (counts),
ε : absolute efficiency of the detector,
I_γ : emission probability of a specific energy photo peak,
t: sample count time (seconds),
m: sample weight.
This calculation was done by assuming that, all correction factors are equal to unity.

2.4 Occupational Risk Estimation for Radiation Exposure Pathways

The estimation of occupational risk for radiation exposure in the coal mine was assessed using the exposure pathways below:

i. External exposure to gamma radiation from mined coal and the exposed old coal waste.
ii. Internal exposure from inhalation of coal dust and contaminated air.
iii. Internal exposure from any accidental ingestion of coal.

The following parameters equations were used to calculate the occupational risk to workers;

2.4.1 External Exposure to Gamma Radiation

$$D_{ext} = \sum_i A_i * C_{ext,i} * T_e \quad \text{Equation 2}$$

Where A_i is the specific activity of the nuclide in Bq/Kg, $C_{ext,i}$ is the effective dose coefficient for nuclide I in the contaminated surface measured in Sv/hg^{-1}, T_e is the exposure duration in number of years.

2.4.2 Internal Exposure from Inhalation of Coal Dust

$$D_{inh} = \sum_i A_i * C_{inh,i} * \eta_{inh} * D_f * T_e \quad \text{Equation 3}$$

Where $C_{inh,I}$ is a dose coefficient for inhalation of nuclei i in Sv/Bq, η_{inh} is the breathing rate measured in m^3/hour, D_f is the dust loading factor and T_e is as above.

2.4.3 Internal Dose from Accidental Ingestion of Radionuclides

$$D_{ing} = \sum_i A_i * C_{ing,i} * \eta_{ing} * T_e \quad \text{Equation 4}$$

Where $C_{ing,I}$ is the dose coefficient for ingestion of nuclide I in Sv/Bq, η_{ing} is the breathing rate for adults Kg/hr and A_i and T_e are as above [4], [13].

3.0 RESULTS

The following results were obtained after analyzing coal, coal waste and soil samples using the HPGe detector.

3.1 Activity concentrations of radionuclides in coal

3.1.1. Activity concentration of radionuclides in coal

Activity concentrations of radionuclides are shown in Table 1. The activity concentration for ^{226}Ra ranged from 34±0.1– 59±8 Bq/kg with a mean activity concentration value of 47±3 Bq/kg above the world average activity concentration of 20 Bq/kg and a median of 46±1 Bq/kg. [14]. ^{232}Th ranged from 28±0.4–50±0.3 Bq/kg with a mean activity concentration value of 37±1

Bq/kg above the world average activity concentration of 20 Bq/kg in coal and a median of 36±3 Bq/kg (UNSCEAR, 1982a) [16]. ^{40}K had the highest activity concentration with a range of 49±5 – 79±3 Bq/kg with a mean activity concentration value of 53±6 Bq/kg slightly higher than the world average of 50 Bq/kg [15].

Table1. Activity Concentration of Radionuclides in Coal

Radionuclide	Mean ± sd (Bq/kg)	Median	Range
^{226}Ra	47 ± 3	46 ± 1	34 ± 0.1 – 59 ± 8
^{232}Th	37 ± 1	36 ± 3	28 ± 0.4 – 50 ± 0.3
^{40}K	58 ± 1	53 ± 6	49 ± 5 – 79 ± 3

Table 2 shows the three possible pathways of exposure (inhalation, ingestion and external). It shows that for coal, soil, and coal waste, almost the entire radiation dose to workers comes from external gamma exposure, contributing more than 99.7% of the total effective dose (0.972 mSv/y). Inhalation of dust adds a very small fraction (less than 1%, slightly higher in coal waste), while ingestion is negligible. Coal and coal waste materials contain gamma-emitting radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in concentrations sufficient to produce measurable external fields.

Table 2. Exposure Pathway Contribution (%)

Sample	External	Inhalation	Ingestion
Coal	99.7	0.31	0.02
Soil	99.8	0.20	0.01
Coal Waste	99.1	0.87	0.03

Table 3. Radionuclide Activity Concentration of Soil Samples (Bq/kg)

Radionuclide	Mean ± sd	Median	Range
^{226}Ra	45 ± 2	42 ± 2	32 ± 0.5 - 78 ± 0.2
^{232}Th	34 ± 1	33 ± 4	0 – 57 ± 1
^{40}K	114 ± 2	119 ± 8	84 ± 6 – 144 ± 5

3.2 Activity concentration of radionuclides in soil

3.2.1 Activity concentration of radionuclides in soil

^{232}Th activity concentrations had the lowest value with a mean of 34±1 Bq/kg, a range of 0 – 57±1 Bq/kg and a median value of 33±4 Bq/kg. For ^{40}K, the value of activity concentrations was the highest and the range was 84±6–114±5 Bq/kg, mean value of 114±2 Bq/kg and a median value of 119±8 Bq/kg (Table 3). The average worldwide measurements for activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K (in Bq/kg) are 32, 45 and 420 respectively. This is according to the UNSCEAR report of 2000 [16]. Therefore, the activity concentrations of ^{226}Ra are below the world averages. The ^{40}K world average documented by UNSCEAR (2000) was almost four times than observed in this study.

3.3 Activity concentration of radionuclides in coal waste

3.3.1 Activity concentration of radionuclides in coal waste

Table 4. Radionuclide Activity Concentration of Coal Waste Samples (Bq/kg)

Radionuclide	Mean ± sd	Median	Range
^{226}Ra	88 ± 1	82 ± 3	78 ± 0.3 – 105 ± 0.4
^{232}Th	72 ± 2	79 ± 4	0 – 96 ± 6
^{40}K	79 ± 3	80 ± 3	70 ± 2 – 90 ± 6

^{226}Ra in coal waste ranged from78±0.3 – 105±0.4 Bq/kg with a mean value of 88±1 Bq/kg and a median value of 82±3 Bq/kg. ^{232}Th activity concentrations had a high value with a mean of 72±2 Bq/kg, range of 0 – 96±6 Bq/kg and a median value of 79±4 Bq/kg. For ^{40}K, the value of activity concentrations was the highest and the range was 70±2 – 90±6 Bq/kg, mean value of 79±3 Bq/kg and a median value of 80±3 Bq/kg (Table 4). The average worldwide measurements for activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K (in Bq/kg) are 20, 20 and 50 respectively. This is according to the UNSCEAR report of 2000 [16] lower than the results in this study for coal waste respectively.

3.3.2 Risk exposure estimation using radium equivalent and hazard indices in soil and coal waste

Radium equivalent activity (Ra_{eq}) was calculated using the equation:

$$Ra_{eq}\left(\frac{Bq}{kg}\right) = A_{Ra} + 1.43A_{Th} + 0.077A_K \qquad \text{Equation 6}$$

Where A_{Ra}, A_{Th} and A_K are the radiological activity concentrations or specific activities of ^{226}Ra, ^{232}Th and ^{40}K respectively. The formula is derived based on the estimation that 1 Bq/kg of ^{238}U, 0.7 Bq/kg of ^{232}Th and 13 Bq/kg of ^{40}K produce the same gamma ray dose rates. Table 5 shows that the mean Ra_{eq} activity in soil and coal waste samples were found to be 101 and 197 Bq/kg respectively. The Ra_{eq} results obtained in this study were lower than the maximum recommended limit or internationally accepted value of 370 Bq/kg and, therefore, do not pose a significant radiological hazard but caution should be taken against cumulative long-term effects.

Table 5. Radiation Hazard Indices

Study area	Sample	Mean	Ra_{eq} (Bq/kg) Median	Mean H_{ex}	Mean H_{in}
Collum coal mine	Soil	101	96	0.3	0.4
	Coal waste	197	199	0.3	0.4
Recommended limit [16]		370	-	1	1

The external hazard index (H_{ex}) was used to evaluate the hazard of the natural γ-radiation. It was calculated using the equation:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4820} \qquad \text{Equation 7}$$

where A_{Ra}, A_{Th} and A_K are the radiological activity concentrations or specific activities in Bq/kg of ^{226}Ra, ^{232}Th and ^{40}K respectively. The formula is derived from the Ra_{eq} expression by assuming that the maximum value allowed corresponds to the upper limit of Ra_{eq} (370 Bq/kg). H_{ex} and H_{in} values must be less than unity so that the radiation hazard is considered insignificant. The external hazard index value obtained were 0.3 and 0.3 respectively as shown in Table 5. These values are less than unity meaning that the soils and coal waste in the study area are considered safe for humans living there. That is, there is no significance threat of exposure to the population.

Internal hazard index (H_{in}) was used to quantify the internal exposure and is defined by as:

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \qquad \text{Equation 8}$$

Equally, the H_{in} of soil and coal waste (table 5) is less than unity meaning the radiation hazard is considered negligible or insignificant.

3.3.3 Absorbed dose rate in air (ADR_{air})

$$ADR\ (nGyh^{-1}) = 0.462A_{Ra} + 0.604A_{Th} + 0.01417A_K$$

The absorbed dose rate in air due to terrestrial gamma rays from the nuclides ^{226}Ra, ^{232}Th and ^{40}K at 1m above ground level was calculated as [16]. Where, A_K, A_{Th} and A_{Ra} are the mean activity concentrations of ^{40}K, ^{232}Th and ^{226}Ra. The calculated mean absorbed dose in air was 43 $nGyh^{-1}$ in soil, 45 $nGyh^{-1}$ in coal and 85 $nGyh^{-1}$ in coal waste making soil and coal to be lower than the world average value of 60 $nGyh^{-1}$ apart from the coal waste. This does not pose any immediate health risk to the population residing in the area; however, continuous monitoring is required to prevent cumulative exposure.

3.4 Correlation Analysis

3.4.1 Correlation analysis of activity concentration, exposure risks and hazard indices

Table 6. Correlation matrix of Radiological Variables of Collum Coal Mine

Variables	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	H_{ex}	H_{in}	ADR
^{226}Ra	1						
^{232}Th	0.759*	1					
^{40}K	-0.280	-0.125	1				
Ra_{eq}	0.896*	0.969*	- 0.162	1			
H_{ex}	0.896*	0.969*	- 0.162	1*	1		
H_{in}	0.945*	0.676*	- 0.200	0.992*	0.992*	1	
ADR	0.905*	0.964*	- 0.184	1*	1*	0.994*	1

2 - tailed test of significance

* Correlation is significant at the 0.05 level

The interdependency of the radiological variables measured in this study is presented in Table 6, which was produced using a graphing and analysis statistical software "OriginPro. 2026" with an alpha-testing level of $P < 0.05$ for the coal, coal ash and soil samples [17] . The degree of association existing between the radionuclides and the radiological hazards are presented in terms of their correlation coefficients (r). The 2-tailed test of significance was used.

The correlation matrix shows that ^{226}Ra and ^{232}Th are strongly correlated (r = 0.76), meaning they tend to co-occur in coal, soil, and waste. ^{40}K is negatively correlated with ^{226}Ra (r = –0.28) and ^{232}Th (r = –0.13), indicating independent behaviour of the uranium/thorium series. Ra_{eq} correlates strongly with ^{226}Ra (0.89) and with ^{232}Th (0.97), confirming both drive the radium equivalent activity. H_{ex} shows strong correlations with ^{226}Ra r=0.90) and ^{232}Th (r=0.97) while it correlates weakly with ^{40}K (r= -0.16), suggesting external hazard is distributed rather than dominated by one isotope. H_{in} correlates strongly with ^{226}Ra (0.95) and ^{232}Th (0.68), and very strongly with Ra_{eq} (0.99), highlighting their importance in internal exposure pathways. ADR has very strong correlations with ^{232}Th (0.96) and ^{226}Ra (0.91), strongly with Ra_{eq} (r=1), H_{ex} (r=1), H_{in} (r=0.99) and weak with ^{40}K (r= –0.18), showing that absorbed dose rate is mainly controlled by ^{232}Th and ^{226}Ra.

^{226}Ra and ^{232}Th are the primary contributors to both external and internal hazards, while ^{40}K, despite its abundance, has little influence on hazard indices or dose rates. This means worker protection and monitoring should focus on uranium/thorium series radionuclides, with gamma monitoring and dust suppression prioritized to manage the risks they drive.

3.4.2 Descriptive Statistical Analysis

Table 7. Descriptive analysis of activity concentration of coal, soil and coal waste

Description	N	Mean	SD	Sum	Min	Max
^{226}Ra	19	63	25	1201	32	105
^{232}Th	19	51	30	962	0	96
^{40}K	19	88	26	1666	49	144
Ra_{eq}	19	142	63	2704	38	247
H_{ex}	19	0.38	0.17	7.3	0.10	0.67
H_{in}	19	0.56	0.23	11	0.19	0.95
ADR	19	61	28	1160	16	107

Across the 19 samples, ^{226} Ra averaged 63 Bq/kg (SD 25, range 32 –105, sum 1201), while ^{232}Th averaged 51 Bq/kg (SD 30, range 0 – 96, sum 962). ^{40}K was much higher, with a mean of 88 Bq/kg (SD 26, range 49 – 144, sum 1666). The derived indices show Ra_{eq} averaged 142 Bq/kg (SD 63, range 38 – 247, sum 2704), H_{ex} averaged 0.38 (SD 0.17, range 0.10–0.67, sum 7.3), and H_{in} averaged 0.56 (SD 0.23, range 0.19 – 0.95, sum 11). The absorbed dose rate (ADR) averaged 61 nGy/h (SD 28, range 16 – 107, sum 1160). These values show that while ^{40}K is the most abundant radionuclide, all hazard indices (Ra_{eq}, H_{ex}, H_{in}) remain well below international safety limits, and ADR is slightly higher than the global soil average (60 nGy/h), indicating slight high radiological risk in coal, soil and coal waste.

4.0 DISCUSSION

Mean activity concentrations of ^{226}Ra (47 Bq/kg in coal; 88 Bq/kg in coal waste) and ^{232}Th (37 Bq/kg in coal; 72 Bq/kg in coal waste) exceeded UNSCEAR world averages of 35 and 30 Bq/kg, respectively [16], consistent with the established enrichment of uranium- and thorium-bearing minerals in carbonaceous sedimentary deposits. Coal extraction and thermal processing mechanically redistribute these minerals into waste fractions [18], and Habib et al. [3] demonstrated that coal combustion residuals contain up to 3.37 times the radionuclide concentration of parent feed coal. Comparable NORM enrichment in coal ash and waste has

been reported in China [19], Turkey[20], India [21], and Nigeria [4]. Elevated concentrations in coal waste stockpiles constitute long-term diffuse contamination sources through erosion, leaching, and aeolian dust transport [22]. The moderate and geochemically independent behaviour of ^{40}K reflects its association with aluminosilicate minerals rather than the uranium–thorium decay chains [22], confirming a TENORM scenario warranting regulatory oversight.

External gamma radiation accounted for more than 99% of the total effective dose (0.972 mSv/y), driven by gamma-emitting progeny of ^{238}U and ^{232}Th decay series, consistent with the IAEA's identification of these nuclides as dominant contributors to gamma dose in open-surface NORM industries [23]. The negligible inhalation and ingestion contributions reflect the open topography of the site, which promotes dust dispersion and limits radon accumulation. Nevertheless, Yadav et al. [21] documented measurable inhalation doses for surface coal mine workers in India during dry-season dust events, and long-term inhalation of alpha-emitting ^{226}Ra and its progeny carries carcinogenic risk not captured by point-in-time assessments [24]. Dust suppression, respiratory protection, and gamma dose-rate monitoring therefore remain essential occupational health priorities.

All derived hazard parameters radium equivalent activity (R_{aeq}; 101 Bq/kg soil, 197 Bq/kg coal waste), external hazard index (H_{ex} = 0.3) and internal hazard index (H_{in}; mean 0.56) remained below internationally accepted limits (370 Bq/kg; unity), indicating no immediate radiological threat, in agreement with Kolo et al. [4], Siraz et al. [25], and Onwuka et al. [26]. However, the absorbed dose rate in coal waste (85 nGy h^{-1}) marginally exceeded the 60 nGy h^{-1} UNSCEAR benchmark [16] a pattern analogous to the 200.1 nGy h^{-1} recorded in Barapukuria combustion residuals [27]. Although sub-threshold values preclude acute risk, the linear no-threshold model under ICRP guidelines [28] supports continued vigilance against cumulative chronic exposure, necessitating proactive waste containment and monitoring.

^{226}Ra and ^{232}Th were strongly inter-correlated (r = 0.76), reflecting co-occurrence within uranium thorium-bearing accessory minerals and parallel geochemical behaviour during weathering consistent with Huang et al. [22] (r = 0.724, South China) and Walencik-Łata and Smołka-Danielowska [29] (Upper Silesian coal combustion products, Poland). Both radionuclides correlated strongly with all hazard indices (R_{aeq}, H_{ex}, H_{in}, ADR), confirming their status as primary radiological risk drivers, as similarly demonstrated by Tettey-Larbi et al. [30] across Ghanaian mining communities. The weak negative correlations of ^{40}K with both series (r = −0.28 with ^{226}Ra; r = −0.13 with ^{232}Th) confirm its geochemical independence, implying that monitoring programmes should prioritise uranium- and thorium-series nuclides as the most resource-efficient risk indicators.

Key limitations include: a small sample size that may underrepresent spatial NORM variability [22]; absence of seasonal data on radon exhalation, dust generation, and hydrological radionuclide transport [31]; no direct ^{222}Rn measurement, despite radon's IARC Group 1 carcinogen classification [32]; and no assessment of co-occurring potentially toxic elements (PTEs) or their synergistic interaction with ionising radiation Yan et al. [33] demonstrated significant carcinogenic and non-carcinogenic PTE risks in Chinese coal-mine water. Radionuclide transfer into groundwater and the food chain was also unquantified, limiting public health characterisation [22]. Future work should adopt multi-compartment, longitudinal designs integrating radionuclides and PTEs, supported by GIS-based radiological mapping, Monte Carlo probabilistic exposure modelling, bioaccumulation factor analysis, and epidemiological surveillance to generate the evidence base needed for robust, site-specific radiation protection policy.

5.0 Conclusion

This study measured the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in coal, soil, and coal waste samples from the investigated mining area and assessed their associated radiological hazards. The mean activity concentrations of ^{226}Ra (47 ± 3 Bq/kg in coal; 88 ± 1 Bq/kg in coal waste) and ^{232}Th (37 ± 1 Bq/kg in coal; 72 ± 2 Bq/kg in coal waste) exceeded the corresponding UNSCEAR world average values, confirming that coal mining and processing activities have enhanced naturally occurring radioactive material (NORM) concentrations, particularly in coal waste products, while ^{40}K concentrations remained within or close to reported global ranges.

External gamma radiation was established as the overwhelmingly dominant exposure pathway, contributing more than 99.7% of the total effective dose (0.972 mSv/y) to workers, with inhalation accounting for less than 1% and ingestion representing a negligible fraction. This finding indicates that occupational radiological risk at this site is governed primarily by direct gamma irradiation from ^{226}Ra, ^{232}Th, and ^{40}K present in coal, soil, and waste materials, underscoring the importance of minimising workers' direct contact time with these matrices and implementing continuous gamma dose-rate monitoring programmes.

All calculated radiological hazard parameters, including radium equivalent activity (R_{aeq}; mean 101 Bq/kg in soil, 197 Bq/kg in coal waste), the external hazard index (H_{ex} = 0.3 for both soil and coal waste), and the internal hazard index (H_{in}; mean 0.56 across all matrices), remained below their respective internationally accepted safety limits, indicating no significant immediate radiological threat to workers or surrounding communities. However, the absorbed dose rate in coal waste (85 nGy h^{-1}) marginally exceeded the global benchmark of 60 nGy h^{-1}, signalling the potential for cumulative long-term exposure if coal waste disposal and management practices are not adequately regulated and monitored.

Correlation analysis confirmed that ^{226}Ra and ^{232}Th are the principal drivers of all radiological hazard indices and absorbed dose rates, exhibiting strong positive inter-correlations (r = 0.76) that reflect a common geological origin and parallel geochemical behaviour in the sampled matrices. In contrast, ^{40}K behaved independently, showing weak negative correlations with the uranium- and thorium-series radionuclides and contributing negligibly to derived hazard metrics. These results establish that environmental monitoring and worker radiation protection programmes should prioritise the uranium- and thorium-series radionuclides, and that gamma radiation monitoring combined with dust suppression measures represents the most effective risk mitigation strategy for this setting.

Declaration

Author Contribution Statement

Phillimon Shaba: Conceived and designed the experiments; performed the experiments; Analysed and interpreted the data; wrote the manuscript article.
Patrick Hayumbu: Contributed through supervision of the works, checked all the experiments, analysed data, results, and manuscript reviews.
Alick Muvundika; Contributed reagents, materials, analysis tools and manuscript reviews.

Funding Statement

Phillimon Shaba was supported by the National Institute for Scientific and Industrial Research through the institutes R&D Funding, Zambia.

Competing Interest Statement

The authors declare no conflict of interest.

Additional information

The authors extend sincere thanks to the management administration of Collum coal mine services limited for granting us access to the mine and their employees.

REFERENCES

[1] S. Jalil and M. Rashid, 'Analysis of natural radioactivity in coal and ashes from a coal fired power plant', *Chem. Eng. Trans.*, vol. 45, pp. 1549–1554, 2015, doi: 10.3303/CET1545259.

[2] P. Hayumbu, M. B. Zaman, and S. S. Munsanje, 'Natural radioactivity of Zambian coal and coal ash', *J. Radioanal. Nucl. Chem.*, vol. 201, no. 4, pp. 333–346, 1995, doi: 10.1007/BF02164053.

[3] M. A. Habib *et al.*, '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.*, vol. 191, no. 1, Jan. 2019, doi: 10.1007/s10661-018-7160-y.

[4] M. T. Kolo, M. U. Khandaker, Y. M. Amin, and W. H. B. Abdullah, 'Radiological Implications of coal-mining Activities in Maiganga coalfield of North-Eastern Nigeria', *Earth Systems and Environment*, vol. 1, no. 2, pp. 1–6, Dec. 2017, doi: 10.1007/s41748-017-0013-y.

[5] World Nuclear Association, 'Naturally Occurring Radioactive Materials (NORM) - Coal', website page. Accessed: Jan. 24, 2024. [Online]. Available: https://www.world-nuclear.org/information-library/safety-and-security/radiation-and-health/naturally-occurring-radioactive-materials-norm.aspx

[6] Q. Wu, L. Han, M. Xu, H. Zhang, B. Ding, and B. Zhu, 'Effects of occupational exposure to dust on chest radiograph, pulmonary function, blood pressure and

electrocardiogram among coal miners in an eastern province, China', *BMC Public Health*, vol. 19, no. 1, p. 1229, Sep. 2020, doi: 10.1186/s12889-019-7568-5.

[7] P. Hayumbu *et al.*, 'Status of radon dosimetry in Zambian underground mines', in *IAEA-TECDOC-1472*, Vienna, Austria: International Atomic Energy Agency, 2005, pp. 162–170.

[8] I. A. Nyambe and O. Dixon, 'Sedimentology of the Madumabisa Mudstone Formation (Late Permian), Lower Karoo Group, mid-Zambezi Valley Basin, Southern Zambia', *Journal of African Earth Sciences*, vol. 30, no. 3, pp. 535–553, Apr. 2000, doi: 10.1016/S0899-5362(00)00037-3.

[9] A. Faanu, E. O. Darko, and J. H. Ephraim, 'Determination of natural radioactivity and hazard in soil and rock samples in a mining area in Ghana', *West African Journal of Applied Ecology*, vol. 19, no. 1, pp. 77–92, 2012.

[10] C. Schandorf, R. Agalga, and E. O. Darko, 'Preliminary study on the levels of natural radionuclides in sediments of the Tono irrigation dam, Navrongo', 2013. [Online]. Available: https://www.researchgate.net/publication/258835849

[11] J. A. Ademola and U. C. Onyema, 'Assessment of Natural Radionuclides in Fly Ash Produced at Orji River Thermal Power Station, Nigeria and the Associated Radiological Impact', *Nat. Sci. (Irvine).*, vol. 06, no. 10, pp. 752–759, 2014, doi: 10.4236/ns.2014.610075.

[12] J. Mudiwa, E. Darko, and A. Faanu, 'Radiological hazard assessment for fly ash and environmental materials from Morupule a coal - fired power station in Botswana', *Int. J. Adv. Res. (Indore).*, vol. 6, no. 10, pp. 825–829, Sep. 2018, doi: 10.21474/IJAR01/7876.

[13] B. A. Almayahi, A. A. Tajuddin, and M. S. Jaafar, 'Radiation hazard indices of soil and water samples in Northern Malaysian Peninsula', *Applied Radiation and Isotopes*, vol. 70, no. 11, pp. 2652–2660, Nov. 2012, doi: 10.1016/j.apradiso.2012.07.021.

[14] UNSCEAR, 'Ionising radiation: sources and biological effects', IOP Publishing Ltd, Geneva, 1982. doi: 10.1887/0750308257/b582v1c7.

[15] UNSCEAR, 'Ionising radiation: sources and biological effects', IOP Publishing Ltd, Geneva, 1982. doi: 10.1887/0750308257/b582v1c7.

[16] UNSCEAR, 'Sources and effects of ionizing radiation, united nations scientific committee on the effects of atomic radiation UNSCEAR 2000 report to the general assembly, with scientific annexes', Geneva, 2000. doi: 10.1097/00004032-199907000-00007.

[17] OriginLab Corporation, 'OriginPro user guide manual 2026', 2025, *Northampton*.

[18] N. E. Lauer, J. C. Hower, H. Hsu-Kim, R. K. Taggart, and A. Vengosh, 'Naturally occurring radioactive materials in Coals and Coal combustion residuals in the United States', *Environ. Sci. Technol.*, vol. 49, no. 18, pp. 11227–11233, Sep. 2015, doi: 10.1021/ACS.EST.5B01978/SUPPL_FILE/ES5B01978_SI_001.PDF.

[19] X. Lu, L. Y. Li, F. Wang, L. Wang, and X. Zhang, 'Radiological hazards of coal and ash samples collected from Xi'an coal-fired power plants of China', *Environ. Earth Sci.*, vol. 66, no. 7, pp. 1925–1932, Aug. 2012, doi: 10.1007/s12665-011-1417-x.

[20] U. Cevik, N. Damla, and S. Nezir, 'Radiological characterization of Cayırhan coal-fired power plant in Turkey', *Fuel*, vol. 86, no. 16, pp. 2509–2513, Nov. 2007, doi: 10.1016/j.fuel.2007.02.013.

[21] A. K. Yadav, S. K. Sahoo, P. Lenka, A. V. Kumar, and R. M. Tripathi, 'Assessment of radionuclide concentration and radiation dose in rock in Singrauli Coalfield, India', *J. Hazard. Toxic Radioact. Waste*, vol. 24, no. 1, Jan. 2020, doi: 10.1061/(ASCE)HZ.2153-5515.0000458.

[22] H. Li *et al.*, 'Geochemical distribution and environmental risks of Radionuclides in soils and sediments runoff of a uranium mining area in South China', *Toxics*, vol. 12, no. 1, Jan. 2024, doi: 10.3390/toxics12010095.

[23] IAEA, 'International Atomic Energy Agency: Workers in industrial processes involving NORM; Occupational radiation protection. Vienna', https://www.iaea.org. Accessed: May 10, 2026. [Online]. Available: https://www.iaea.org/services/networks/orpnet/workers-and-radiation-at-workplaces/workers-in-industrial-processes-involving-norm

[24] M. Wysocka, K. Skubacz, I. Chmielewska, P. Urban, and M. Bonczyk, 'Radon migration in the area around the coal mine during closing process', *Int. J. Coal Geol.*, vol. 212, p. 103253, Aug. 2019, doi: 10.1016/j.coal.2019.103253.

[25] M. M. M. Siraz *et al.*, 'Radioactivity in soil and coal samples collected from the vicinity of the coal-fired thermal power plant and evaluation of the associated hazard parameters', *Int. J. Environ. Anal. Chem.*, vol. 104, no. 19, pp. 8185–8202, Dec. 2024, doi: 10.1080/03067319.2023.2196021.

[26] J. C. Onwuka, E. E. Jasper, and S. T. Orunsami, 'Influence of open cast mining on radiological health risk of agricultural soils around Adudu lead–zinc mine, Nasarawa State, Nigeria', *Environ. Forensics*, vol. 27, no. 1, pp. 22–36, Jan. 2026, doi: 10.1080/15275922.2022.2125117.

[27] M. A. Habib *et al.*, '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.*, vol. 191, no. 1, Jan. 2019, doi: 10.1007/s10661-018-7160-y.

[28] ICRP, 'Use of dose quantities in radiological protection. ICRP Publication 147. Ann. ICRP 50(1)', 2021. [Online]. Available: http://journals.sagepub.com.

[29] A. Walencik-Łata and D. Smołka-Danielowska, '234U, 238U, 226Ra, 228Ra and 40K concentrations in feed coal and its combustion products during technological processes in the Upper Silesian Industrial Region, Poland', *Environmental Pollution*, vol. 267, p. 115462, Aug. 2020, doi: 10.1016/j.envpol.2020.115462.

[30] L. Tettey-Larbi *et al.*, 'Industrial activities and their role in future radiological pollution in developing countries: Comprehensive environmental radiation assessment

of enhanced radionuclide dispersion in Ghanaian mining areas', *Int. J. Environ. Res.*, vol. 20, no. 3, p. 129, Apr. 2026, doi: 10.1007/s41742-026-01085-6.

[31] M. L. Legasu and A. K. Chaubey, 'Evaluation of natural radioactivity level in Delanta-Dawunt, Wollo District, Ethiopia', *Int. J. Environ. Anal. Chem.*, vol. 103, no. 20, pp. 9452–9465, Dec. 2023, doi: 10.1080/03067319.2021.2011257.

[32] K. Skubacz, B. Michalik, and M. Wysocka, 'Occupational radiation risk caused by NORM in coal mining industry', *Radioprotection*, vol. 46, no. 6, pp. S669–S674, Jan. 2011, doi: 10.1051/radiopro/20116735s.

[33] Y. Yan *et al.*, 'Source apportionment and human health risks of potentially toxic elements in the surface water of coal mining areas', *Toxics*, vol. 12, no. 9, p. 673, Sep. 2024, doi: 10.3390/toxics12090673.