

Gamma Spectrometric Analysis of Natural Radionuclides and Radiological Hazards in Ilmenite Sand

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ABSTRACT. Ilmenite sand, categorized as Naturally Occurring Radioactive Material (NORM), contains radionuclides derived from the uranium and thorium decay series. The present work investigates radionuclide concentrations in ilmenite sand collected from a mineral processing facility to evaluate associated radiological hazards using gamma spectrometry. Activity measurements were performed with a gamma spectrometry system calibrated for energy and efficiency using a Eu-152 reference source. Environmental background radiation was measured separately to correct spectral data during analysis. Prior to measurement, samples were dried, homogenized, and sealed in airtight containers to establish radioactive equilibrium between parent radionuclides and their progeny. Radionuclide activities were quantified based on characteristic gamma-ray peak energies. The measured activity concentrations were 472.98 Bq/kg for Ra-226, 302.20 Bq/kg for Th-232, and 10.68 Bq/kg for K-40. Radiological hazard parameters, including radium equivalent activity (Raeq), external hazard index (Hex), internal hazard index (Hin), and absorbed dose rate, were subsequently calculated. The estimated annual effective dose was 0.492 mSv/year, remaining below the recommended public exposure limit of 1 mSv/year. These findings indicate that, despite relatively elevated radionuclide activities, the resulting radiation exposure levels remain within acceptable safety limits. Overall, gamma spectrometry demonstrates reliable capability for radionuclide identification and radiological risk assessment in mineral-based materials.

1. INTRODUCTION

Ilmenite sand is an iron–titanium oxide mineral (FeTiO_3) that is widely used as an industrial raw material, particularly in the production of titanium dioxide, pigments, and various advanced material applications. In addition to its primary mineral constituents, ilmenite deposits may include naturally occurring radionuclides derived from uranium (^{238}U) and thorium (^{232}Th) decay chains. Naturally Occurring Radioactive Materials (NORM) describe materials that contain radionuclides derived from natural sources and may represent a source of radiation exposure to humans and the surrounding environment [1].

Mining and mineral processing activities can lead to the redistribution and increased concentration of natural radionuclides due to separation and mineral beneficiation processes. Radionuclides such as Ra-226, Th-232, and K-40 emit gamma radiation with high penetration capability, potentially leading to both external and internal radiation exposure pathways [2]. Consequently, assessing radionuclide activity concentrations together with radiological hazard indices is important for radiation protection and environmental safety evaluation in mineral-related studies.

Gamma spectrometry is a widely used technique in environmental radioactivity analysis because it allows for non-destructive identification of radionuclides based on their characteristic gamma-ray energies. This method offers several advantages, including high sensitivity, simultaneous multi-nuclide analysis capability, and good accuracy in determining radionuclide activity concentrations [3]. The obtained radionuclide activity data can subsequently be used to calculate radiological hazard parameters such as radium equivalent activity (Raeq), external hazard index (Hex), internal hazard index (Hin), and absorbed dose rate as indicators of radiation exposure risk levels [4].

Several previous studies have reported the presence of natural radionuclides in heavy mineral sands from various regions worldwide [5,6,7], with concentration variations influenced by geological conditions and mineral

processing techniques. In addition to natural geological variation, the distribution of radionuclides in ilmenite can be significantly influenced by mineral processing steps such as gravity separation, magnetic separation, and chemical treatments. These processes may selectively concentrate heavy mineral fractions, where uranium- and thorium-bearing phases are preferentially accumulated, leading to potential radionuclide enrichment in the processed product [2,8].

While previous studies have predominantly focused on natural or raw heavy mineral sands, this study specifically investigates ilmenite sand obtained from a mineral processing facility. This distinction is important because processing conditions can alter the distribution, concentration, and radiological characteristics of radionuclides. Therefore, this work not only provides baseline activity data but also offers insight into the effect of mineral processing on radionuclide enrichment and associated radiological hazards.

In this work, the activity concentrations of natural radionuclides in ilmenite sand were measured using gamma spectrometry, followed by an evaluation of radiological hazard parameters to assess environmental radiation safety. In addition to physical separation processes, chemical treatments such as acid leaching are commonly applied in ilmenite processing to remove impurities and improve mineral purity. These processes can significantly influence the behavior of radionuclides, as uranium- and thorium-bearing phases may be partially dissolved, redistributed, or concentrated depending on their chemical stability and association with mineral matrices. During acid treatment, more reactive mineral components may be selectively removed, while less soluble radionuclide-bearing phases remain, potentially leading to relative enrichment in the final product. Such geochemical processes highlight the importance of considering both physical and chemical transformations when evaluating radionuclide distribution in processed mineral materials [2,8].

2. MATERIALS AND METHODS

2.1 Materials and Sample Preparation Procedures

The analyzed samples consisted of ilmenite sand categorized as Naturally Occurring Radioactive Material (NORM), referring to naturally derived materials that may contain radionuclides originating from the uranium (^{238}U) and thorium (^{232}Th) decay chains. NORM materials are known to contribute to environmental radiation exposure due to the accumulation of natural radionuclides in heavy minerals [1,2,9,10].

Sample preparation was conducted to obtain homogeneous and representative conditions for radioactivity measurements. Prior to measurement, the collected samples were oven-dried at approximately 105 °C for 24 h to eliminate residual moisture. The dried material was subsequently ground and thoroughly homogenized to obtain a uniform particle distribution. Each homogenized sample was then weighed and transferred into polyethylene containers of fixed geometry, which were tightly sealed to minimize radon gas escape. After sealing, the samples were stored for approximately 28 days to allow secular equilibrium to be established between parent radionuclides and their progeny, ensuring optimal detection of gamma-emitting radionuclides during measurement [1,11].

A total of 3 ilmenite sand samples were collected from a mineral processing facility to represent processing variability. The samples were obtained from the processed ilmenite fraction. Each sample had an approximate mass of 1 kg prior to gamma spectrometric analysis.

2.2 Gamma Spectrometric Measurement

Radionuclide activity measurements were performed using a gamma spectrometry system consisting of a high-purity germanium (HPGe) detector, a multichannel analyzer (MCA), and dedicated spectrum analysis software. The detector was enclosed in a lead shielding system to minimize background radiation. Gamma spectrometry is a non-destructive technique widely used in environmental radioactivity studies due to its high energy resolution and ability to identify radionuclides through characteristic gamma-ray emissions [3,12,13].

Before sample analysis, energy calibration was performed using a Eu-152 reference source to establish the relationship between gamma-ray energy and channel number, as described in Equation (1):

$$E = a + bC \quad (1)$$

where E represents the gamma-ray energy (keV), C denotes the channel number, while a and b correspond to the calibration constants. Detector efficiency calibration was subsequently determined using Equation (2):

where ε denotes the detector efficiency, N represents the net count, A corresponds to the activity of the standard source (Bq), P_γ indicates the gamma emission probability, and t refers to the counting time (s) [3]. Background measurements were carried out using an empty container with identical geometry prior to sample counting to minimize the contribution of environmental radiation to the measured spectra. Each sample was counted for a live time of 24 h to ensure adequate counting statistics. Spectrum acquisition and peak identification were performed using a dedicated gamma spectrometry analysis software (GENIE 2000 system), applying standard peak fitting and net peak area analysis procedures.

The minimum detectable activity (MDA), also referred to as the detection limit, was considered to evaluate the capability of the gamma spectrometry system in detecting low-activity radionuclides. The MDA depends on background count rates, counting time, detector efficiency, and gamma emission probability, following the Currie method, which is widely used in radiation measurement analysis. Although the MDA values were not explicitly calculated in this study, the relatively long counting time (24 h) and the use of a low-background shielding system are expected to enhance the detection sensitivity. Therefore, low-intensity gamma peaks are likely distinguishable from background fluctuations under the applied measurement conditions.

2.3 Determination of Activity Concentration

Radionuclide activity was determined based on the characteristic gamma-ray peak energies identified in the measured spectra. The radionuclide activity concentration was calculated using Equation (3):

$$A = \frac{C}{\varepsilon \cdot P_\gamma \cdot m \cdot t} \quad (3)$$

where A is the radionuclide activity (Bq/kg), C is the net count, ε is the detector efficiency, P_γ is the gamma emission probability, m is the sample mass (kg), and t is the counting time (s). This method is commonly used in environmental radioactivity analysis using gamma spectrometry [4,12,14]. Radionuclides from the uranium and thorium decay series were identified through the gamma-ray energies of their decay products under radioactive equilibrium conditions.

2.4 Radiological Hazard Assessment

Radiological hazard assessment was carried out using standard parameters recommended by UNSCEAR to evaluate environmental radiation exposure levels [1]. The radium equivalent activity (R_{aeq}) was determined according to Equation (4):

$$R_{aeq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (4)$$

The external hazard index (H_{ex}) was determined using:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (5)$$

The internal hazard index was calculated using:

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (6)$$

These parameters are commonly applied in radiological risk evaluations of natural materials and Naturally Occurring Radioactive Materials (NORM) [6,8].

2.5 Absorbed Dose Rate and Annual Effective Dose Assessment

The absorbed dose rate in air was estimated using conversion factors recommended by UNSCEAR:

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (7)$$

The annual effective dose was subsequently estimated using:

$$AED = D \times 8760 \times 0.7 \times 0.2 \quad (8)$$

where 8760 represents the total number of hours in one year, 0.7 Sv/Gy denotes the dose conversion coefficient, and 0.2 corresponds to the outdoor occupancy factor. These parameters are widely used in the evaluation of environmental radiation exposure from NORM materials [1,15].

3. RESULTS AND DISCUSSION

3.1 Gamma Spectrometer Energy Calibration

The uncertainty in the activity concentration primarily arises from counting statistics, detector efficiency calibration, and energy calibration. In this study, the uncertainty of the final activity was represented by the standard deviation of replicate measurements.

Energy calibration was conducted to establish the relationship between gamma-ray energy and the corresponding detector channel number, as described in Equation (1). This step is crucial because radionuclide identification depends on the accuracy of the energy peak positions detected by the gamma spectrometry system [3]. The calibration data obtained from the Eu-152 standard source are presented in Table 1.

Table 1. Energy calibration results of the Eu-152 standard source

Energy (keV)	121.78	244.69	344.28	443.98	778.9	963.43	1112.08	1498.03
Channel Number	459	924	1303	1676	2941	3640	4200	5318

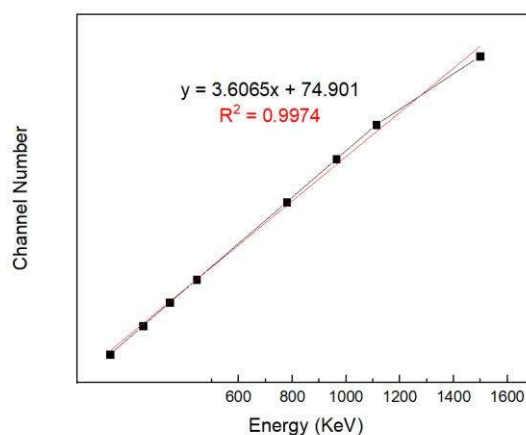


Figure 1. Energy calibration curve using Eu-152 standard source

The relationship between gamma-ray energy and channel number is illustrated in Figure 1. The calibration results demonstrate a strong linear correlation ($R^2 > 0.99$), confirming the stability and reliability of the detection system. This linearity ensures accurate identification of characteristic gamma-ray energies without significant deviation. A reliable energy calibration is essential for subsequent analyses, as inaccuracies in energy determination may directly affect radionuclide activity calculations [3].

3.2 Detector Efficiency Calibration

The detector efficiency was calculated using Equation (2). Detector efficiency describes the ability of the system to record gamma photons emitted by radioactive sources and serves as a correction factor in radionuclide activity calculations to ensure accurate results [3,12]. The efficiency calibration data obtained from the Eu-152 standard source are presented in Table 2.

Table 2. Efficiency calibration data of Eu-152 standard source

Energy (keV)	Counts	CPS	Activity (dps)	Probability	Efficiency
121.6	536849	149.1247	25308.66011	0.282	0.020894
244.56	105388	29.27444	25308.66011	0.0738	0.015673
343.92	320305	88.97361	25308.66011	0.264	0.013316
443.79	31945	8.873611	25308.66011	0.0308	0.011384
778.57	79508	22.08556	25308.66011	0.13	0.006713
963.64	74827	20.78528	25308.66011	0.1448	0.005672
1111.35	61418	17.06056	25308.66011	0.1335	0.005049
1406.95	71016	19.72667	25308.66011	0.207	0.003765

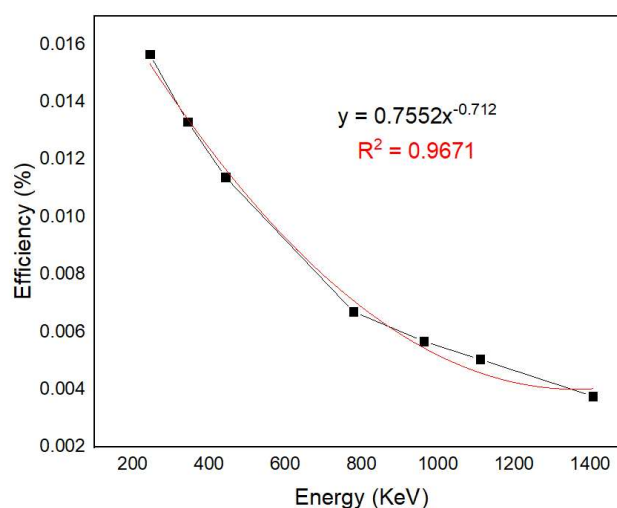


Figure 2. Efficiency calibration curve of the Eu-152 standard source

The variation of detector efficiency as a function of gamma-ray energy is illustrated in Figure 2. The calibration results show that the detector efficiency decreases with increasing gamma-ray energy. This behavior is consistent with radiation interaction theory, in which the probability of the photoelectric effect decreases at higher energies

while Compton scattering becomes dominant [3]. The resulting efficiency curve was subsequently used in the calculation of radionuclide activities in Equation (3).

3.3 Gamma Spectrum and Radionuclide Identification

The gamma spectrum obtained from sample counting exhibits several characteristic energy peaks originating from natural radionuclides. The background counting results used for spectral correction are presented in Table 3. The identification of radionuclides was performed by considering peak significance relative to background counts, ensuring that only statistically reliable peaks were included in the analysis.

Table 3. Background counting results

Nuclide	Energy (keV)	Background Counts	Background CPS
Pb 210	46.52	38	0.000439815
Th 234	63.29	105	0.001215278
U 235	143.76	172	0.001990741
Ra 226	185.99	541	0.006261574
Pb 212	238.63	562	0.00650463
Pb 214	295.22	75	0.000868056
Ac 228	338.40	80	0.000925926
Pb 214	351.99	414	0.004791667
Tl 208	583.14	161	0.001863426
Bi 214	609.32	811	0.009386574
Bi 212	727.17	98	0.001134259
Tl 208	860.47	21	0.000243056
Ac 228	911.07	190	0.002199074
Ac 228	968.90	160	0.001851852
Bi 214	1120.28	163	0.001886574
K 40	1460.75	3337	0.038622685
Bi 214	1764.51	248	0.00287037

Radionuclides detected in the samples originated from the uranium (^{238}U) decay series, represented by ^{214}Pb and ^{214}Bi , and from the thorium (^{232}Th) decay series, represented by ^{228}Ac and ^{208}Tl , along with the naturally occurring radionuclide ^{40}K observed at an energy of 1460 keV. The identification of low-intensity peaks such as ^{210}Pb and ^{235}U was evaluated with respect to the calculated MDA, ensuring that the detected signals are above the minimum detection limits of the system.

The presence of these radionuclides confirms that the material falls into the category of Naturally Occurring Radioactive Material (NORM), which is commonly found in heavy minerals due to natural geochemical enrichment processes [1,2]. Similar phenomena have been reported in various studies on sediment radioactivity

and mineral materials across different regions worldwide [5,6,10]. The storage of samples for approximately 28 days allowed secular equilibrium to be achieved, enabling the activity of parent radionuclides to be accurately represented by their decay products [1].

3.4 Activity Concentration of Natural Radionuclides

The activity concentration of radionuclides was determined using Equation (3). The calculated activity concentrations are presented in Table 4. The reported values represent the mean of three samples, and the associated uncertainties correspond to the standard deviation (SD).

Table 4. Calculated radionuclide activities

Sample	Ra 226 (Bq/kg)	Th 232 (Bq/kg)	K 40 (Bq/kg)
Ilmenite Sand (Mean \pm SD)	473 \pm 30	302 \pm 4	10.7 \pm 0.43

The activity concentrations of ^{226}Ra (473 Bq/kg) and ^{232}Th (302 Bq/kg) measured in this study significantly exceed the global average values reported by UNSCEAR, which are 35 Bq/kg and 30 Bq/kg, respectively [1]. Specifically, the Ra-226 activity is approximately 13.5 times higher, while Th-232 is about 10 times higher than the corresponding global averages. Compared to previous studies on natural and processed mineral materials, the obtained values are also higher than those reported by El-Taher [16] and Uosif and El-Taher [6], indicating a notable enrichment of radionuclides in the processed ilmenite fraction. This enrichment is likely associated with mineral processing techniques that preferentially concentrate heavy mineral phases containing uranium and thorium during beneficiation processes [2,8]. In addition, chemical treatments such as acid leaching may further enhance radionuclide concentration through selective dissolution of mineral phases [8].

Therefore, the elevated radionuclide levels observed in this study are not solely controlled by geological formation but are also influenced by processing-induced redistribution mechanisms. This highlights the importance of evaluating processed mineral products separately from raw deposits in radiological assessments. In contrast, the activity of ^{40}K remains relatively low due to the limited presence of potassium-bearing phases in ilmenite mineral structures.

3.5 Radiological Hazard Assessment

The radionuclide activities were used as input to calculate the radiological hazard parameters using Equations (4)–(6). The calculated values of radium equivalent activity (Raeq), external hazard index (Hex), internal hazard index (Hin), absorbed dose rate (D), and annual effective dose (E) are presented in Table 5.

Table 5. The radium equivalent activity (Raeq), internal hazard index (Hin), external hazard index (Hex), and absorbed dose rate (D) were determined for each sample.

Sample	Raeq	Hex	Hin	D (nGy/h)	E (mSv/y)
Ilmenite Sand	906	2.45	3.73	401	0.49

It should be noted that the calculated hazard indices are based on mean activity values and may be influenced by measurement uncertainties associated with radionuclide determination. Although the annual effective dose (0.492 mSv/year) remains below the recommended public exposure limit of 1 mSv/year, the calculated Raeq value (906 Bq/kg) significantly exceeds the recommended limit of 370 Bq/kg established by UNSCEAR [1]. Furthermore, the external hazard index (Hex = 2.45) and internal hazard index (Hin = 3.73) are both greater than unity, indicating potential radiological risks, particularly under conditions of prolonged exposure or occupational handling. These findings suggest that relying solely on the annual effective dose may lead to an underestimation of radiological impacts. Therefore, a more cautious interpretation is required when evaluating the safety of the material, especially in the context of long-term exposure or industrial applications. This hazard index approach has been widely used in the radiological risk assessment of environmental materials and industrial NORM materials [15,16,17].

3.6 Absorbed Dose Rate and Annual Effective Dose Assessment

The absorbed dose rate was determined using Equation (7), resulting in a value of:

$$D = 401.49 \text{ nGy/h}$$

This value exceeds the global average of 59 nGy/h reported by UNSCEAR [1], suggesting a notable contribution of natural radionuclides to environmental radiation exposure.

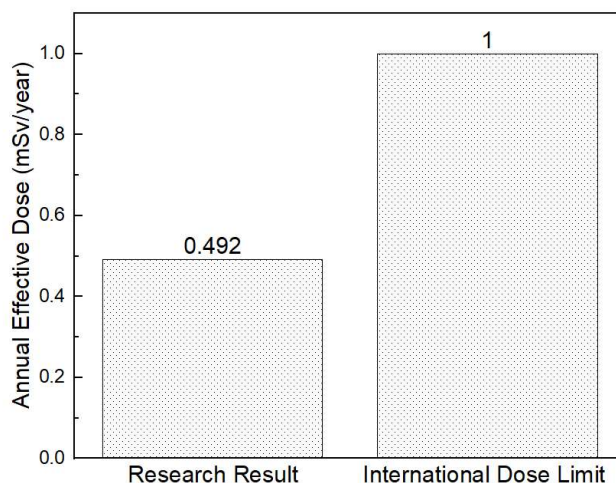


Figure 3. Comparison of the annual effective dose with international safety limits

The comparison of the annual effective dose with international safety limits is illustrated in Figure 3. The annual effective dose calculated using Equation (8) was 0.492 mSv/year, which is still below the international limit for public exposure of 1 mSv/year. These results indicate that although the radionuclide activities and hazard indices are relatively high, the actual exposure level to the public remains within safe limits. Similar findings have also been reported in radiological evaluation studies of mineral materials and other industrial NORM materials [6,7,16].

3.7 Scientific Interpretation

Overall, the findings of this study suggest that the natural radionuclide content in heavy minerals is affected by geochemical concentration mechanisms that promote the enrichment of uranium and thorium within specific mineral phases. This phenomenon represents a common characteristic of NORM materials in the mineral processing industry [2,6,8].

Gamma spectrometry has been demonstrated to be an effective non-destructive technique for radionuclide identification and quantitative radiological risk assessment. The combination of radionuclide activity analysis, hazard indices, and effective dose provides a comprehensive approach to environmental radiation safety assessment, as recommended in numerous previous environmental radioactivity studies [3,4,15,16].

4. CONCLUSION

This study successfully identified the presence of natural radionuclides in ilmenite sand samples using gamma spectrometry. The primary radionuclides originate from the decay series of uranium and thorium, confirming that the material can be classified as Naturally Occurring Radioactive Material (NORM). The activity analysis shows that radionuclides from the uranium and thorium series contribute more significantly than naturally occurring potassium.

The assessment of radiological hazard parameters indicates that the annual effective dose (0.492 mSv/year) remains below the recommended public exposure limit of 1 mSv/year. However, the elevated values of R_{aeq} , H_{ex} , and H_{in} suggest that the material may pose potential radiological concerns under certain exposure scenarios, particularly for long-term or occupational exposure. Therefore, the classification of the material as “safe” should

be interpreted with caution and depends on specific usage and exposure conditions.

Gamma spectrometry has proven to be an effective method for radionuclide identification and radiological risk assessment of mineral materials. This study provides baseline data for radiation safety assessments of mineral processing products and may serve as a reference for further studies involving broader sample coverage and wider geographical areas.

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