

## Environmental Radiological Assessment of Natural Radioactivity Around Al-Fatai'h Cement Plant in Derna, Libya

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التقييم الإشعاعي البيئي للنشاط الإشعاعي الطبيعي حول مصنع أسمنت الفتاح درنة، ليبيا

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### Abstract:

Naturally occurring radioactive materials (NORM) in the environment originate mainly from primordial radionuclides associated with the uranium- (<sup>238</sup>U) and thorium-(<sup>232</sup>Th) decay series, in addition to naturally occurring potassium- (<sup>40</sup>K) present in geological formations and soils. Artificial radionuclides such as Cesium-137 (<sup>137</sup>Cs) and Cobalt-60 (<sup>60</sup>Co) may also be detected in soils, food products, and building materials as a result of radioactive fallout and anthropogenic activities. This study presents the results of a field investigation of natural background radiation levels in agricultural and residential areas surrounding the Al-Fatai'h Cement Plant in Derna , Libya , the surveyed area extended from the coastal highway bridge through the dry valley adjacent to the road leading to the cement plant, up to the satellite district area The study also included raw material quarries, storage hangars, crushers, silos, and residential areas for plant staff. A total of 190 environmental and industrial samples were collected and analyzed using direct gamma-ray spectrometry with a High-Purity Germanium (HPGe) detector. The results showed relatively similar average activity concentrations of radionuclides within each location, with generally low overall natural radiation levels despite geological variations. However, elevated concentrations of Potassium-40 were observed across most sampling sites. This study evaluates the natural radioactivity levels of Potassium-40; Thorium-232; Radium-226 in different locations. The absorbed dose rate (D) and annual effective dose (AED) were calculated using standard radiological conversion factors. The results showed that the absorbed dose rate (D) ranged from 11.92 to 28.16 nGy/h, while the annual effective dose (AED) ranged from 0.015 to 0.035 mSv/y, with mean values of 20.79 nGy/h and 0.026 mSv/y, respectively. These values are lower than the worldwide average values reported by UNSCEAR (59 nGy/h for D and 0.07 mSv/y for AED), indicating that the studied area does not present significant radiological risk. Higher values were observed in mining and industrial-related locations such as Southern Raw Material Processing Area and Crusher & Storage, which may be attributed to elevated concentrations of natural radionuclides in these areas. Overall, all measured values remain within internationally recommended radiological limits, suggesting that the area is radiologically safe for public exposure.

**Keywords:** Natural radioactivity; Gamma-ray spectrometry; Cement raw materials; Potassium 40 - <sup>40</sup>K; Radium- 226- <sup>226</sup>Ra; Thorium- 232 -<sup>232</sup>Th; Annual effective dose.

## المخلص:

تنشأ المواد المشعة الطبيعية (*NORM*) في البيئة بشكل رئيسي من النويدات المشعة الأولية المرتبطة بسلسلة تحلل اليورانيوم- $^{238}U$  والثوريوم- $^{232}Th$ ، بالإضافة إلى البوتاسيوم- $^{40}K$  الموجود طبيعيًا في التكوينات الجيولوجية والتربة، كما يمكن الكشف عن النويدات المشعة الاصطناعية، مثل السيزيوم- $^{137}Cs$  والكوبالت- $^{60}Co$ ، في التربة والمنتجات الغذائية ومواد البناء نتيجةً للتساقط الإشعاعي والأنشطة البشرية. تقدم هذه الدراسة نتائج تحقيق ميداني لمستويات الإشعاع الخلفي الطبيعي في المناطق الزراعية والسكنية المحيطة بمصنع أسمنت الفتاح بمدينة درنة، ليبيا.

امتدت المنطقة التي شملها المسح من جسر الطريق الساحلي السريع مرورًا بالوادي الجاف المجاور للطريق المؤدي إلى مصنع الأسمنت، وصولًا إلى منطقة الحي التابع للمصنع، شملت الدراسة أيضًا محاجر المواد الخام، ومخازن التخزين، والكسارات، والصوامع، والمناطق السكنية للعاملين في المصنع، جُمع ما مجموعه 190 عينة بيئية وصناعية وحُللت باستخدام مطيافية أشعة غاما المباشرة مع كاشف من الجرمانيوم عالي النقاء (*HPGe*). أظهرت النتائج تشابهًا نسبيًا في متوسط تركيزات النشاط الإشعاعي للنويدات المشعة في كل موقع، مع انخفاض عام في مستويات الإشعاع الطبيعي على الرغم من التباينات الجيولوجية. ومع ذلك، لوحظت تركيزات مرتفعة من البوتاسيوم-40 في معظم مواقع أخذ العينات. تقيّم هذه الدراسة مستويات النشاط الإشعاعي الطبيعي للبوتاسيوم-40، والثوريوم-232، والراديوم-226 في مواقع مختلفة. حُسب معدل الجرعة الممتصة (*D*) والجرعة الفعالة السنوية (*AED*) باستخدام معاملات التحويل الإشعاعي القياسية. أظهرت النتائج أن معدل الجرعة الممتصة (*D*) تراوح بين 11.92 و28.16 نانوغراي/ساعة، بينما تراوحت الجرعة الفعالة السنوية (*AED*) بين 0.015 و0.035 ملي سيفرت/سنة، بمتوسط 20.79 نانوغراي/ساعة و0.026 ملي سيفرت/سنة على التوالي. هذه القيم أقل من المتوسطات العالمية التي أوردتها لجنة الأمم المتحدة العلمية المعنية بآثار الإشعاع الذري (59 نانوغراي/ساعة لمعدل الجرعة الممتصة و0.07 ملي سيفرت/سنة للجرعة الفعالة السنوية)، مما يشير إلى أن المنطقة المدروسة لا تشكل خطرًا إشعاعيًا كبيرًا. لوحظت قيم أعلى في مواقع التعدين والمواقع الصناعية، مثل منطقة "ساوث رو إم إنسايد ومنطقة كراشر أند ستوريج، وهو ما قد يُعزى إلى ارتفاع تركيزات النويدات المشعة الطبيعية في هذه المناطق. عمومًا، تقع جميع القيم المقاسة ضمن الحدود الإشعاعية الموصى بها دوليًا، مما يوحي بأن المنطقة آمنة إشعاعيًا للتعرض العام.

**الكلمات المفتاحية:** النشاط الإشعاعي الطبيعي؛ قياس طيف أشعة غاما؛ الأسمنت؛ البوتاسيوم- $^{40}K$ ؛ الراديوم- $^{226}Ra$ ؛ الثوريوم- $^{232}Th$ ؛ الجرعة الفعالة السنوية.

## 1. Introduction:

Naturally occurring radioactive materials (*NORM*) are widely distributed in the Earth's crust and constitute the primary source of environmental ionizing radiation exposure to humans [1,2]. These radionuclides mainly originate from primordial radioactive decay series such as Uranium- ( $^{238}U$ ), Thorium- ( $^{232}Th$ ), and Radium- ( $^{226}Ra$ ), in addition to naturally occurring Potassium- ( $^{40}K$ ). They are commonly present in soils, rocks, sediments, groundwater, and construction materials, while artificial radionuclides may also enter the environment through industrial and anthropogenic activities [1].

Exposure to ionizing radiation is considered an important environmental and public health issue because of its potential long-term biological and radiological effects [2]. Although natural background radiation is unavoidable, elevated exposure levels may increase the risk of genetic damage, carcinogenic effects, and other environmental health hazards. Consequently, continuous environmental monitoring and radiological assessment have become essential components of international radiation protection and environmental safety programs [1,3].

The cement industry is of particular radiological interest because cement manufacturing depends mainly on geological raw materials such as limestone, clay, shale, and gypsum, which may contain varying concentrations of naturally occurring radionuclides depending on their

geological origin [4]. Industrial activities including quarrying, crushing, grinding, clinker production, and raw material storage may further contribute to the redistribution and accumulation of radioactive dust within industrial facilities and surrounding environments [5]. Several international investigations have evaluated natural radioactivity levels and radiological hazards associated with cement raw materials and industrial products in different countries [4–8]. Qadr [4] reported variations in natural radionuclide concentrations and radiological parameters in cement materials from Iraqi Kurdistan, while Turhan et al. [5] investigated radioactivity levels in Turkish cement and associated raw materials. Similarly, Shrestha et al. [6] evaluated radiological hazards in Nepalese cement industries and reported noticeable variations associated with geological composition and industrial processing conditions. These studies demonstrated that cement industries may represent localized sources of technologically enhanced naturally occurring radioactive materials (TENORM), particularly in quarry and dust accumulation zones.

International organizations such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Atomic Energy Agency (IAEA) have emphasized the importance of continuous radiological monitoring in industrial environments associated with naturally occurring radioactive materials [1,3]. However, site-specific environmental radiological data remain essential because radionuclide distribution is strongly influenced by geological, mineralogical, and industrial factors.

In Libya, environmental radiological studies related to cement production facilities remain limited despite the environmental and industrial importance of such regions. To the best of the authors' knowledge, comprehensive radiological assessments of residential, agricultural, quarry, and industrial areas surrounding cement plants are still scarce.

Therefore, establishing baseline radiological data for these industrial environments is important for future environmental monitoring, industrial safety assessment, and sustainable radiological protection planning.

Accordingly, the present study aims to assess natural radioactivity levels and associated radiological hazards in soil and raw material samples collected from agricultural, residential, quarry, and industrial locations surrounding the Al-Fatai'h Cement Plant in Derna, Libya. The activity concentrations of  $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$  were determined using gamma-ray spectrometry with a High-Purity Germanium (HPGe) detector. In addition, absorbed gamma dose rate (D), annual effective dose (AED), radium equivalent activity (Raeq), and external hazard index (Hex) were evaluated using internationally accepted radiological assessment methodologies. The investigated sites included residential areas, agricultural lands, dry valleys, raw material quarries, crushers, silos, storage facilities, and dust accumulation zones associated with cement production activities.

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## 2. Materials and Methods:

The materials and methods applied in the present study were designed to evaluate the natural radioactivity levels and associated radiological parameters in environmental and industrial areas surrounding the Al-Fatai'h Cement Plant in Derna, Libya. The methodology included systematic sample collection, geographical mapping of sampling locations, laboratory preparation of samples, gamma-ray spectrometric measurements using a High-Purity Germanium (HPGe) detector, and calculation of standard radiological indices following internationally accepted procedures. No significant artificial radionuclides such as  $^{137}\text{Cs}$  were detected in the investigated samples above the minimum detectable activity limits.

### 2.1 Sample Collection

A total of **190** environmental and industrial samples were collected from selected residential, agricultural, quarry, and industrial operational zones surrounding the cement plant. Sampling

locations were initially identified using a portable radiation survey meter to ensure representative coverage of areas potentially influenced by cement production activities and raw material handling processes.

### 2.1.1 Study Area Mapping and Geographical Description:

A detailed geographical characterization of the investigated area was performed to enhance the spatial accuracy, methodological robustness, and reproducibility of the radiological assessment. The area surrounding the Al-Fatai'h Cement Plant in Derna, Libya was systematically mapped using Geographic Information System (GIS) techniques in order to identify and visualize the spatial distribution of all environmental and industrial sampling locations.

All generated maps and spatial analyses were produced using GIS software to improve the spatial interpretation and environmental reproducibility of the radiological assessment.



Figure 1

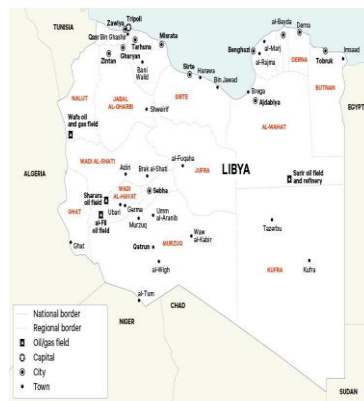


Figure 2



Figure 3

The study area surrounding the Al-Fatai'h Cement Plant in Derna, Libya was systematically mapped using Geographic Information System (GIS) techniques to define the spatial distribution of all sampling locations.

The geographic location map shown in Figures 1, 2, and 3 illustrates the spatial location of the Al-Fatai'h Cement Plant in Derna, Libya in eastern Libya and provides a regional geographic context for the studied environmental and industrial areas. This map supports the spatial Each sampling point was assigned accurate geographic coordinates using a Global Positioning System (GPS) device, allowing precise spatial referencing of residential, agricultural,

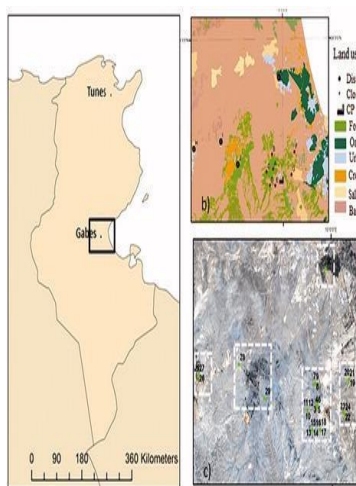


Figure 4



Figure 5

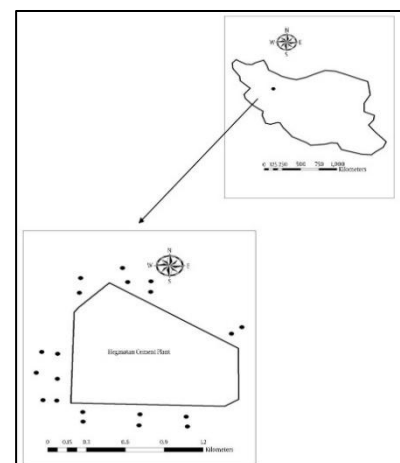


Figure 6

industrial, and quarry locations included in the investigation, The generated spatial distribution maps enhanced the interpretation of radiological variations across the study area and contributed to the identification of potential radiological hotspots associated with industrial activities and raw material processing operations. interpretation of the radionuclide distribution and enhances the reproducibility of future environmental radiological studies in the study area. Figure 4. GIS-based spatial distribution maps of sampling locations surrounding Al-Fatai'h Cement Plant in Derna, Libya.

The spatial mapping approach improves the spatial consistency of the study and facilitates the interpretation of radiological variations associated with industrial activities and raw material processing operations.

The investigated region is geologically characterized by sedimentary formations dominated by carbonate and clay-rich materials commonly utilized in cement manufacturing. Such geological formations may contribute to relatively elevated concentrations of potassium-40 due to the occurrence of feldspar-bearing and clay minerals within soils and quarry materials surrounding the plant. The integration of GIS-based mapping with radiological measurements improves the methodological robustness, of the present study.

The sampling program was divided into two main categories: environmental samples collected from residential, agricultural, and surrounding areas, and industrial operational samples collected from raw material handling and cement processing zones inside the plant, The overall sampling framework consisted of 190 samples, including 150 environmental samples and 40 industrial samples.

**Table 1.** Spatial distribution of environmental sampling locations around Al-Fatai'h Cement Plant, Derna, Libya.

Location	Number of Samples	Direction
Dry valley (right side of road)	10	Right side
Adjacent farms	20	Both sides
Satellite area	20	Both sides
Residential area	50	All directions
Employees camps	50	All around

**Source:** Prepared by the authors based on field sampling and site survey conducted around Al-Fatai'h Cement Plant in Derna, Libya.

Table 1 shows that the sampling design was spatially comprehensive and environmentally representative, with 150 samples collected from five different zones surrounding the Al-Fatai'h Cement Plant in Derna, Libya the higher sampling density in the residential area and employees' camps reflects a human exposure-oriented approach aimed at improving the reliability of radiological risk assessment in populated locations. In contrast, samples collected from farms, satellite areas, and the dry valley provided broader environmental coverage for evaluating the spatial distribution and possible transport of radionuclides and cement-related particulates.

The directional distribution of samples (“both sides,” “all directions,” and “all around”) indicates that the study considered the potential influence of wind patterns and dust dispersion associated with cement production activities. Overall, the adopted sampling strategy enhances the representativeness, statistical reliability, and environmental validity of the radiological assessment conducted in the study area.

**Table 2.** Industrial operational sampling locations inside Al-Fatai’h Cement Plant, Derna, Libya.

Location	Number of Samples	Notes
Northern raw material collection points	10	Nearby quarries
Southern raw material (Wadi Al-Shati)	10	Imported raw materials
Crusher and storage hangars	10	Inside factory
Dust under silos and kilns	10	Inside factory

**Source:** Authors’ industrial field survey and sampling campaign inside the cement plant (2025).

Therefore, the overall sampling framework consisted of 190 samples, including 150 environmental samples and 40 industrial operational samples.

Table 2 indicates that the industrial sampling program was systematically designed to cover the major operational stages and potential radiological sources within the cement production cycle. The equal distribution of samples across raw material zones, crushing and storage facilities, and dust accumulation areas reflects a balanced and process-oriented sampling strategy that enhances the comparability and representativeness of the collected data.

The inclusion of both northern local quarries and imported southern raw materials from Wadi Al-Shati demonstrates that the study considered geological variability as a potential factor influencing radionuclide concentrations in cement raw materials. This is particularly important because natural radioactivity levels in cement industries are strongly affected by the mineralogical composition and origin of raw materials.

Moreover, sampling from crushers, storage hangars, and dust deposits beneath silos and kilns provides direct assessment of areas with high particulate generation and accumulation, which are considered critical zones for occupational and environmental exposure. Dust collected from these locations is especially significant because fine particles may concentrate naturally occurring radionuclides and facilitate their dispersion within and outside the factory environment.

Overall, the sampling framework presented in Table 2 reflects an integrated industrial radiological assessment approach that combines source characterization, operational process monitoring, and exposure pathway evaluation, thereby strengthening the scientific reliability and environmental relevance of the study.

## 2.2 Sample Preparation:

- Samples were dried under direct sunlight or in a conventional oven.
- 1000 g of each sample was placed in Marinelli beakers.
- Samples were sealed and stored for at least 28 days to ensure secular equilibrium between radium and its progeny before gamma-ray measurement.
- 3–5 repeated measurements were taken per sample to obtain average values.

## 2.3 Gamma-Ray Measurement System:

Measurements were carried out using a High-Purity Germanium (HPGe) detector cooled with Figure 7. HPGe gamma-ray spectrometry system used in the present study.

Figure 7

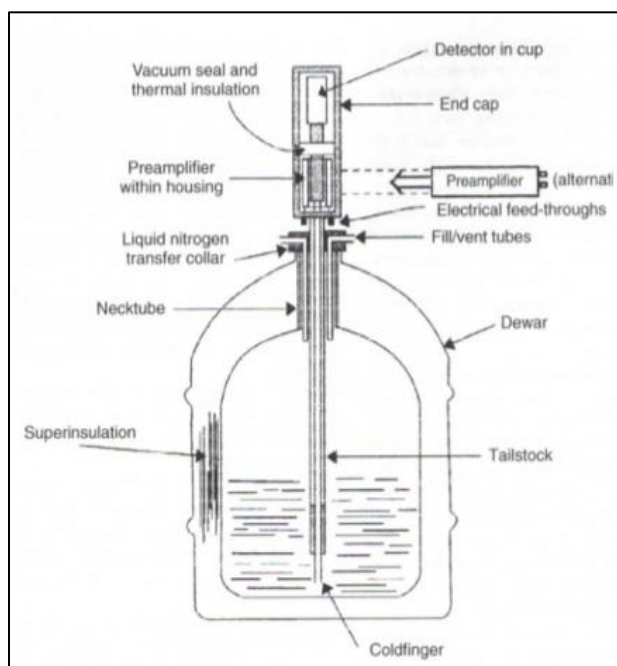
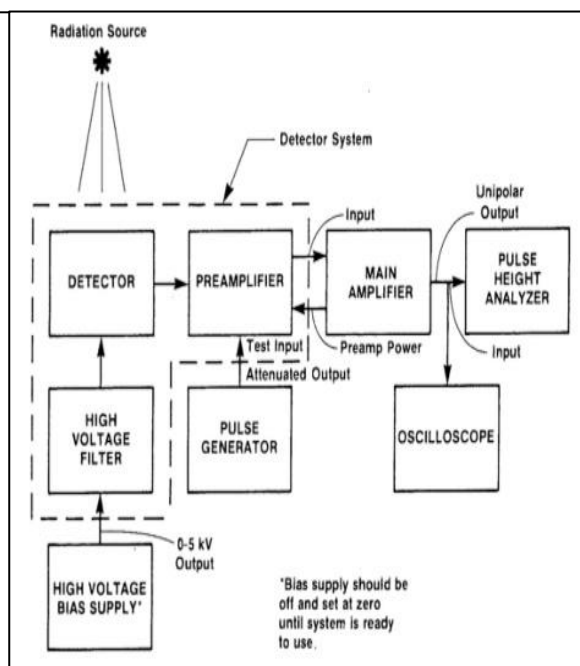


Figure 8



The HPGe gamma-ray spectroscopy system shown in Figures 7–8 was used to qualitatively and quantitatively determine the radioactivity concentrations of radionuclides in environmental and industrial samples.

The detector provides high energy resolution and reliable identification of the characteristic gamma-ray emission lines associated with naturally occurring radionuclides.

Background radiation spectra were periodically measured under identical experimental conditions and subtracted from sample spectra prior to radionuclide activity calculations.

### Detector specifications:

- Energy resolution: **1.96 keV at 1332.56 keV (<sup>60</sup>Co)**
- Relative efficiency: **30%**
- Operating voltage: **2400 V**
- Counting time per sample: **5000 s**

The activity concentrations of radionuclides were determined using their characteristic gamma-ray emission lines. Potassium-40 was measured through the 1460 keV gamma line, while radium-226 was estimated indirectly via its progeny radionuclides including <sup>214</sup>Pb (352 keV) and <sup>214</sup>Bi (609 keV), while thorium-232 activity was determined using gamma emissions from <sup>228</sup>Ac (911 keV) and <sup>208</sup>Tl (583 keV). The identification and quantification procedures were carried out using standard gamma spectrometric analysis techniques.

### 2.3.1 Energy and Efficiency Calibration and Quality Assurance:

To ensure the accuracy and reliability of gamma-ray spectrometric measurements, the HPGe detector was calibrated for energy and efficiency using standard gamma-emitting reference sources covering the energy range of interest.

Energy calibration was performed to establish the relationship between channel number and gamma-ray energy, while efficiency calibration was applied to correct for detector response variations across different energies.

Quality assurance procedures included routine background subtraction, stability checks of the detection system, and verification of peak resolution. These procedures were implemented to maintain measurement consistency and minimize systematic uncertainties.

Although certified reference materials (CRMs) were not used in the present study, their application is recommended in future work to further validate radionuclide activity concentrations and strengthen analytical accuracy.

In addition, repeated measurements and statistical consistency checks were performed to evaluate the reproducibility of the detector response and reduce random measurement uncertainties.

The application of standardized quality assurance procedures enhances the credibility and reliability of the obtained environmental radioactivity data.

## 2.4 Equations Used for Annual Gamma Dose and Annual Effective Dose Calculations

The absorbed gamma dose rate in air was calculated using the following equation:

**Dose rate:**

$$D \text{ (nGy/h)} = 0.0417A_K + 0.462A_{Ra} + 0.604A_{Th}$$

**AED:**

$$AED \text{ (mSv/y)} = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6}$$

**Raeq:**

$$Raeq = A_{Ra} + 1.43A_{Th} + 0.077A_K$$

**Hex:**

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

Where  $A_{Ra}$ ,  $A_{Th}$ , and  $A_K$  denote the activity concentrations of radium-226, thorium-232, and potassium-40, respectively, expressed in Bq/kg.

### 2.4.1 Minimum Detectable Activity (MDA):

The sensitivity of the gamma-ray spectrometry system was evaluated through the determination of the minimum detectable activity (MDA), which represents concentration that can be statistically distinguished from the background radiation.

The MDA was estimated using the classical Currie formalism, which is widely adopted in environmental radioactivity measurements, and is expressed as:

$$MDA = \frac{2.71 + 4.65\sqrt{B}}{\varepsilon \cdot P_\gamma \cdot t \cdot m}$$

**Where:**

- $B$  = background counts under the photopeak
- $\varepsilon$  = full-energy peak efficiency
- $P_\gamma$  = gamma emission probability
- $t$  = counting time
- $m$  = sample mass
- 

The MDA values provide an important indicator of the detection capability of the HPGe system and ensure proper interpretation of low-level environmental radioactivity results.

No statistically significant artificial radionuclides, particularly  $^{137}\text{Cs}$  and  $^{60}\text{Co}$ , were detected above the minimum detectable activity limits in any of the investigated samples. This confirms the absence of measurable anthropogenic radioactive contamination within the studied environment under the applied gamma spectrometric measurement conditions. The obtained detection sensitivity of the HPGe system was considered adequate for low-level environmental radioactivity assessment, with detection limits remaining within the typical environmental monitoring range for HPGe gamma spectrometry systems.

### 2.4.2 Statistical Analysis:

Basic statistical analysis was performed to evaluate the distribution and variability of radionuclide activity concentrations and radiological parameters in the investigated samples. Arithmetic mean, minimum, maximum, and standard deviation values were calculated using Microsoft Excel 2019 software.

The statistical treatment was applied to assess spatial variations among residential, agricultural, industrial, and quarry locations surrounding the cement plant. The obtained statistical indicators provide an additional level of reliability for interpreting the radiological assessment results.

**Table 3:** Descriptive Statistical Analysis of Measured Radiological Parameters ( ).

Parameter	Mean	Minimum	Maximum	Standard Deviation
<sup>40</sup> K (Bq/kg)	60.96	20.36	103.51	35.61
<sup>226</sup> Ra (Bq/kg)	20.36	11.30	28.02	5.56
<sup>232</sup> Th (Bq/kg)	14.64	9.69	20.45	3.82
D (nGy/h)	20.79	11.92	28.16	5.78
AED (mSv/y)	0.026	0.015	0.035	0.007

**Source:** Authors' statistical analysis based on gamma spectrometric measurements (2025).

The descriptive statistical analysis presented in Table3 demonstrates moderate spatial variability in radionuclide activity concentrations and radiological parameters across the investigated locations surrounding the Al-Fatai'h Cement Factory in Libya

The relatively higher standard deviation observed for potassium **40** reflects geological heterogeneity and variations in raw material composition within quarry and industrial operational zones, In contrast, radium **226** and thorium **232** exhibited comparatively lower variability, indicating relatively stable distribution patterns across the investigated environment, The obtained statistical indicators enhance the reliability, reproducibility, and scientific interpretation of the environmental radiological assessment conducted in the present study.

Measurement uncertainty was evaluated considering counting statistics, detector efficiency uncertainty, background fluctuation, and sample heterogeneity, The combined uncertainties were maintained within acceptable limits for environmental gamma spectrometric measurements

### 2.4.3 Measurement Uncertainty Assessment:

The overall measurement uncertainty associated with gamma spectrometric analysis was estimated by considering counting statistics, detector efficiency calibration uncertainty, background fluctuation, and sample preparation variability. The combined relative uncertainty for radionuclide activity concentration measurements was maintained within acceptable limits for environmental radioactivity studies and generally remained below 10%.

The estimated combined relative uncertainties associated with radionuclide activity concentration measurements were approximately  $\pm 6.3\%$  for <sup>40</sup>K,  $\pm 7.1\%$  for <sup>226</sup>Ra, and  $\pm 6.8\%$  for <sup>232</sup>Th, which fall within the acceptable uncertainty range commonly reported for environmental HPGe gamma spectrometric analyses.

### 2.4.4 GIS-Based Spatial Interpretation:

Geographic Information System (GIS) tools were utilized to support the spatial interpretation of radiological data and visualize the distribution of radionuclide concentrations across the investigated area. The integration of GPS coordinates with radiological measurements enabled improved identification of spatial variability associated with industrial operations, quarry zones, residential sectors, and dust accumulation areas surrounding the cement plant. GIS-based interpretation enhances the methodological robustness and future reproducibility of the radiological assessment.

#### 2.4.5 Radium Equivalent Activity and Hazard Index:

To evaluate the overall radiological hazard associated with the investigated samples, the radium equivalent activity (Raeq) and external hazard index (Hex) were calculated using internationally adopted equations. These indices provide integrated assessment of the combined radiological effects of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  in environmental materials.

$$\text{Raeq} = A_{\text{Ra}} + 1.43A_{\text{Th}} + 0.077A_{\text{K}}$$

$$H_{\text{ex}} = \frac{A_{\text{Ra}}}{370} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810}$$

**Table 4:** Radium Equivalent Activity (Raeq) and External Hazard Index (Hex).

Location	Raeq (Bq/kg)	Hex
Residential Area	44.13	0.12
Dry Valley	45.75	0.12
Adjacent Farms	33.83	0.09
Satellite Area	26.57	0.07
Raw Material Collection Point	50.66	0.14
Southern Raw Material Processing Area	61.48	0.17
Crusher & Storage	59.03	0.16

**Source:** Authors' calculations based on radionuclide activity concentrations (2025).

The internationally accepted safety limits for Raeq and Hex are 370 Bq/kg and unity (Hex < 1), respectively.

The calculated radium equivalent activity (Raeq) and external hazard index (Hex) values for all investigated locations remained well below the internationally recommended safety limits of 370 Bq/kg and unity (Hex < 1), respectively, the relatively higher values observed in the South Raw Material Inside and Crusher & Storage areas reflect the influence of raw material processing and dust accumulation activities. Nevertheless, all investigated sites remained within acceptable radiological safety levels, indicating no significant external radiation hazard under the current environmental conditions.

### 3. Radiological Assessment Results:

The present study evaluated the natural radioactivity levels of  $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$  in samples collected from different industrial and residential locations.

The absorbed dose rate (D) was calculated based on the measured radionuclide activity concentrations and subsequently converted into the annual effective dose (AED).

The absorbed dose rate values ranged from 11.92 to 28.16 nGy/h, with an average value of 20.79 nGy/h. These values are considerably lower than the worldwide average outdoor absorbed dose rate of 59 nGy/h reported by UNSCEAR, indicating that the investigated area does not pose abnormal external gamma radiation exposure risks.

The calculated annual effective dose values ranged between 0.015 and 0.035 mSv/y, with an average value of 0.026 mSv/y. These values are also below the global average outdoor annual effective dose of approximately 0.07 mSv/y recommended by UNSCEAR, suggesting that the radiological impact associated with the investigated industrial activities remains within internationally accepted safety limits, as presented in Table 4.

- $^{40}\text{K} = 27.52$
- $^{226}\text{Ra} = 20.07$
- $^{232}\text{Th} = 15.35$

1.  $R_{aeq}$

$$R_{aeq} = A_{Ra} + 1.43A_{Th} + 0.077A_K$$

2.  $R_{aeq}$ :

$$R_{aeq} = 20.07 + (1.43 \times 15.35) + (0.077 \times 27.52)$$

$$R_{aeq} = 20.07 + 21.95 + 2.11$$

$$R_{aeq} \approx 44.13 \text{ Bq/kg}$$

3.  $H_{ex}$

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

4.  $H_{ex}$ :

$$H_{ex} = \frac{20.07}{370} + \frac{15.35}{259} + \frac{27.52}{4810}$$

$$H_{ex} = 0.054 + 0.059 + 0.006$$

$$H_{ex} \approx 0.12$$

**Table 5:** Preliminary radiological indices based on radionuclide activity concentrations in investigated locations.

Location	$^{40}\text{K}$	$^{226}\text{Ra}$	$^{232}\text{Th}$	D (nGy/h)	AED (mSv/y)
<b>Residential Area</b>	<b>27.52</b>	<b>20.07</b>	<b>15.35</b>	<b>19.69</b>	<b>0.024</b>
<b>Dry Valley</b>	80.03	20.88	12.65	20.62	0.025
<b>Adjacent Farms</b>	32.55	16.15	10.64	15.25	0.019
<b>Satellite Area</b>	20.36	11.3	9.69	11.92	0.015
<b>Raw Material Collection Point</b>	100.2	20.63	15.63	23.15	0.028
<b>Southern Raw Material Processing Area</b>	103.51	28.02	18.04	28.16	0.035
<b>Crusher &amp; Storage</b>	62.55	25.5	20.45	<b>26.74</b>	0.033

Source : Authors' gamma spectrometric analysis (2025).

Values presented in Table 5 represent arithmetic mean activity concentrations and radiological indices for samples collected from each investigated location.

Table 5 shows significant spatial variation in radionuclide concentrations and radiological indices across the investigated locations, reflecting the influence of cement production activities and raw material composition. The highest values of  $^{40}\text{K}$ ,  $^{232}\text{Th}$ , absorbed dose rate (D), and annual effective dose (AED) were observed in the southern raw material and crusher/storage areas, indicating that material processing and dust accumulation are the main contributors to radiological enhancement inside the plant.

In contrast, lower values recorded in the satellite area and adjacent farms suggest reduced industrial impact outside the main operational zones.

Although industrial operational zones exhibited relatively higher AED values compared with residential and agricultural areas, all measured values remained below the worldwide average outdoor annual effective dose of 0.07 mSv/y reported by UNSCEAR.

#### 4. Radiological Hazard Assessment Results:

The absorbed dose rate (D) and the annual effective dose (AED) were calculated for the investigated locations using internationally adopted conversion factors.

The obtained values were compared with the worldwide permissible limits reported by UNSCEAR and IAEA references.

#### 5. Study Limitations:

The present study represents an environmental radiological assessment based on field sampling and HPGe gamma-ray spectrometric analysis. Some uncertainties may arise from sample heterogeneity, detector efficiency, counting statistics, and environmental variations. In addition, seasonal changes and long-term industrial operational effects were not investigated. Therefore, future studies are recommended to include long-term monitoring and advanced statistical analysis for improved radiological assessment.

##### 5.1 Equations Used:

- Absorbed Gamma Dose Rate (D) =  $0.0417A_{\text{K}} + 0.462A_{\text{Ra}} + 0.604A_{\text{Th}}$
- Annual Effective Dose (AED) =  $D \times 8760 \times 0.2 \times 0.7 \times 10^{-6}$

Average D value = 20.79 nGy/h

Average AED value = 0.026 mSv/y

#### 6. Discussion and Advanced Radiological Interpretation:

The obtained radiological parameters demonstrated noticeable spatial variability across the investigated locations, reflecting the influence of geological composition and cement-related industrial activities.

The absorbed dose rate values ranged from 11.92 to 28.16 nGy/h, with an average value of 20.79 nGy/h, while the annual effective dose values ranged between 0.015 and 0.035 mSv/y, with an average value of 0.026 mSv/y.

These values are significantly lower than the worldwide average outdoor absorbed dose rate of 59 nGy/h and the global average annual effective dose of 0.07 mSv/y reported by UNSCEAR, indicating that the investigated area does not present abnormal external gamma radiation exposure or significant radiological health hazards.

The relatively elevated radiological values observed in the Southern Raw Material Processing Area and Crusher & Storage locations indicate localized accumulation of naturally occurring radioactive materials (NORM), particularly in zones associated with intensive crushing, grinding, raw material handling, and dust accumulation processes. Similar observations have been widely reported in radiological studies of cement industries and quarry environments, where radionuclide enrichment is commonly linked to fine particulate accumulation and mineral phases containing potassium-, uranium-, and thorium-bearing materials. Nevertheless, all calculated radiological indices, including Raeq and Hex, remained well below internationally recommended safety limits, confirming that the investigated environment

remains radiologically safe for workers and nearby residents under current operational conditions.

The predominance of potassium-40 activity concentrations compared to radium-226 and thorium-232 may be attributed to the geological characteristics of the investigated area, which is dominated by clay-rich and sedimentary formations commonly used in cement manufacturing. Potassium-bearing feldspars and clay minerals are recognized contributors to elevated  $^{40}\text{K}$  concentrations in industrial raw materials. Similar radionuclide distribution patterns have been reported in radiological investigations conducted in cement-related industrial environments in Iraq, Turkey, Nepal, and Uganda.

The relatively elevated  $^{40}\text{K}$  activity concentrations observed in several industrial and quarry locations may be associated with the mineralogical composition of clay-rich sedimentary materials and feldspathic components commonly utilized in cement manufacturing. Potassium-bearing aluminosilicate minerals are recognized contributors to enhanced natural potassium radioactivity in industrial geological formations. In contrast, the comparatively lower concentrations of  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  may indicate limited uranium- and thorium-rich mineralization within the investigated raw materials.

In contrast, the relatively low radiological levels observed in residential and agricultural areas suggest limited environmental migration of radionuclides from industrial zones to surrounding communities. This may be associated with atmospheric dispersion processes, soil dilution effects, and the absence of significant radioactive waste accumulation in the investigated region. Overall, The present study

provides important baseline radiological data for the Al-Fatai'h Cement Factory in Libya, industrial region and contributes to the limited database of environmental radioactivity studies. The obtained results may support future environmental monitoring programs, industrial expansion assessments, land-use planning, and sustainable radiological protection strategies associated with NORM-related cement industries.

**Table 6:** Comparative Assessment with International Studies.

Country	Average D (nGy/h)	Reference
Libya (Present Study)	20.79	Present study
Iraq	~45–70	Qadr (2024)
Turkey	~50–80	Turhan et al. (2020)
Nepal	~35–60	Shrestha et al. (2023)

**Source:** Researchers from the International Radiation Assessment Studies of Industrial Cement Environments.

Table 6 demonstrates that the average absorbed dose rate obtained in the present study (20.79 nGy/h) is considerably lower than the corresponding values reported in cement industrial environments in Iraq, Turkey, and Nepal.

The observed differences may primarily reflect variations in geological composition, mineralogical characteristics of raw materials, industrial processing intensity, and the degree of technologically enhanced naturally occurring radioactive material (TENORM) accumulation associated with cement production activities. In many international studies, elevated radiological levels were linked to higher concentrations of uranium-, thorium-, and potassium-bearing minerals within quarry materials and industrial residues. In contrast, the

comparatively lower dose rates recorded in the investigated Libyan cement environment suggest limited radiological enrichment and relatively weak environmental accumulation of radionuclides despite ongoing industrial operations. These findings indicate that the geological nature of the investigated raw materials, together with local environmental dispersion conditions, may contribute to maintaining external radiation exposure levels within relatively low ranges compared with similar cement-producing regions worldwide.

The relatively low radiological indices observed in the present study may also reflect the limited contribution of uranium-rich mineral phases within the investigated carbonate formations.

This geological characteristic likely reduced the overall gamma dose contribution from the uranium decay series compared with other cement-producing regions reported in the literature. Furthermore, the results reinforce the conclusion that the investigated area remains within internationally accepted radiological safety limits and may therefore be considered environmentally safe under current operational conditions.

## **7. Compliance with International Radiological Safety Standards:**

The calculated radiological parameters obtained in the present study were evaluated in accordance with internationally recognized radiological protection guidelines established by UNSCEAR, IAEA, and ICRP.

The obtained absorbed dose rate, annual effective dose, radium equivalent activity, and external hazard index values remained considerably below the internationally recommended safety limits for public exposure and environmental protection.

In particular, all calculated Raeq values were significantly lower than the recommended maximum value of 370 Bq/kg, while all external hazard index (Hex) values remained below unity.

These findings indicate the absence of significant external radiological hazards associated with the investigated cement industrial environment under the current operational conditions.

## **Conclusion:**

Based on the calculated radiological parameters, all investigated locations exhibited dose values below the internationally recommended permissible limits. The results suggest that the study area is radiologically safe and suitable for human activities without significant health risks associated with natural radioactivity.

The study indicates generally low levels of natural background radiation in residential and agricultural areas surrounding the cement plant, despite geological variations. However, elevated activity concentrations were detected in raw material collection and processing areas inside the factory.

Although the current radiological conditions are considered safe according to international standards, periodic radiological surveillance is recommended to ensure the continued protection of workers, nearby residents, and agricultural environments.

Continuous occupational radiological monitoring is particularly recommended in high-dust operational zones such as crushers, silos, and raw material handling areas in order to ensure long-term worker protection and early detection of any potential radiological accumulation associated with industrial activities.

Future investigations may also include radionuclide transfer studies, airborne dust analysis, seasonal monitoring, and advanced GIS-based radiological mapping for comprehensive environmental assessment.

The present study provides baseline radiological data for the Al-Fatai'h Cement Plant region in Derna, Libya and may serve as a scientific reference for future environmental monitoring,

industrial safety assessment, and sustainable management of NORM-associated cement industries.

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