

Assessment of natural and anthropogenic radioactivity and associated radiological hazards in industrialized soils of eastern Algeria

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Abstract. This study presents a comprehensive assessment of natural and anthropogenic radioactivity in industrialized soils from two key zones in Bordj Bou Arreridj and M'sila, eastern Algeria. Utilizing high-resolution gamma-ray spectrometry with a high-purity germanium (HPGe) detector, the investigation determined the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K radionuclides. The obtained mean activity concentrations were 20.6 ± 1.4 , 27.3 ± 0.7 , and $464 \pm 9 \text{ Bq}\cdot\text{kg}^{-1}$, respectively. Notably, ^{137}Cs was detected only in the Bordj Bou Arreridj zone at trace levels, attributed to historical radioactive fallout. The air absorbed dose rates yielded a mean value of $45.6 \pm 1.4 \text{ nGy}\cdot\text{h}^{-1}$, while the outdoor annual effective doses remained significantly below the International Commission on Radiological Protection (ICRP) limit of $1 \text{ mSv}\cdot\text{y}^{-1}$. All calculated radiological indices were within safety limits, indicating no significant public health hazards. These results provide a critical radiological characterization of Algerian industrial soils, offering essential baseline data for environmental monitoring and the development of radiation protection standards in Algeria.

Keywords: Activity concentration • Gamma spectrometry • Radiological hazard indices • Terrestrial radionuclides

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Introduction

Radiation in the environment can originate from cosmic rays, terrestrial radiation, and anthropogenic sources [1]. Cosmic radiation arises from outer space as primary cosmic rays, while terrestrial radiation is derived from radionuclides present in the soil, rocks, building materials, food, and water [2, 3]. Natural radionuclides consist primarily of ^{40}K and the decay products of the ^{238}U and ^{232}Th series, which have been present in the environment since the formation of the universe [4]. The distribution and concentration of radionuclides in soil vary both spatially and temporally, depending on geological and geographical factors, climatic conditions, and human activities such as mining, milling, agriculture, atmospheric emissions, and industrial solid and liquid waste [1, 5–7]. Multiple studies have been conducted to evaluate the levels of natural and artificial radioactivity in Algerian soils using gamma spectrometry. A study revealed the presence of both natural radionuclides and artificial ^{137}Cs at varying concentrations and concluded that Algeria was indeed affected by the Chernobyl accident [8]. Similarly, an examination of unfertilized soil samples from the Setif and El Athmania agricultural regions showed values within global averages; however, the use of fertilizers, particularly the mono ammonium

phosphate and the prolonged use of farmyard manure fertilizer, induced a significant elevation in ^{40}K concentration, suggesting potential health risks for farmers and consumers [9, 10]. Furthermore, potential health hazards associated with phosphate ores from eastern Algeria (Ouanzae-Tebessa and Bordj Ghdire-Setif) were reported in another study due to the high activity concentrations of ^{238}U and ^{232}Th [11]. In another study, gamma-ray spectrometry measurements of ^{238}U , ^{232}Th , and ^{40}K in natural spring and groundwater from three areas in Bordj Bou Arreridj (Chenia well, Zemala spring, and Ksir El Ghouli spring) showed that most samples had activity concentrations below the recommended safety limits. However, the Zemala spring exhibited relatively high concentrations of ^{238}U , likely due to the interaction between the spring water and the underlying bedrock in the area, rendering it unsuitable for drinking [12]. Construction materials in the region were also evaluated for naturally occurring radionuclides from the uranium and thorium series, as well as ^{40}K . Most materials showed activity concentrations within global reference levels, although elevated ^{40}K was detected in ceramics and certain bricks. Radiological indices remained below international limits, indicating no significant hazard, though ceramics exhibited comparatively higher activity. Low levels of ^{137}Cs were also detected in three sand samples [13]. Despite these contributions, most research has focused on fertilizers, agricultural soils, groundwater, building materials, and phosphate ores, whereas research on soil radioactivity in Algeria's intensive industrial areas remains scarce. To date, no field-based assessments are available to measure the accumulation of radionuclides, whether natural or artificial, in major industrial regions such as M'sila and Bordj Bou Arreridj. These regions comprise ceramic and cement plants, metal processing facilities, raw material storage sites, and other establishments with potential technologically enhanced natural radiation (TENORM) emissions. This deficiency in available data constitutes a critical knowledge gap, significantly impeding the precise evaluation of environmental radiological risks and associated public health hazards. The primary objective of this study is to establish a comprehensive radiological baseline and determine the activity concentrations of natural radionuclides in soil samples collected from the industrial zones of Bordj Bou Arreridj and M'sila, eastern Algeria. Using high-resolution gamma-ray spectrometry with a HPGe detector, this work employs a composite sampling strategy to ensure representative environmental mapping. Several parameters related to radiological risk, such as specific activity, internal and external hazard indices, radium equivalent activity, excess lifetime cancer risk, and annual effective dose, were evaluated to estimate the radiological impact of natural radioactivity in the samples. The investigation of their distribution in soil samples provides essential data for environmental radiation monitoring and the development of local safety standards. The radiological measurements were performed at the laboratory of the Nuclear Research Centre of Birine (NRCB),

Algeria, in collaboration with the Laboratory of Materials Physics, Radiation and Nanostructures (LMPRN).

Study area

The regions of Bordj Bou Arreridj and M'sila are strategically located within the High Plateaus of eastern Algeria and exhibit diverse geographical, climatic, agricultural, and industrial characteristics. In Bordj Bou Arreridj, the topography varies between mountainous heights in the north, such as the Biban chain, wide plains in the central part including the Medjana plain, and plateaus extending southwards towards the steppe areas. The region experiences a semi-arid continental climate characterized by hot, dry summers and cold winters, contributing to a pedological diversity that includes steppe soils, clayey agricultural soils, and calcareous (limestone-dominated) soils. Bordj Bou Arreridj is recognized as a major industrial and agricultural hub; it hosts sectors such as construction materials, processing industries, and electronics production, in addition to intensive limestone quarries and clay extraction mines. Similarly, the region of M'sila is defined by a rugged continental climate with hot summers and cold winters. It displays a diverse topographical profile that includes mountainous areas such as Mount El-Hodna and Mount El Gergueur, high plateaus, steppe regions, and semi-arid zones. Its soils are complex and varied, including alluvial, calcareous, steppe, sandy, and saline (sabkha-related) types. M'sila is also a critical center for building materials production, with factories producing cement, bricks, tiles, iron, and aluminum, as well as numerous open-pit quarries and stone mines. Agriculturally, the region supports diverse crop and livestock production, with widespread cultivation of grains and various fruit trees. Additionally, M'sila is working on establishing food-processing units and promoting the production of organic fertilizers. The coexistence of diverse geological formations and extensive industrial activities in the study area necessitates a rigorous radiological assessment to establish a baseline for environmental safety and public health protection. Accordingly, soil samples were collected from industrial zones located in Bordj Bou Arreridj and M'sila in eastern Algeria, as illustrated in Fig. 1.

Materials and measurement methods

Preparation of samples

In this study, a total of two composite samples were collected from industrial zones located in Bordj Bou Arreridj and M'sila, in the eastern region of Algeria. The sampling locations are shown in Fig. 1. To ensure a high degree of spatial representation and to minimize local variability within these industrial areas, a composite sampling strategy was implemented. Each composite sample was taken from a representative area of approximately $100 \times 100 \text{ m}^2$

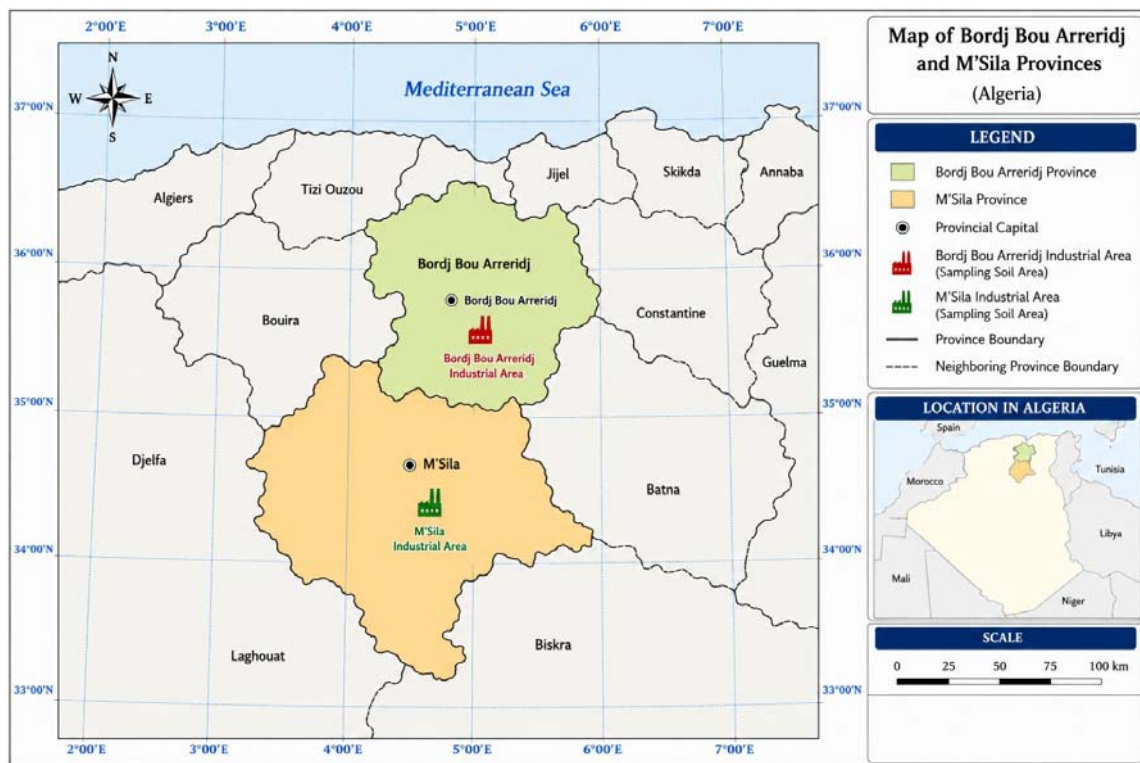


Fig. 1. Location map of Bordj Bou Arreridj and M'sila provinces in Algeria showing the industrial sampling areas [14].

using the diagonal sampling method. Five to ten sub-samples were collected at an approximate depth of 5 cm, including one from each of the four corners and one from the center of the sampling grids. These sub-samples were thoroughly mixed to obtain a single homogenized composite sample after removing plant roots, stones, and other extraneous materials. This approach provides a more reliable assessment of the average radioactivity levels compared to individual point samples. The resulting composite sample was then dried in an oven, ground into a fine powder, and sieved. Finally, it was placed in a labeled airtight container with essential metadata (collection site, date, weight, etc.) before being sent to the laboratory of the Nuclear Research Centre of Birine (CRNB), Algeria, for high-precision gamma spectrometry analysis [15].

Materials and calibration of the measurement chain

The experimental measurements were carried out using a gamma spectrometry system equipped with a p-type coaxial HPGe detector (model GC3018, Canberra Industries). The relative efficiency of the detector is specified as 36%. The energy resolution (FWHM) and the peak-to-Compton ratio (P/C) for the 1.335 MeV gamma line of ^{60}Co were found to be 1.98 keV and 69.6:1, respectively. These values are in good agreement with the manufacturer's specifications (1.8 keV and 70.6:1) for the same energy. The detector was housed in a 10 cm thick lead shield (model 650N) and further protected from X-rays generated in the lead by two additional layers: 1 mm of tin and 1.6 mm of copper. The HPGe detector was coupled to a preamplifier (model 2012C) and a digital signal analyzer (Lynx Digital Signal Analyzer,

LDSP) with a shaping time of 4 μs . The coarse and fine gains were set to 4 and 0.96420 $\times$, respectively. A recommended high voltage of 4000 V was applied to the detector. Spectrum acquisition and radionuclide identification were performed using the Genie 2000 analysis software. Energy and efficiency calibrations were performed prior to sample analysis to ensure accurate radionuclide identification and quantitative determination. Energy calibration was conducted using a certified ^{152}Eu standard source, employing its well-defined gamma-ray emission lines to establish the relationship between channel numbers and gamma-ray energies over the energy range up to approximately 2000 keV. This procedure ensured reliable energy assignment for all measured spectra under identical acquisition conditions. The absolute full-energy peak efficiency calibration was experimentally established using certified multi-nuclide reference sources ^{133}Ba and ^{152}Eu supplied by LEA-CERCA (France). The radionuclides were uniformly distributed in a gel matrix and contained in 1-L Marinelli beaker geometry. This geometry was specifically selected to replicate the same counting configuration, density, and sample volume of the investigated soil samples, thereby minimizing systematic uncertainties associated with geometry mismatch and gamma-ray self-attenuation. For each calibration energy, the net peak areas were determined after background subtraction and used to calculate the absolute full-energy peak efficiency according to the known source activity, gamma emission probabilities, and counting time. The efficiency values were derived across a wide energy range using the principal gamma-ray emissions of ^{133}Ba (81.0, 276.4, 302.9, 356.0, and 383.8 keV) and ^{152}Eu (121.8, 244.7, 344.3, 778.9, 964.1, 1112.1,

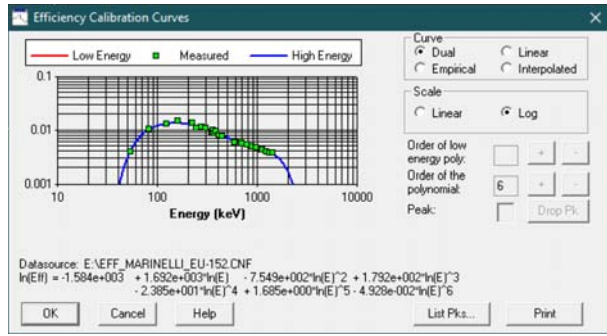


Fig. 2. The efficiency calibration curve of the gamma spectrometry system.

1408.0, and 1457.6 keV). These experimentally determined efficiency points were then fitted using a sixth-order logarithmic polynomial function employing the APOLOG algorithm implemented in Genie 2000 software. As illustrated in Fig. 2, the detector efficiency exhibits a smooth energy-dependent behavior described by a sixth-order logarithmic polynomial fit, providing a continuous efficiency model over the full energy range required for gamma-ray spectrometric analysis. To account for environmental and detector-related background radiation, a background spectrum was acquired using an empty Marinelli beaker under identical shielding and experimental conditions as those used for the samples. The background measurement was performed for 50 h (180 000 s) to ensure high statistical accuracy. Each soil sample was measured for a total counting time of 48 h (172 800 s). The background spectrum was subtracted from each gross sample spectrum prior to peak analysis to obtain net peak areas. This procedure is essential to eliminate contributions from ambient radiation and detector background, thereby preventing systematic overestimation of radionuclide activity concentrations, particularly for low-activity samples.

Uncertainty analysis

The experimental uncertainties associated with the activity concentrations of the directly measured radionuclides (^{40}K and ^{137}Cs) and those derived from the ^{226}Ra and ^{232}Th decay series are initially expressed as percentages. These experimental uncertainties were calculated by propagating the individual sources of error using the standard error propagation law, taking into account the counting statistics of the net peak areas (obtained from Genie 2000 software), detector efficiency calibration, and sample geometry. The total standard uncertainty ($\pm 1\sigma$) was calculated according to the following mathematical formula:

$$(1) \quad \sigma_A \times \sqrt{\left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_\varepsilon}{\varepsilon}\right)^2 + \left(\frac{\sigma_m}{m}\right)^2 + \left(\frac{\sigma_P}{P}\right)^2}$$

where σ_N , σ_ε , σ_m , and σ_P represent the uncertainties in the net peak area, detector efficiency, sample mass, and gamma-ray emission probability, respectively. All reported error percentages in the tables

correspond to a standard confidence level of 68% ($\pm 1\sigma$). To comply with international metrological standards, these standard values were subsequently converted into the expanded uncertainty (U) by applying a coverage factor of $k = 2$ to ensure a 95% confidence level [16, 17]:

$$(2) \quad U = 2 \times \sigma_A$$

The estimated expanded uncertainties remained within acceptable limits, demonstrating the high precision and reproducibility of the HPGe gamma-ray spectrometry measurements. Their contribution to the overall uncertainty budget was limited, thereby ensuring the reliability of the calculated activity concentrations and the associated radiological parameters.

Radioactivity measurement

A total of two composite samples were analyzed for natural radioactivity using high-resolution gamma-ray spectrometry with an HPGe detector. Prior to measurement, the samples were dried, homogenized, sieved, and sealed in airtight containers. The activity concentration of ^{226}Ra was determined indirectly through the measurement of gamma emissions from its short-lived progeny, assuming secular equilibrium within the ^{226}Ra decay series. To ensure equilibrium, the sealed samples were stored for at least four weeks prior to analysis, allowing the in-growth of ^{214}Pb and ^{214}Bi via ^{222}Rn decay. The activity concentration of ^{226}Ra was calculated as the weighted mean of values obtained from the gamma-ray lines at 351.9 keV of ^{214}Pb , and 609.3 keV of ^{214}Bi . Similarly, the activity concentration of ^{232}Th was determined from its daughter radionuclides, typically using the gamma-ray lines of ^{228}Ac (911.2 keV), ^{212}Pb (238.6 keV), and ^{208}Tl (583.2 keV), depending on the analysis protocol. The final ^{232}Th activity concentration was calculated as the weighted average of the activities obtained from the selected daughter-product gamma lines, after confirming radioactive equilibrium within the ^{232}Th decay series. Finally, the activity concentrations of ^{40}K and ^{137}Cs were directly determined from their characteristic gamma emissions at 1460.8 keV and 661.66 keV, respectively.

The activity concentration A_s ($\text{Bq}\cdot\text{kg}^{-1}$) was calculated according to:

$$(3) \quad A_s = N / (\varepsilon \times p \times t \times m)$$

where: N – net area of the peak; ε – detector efficiency corresponding to the specific gamma-ray energy line E_γ ; p – branching ratio; t – counting time (s); m – mass of the sample (kg).

Gamma dose rate

The absorbed gamma dose rate in air was determined from the measured activity concentrations of radionuclides in the soil samples. For a uniform distribution of the natural radionuclides ^{226}Ra , ^{232}Th ,

and ^{40}K , the absorbed gamma dose rate at 1 m above the ground surface was calculated using the following formula [18]:

$$(4) \quad D(\text{nGy} \cdot \text{h}^{-1}) = 0.462A_{\text{Ra}} + 0.604A_{\text{Th}} + 0.0417A_{\text{K}}$$

where A_{Ra} , A_{Th} , and A_{K} represent the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in the samples ($\text{Bq} \cdot \text{kg}^{-1}$), respectively. The coefficients 0.462, 0.604, and 0.0417 are the absorbed dose conversion factors (in $\text{nGy} \cdot \text{h}^{-1}$ per $\text{Bq} \cdot \text{kg}^{-1}$) for ^{226}Ra , ^{232}Th , and ^{40}K , respectively, as reported in [19].

Because the study area is contaminated by ^{137}Cs , the activity of this isotope was considered in the calculations, and the dose was calculated accordingly [20]:

$$(5) \quad D(\text{nGy} \cdot \text{h}^{-1}) = 0.427A_{\text{Ra}} + 0.662A_{\text{Th}} + 0.0043A_{\text{K}} + 0.03A_{\text{Cs}}$$

Annual effective dose

To estimate the outdoor annual effective dose, the conversion coefficient from absorbed dose in air to effective dose and the outdoor occupancy factor were taken into account. A dose conversion coefficient (DCF) of $0.7 \text{ Sv} \cdot \text{Gy}^{-1}$ and an outdoor occupancy factor (OF) of 0.2 were adopted in the present analysis. The outdoor annual effective dose was calculated using the following relationship [19]:

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

where AED_{out} is the outdoor annual effective dose ($\text{mSv} \cdot \text{y}^{-1}$), D is the absorbed dose rate in air ($\text{nGy} \cdot \text{h}^{-1}$), DCF is the dose conversion factor ($0.7 \text{ Sv} \cdot \text{Gy}^{-1}$), OF is the outdoor occupancy factor (0.2), and T is the exposure time ($8760 \text{ h} \cdot \text{y}^{-1}$). The factor 10^{-6} is the unit conversion factor accounting for the conversion from nGy to Gy and from Sv to mSv.

Radium equivalent activity

The radium equivalent activity (Ra_{eq}) is an index used to estimate the potential radiological hazard and to predict the radiation exposure to the human body from the perspective of total radiation dose. It provides a single quantity that represents the combined activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K considering their different gamma-ray dose contributions [21]. The expression for the radium equivalent activity was first proposed in [22]:

$$(7) \quad \text{Ra}_{\text{eq}}(\text{Bq} \cdot \text{kg}^{-1}) = A_{\text{Ra}} + 1.43A_{\text{Th}} + 0.077A_{\text{K}}$$

where A_{Ra} , A_{Th} and A_{K} are the activities of ^{226}Ra , ^{232}Th and ^{40}K in $\text{Bq} \cdot \text{kg}^{-1}$, respectively.

External hazard index

The external hazard index (H_{ex}) is used to estimate the external radiation exposure due to gamma

radiation [23]. The external hazard index (H_{ex}) is defined as:

$$(8) \quad H_{\text{ex}} = \frac{A_{\text{Ra}}}{370} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1$$

where A_{Ra} , A_{Th} , and A_{K} are the specific activities of ^{226}Ra , ^{232}Th , and ^{40}K in $\text{Bq} \cdot \text{kg}^{-1}$, respectively.

The external hazard index value must not exceed unity to ensure that the radiation hazard remains insignificant. The maximum value of H_{ex} equal to unity which corresponds to the upper limit of radium equivalent activity of $370 \text{ Bq} \cdot \text{kg}^{-1}$ [22, 24].

Internal hazard index

The internal hazard index is used to assess the internal gamma-ray exposure [25]. This parameter is calculated using Eq. (9):

$$(9) \quad H_{\text{in}} = \frac{A_{\text{Ra}}}{185} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1$$

where A_{Ra} , A_{Th} , and A_{K} are the specific activities of ^{226}Ra , ^{232}Th , and ^{40}K in $\text{Bq} \cdot \text{kg}^{-1}$, respectively. The internal hazard index must be less than unity for the radiation hazard to be considered negligible.

Excess lifetime cancer risk

The excess lifetime cancer risk (ELCR) was calculated to estimate the cancer risk associated with continuous exposure to environmental radiation. The outdoor ELCR was assessed using Eq. (10):

$$(10) \quad \text{ELCR} = \text{AED}_{\text{out}} \times \text{DL} \times \text{RF}$$

where AED_{out} is the outdoor annual effective dose ($\text{Sv} \cdot \text{y}^{-1}$), DL is the average lifetime duration, taken as 70 years, and RF is the risk factor for stochastic effects, taken as 0.05 Sv^{-1} for the public [5, 26, 27].

Results and discussion

The radiological assessment data obtained from the analyzed soil samples are presented in Tables 1 and 2. Table 1 summarizes the activity concentrations of natural radionuclides, absorbed dose rate, and annual effective dose. The evaluated radiological hazard parameters, including radium equivalent activity, external and internal hazard indices, and outdoor excess lifetime cancer risk are presented in Table 2. These results provide an overall assessment of the radiological status of the investigated area.

The activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in the soil samples were 12.5 ± 1.2 , 11.4 ± 0.3 , and $136.5 \pm 3.3 \text{ Bq} \cdot \text{kg}^{-1}$ for the industrial zone of Bordj Bou Arreridj, and 28.7 ± 1.6 , 43.3 ± 1.0 , and $792 \pm 15 \text{ Bq} \cdot \text{kg}^{-1}$ for the industrial zone of M'sila, respectively. The corresponding mean activity concentrations were $20.6 \pm 1.4 \text{ Bq} \cdot \text{kg}^{-1}$ for ^{226}Ra , $27.3 \pm 0.7 \text{ Bq} \cdot \text{kg}^{-1}$ for ^{232}Th , and $464 \pm 9 \text{ Bq} \cdot \text{kg}^{-1}$ for ^{40}K . According to the obtained data, ^{40}K exhibits the

Table 1. Activity concentrations of natural radionuclides, absorbed dose rate, and annual effective dose

Location	Activity concentration (Bq·kg ⁻¹)				Absorbed dose rate <i>D</i> (nGy·h ⁻¹)	Outdoor annual effective dose (mSv·y ⁻¹)
	²²⁶ Ra	²³² Th	⁴⁰ K	¹³⁷ Cs		
Industrial zone Bordj Bou Arreridj	12.5 ± 1.2	11.4 ± 0.3	136.5 ± 3.3	0.69 ± 0.06	18.7 ± 0.9	0.02
Industrial zone M'sila	28.7 ± 1.6	43.3 ± 1.0	792 ± 15	–	72.4 ± 2.0	0.09
Mean	20.6 ± 1.4	27.3 ± 0.7	464 ± 9	–	45.6 ± 1.4	0.06

Table 2. Radium equivalent activity, external, internal hazard indices, and outdoor excess lifetime cancer risk

Location	Ra _{eq} (Bq·kg ⁻¹)	H _{ex}	H _{int}	ELCR
Industrial zone Bordj Bou Arreridj	39.23	0.11	0.14	7 × 10 ⁻⁵
Industrial zone M'sila	151.58	0.41	0.49	3.15 × 10 ⁻⁴
Mean	95.41	0.26	0.32	1.93 × 10 ⁻⁴

highest specific activity compared with ²²⁶Ra and ²³²Th, as presented in Table 1. The industrial zone of M'sila shows higher radiological levels, while ¹³⁷Cs was detected exclusively in the industrial zone of Bordj Bou Arreridj with a measured activity of 0.69 ± 0.06 Bq·kg⁻¹. The presence of ¹³⁷Cs at this trace concentration is attributed to global radioactive fallout from past atmospheric nuclear tests and historical nuclear accidents. However, it does not constitute a significant radiological risk in the studied area. The worldwide average activity concentrations are 35 Bq·kg⁻¹ for ²²⁶Ra, 30 Bq·kg⁻¹ for ²³²Th and 400 Bq·kg⁻¹ for ⁴⁰K [19]. The resulting average activity concentrations of ²²⁶Ra and ²³²Th in this work remained below these global reference values. In contrast, although the average activity concentration of ⁴⁰K slightly exceeded the global reference value, a notable difference was observed between the investigated industrial zones. The activity concentration in the industrial zone of Bordj Bou Arreridj was 136.5 ± 3.3 Bq·kg⁻¹, whereas it reached 792 ± 15 Bq·kg⁻¹ in the industrial zone of M'sila, the latter being nearly twice the worldwide average. This enrichment is likely associated with geological formations, soil geochemistry, and local environmental conditions. This enrichment is likely associated with the prevalence of mineral-based construction materials and the proximity to agricultural lands utilizing potassium-based fertilizers. Furthermore, the contribution of industrial activities through the resuspension of potassium-enriched dust particles from cement and ceramic facilities may play a significant role in these observed levels. The absorbed dose rate and annual effective dose values are presented in Table 1. The absorbed dose rate in air for the two investigated locations yielded a mean value of 45.6 ± 1.4 nGy·h⁻¹, which is lower than the population-weighted global average of 59 nGy·h⁻¹ [19]. The maximum absorbed dose rate was observed in the M'sila industrial zone (72.4 ± 2.0 nGy·h⁻¹), exceeding this global reference level, while the minimum value was recorded in the Bordj Bou Arreridj industrial zone (18.7 ± 0.9 nGy·h⁻¹), remaining well below the threshold. The outdoor annual effective dose for the two investigated locations was 0.02 mSv·y⁻¹ and 0.09 mSv·y⁻¹, respectively. These values represent only a small fraction of the

recommended public exposure limit of 1 mSv·y⁻¹ [27], indicating a low level of radiological risk associated with outdoor exposure in the studied area. The results for radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}) and internal hazard index (H_{in}) are summarized in Table 2. The Ra_{eq} values for the two composite soil samples were 39.23 Bq·kg⁻¹ and 151.58 Bq·kg⁻¹, respectively, yielding an average value of 95.41 Bq·kg⁻¹. These results are well within the recommended safety limit of 370 Bq·kg⁻¹ [28]. The calculated hazard indices (H_{ex} and H_{in}) remained below unity, with average values of 0.26 and 0.32, respectively. However, the maximum values were recorded in the industrial zone of M'sila, reaching 0.41 for H_{ex} and 0.49 for H_{in}. Nonetheless, all these values indicate that the studied soils remain well within the acceptable safety limits for radiological hazards. Additionally, the ELCR averaged 1.93 × 10⁻⁴, which is lower than the global mean of 0.29 × 10⁻³ [29]. To better contextualize the measured radionuclide activity concentrations, a comparison with data reported in previous studies was conducted. Table 3 summarizes the activity concentrations of natural radionuclides in the present study and compares them with values reported for similar industrial and environmental settings in different regions.

A comparative analysis with previous literature presented in Table 3 reveals that the radionuclide distribution is strongly influenced by regional geology and specific industrial activities. For instance, the moderate ²³²Th and ⁴⁰K levels in this study are consistent with values reported for similar industrial sites, whereas elevated levels in other regions are often related to technologically enhanced naturally occurring radioactive materials (TENORM) associated with intensive rock extraction. Overall, these findings indicate that the radiological profile of the investigated Algerian industrial zones is predominantly natural, with minimal anthropogenic influence, and remains within safe environmental limits.

It should be noted that the analysis is based on two composite samples, which were prepared by mixing several sub-samples to ensure a representative bulk composition of the industrialized soils. While these composite samples provide a reliable screening of the area, the reported range of activity concentrations should be interpreted with caution

Table 3. Activity concentrations of ^{226}Ra , ^{232}Th , ^{40}K , and ^{137}Cs of soil samples in different countries

Country	Type of soil	Activity concentration ($\text{Bq}\cdot\text{kg}^{-1}$)				Ref.
		^{226}Ra	^{232}Th	^{40}K	^{137}Cs	
Turkey	Natural soil	48.4	20.5	744.8	3.3	[30]
Jordan	Natural soil	42 ± 3	23 ± 3	310 ± 20	3.7 ± 0.9	[31]
Algeria	Fertilized soil	50 ± 10	50 ± 7	311 ± 18	7.7 ± 0.4	[9]
Algeria	Fertilized soil	46.7	26.7	246.5	3.1	[10]
Nigeria	Soil from quarry sites	53.8 ± 1.6	162.3 ± 1.6	503 ± 3	–	[32]
Ethiopia	Soil from quarry sites	33 ± 2	70 ± 10	220 ± 2	–	[33]
Nigeria	Soil near cement factories (Zone 1)	–	29 ± 15	380 ± 30	–	[34]
	Soil near cement factories (Zone 2)	–	35 ± 19	800 ± 300	–	
Egypt	Soil near cement factories	31 ± 4	40 ± 2	113 ± 6	–	[35]
Iraq	Soil near cement factories	11.2 ± 1.7	13.4 ± 0.7	158 ± 5	1.5 ± 0.1	[36]
Bangladesh	Brick factory soil	30 ± 4	45 ± 6	490 ± 60	–	[37]
Nigeria	Soil from mining sites	19 ± 1	19.0 ± 0.9	350 ± 10	–	[38]
Bangladesh	Industrial soil	23.31	42.24	733.19	–	[39]
Algeria	Industrial soil	20.6 ± 1.4	27.3 ± 0.7	464 ± 9	0.69 ± 0.06	Present work

due to the limited number of final pooling observations ($n = 2$).

Conclusion

This study presents a rigorous radiological assessment of soils from key industrial zones in eastern Algeria (Bordj Bou Arreridj and M'sila), utilizing high-resolution gamma-ray spectrometry (HPGe). By adopting a composite sampling strategy, the research ensured a high degree of spatial representation, effectively addressing the inherent variability of radionuclides in industrialized landscapes. The findings reveal that while ^{137}Cs was detected exclusively in Bordj Bou Arreridj at trace levels, the overall radiological profile is dominated by natural sources. The mean activity concentrations of ^{226}Ra and ^{232}Th remained within global averages, whereas ^{40}K exhibited a slight elevation, likely related to the local geological background and the influence of mineral dust from surrounding industrial and agricultural activities. Crucially, all calculated radiological hazard parameters were within internationally reported background levels, with the outdoor ELCR remaining below the worldwide average value of (0.29×10^{-3}) . These results provide conclusive evidence that the studied industrial areas do not currently pose a significant radiological threat to public health. Beyond its immediate findings, this work establishes a critical and rare radiological baseline for Algeria's industrial sector, offering a scientific reference for future environmental monitoring. The Nuclear Research Centre of Birine (CRNB) underscores the technical reliability of this database. While this study serves as a foundational step, it advocates for an expanded national monitoring program to cover broader geographical areas and greater soil depths, ensuring long-term environmental protection and sustainable industrial development in the region.

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