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ORIGINAL

Measurement of environmental soil radioactivity using gamma-ray spectrometry

Medición de la radiactividad ambiental del suelo mediante espectrometría de rayos gamma

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ABSTRACT

Introduction: exposure to naturally occurring and anthropogenic radionuclides is a ubiquitous feature of the environment. Consequently, establishing baseline levels of environmental radiation is imperative for ensuring public safety and for the timely assessment of potential contamination events.
Objective: this study aims to develop a preliminary database and a spatial map of natural background radiation levels in the air within Ba Ria-Vung Tau province, Vietnam.
Method: a total of 42 soil samples were systematically collected from the study area. These samples were subsequently analyzed to determine their radioactive content through the indexes: Radium Equivalent Activity, Representative Level Index, Absorbed Dose Rate, Annual Effective Dose Rate, External hazard index, Internal hazard index. The resulting data was then utilized to construct a foundational map of natural background radiation.
Results: the research successfully established a preliminary database and a spatial map depicting natural radiation background. This foundational dataset is critical for ongoing radiological monitoring and serves as an important reference for regional economic and tourism development initiatives.
Conclusions: detailed analysis and discussion of the study's conclusions are presented in the corresponding section at the end of this paper.

Keywords: Soil Radioactivity; Radiation Hazard; Environmental Radioactivity; Gamma-Ray Spectrometry.

RESUMEN

Introducción: la exposición a radionúclidos de origen natural y antropogénico es una característica omnipresente del medio ambiente. Por lo tanto, establecer los niveles de referencia de la radiación ambiental es fundamental para garantizar la seguridad pública y para la evaluación oportuna de posibles eventos de contaminación.
Objetivo: este estudio tiene como objetivo desarrollar una base de datos preliminar y un mapa espacial de los niveles de radiación de fondo natural en el aire dentro de la provincia de Ba Ria-Vung Tau, Vietnam.
Método: se recolectaron sistemáticamente un total de 42 muestras de suelo del área de estudio. Posteriormente, estas muestras fueron analizadas para determinar su contenido radiactivo mediante los índices: Actividad de Radio Equivalente, Índice de Nivel Representativo, Tasa de Dosis Absorbida, Tasa de Dosis Efectiva Anual, Índice de Peligro Externo e Índice de Peligro Interno. Los datos resultantes se utilizaron luego para construir un mapa fundamental de la radiación de fondo natural.
Resultados: la investigación estableció con éxito una base de datos preliminar y un mapa espacial que representa el fondo de radiación natural. Este conjunto de datos fundamental es crucial para el monitoreo radiológico continuo y sirve como una referencia importante para las iniciativas de desarrollo económico y

turístico de la región.
Conclusiones: el análisis detallado y la discusión de las conclusiones del estudio se presentan en la sección correspondiente al final de este artículo.

Palabras clave: Radiactividad del Suelo; Peligro de Radiación; Radiactividad Ambiental; Espectrometría de Rayos Gamma.

INTRODUCTION

As per the guidelines of the International Atomic Energy Agency (IAEA), environmental background radiation is defined as the dose, dose rate, or activity concentration from essential occurring or human-made radiation sources in the environment that are beyond human control.[1] Uncontrollable sources of radioactivity include, but are not limited to, fallout from nuclear weapons testing and major nuclear power facility disasters. It is evident that environmental background radiation is composed of both essential occurring and man-made radionuclides. The natural radionuclides originate from two primary sources: cosmic radiation and the Earth's crust. Specifically, these include cosmogenic isotopes like 3H and 7Be, as well as primordial radionuclides such as Kali (^{40}K) and the decay series of uranium (^{238}U) and thorium (^{232}Th), which are found in crustal materials.[2] Anthropogenic radionuclides are introduced into the environment through several sources. These testing, specifically in the atmosphere and oceans; the deep-sea disposal of radioactive waste; controlled low-level discharges from nuclear facilities like power plants and fuel reprocessing sites; and major nuclear accidents. The initial release of these materials leads to their widespread dispersion and subsequent accumulation within the environment. This process is of particular concern for long-lived and highly radiotoxic radionuclides, such as ^{90}Sr, ^{137}Cs, and ^{239}Pu, as well as ^{3}H.[3]

Humans are exposed to both external and internal radiation from a combination of natural and anthropogenic sources. This leads to a global average effective dose estimated at approximately 2,96 mSv per year. Of the total dose, essential occurring radionuclides are responsible for the majority (82 %, or 2,42 mSv/y), with man-made sources contributing the smaller fraction (18 %, or 0,54 mSv/y).[4]

This research was conducted to determine the natural radioactivity and assess several radiological hazard indices in soil samples collected from a residential area. The key indices to be evaluated include the radium equivalent activity (Raeq), the representative level index (I_{yr}), the external and internal hazard indices (H_{ex} and H_{in}), as well as the absorbed dose rate and effective dose rate. This research provides essential baseline data on natural background radioactivity within the area. This information is essential for agencies tasked with enforcing radiation protection standards and will be compared with existing literature to provide a broader scientific context.

METHOD

Sample Collection

For this research, a collection of 42 soil samples was procured from residential zones in Ba Ria-Vung Tau province, Vietnam, throughout 2018. The sampling locations were strategically selected based on two key criteria: population density and proximity to industrial zones. The province spans an area of 1980,80 km2, and the distribution of samples among its districts is presented in table 1.

Table 1. the number of samples analyzed by district in Ba Ria-Vung Tau Province

No.	Location	Number of Soil Samples
1	Vung Tau City	7
2	Ba Ria City	5
3	Long Dien District	3
4	Xuyen Moc District	15
5	Dat Do District	3
6	Chau Duc District	3
7	Tan Thanh District	1
8	Phu My Town	5

In the selected survey area, soil was collected from a pit measuring 20 cm x 40 cm, at a depth extending to 30 cm. The soil excavated from the pit was placed on a plastic sheet, broken up, and sorted to remove

roots and gravel. This material was then mixed and formed into a conical pile. The cone was divided into four equal quarters by two perpendicular cuts. Two opposite quarters were discarded, and the remaining two were re-mixed. This process of coning and quartering was repeated until the sample was reduced to a final mass of approximately 2 kg, which was then sealed in a large plastic bag for transport to the laboratory.

Prior to sealing the bag, a sample data sheet was inserted between the two plastic layers. This sheet documented essential information, including the sampling location, sample ID, position, depth, collection date, weather conditions, and the name of the collector. The GPS coordinates for each sampling point were also logged in a field notebook.

The overall distribution of the sampling locations is illustrated in figure 1.

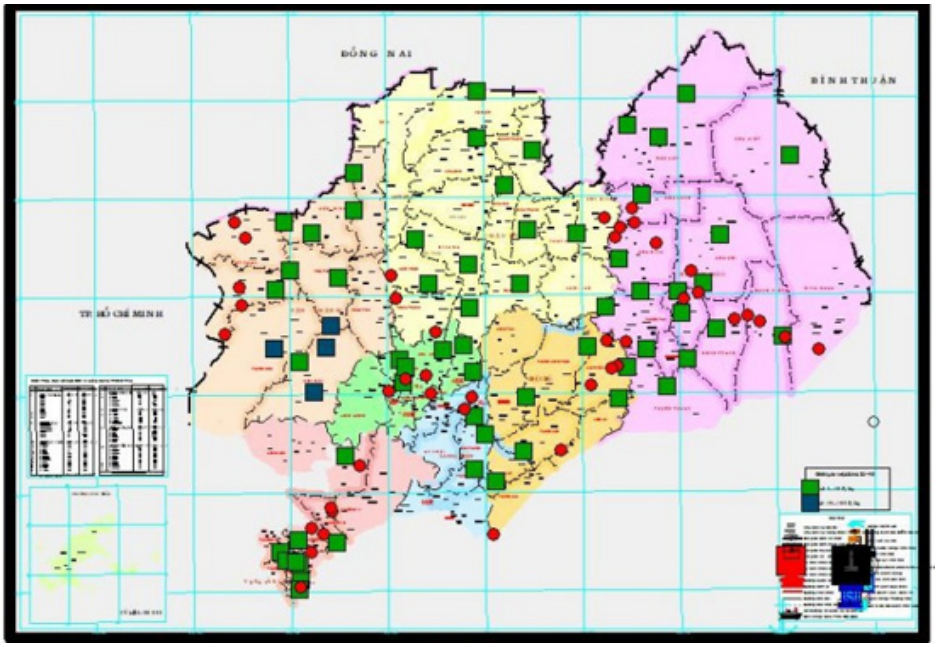

Figure 1. Soil Sample Locations across Ba Ria-Vung Tau Province

Sample Preparation for Analysis

Upon receipt, the soil samples were processed by crushing them to a particle size of less than 1 cm and spreading them on trays. Oven-drying was performed on the samples at 70°C until they became friable, they were then ground using a mortar and pestle before being sieved through a 1 mm mesh. This fine fraction was deemed suitable for analysis.

For measurement, each sample container's tare mass was first recorded. The sieved soil was packed into the container to a height of 2,0 cm, matching the geometry of the standard reference material (figure 2). The total mass of the container and sample was then measured to determine the net sample mass. The container was sealed, labeled with the sample ID and net mass, and submitted for gamma-ray spectrometry to determine its activity.

Figure 2. Soil Sample in Measurement Container

Procedure for the Determination of Radionuclide Specific Activity

Specific radionuclide activities in the soil samples were measured by a Falcon 5000 Gamma Spectrometry system. This system is configured with an 18 % relative efficiency High-Purity Germanium (HPGe) detector, capable of analyzing gamma energies within a range of 20 keV to 3,0 MeV. The device utilizes an electric cooling system and an analyzer with channel options ranging from 256 to 8192.[5]

The analytical procedure involved four main steps. First, both energy and efficiency calibrations were conducted before any sample measurements. Energy calibration was performed using a ^{137}Cs source with an activity of 0,98690 µCi, while a certified RGU 1 standard source. To calibrate the detector's efficiency, a standard source consistent with the samples was utilized. The prepared soil samples were then measured for 24 hours using the Falcon 5000 system. Finally, gamma-ray spectral analysis was performed using the Gamma vision 32 software, where a standard library was created to determine the specific activity of ^{210}Pb, ^{40}K, ^{137}Cs, ^{214}Pb, ^{214}Bi, ^{238}U, and ^{232}Th.[6,7]

Radiation Hazard Indices

To quantify the radiological hazard from essential occurring radionuclides, a set of key indices is employed. These indices consolidate the specific activity concentrations of crucial isotopes into a single, comprehensive value to assess the overall radiation risk.

Radium Equivalent Activity (R_{aeq})

The combined activity of ^{226}Ra, ^{232}Th, and ^{40}K is often represented by a single radiological index known as the Radium Equivalent Activity (R_{aeq}). This value is important for quantifying the overall radiological hazard from these three natural radionuclides, and the value is derived from the equation below:[6,8]

$$R_{aeq} = A_{Ra} + 1{,}43 \times A_{Th} + 0{,}077 \times A_K \qquad (1)$$

Where A_{Ra}, A_{Th}, and A_K are the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, expressed in Bq/kg.

Representative Level Index ($I_{\gamma r}$)

Another radiation index, the Representative Level Index ($I_{\gamma r}$), is defined by the following formula:[6,8]

$$I_{\gamma r} = \frac{1}{150\ Bq/kg} \times A_{Ra} + \frac{1}{100\ Bq/kg} \times A_{Th} + \frac{1}{1500\ Bq/kg} \times A_K \qquad (2)$$

Here, A_{Ra}, A_{Th}, and A_K are the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K, expressed in Bq/kg. This index is used to estimate the dose rate from gamma radiation. The acceptable range for this index is defined as being less than or equal to 1.

Absorbed Dose Rate (D)

The absorbed dose rate in outdoor air, measured at 1 meter above the ground, quantifies the gamma radiation exposure originating from naturally occurring radionuclides in the soil. This rate is calculated based on the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, using specific dose conversion factors of 0,462, 0,621, and 0,0417 nGy.h^{-1} per Bq/kg, respectively.[9,10,11]

$$D\ (nGyh^{-1}) = 0{,}462 \times A_{Ra} + 0{,}621 \times A_{Th} + 0{,}0417 \times A_K \qquad (3)$$

Annual Effective Dose Rate

The absorbed dose rate is used to calculate the annual effective dose rate (E_{eff}), which quantifies the health risk from radiation exposure. This calculation takes into account the dose-to-effective dose conversion coefficient and the average outdoor occupancy time. The standard conversion coefficient is 0,7 Sv.Gy^{-1}, and the average outdoor occupancy time is often assumed to be 20 % of a year (approximately 1752 hours/year).[12]

$$E_{eff} = D \times 1{,}2264 \times 10^{-3} \qquad (4)$$

The global average annual effective dose due to natural radioactivity is estimated at 1 mSv.y^{-1}

External hazard index (H_{ex})

A commonly employed hazard index, which quantifies external exposure, is known as the external hazard index and is calculated as follows:[12,13]

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

Internal hazard index (H_{in})

Radon and its progeny pose a documented hazard to the respiratory system, a risk that is distinct from the external hazard index. The internal exposure from these radionuclides is measured by the internal hazard index (H_{in}), calculated using the following formula:

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

To ensure a negligible radiation hazard, the index values (H_{ex}, H_{in}) must not exceed unity.[12,13]

RESULTS AND DISCUSSION

Table 1 presents the specific radioactivity values and radium equivalent values for the natural radionuclides, including their standard deviations (SD).

Table 1. The specific activity levels of the natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in soil samples, along with the corresponding radium equivalent activity (Bq/kg)

Samples	Activity concentration Bq/kg (±SD)			R_{aeq} (Bq/kg)
	^{226}Ra	^{232}Th	^{40}K	
A01	38,67 ± 2,30	25,87 ± 3,54	34,38 ± 2,32	75,90 ± 7,39
A02	17,3 ± 5,30	19,78 ± 3,59	39,82 ± 2,39	45,85 ± 10,45
A03	23,69 ± 4,56	19,97 ± 3,20	37,97 ± 2,73	52,50 ± 9,16
A04	45 ± 2,91	31,92 ± 3,62	295,57 ± 2,25	92,70 ± 8,09
A05	45,23 ± 2,67	55,69 ± 4,39	403,74 ± 2,53	127,70 ± 8,96
A06	6,59 ± 2,79	3,84 ± 0,53	9,49 ± 4,45	12,14 ± 3,58
A07	23,50 ± 1,09	32,50 ± 3,10	167,59 ± 3,42	71,15 ± 5,55
A08	29,59 ± 4,25	29,13 ± 5,11	71,73 ± 1,80	71,75 ± 11,58
A09	35,78 ± 2,72	23,72 ± 1,89	18,15 ± 2,23	69,82 ± 5,43
A10	15,37 ± 3,14	9,44 ± 1,98	178,34 ± 2,27	30,11 ± 5,98
A11	19,75 ± 1,40	32,55 ± 3,87	62,18 ± 2,66	66,73 ± 6,95
A12	20,45 ± 1,24	12,93 ± 3,17	113,34 ± 2,65	39,73 ± 5,79
A13	19,66 ± 4,85	20,46 ± 4,43	38,33 ± 1,62	49,19 ± 11,20
A14	35,52 ± 3,09	27,03 ± 3,92	41,78 ± 2,47	74,47 ± 8,72
A15	42,05 ± 3,46	39,08 ± 2,96	71,54 ± 4,10	98,44 ± 7,72
A16	36,2 ± 2,48	33,84 ± 3,36	286,87 ± 1,06	86,59 ± 7,29
A17	48,65 ± 2,88	48,31 ± 3,62	177,48 ± 3,58	118,97 ± 8,08
A18	45,28 ± 2,93	36,90 ± 3,64	144,20 ± 3,15	99,06 ± 8,16
A19	27,50 ± 1,82	17,69 ± 2,86	47,14 ± 1,79	53,13 ± 5,92
A20	17,25 ± 2,89	5,86 ± 3,94	56,11 ± 1,61	26,02 ± 8,53
A22	42,94 ± 2,33	37,34 ± 4,09	144,92 ± 3,78	97,35 ± 8,20
A23	21,11 ± 4,86	17,59 ± 3,84	97,77 ± 3,39	46,95 ± 10,37
A24	42,28 ± 2,13	22,12 ± 3,80	45,95 ± 1,92	74,24 ± 7,57
A25	20,73 ± 1,24	20,57 ± 4,14	86,70 ± 3,30	50,75 ± 7,18
A26	33,23 ± 1,13	26,52 ± 3,79	93,89 ± 3,92	71,81 ± 6,58
A27	29,51 ± 1,32	23,3 ± 4,01	114,64 ± 3,88	63,63 ± 7,07
A28	32,22 ± 2,81	21,35 ± 4,01	123,99 ± 1,18	63,61 ± 8,55
A29	37,95 ± 1,27	28,74 ± 4,01	174 ± 2,18	80,27 ± 7,03
A30	42,88 ± 2,10	31,24 ± 3,67	89,4 ± 3,68	88,17 ± 7,38
A31	30,39 ± 2,15	28,92 ± 3,40	74,14 ± 2,68	72,27 ±7,03
A32	30,56 ± 1,73	32,59 ± 2,95	230,59 ± 2,88	78,77 ± 5,96

A33	24 ± 1,62	17,95 ± 2,68	81,67 ± 4,85	50,24 ± 5,48
A34	45,07 ± 2,97	35,19 ± 3,18	249,52 ± 2,58	97,14 ± 7,54
A35	32,36 ± 1,67	23,85 ± 4,36	120,49 ± 3,94	67,31 ± 7,93
A36	18,82 ± 3,63	13,54 ± 3,86	204,09 ± 2,88	39,61 ± 9,17
A37	20,66 ± 4,64	17,99 ± 5,07	44,16 ± 2,48	46,69 ± 11,91
A38	23,62 ± 4,87	17,31 ± 4,43	262,41 ± 3,38	50,21 ± 9,79
A39	15,02 ± 4,50	15,81 ± 2,84	112,18 ± 1,51	38,41 ± 8,57
A40	13,18 ± 3,55	13,31 ± 4,75	139,21 ± 2,89	33,18 ± 10,36
A41	19,54 ± 4,26	18,14 ± 4,51	157,67 ± 2,48	46,59 ± 10,73
A42	35,57 ± 1,11	18,71 ± 3,29	39,9 ± 1,38	62,60 ± 5,82

Measurements of the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were performed using gamma-ray spectrometry. The resulting radium equivalent activity (R_{aeq}) values for 42 soil samples, along with their standard deviations (SD), are presented in table 1. These values were calculated using equation 1.

With a mean value of 29,38 Bq/kg, the activity concentration of ^{226}Ra in the study area varied from 6,59 Bq/kg to 48,65 Bq/kg. This mean concentration is less than the worldwide mean of 50 Bq/kg for ^{226}Ra.[9,12]

For ^{232}Th, the activity concentration varied from 3,84 Bq/kg to 55,69 Bq/kg across the investigated soil samples, with a mean value of 24,60 Bq/kg. The measured values fall within the range of the global standard values.[9,12]

The activity concentration of ^{40}K fluctuated between 4,49 Bq/kg and 403,74 Bq/kg. The mean ^{40}K concentration in the study region was 121,53 Bq/kg. This is significantly lower than the worldwide average value of 400 Bq/kg.[12]

The radium equivalent activity (R_{aeq}) for the surveyed soil samples was calculated based on the activity concentrations of the three natural radionuclides., ranged from 12,14 Bq/kg to 127,70 Bq/kg. The mean R_{aeq} value of 65,41 Bq/kg is considerably lower than the global threshold of 370 Bq/kg.[12,14]

Table 2. Calculated radiological hazard indices for soil samples in the study area

Samples	I_γ (Bq/kg)	D (nGyh^{-1})	E_{eff} dose (mSv.y^{-1})	Hazard index	
				H_{ex}	H_{in}
A01	0,54 ± 0,05	35,36 ± 3,35	0,043 ± 0,004	0,21 ± 0,02	0,31 ± 0,03
A02	0,34 ± 0,06	21,93 ± 4,77	0,026 ± 0,005	0,13 ± 0,03	0,18 ± 0,04
A03	0,38 ± 0,06	24,93 ± 4,21	0,030 ± 0,005	0,15 ± 0,03	0,21 ± 0,03
A04	0,82 ± 0,06	52,93 ± 3,68	0,064 ± 0,004	0,30± 0,02	0,30 ± 0,02
A05	1,13 ± 0,05	72,32 ± 4,06	0,088 ± 0,005	0,42 ± 0,02	0,54 ± 0,03
A06	0,08± 0,01	5,82 ± 1,81	0,007 ± 0,002	0,03 ± 0,01	0,05 ± 0,01
A07	0,59 ± 0,04	38,03 ± 2,57	0,046 ± 0,003	0,22 ± 0,01	0,28 ± 0,01
A08	0,54 ± 0,06	34,75 ± 5,21	0,042 ± 0,006	0,21 ± 0,03	0,28 ± 0,04
A09	0,49 ± 0,06	32,02 ± 2,52	0,039 ± 0,003	0,19 ± 0,01	0,29 ± 0,02
A10	0,32 ± 0,06	20,39 ± 2,77	0,025 ± 0,003	0,11 ± 0,01	0,15 ± 0,02
A11	0,49 ± 0,04	31,93 ± 3,16	0,039 ± 0,004	0,19 ± 0,02	0,24 ± 0,02
A12	0,34 ± 0,01	22,2 ± 2,65	0,027 ± 0,003	0,13 ± 0,01	0,18 ± 0,02
A13	0,36 ± 0,03	23,3 ± 5,05	0,028 ± 0,006	0,14 ± 0,03	0,19 ± 0,04
A14	0,53 ± 0,02	34,94 ± 3,96	0,042 ± 0,005	0,20 ± 0,02	0,31 ± 0,03
A15	0,72 ± 0,02	46,68 ± 3,61	0,057 ± 0,004	0,28 ± 0,02	0,39 ± 0,03
A16	0,77 ± 0,02	49,70 ± 3,27	0,061 ± 0,004	0,29 ± 0,02	0,38 ± 0,03
A17	0,92 ± 0,02	59,87 ± 3,73	0,073 ± 0,004	0,35 ± 0,02	0,48 ± 0,03
A18	0,76 ± 0,02	49,85 ± 3,74	0,061 ± 0,004	0,29 ± 0,02	0,41 ± 0,03
A19	0,39 ± 0,01	25,65 ± 2,69	0,031 ± 0,003	0,15 ± 0,01	0,22 ± 0,02
A20	0,21± 0,02	13,94 ± 3,84	0,017 ± 0,005	0,08 ± 0,02	0,13 ± 0,03
A22	0,75± 0,01	49,07 ± 3,77	0,060 ± 0,004	0,29 ± 0,02	0,41 ± 0,03
A23	0,38 ± 0,03	24,75 ± 4,77	0,030 ± 0,005	0,14 ± 0,02	0,20 ± 0,04
A24	0,53 ± 0,01	35,19 ± 3,42	0,043 ± 0,004	0,21 ± 0,02	0,32 ± 0,02

A25	0,40 ± 0,01	25,97 ± 3,28	0,032 ± 0,004	0,15 ± 0,02	0,21 ± 0,02
A26	0,55 ± 0,01	35,73 ± 3,04	0,043 ± 0,003	0,21 ± 0,02	0,30 ± 0,02
A27	0,51 ± 0,01	32,88 ± 3,26	0,040 ± 0,004	0,19 ± 0,02	0,27 ± 0,02
A28	0,51 ± 0,01	33,31 ± 3,83	0,041 ± 0,005	0,20 ± 0,02	0,28 ± 0,03
A29	0,65 ± 0,01	42,63 ± 3,17	0,052 ± 0,004	0,25 ± 0,02	0,35 ± 0,02
A30	0,66 ± 0,01	42,94 ± 3,40	0,052 ± 0,004	0,26 ± 0,02	0,37 ± 0,03
A31	0,54 ± 0,01	35,09 ± 3,21	0,043 ± 0,004	0,21 ± 0,02	0,29 ± 0,02
A32	0,68 ± 0,01	43,97 ± 2,75	0,054 ± 0,003	0,25 ± 0,01	0,34 ± 0,02
A33	0,39 ± 0,01	25,64 ± 2,61	0,031 ± 0,003	0,15 ± 0,01	0,21 ± 0,02
A34	0,82 ± 0,02	53,08 ± 3,45	0,065 ± 0,004	0,30 ± 0,02	0,43 ± 0,02
A35	0,53 ± 0,01	34,78 ± 3,64	0,042 ± 0,004	0,20 ± 0,02	0,29 ± 0,03
A36	0,39 ± 0,02	25,61 ± 4,19	0,031 ± 0,005	0,14 ± 0,02	0,19 ± 0,03
A37	0,34 ± 0,03	22,56 ± 5,39	0,028 ± 0,006	0,13 ± 0,03	0,13 ± 0,04
A38	0,51 ± 0,03	32,60 ± 4,52	0,040 ± 0,005	0,18 ± 0,02	0,25 ± 0,04
A39	0,33 ± 0,03	21,43 ± 3,90	0,026 ± 0,004	0,12 ± 0,02	0,17 ± 0,03
A40	0,31 ± 0,02	20,16 ± 4,71	0,025 ± 0,005	0,11 ± 0,03	0,15 ± 0,04
A41	0,41 ± 0,03	26,87 ± 4,87	0,033 ± 0,006	0,15 ± 0,03	0,21 ± 0,04
A42	0,45 ± 0,01	29,72 ± 2,61	0,036 ± 0,003	0,17 ± 0,01	0,27 ± 0,01

The absorbed dose rate (D) and the effective dose rate (Eeff) for the analyzed samples were determined using equations (3) and (4), respectively. The results are summarized in table 2.

The absorbed dose rates ranged from 5,82 to 72,31 nGy/h, with an average value of 33,92 nGy/h, lower than the worldwide average value of 59 nGy/h, as reported by UNSCEAR (2000).[9] The maximum calculated value for the effective dose rate was 0,88 mSv/y, which is well below the 1,0 mSv/y limit recommended by UNSCEAR (1993).[15,16]

Although radon and its short-lived decay chain are known to pose a significant health risk to the respiratory system, this study found no evidence of such a risk. This is based on the calculation of the external hazard index (H_{ex}) and internal hazard index (H_{in}).

The external hazard index (H_{ex}) was determined to have a mean value of 0,20, with results spanning from 0,03 to 0,42. All calculated values were below the recommended safety limit of 1.[16]

The internal hazard index (H_{in}), which assesses the risk from radon and its progeny, had a mean value of 0,28. The highest value recorded was 0,54, which remains below the internationally recommended limit of 1. For radiological safety, standards established by organizations such as UNSCEAR and the IAEA mandate that the external (H_{ex}) and internal (H_{in}) hazard indices do not exceed a value of 1.[17,18]

CONCLUSIONS

Gamma-ray spectrometry was used to determine the natural radioactivity levels of ^{226}Ra, ^{232}Th, and ^{40}K in soil samples from the study area. All radionuclide concentrations were found to be below the established regulatory limits. Additionally, calculations of the potential radiological health hazard indices from these natural radionuclides indicate no significant health impact on the local population.

By providing essential baseline information on the natural radiation background of the area, this study serves as a key reference for future research and monitoring initiatives

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CONFLICT OF INTEREST

Declare potential conflicts of interest.

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