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Gamma-ray spectrometric analysis of bore-well rock samples from agricultural area of Tamil Nadu

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ABSTRACT

Natural gamma radiation exposure to humans can possess significant health risks when exposed either externally or internally. Though risks are not established at low doses, the exposure levels are set based on conservative approach. In this work, 22 bore-well rock samples were collected from the agricultural area of Dharmapuri district, Tamil Nadu to evaluate the radiation exposure to humans living in that area using a gamma-ray spectrometer. The results shows that, the activity concentration of ^{238}U ranges from MDA to 87±2 Bq kg^{-1} with an average value of 25 Bq kg^{-1}, and for ^{232}Th it ranges from MDA to 10±2 Bq kg^{-1}, and for the ^{40}K it ranges from 167±9 to 669±10 Bq kg^{-1} with the mean value of 310 Bq kg^{-1}. The various radiological parameters are calculated and compared with the world-recommended limit to assess the radiation hazards. To identify the relation among the natural radioisotopes, Pearson correlation analysis was performed between the radiological variables. It reveales that radionuclides ^{238}U and ^{232}Th strongly correlated with each other and radiological parameters. This implies that ^{238}U and ^{232}Th originated from the same source and ^{40}K was derived from different sources.

1. Introduction

Natural background radiation is primarily caused by land-based radioactive nuclides such as ^{238}U and ^{232}Th found in various concentrations in rocks, soil, water, and building materials [1,2]. Radionuclides such as ^{238}U, ^{232}Th, and ^{40}K, radon, thoron, and their progeny, contribute a significant portion of the background radiation [3]. Nearly 97% of total radiation exposure comes from natural sources, with only about 3 % coming from artificial sources [4]. The radiation decay series of ^{238}U comprises a range of radionuclides with complex characteristics and release alpha, beta, and gamma radiation throughout the decay process [3]. Long-term exposure to the short-lived progeny of uranium and thorium precursors (such as ^{226}Ra and ^{228}Ra) through inhalation has several health effects. Through the natural decay process, the high concentration of uranium and thorium in dwelling media can cause lung cancer, kidney damage, cancer of the bone or liver, leucopenia, anemia, and necrosis of the mouth [5].

Several types of rock samples were quantitatively determined for radionuclides. The concentrations are widely distributed in nature, they have been found to be dependent on local geological conditions and thus vary from place to place [5,6]. In daily life, we inhale and breathe the radionuclides from the air, we ingest them from food and water intake, for instance, the water obtained from bore well contains a greater concentration of radionuclides and a non-negligible number of people from some countries/areas usually drink and utilize such water regularly for daily household purpose and received radiation exposure both externally and internally [7,8]. This is due to underground water frequently flows through the rock and soil, hence the radioactive materials available in such media may easily dissolve in the water.

The natural radioactivity on rock samples is critical for understanding the radionuclide migration processes in the lithosphere. Drilling is utilized for a variety of purposes, including the extraction of oil, groundwater, minerals, and some other previously unknown forms of rocks from the ground [9]. It is also crucial to recognize the importance of geological structure and rock type as sources of radionuclides in rock samples. During the drilling process, different types of rocks such as

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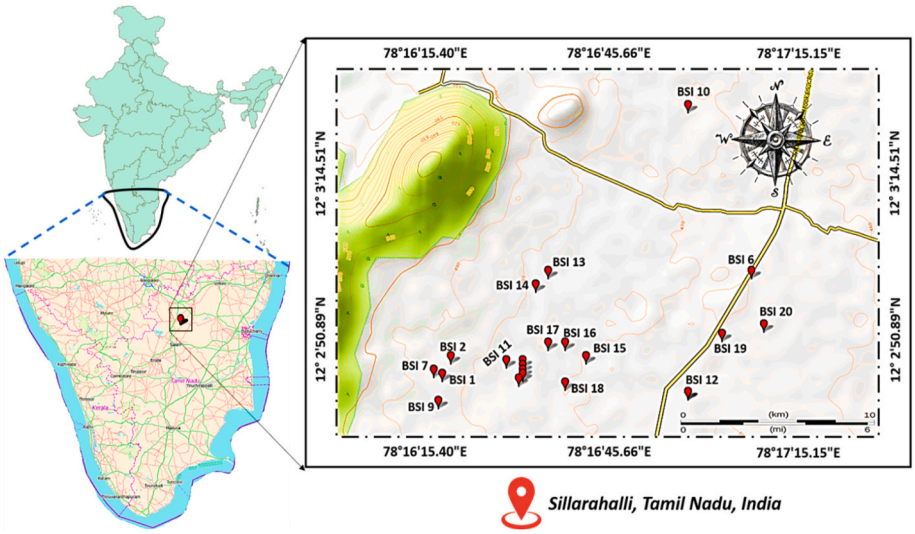

Fig. 1. Sampling points in the study area.

sedimentary rock, sandstone, limestone, etc., were unearthed in the form of a fine powder, and a huge amount is deposited in the agricultural land. Hydrothermally metamorphosed rocks are those that have been altered by hydrothermal fluids at high temperatures and moderate pressures [10].

Understanding the radionuclide concentrations and distributions is interesting because it provides useful information for environmental radioactivity monitoring [11]. Natural environmental radioactivity and the associated external exposure due to gamma radiation are primarily determined by geological and geographical conditions and appeared rocks at different depths in each drilled rock [12]. Since the agricultural soil in the study area contains a non-negligible amount of rocky texture, there is a high possibility of receiving a significant amount of radiation dose by the local populace via external (direct gamma ray exposure) and internal (ingestion of radionuclides through the soil-to-foodstuffs pathways). Therefore, the present study is important from the perspectives of health, hygiene, and radiology to assess doses and health risks resulting from gamma-emitting radionuclides in agricultural soil [11,13]. Hence the main objectives of the present study are (i) to determine the activity concentration of ^{238}U, ^{232}Th, and ^{40}K using NaI(Tl) gamma-ray spectrometry in bore-well rock samples and (ii) to calculate the associated radiological parameters and compared with recommended limit (iii) to assess the source of radionuclides from Pearson correlation and cluster analysis.

2. Materials and methods

2.1. Study area

The latitude and longitude are noted in every sampling point and bore-well rock samples were collected from the agricultural area of Dharmapuri district, Tamil Nadu [5]. Nearly 2000 houses and many cultivated crops like vegetables, paddy, sugarcane, maize, and cotton were nearby. Therefore, people have been living in these places for more than tens of hundreds of years. In the last few years, the Dharmapuri district has drilled large numbers of bore-well to extract groundwater for farming and domestic uses. The sampling points are shown in Fig. 1.

2.2. Sample collection and preparation

A total of 22 borewells with a huge amount of powdered rock samples deposition was found in the study area. At each sampling point, about 1–2 kg of samples are collected and it was stored in polythene bags and labeled as BSI-1 to BSI-22 and transported to the laboratory [14]. In the laboratory, samples are air-dried for 2–3 days, and oven dried at a temperature of 110 °C for 2 h until all moisture content was completely removed [15]. The dried samples were then ground into a fine powder, using an agate mortar and pestle, and sieved through a 63 μm mesh size to reach homogenize and stored in Marinelli beakers and sealed by using Teflon tape and kept for four weeks to reach an equilibrium of short-lived daughters of the ^{222}Rn and ^{220}Rn with their long-lived parent radionuclides ^{238}U and ^{232}Th [5,7].

2.3. Gamma-ray spectrometry

Gamma-ray spectrometry is a fast and widespread method used to identify the activity concentration of radionuclides. Here, NaI(Tl) scintillation detector 3"×3″ integrated with PC-MCA was used to measure the activity concentration of radionuclides in the rock samples. The cylindrical lead shield is covered in an outer layer (15 cm thick) to reduce the background of the detector [14]. The lead shield contained an inner concentric cylinder of copper (0.03 mm) to observe the X-ray generated in the lead. In the gamma-ray spectrum, three counting windows or regions of interest (ROI) were noted [15]. They were centered on the three-characteristic photo-peaks, which corresponded to the ^{238}U, ^{232}Th, and ^{40}K, decay series, at approximately 1.76 MeV ^{214}Bi, 2.62 MeV ^{208}Tl, and 1.46 MeV ^{40}K. For ^{238}U, ^{232}Th, and ^{40}K activity measurements, the system was calibrated using International Atomic Energy Agency [16] certified reference grade materials such as RG-U (4940 ± 30 Bq kg^{-1}), RG-Th (3250 ± 90 Bq kg^{-1}), and RG-K (14000 ± 400 Bq kg^{-1}) [17,18]. Additionally, the geometry of the Marinelli beakers for reference grade materials and prepared samples are similar (height: 12 cm and dia: 6 cm). The energy calibration was done by positioning the different gamma sources ^{60}Co (1170 keV and 1330 keV) and ^{137}Cs (662 keV), of the known energies on the inside of the detector [15]. The prepared samples were placed at the top of the detector in a closed system of lead shield and the spectra were recorded in "Anuspect gamma spectral analysis software v.1.0" (built by Bhabha Atomic Research Centre, Mumbai, India) for 10,000 s. From this duration, the peak ranges were executed in the multi-channel analyzer MCA [17]. According to Currie's relation, the minimum detectable activity (MDA) was calculated by the following equation [19],

$$\mathrm{MDA} = \frac{4.65\ \sigma_B}{\epsilon \times \mathrm{T}} \quad (1)$$

Where σ_B is the standard deviation of background counts per second, T is counting time (s), and ϵ is absolute efficiency for photo peak. From this

Table 1
The activity concentrations of radionuclides ^{238}U, ^{232}Th, ^{40}K, and radiological parameters for bore-well rock samples.

Sample ID	Latitude	Longitude	Activity concentrations (Bq kg^{-1})			Ra_{eq} (Bq kg^{-1})	D_{Rout} (nGy h^{-1})	$AEDE_{out}$ (mSv y^{-1})	H_{in}	H_{ex}	ELCR ($\times 10^{-3}$)
			$^{238}U\pm2\sigma$	$^{232}Th\pm2\sigma$	$^{40}K\pm2\sigma$						
BSI 1	12′2′59′′N	78′15′45′′E	MDA	MDA	271±10	21	22	0.03	0.06	0.06	0.09
BSI 2	13′3′3′′N	78′15′47′′E	26±3	MDA	255±10	46	44	0.05	0.19	0.12	0.19
BSI 3	12′2′5′′N	78′16′43′′E	15±2	MDA	356±10	42	43	0.05	0.16	0.11	0.18
BSI 4	12′3′2′′N	78′16′4′′E	24±3	MDA	290±10	46	45	0.06	0.19	0.13	0.20
BSI 5	12′2′58′′N	78′16′3′′E	22±3	MDA	291±10	44	44	0.05	0.18	0.12	0.19
BSI 6	12′3′22′′N	78′16′58′′E	MDA	MDA	530±12	41	43	0.05	0.11	0.11	0.18
BSI 7	12′3′0′′N	78′15′43′′E	19±2	MDA	261±9	39	39	0.05	0.16	0.11	0.17
BSI 8	12′2′59′′N	78′16′4′′E	24±2	MDA	315±9	48	48	0.06	0.20	0.13	0.20
BSI 9	12′2′53′′N	78′15′44′′E	17±3	MDA	167±9	30	29	0.04	0.13	0.08	0.12
BSI 10	12′3′59′′N	78′16′43′′E	19±3	MDA	234±10	37	36	0.04	0.15	0.10	0.16
BSI 11	12′3′2′′N	78′16′0′′E	24±3	MDA	255±9	44	43	0.05	0.18	0.12	0.18
BSI 12	12′2′55′′N	78′16′43′′E	28±3	MDA	249±9	47	46	0.06	0.20	0.13	0.20
BSI 13	12′3′22′′N	78′16′10′′E	87±2	10±2	266±8	122	113	0.14	0.56	0.33	0.48
BSI 14	12′3′19′′N	78′16′7′′E	29±2	MDA	275±9	50	49	0.06	0.21	0.14	0.21
BSI 15	12′3′3′′N	78′16′19′′E	36±3	MDA	240±9	54	52	0.06	0.24	0.15	0.23
BSI 16	12′3′6′′N	78′16′14′′E	MDA	MDA	328±10	25	26	0.03	0.07	0.07	0.11
BSI 17	12′3′6′′N	78′16′10′′E	50±3	MDA	317±10	74	72	0.09	0.34	0.20	0.31
BSI 18	12′2′57′′N	78′16′14′′E	52±3	MDA	231±9	70	66	0.08	0.33	0.19	0.29
BSI 19	12′3′8′′N	78′16′51′′E	52±3	MDA	669±10	104	102	0.12	0.42	0.28	0.44
BSI 20	12′3′10′′N	78′17′1′′E	21±2	MDA	516±9	61	61	0.07	0.22	0.16	0.26
BSI 21	12′3′1′′N	78′16′4′′E	14±2	MDA	243±9	33	32	0.04	0.13	0.09	0.14
BSI 22	12′3′0′′N	78′16′4′′E	MDA	MDA	256±9	20	21	0.03	0.05	0.05	0.09
Mean value			25	–	310	50	49	0.06	0.20	0.13	0.21
World average value			33	45	420	370	59	0.07	1	1	0.29 $\times 10^{-3}$

Note: Ra_{eq} – Radium equivalent activity; D_{Rout} – Outdoor absorbed dose rate; $AEDE_{out}$ – Outdoor annual effective dose; H_{in} – Internal hazard index; H_{ex} – External hazard index; ELCR – Excess lifetime cancer risk.

Table 2
Comparison of activity concentration of ^{238}U, ^{232}Th, and ^{40}K in rock samples with similar works carried out in other countries.

Country	No. of Samples	Activity concentration (Bq kg^{-1})			Reference
		^{238}U	^{232}Th	^{40}K	
Austria	22	55.4	24.6	911	[25]
Weibei area, Shaanxi, China	9	22.0	75.9	968.5	[26]
Pakistan	20	439.5	50.5	207.3	[27]
Okene, Nigeria	19	31.94	23.27	828.02	[28]
Bir El-Sid (Egypt)	100	57.4	53.4	1041.4	[29]
Wadi El-Germal (Egypt)		39	47.9	1031	
Germany		76.1	70	1465.4	
North of Sana'a, Yemen	18	22.4	19.15	399.8	[30]
Egypt	11	28.4	37.7	1167.6	[31]
Jharkhand, India	5	3.01	18.45	311.74	[32]
Nigeria	44	13.376	3.308	4.751	[33]
Amman City, Jordan	40	29.0*	35.5	265.7	[34]
Dharmapuri, India	22	25	–	310	**Present work**

Note: * refers to ^{226}Ra.

equation, the calculated minimum detectable activity (MDA) of the NaI (Tl) system for the three nuclides ^{238}U, ^{232}Th, and ^{40}K are 8 Bq kg^{-1}, 8 Bq kg^{-1}, and 30 Bq kg^{-1} respectively [18].

Activity concentrations of ^{238}U, ^{232}Th, and ^{40}K are calculated by using the following formula [20],

$$A\left(\text{Bq kg}^{-1}\right) = \frac{NCPS}{W \times \eta} \tag{2}$$

Where NCPS is the gross count of each radionuclide in the spectrum, W is the net weight of the sample, and η – photo peak's efficiency from efficiency calibration.

In addition, the level of potential error or variation related to the estimated activity concentration values of ^{238}U, ^{232}Th, and ^{40}K in samples was calculated by using the following formula [21],

$$\sigma = \frac{\sqrt{GC + BKG}}{t \times W \times \eta} \tag{3}$$

Where GC is the gross count of each radionuclide, BKG is the background count rates, t is the acquisition time in seconds, W is the mass of the samples, and η is the efficiency of the detector.

3. Results and discussion

3.1. Activity concentration of ^{238}U, ^{232}Th and ^{40}K

Table 1 gives the specific activity concentrations of naturally occurring radionuclides ^{238}U, ^{232}Th, and ^{40}K in rock samples. The calculated activity concentration of ^{238}U ranges from MDA to 87±2 Bq kg^{-1} with a mean of 25 Bq kg^{-1} and the ^{232}Th range is MDA to 10±2 Bq kg^{-1} with a mean of MDA and the ^{40}K range from 167±9 to 669±10 Bq kg^{-1} with a mean of 310 Bq kg^{-1}. The activity concentration of the radionuclides increases in the order of $^{232}Th < ^{238}U < ^{40}K$. In this study, the mean activity concentration of natural radionuclides is lower than the world average values 33, 45, and 420 Bq kg^{-1} for ^{238}U, ^{232}Th, and ^{40}K respectively [22–24]. This indicates that activity concentration is due to the natural origin in rock samples.

Table 2 compares the activity concentration of the radionuclides ^{238}U, ^{232}Th, and ^{40}K found in rock samples from various countries with the current study. As reported by Refs. [25–34], the activity concentration of ^{238}U in the rock samples in this study area was significantly lower than in other nations such as Austria [25], Pakistan [27], Nigeria [28], Egypt & Germany (Bir El-Sid, Wadi El-Germal, and Germany) [29] and Egypt [31]. Similarly, ^{232}Th of the collected rock samples were lower than the other countries shown in Table 2. For ^{40}K, the activity concentration in the present study was almost equal to that in Jharkhand, India, as reported by Zubair [32] and higher than Pakistan [27], Nigeria [33], and Jordan [34].

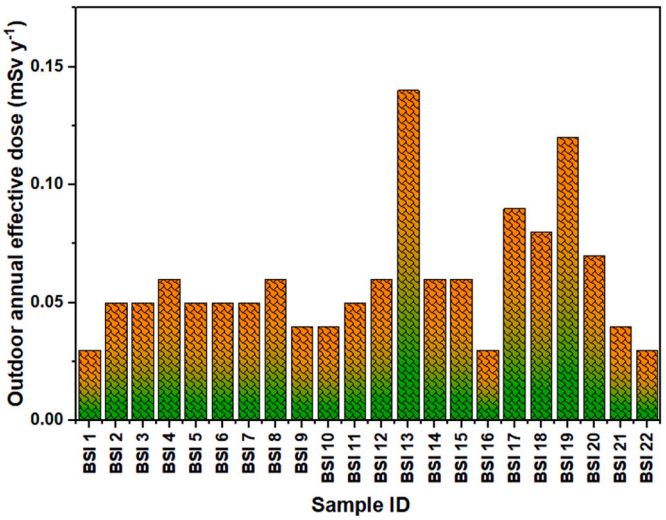

Fig. 2. The variation of an outdoor annual effective dose of collected bore-well rock samples.

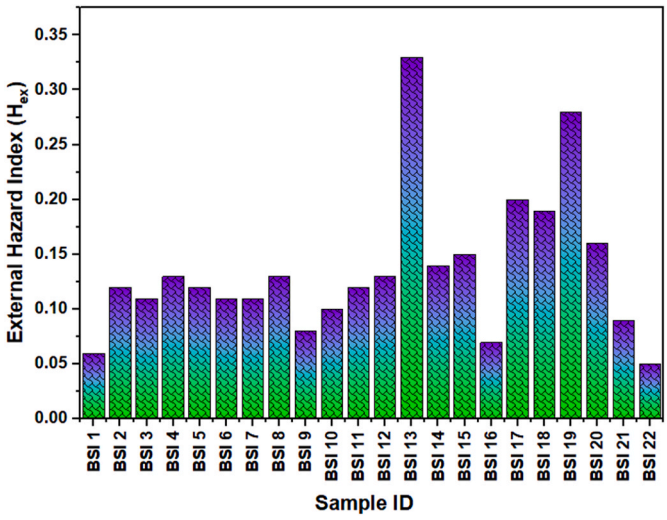

Fig. 3. Variation of external hazard index in the collected bore-well rock samples.

3.2. Radiological parameters

3.2.1. Radium equivalent activity (Ra_{eq})

The distribution of natural radionuclides in the samples under study is not uniform. As a result, a common radiological index has been developed to assess actual activity levels ^{238}U, ^{232}Th, and ^{40}K in the bore-well rock samples, as well as the radiation hazards associated with these radionuclides, which can be calculated by using the formula [35]. This index is known as radium equivalent activity.

$$\mathbf{Ra_{eq} = A_U + (1.43 \times A_{Th}) + (0.077 \times A_K)} \quad (4)$$

Where, A_U, A_{Th}, and A_K are the activity concentration of the ^{238}U, ^{232}Th, and ^{40}K respectively in Bq kg^{-1} [10]. The average value of the Ra_{eq} is 50 Bq kg^{-1} which is less than the world average value of 370 Bq kg^{-1}. This indicates the origin of these radionuclides is local origin in the study area.

3.2.2. Outdoor absorbed dose rate (D_{Rout})

The absorbed dose rate is determined by measuring the equal distribution of gamma radiation from natural radionuclides such as ^{238}U, ^{232}Th, and ^{40}K above 1 m from the earth's surface [36]. It can be calculated by using the following UNSCEAR relation (Eq. (5)) [37].

$$\mathbf{D_{Rout}\ (nGy\ h^{-1}) = 0.92A_U + 1.1A_{Th} + 0.0807A_K} \quad (5)$$

where, A_U, A_{Th}, and A_K are the activity concentration of the ^{238}U, ^{232}Th, and ^{40}K.The calculated mean value of the absorbed dose rate is 49 nGy h^{-1}, below the world average value of 59 nGy h^{-1} [36]. Therefore, these rock samples do not possess any health effects.

3.2.3. Outdoor annual effective dose (AED_{Out})

The outdoor annual effective dose rate was calculated for the public using the conversion coefficient ($CF = 0.7$ SvG y^{-1}) from the absorbed dose in the air and the outdoor occupancy factor ($OF = 20\%$ of 8760 h in a year) [38]. Outdoor annual effective dose rates (AED_{out}) were calculated using Eq. (6). [39],

$$\text{Outdoor AED (mSv/y)} = D_{Rout}(nGyh^{-1}) \times 8760\ (h/y) \times 0.2 \times 0.7\ (Sv/Gy) \times 10^{-6} \quad (6)$$

The calculated Outdoor AED values are presented in Table 1. From this table, the average value of 0.06 mSv/y was noted, and which is comparatively lower than the world recommended limit of 1 mSv/y hence collected bore-well rock samples are free from radiation hazards in the study area. The variation of the outdoor annual effective dose is shown in Fig. 2.

3.2.4. Internal hazard index (H_{in})

The internal hazard index (H_{in}) calculates the internal exposure to radiotoxicity of ^{238}U is enhanced by a factor of two to account for the contribution of carcinogenic ^{222}Rn and its short-lived progeny. In other gamma rays, ^{222}Rn is important for internal exposure in an environment. The internal exposure to radon and its daughter products can be calculated, by using the formula [40],

$$H_{in} = \frac{A_U}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (7)$$

The internal hazard index is varying ranges from 0.05 Bq kg^{-1} in BSI-22 and 0.56 Bq kg^{-1} in sample BSI-13 the mean average value is 0.20 Bq kg^{-1} which is below the recommended values $H_{in} \leq 1$. In this study, the collected bore-well rock samples are under the safety level (permissible level).

3.2.5. External hazard index (H_{ex})

The external hazard index is evaluated for assessing the external exposure of gamma radiation from uranium and thorium and its daughter product of the radionuclide is a short-lived progeny [41–43]. Eq. (8) was used to calculated the external hazard index [35] and the values are given in Table 1.

$$H_{ex} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (8)$$

The external hazard index ranges from 0.05 to 0.33 with an average value of 0.13 which is below the recommended value of 1 hence the collected samples are under the safety level (permissible level) [24]. Fig. 3 shows the variation of the external hazard index in the study area.

3.2.6. Excess lifetime cancer risk (ELCR)

The excess lifetime cancer risk refers to the probability of developing cancer as the result of exposure to specific carcinogen effects due to the accumulation of radionuclides intake of water and air bore-well is one of the most important in daily commercial uses the water taken from the bore-well inside of several different sedimentary rocks are present in this case we calculated the ranges of nuclides in bore-well rock samples by using the formula [44].

$$\text{ELCR} = \text{AEDE}_{out} \times \text{DL} \times \text{RF} \quad (9)$$

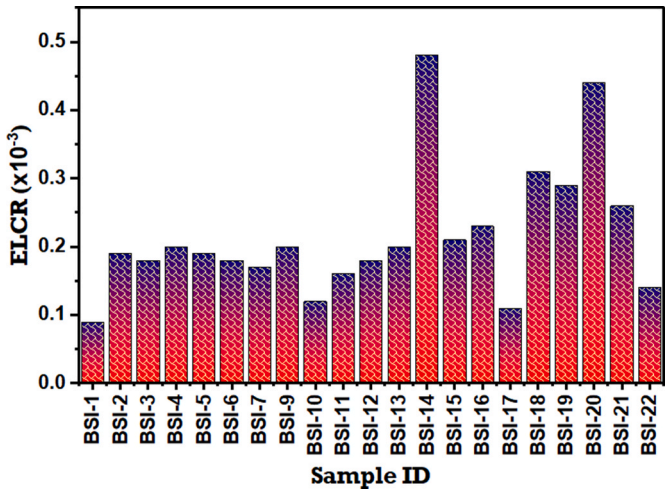

Fig. 4. Variation of excess lifetime cancer risk in the collected bore-well rock samples.

Where, AEDE, DL, and RF annual effective dose effect, duration of life (70 years), and risk factor (0.05 Sv^{-1}) are calculated in Table 1. The calculated mean value is 0.21 $\times$ 10^{-3} which comes below the recommended value (UNSCEAR 2000) [45]. The variations of ELCR in rock samples is shown in Fig. 4.

3.3. Pearson correlation analysis

Pearson correlation was a statistical analysis to measure the intensity and direction of the radioactive variables. Correlation is commonly classified into two types of positive and negative correlation. The values of the variables lie between linear correlation range from minus one to plus one ($-1 \leq r \leq 1$). The r value is denoted by the strong bond. When the variable moves to one side, the correlation is said to be positive. And the negative variables are moved together in opposite directions. A high value of r is said to be a strong relationship when it is focused on $+1$ or -1. A low value of r shows a weak linear relationship. When its value is close to zero, it is said to be low [19]. In this statistical analysis, Pearson correlation of the strong high positive linear correlation coefficient was observed uranium and thorium.

Table 3 shows a weak correlation between ^{238}U and ^{232}Th (r = 0.269), a very weak correlation between ^{238}U and ^{40}K (r = 0.021), and between ^{232}Th and ^{40}K (r = 0.063). These correlations indicate that the origin of ^{40}K is significantly different from the origin of the other two ^{238}U and ^{232}Th radionuclides, although both may be controlled and influenced by the same origin or sources. Besides this, the correlation coefficients (r) of the radiological parameters such as radium equivalent activity, absorbed dose rate, annual effective dose equivalent, internal hazard index, external hazard index, and excess lifetime cancer risk imply that the radiological parameters D_{Rout}, AEDE, H_{in}, H_{ex}, and ELCR were strongly correlated to the activity of ^{238}U in the bore-well rock samples while, Ra_{eq} was strongly correlated to the concentration of ^{40}K. On the other hand, most of the hazard parameters show relatively weak correlations with the ^{232}Th radionuclide compared to the ^{238}U. Although, in principle, uranium and thorium decay series occur happen together in nature, however, Table 3 indicates that the activity of uranium in bore well rock samples might be influenced by some other origins in the study region in addition to the common natural sources. However, ^{238}U and ^{232}Th radionuclides are primarily contributing to the Gamma radiation emission in the study area [23].

3.4. Cluster a nalysis

Cluster analysis is a statistical technique commonly used in environmental studies to group similar samples based on multiple variables of interest. It has been widely utilized to identify patterns of variables in radioactive studies. It can be applied to multivariate datasets, where multiple variables have been measured from various samples [46]. Multivariate datasets analyzing radioactive elements such as ^{238}U, ^{232}Th, ^{40}K, Ra_{eq}, D_{Rout}, AEDE, H_{ex}, H_{in}, and ELCR have been processed using cluster analysis to identify relationships between different variables and to group similar samples using a variety of techniques. In addition, hierarchical clustering is one of the most used methods in radioactive studies. This method involves calculating the distance between the samples, where the distance metric is typically the Euclidean distance, and then grouping the samples based on the calculated distance [47]. The result is a dendrogram that visualizes the clustering results, which can be seen in Fig. 5. In this figure, all 9 parameters were grouped into two statistically significant clusters. Cluster I separately

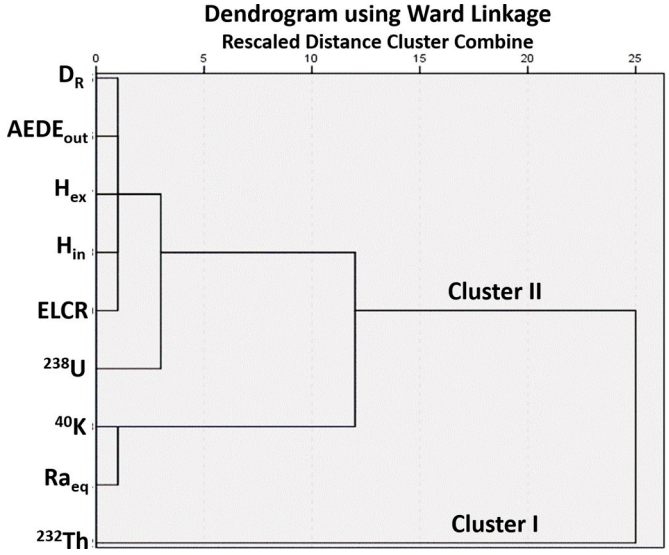

Fig. 5. Dendrogram using average linkage of hierarchical cluster analysis for 9 variables.

Table 3
Pearson correlation of the radiological variables.

	^{238}U	^{232}Th	^{40}K	Ra_{eq}	D_{Rout}	AEDE	H_{in}	H_{ex}	ELCR
^{238}U	1								
^{232}Th	0.269	1							
^{40}K	0.021	0.063	1						
Ra_{eq}	0.298	0.313	**0.942****	1					
D_{Rout}	**0.814****	**0.688****	0.363	**0.653****	1				
AEDE	**0.780****	**0.682****	0.411	**0.688****	**0.990****	1			
H_{in}	**0.939****	0.522*	0.222	0.519*	**0.960****	**0.942****	1		
H_{ex}	**0.922****	0.398	0.349	**0.608****	**0.928****	**0.919****	**0.973****	1	
ELCR	**0.887****	0.469*	0.407	**0.668****	**0.957****	**0.952****	**0.974****	**0.992****	1

Note: ** Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed).

accounted for ^{232}Th, whereas, Cluster II consisted of ^{238}U, ^{40}K, Ra_{eq}, D_{Rout}, AEDE, H_{ex}, H_{in}, and ELCR. Cluster II suggests that ^{232}Th does not contribute to any radiological parameters in the borewell rock samples. This is because the ^{232}Th is below the minimum detectable activity for most of the samples.

4. Conclusion

Gamma-ray spectrometry was used to assess the level of natural radioactivity in powdered rock samples collected from various depths. The mean activity concentration of ^{238}U, ^{232}Th, and ^{40}K is lower than the world average value given by UNSCEAR 2000 report. From the obtained results, the mean value of radiological parameters such as radium equivalent activity (50 Bq kg^{-1}), outdoor absorbed dose rate (49 nGy h^{-1}), annual effective dose (0.06 mSv y^{-1}), internal hazard index (0.20), external hazard index (0.13), and excess lifetime cancer risk (0.21 × 10^{-3}) are less than the world recommended limit. Pearson correlation and cluster analysis results indicates that ^{238}U and ^{232}Th only contribute to the radioactivity whereas the contribution of ^{40}K is insignificant. This indicates that samples do not possess a significant radiation hazard in the study area.

CRediT authorship contribution statement

G. Poongodi: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **A. Chandrasekaran:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization, Supervision. **V. Sathish:** Validation, Data curation, Software. **S. Karthikayini:** Formal analysis. **A. Tamilarasi:** Data curation. **Mayeen Uddin Khandaker:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work repor

Data availability

All data are available in the manuscript

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