

Assessment of natural radioactivity and radiological hazard index in the soil of Shrimadhopur, Rajasthan, India

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ABSTRACT

Background: Environmental accumulation of naturally occurring radioactive substances and their decay products may harm local populations' health. In this investigation, soil samples collected from many sites in Shrimadhopur, Rajasthan, India, were examined for the specific activities of radioisotopes and their potential health risks. **Materials and Methods:** Ten samples of soil were collected from various parts of Shrimadhopur. The samples were prepared and analysed for activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K using a p-type High Purity Germanium (HPGe) detector, and the activity concentrations were calculated by the comparative approach; radiation hazard parameters were also evaluated. **Results:** The mean activity concentrations were determined to be 20.23, 34.17, and 335.09 Bq kg⁻¹ for ²²⁶Ra, ²³²Th, and ⁴⁰K, respectively. The Radium equivalent activity varies between 44.27 and 138.19 Bq kg⁻¹ with an average of 84.91 Bq kg⁻¹. It was discovered that hazard parameters like H_{ex}, H_{in}, I_γ, and I_α were below the safe limit of unity. The average absorbed gamma dose rate was measured at 127.92 nGy h⁻¹, while the average total annual effective dose equivalent was 0.024 mSv. Furthermore, the average excess lifetime cancer risk is 0.086 × 10⁻³. **Conclusion:** These findings suggest that no substantial health hazards are associated with the radiological characteristics of the soil samples.

INTRODUCTION

Background radiation has been present since the formation of the Earth. Nearly 87% of the total radiation dose received by humans comes from natural sources, which may cause harmful health effects. The radionuclides most frequently found in nature are ²²⁶Ra, ²³²Th, and ⁴⁰K (1). Aside from this, radon (²²²Rn) is a decay product of radium (²²⁶Ra), contributing nearly half of the total effective dose from terrestrial origins to humans and is the primary cause of lung cancer associated with natural radiation (2). Apart from the above sources, artificial radionuclides, including ¹³⁷Cs, ¹³¹I, ⁹⁰Sr, and ²³⁹Pu, can also be found in the environment, originating from nuclear weapons testing fallout and by-products generated by nuclear power plants (3-4). Among the various environmental media, soil plays a critical role in harbouring and moderating the concentration of radioactive substances. The levels of terrestrial radioisotopes in soil are subject to considerable variation due to various influencing factors like geological composition, Soil pH, moisture content, and biological substance (5).

The principal health hazards associated with natural radioactivity in soil primarily arise from exposure to ionising radiation. The radiobiological

effects of ionising radiation on living tissues include nausea, vomiting, fatigue, acute radiation syndrome, skin erythema, cancer, and hereditary effects (6). Radioactive elements in soil can also significantly affect flora. Plants may absorb radionuclides through their roots, particularly isotopes like ⁴⁰K that mimic essential nutrients, potentially influencing germination, growth and cellular health (7). Given the potential health risks associated with natural radioactivity in soil, it is imperative to assess radiation doses.

The presence of naturally occurring radionuclides in rocks within the study area indicates that the local soil may contribute to elevated background radiation levels (8). Additionally, with nearly half of the region's population engaged in agriculture, it has been surveyed that the widespread use of chemical fertilizers, such as NPK, urea, and diammonium phosphate (DAP), is of concern. These fertilizers, while essential for improving crop yields, have been reported to contain trace levels of naturally occurring radioactive materials (NORMs) (9). Continuous and intensive application of such fertilizers over time may lead to a gradual accumulation of radionuclides in agricultural soils, potentially increasing environmental radioactivity. Despite these contributing factors, no prior investigations have

been conducted to quantify soil radioactivity in the Shrimadhapur area. This lack of data emphasizes the need for baseline radiological assessment to evaluate potential exposure risks to the local population and ensure long-term environmental safety.

The present study used high-resolution gamma-ray spectroscopy to measure the specific activity of ^{226}Ra , ^{232}Th , and ^{40}K radionuclides and associated radiological parameters in soil samples collected from Shrimadhapur Tehsil, located in the Sikar district of Rajasthan, India. The specific activity of soil samples was calculated using comparative method. Using the specific activities of these radionuclides, radium equivalent activity (R_{eq}), hazard indices (H_{in} and H_{ex}), level indices (I_{α} and I_{γ}), absorbed gamma dose rates (GD indoor and GD outdoor), annual effective doses (ED_{in} and ED_{out}), and activity utilisation index (AUI) were evaluated for potential health risk assessment. Such studies are very important for monitoring the environmental impact of radioactivity and ensuring that radiation levels remain within safe limits.

MATERIALS AND METHODS

Study area

Shrimadhapur Tehsil is situated in the Sikar district of Rajasthan, India. It is located in the south-eastern part of the district. The study area is delineated by its geographical coordinates, with latitudes extending from $27^{\circ}22'42''\text{N}$ to $27^{\circ}38'41''\text{N}$ and longitudes ranging from $75^{\circ}36'49''\text{E}$ to $75^{\circ}59'29''\text{E}$. Figure 1 offers a visual depiction of this region. This geographical map was created using QGIS software maintained by the QGIS.org Association, Switzerland. The region of Shrimadhapur encompasses an area of $1,373\text{ km}^2$ and has a population density of 425 individuals per km^2 . In the Shrimadhapur region, agriculture serves as the main livelihood, combining both livestock rearing, such as cattle and poultry, and the cultivation of various crops, including mustard, vegetables, horticultural produce, bajra, and wheat. The geology of the region has been shaped over millions of years by weathering, erosion, and tectonic activity, leading to the formation of distinct rock types and mineral deposits. Shrimadhapur Tehsil's rock formations consist of the Delhi Supergroup, which includes different kinds of rock such as quartzites, marbles, schists, and phyllites. These formations underwent significant metamorphic processes over time, contributing to the mineral wealth of the region. Notable mineral resources found in this area include marble, limestone, granite, and quartz. Because of the weathering of the underlying rocks, sandy loam is the most common soil type in this area. Topographically, Shrimadhapur exhibits an undulating terrain, transitioning from flat alluvial plains in the west to rugged rocky hills in the east.

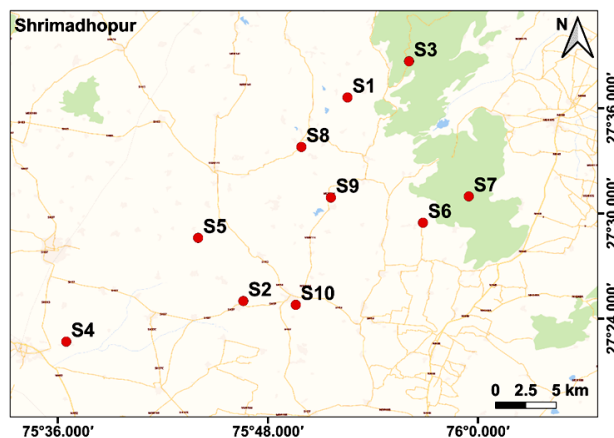


Figure 1. Geological Map of the research area with the soil sampling points.

Sample collection

Ten soil samples were collected from the research region. To prevent contamination from surface materials such as leaves and organic debris, samples were obtained from a depth of 1 m. Each sampling site's geographical coordinates were precisely captured using GPS. After collection, the samples were sealed in clean plastic bags and labelled according to their locations to avoid any risk of cross-contamination. Subsequently, they were taken to the research facility for initial preparation and assessment.

Sample preparation

The soil samples were first sieved using a 1 mm sieve in the research facility. Subsequently, they were placed in an oven set to 110°C for 24 hours to evaporate moisture content and attain a stable weight. After drying, the samples were placed in airtight, radon-impermeable petri dishes (90mm diameter and 15 mm thickness) and weighed with high precision using an electronic balance (accurate to 10^{-5} g). The samples were stored for four weeks to allow ^{238}U and ^{232}Th , along with their decay products, to achieve secular equilibrium prior to performing gamma spectroscopic measurements.

Preparation of standard source

Standard sources of ^{226}Ra , ^{232}Th , and ^{40}K were prepared using pitchblende (U_3O_8), thorium dioxide (ThO_2 , 99% pure), and potassium chloride (KCl, 99.5% pure), respectively. Pitchblende (U_3O_8) and potassium chloride (KCl) were manufactured by Sigma-Aldrich, Germany, while thorium dioxide (ThO_2 , 99% pure) was manufactured by Otto Chemie Pvt. Ltd., India. These compounds were uniformly mixed with silica gel in carefully measured amounts to ensure different activity levels. The mass of each compound was measured using a highly sensitive electronic balance with an accuracy of 10^{-5} g . Each sample was weighed, packed, and sealed in an airtight, radon-impermeable Petri dish to achieve secular equilibrium. To obtain 5 Bq and 10 Bq activity

of ^{238}U (or ^{226}Ra) standard sources, 0.35 g and 0.70 g of U_3O_8 were used, respectively, while for ^{232}Th standard sources, 10 Bq and 20 Bq activity were obtained using 0.00283 g and 0.00566 g of ThO_2 , respectively. Similarly, to obtain 5 Bq and 15 Bq activity of ^{40}K standard sources, 0.30 g and 0.90 g of KCl were used, respectively⁽¹⁰⁻¹³⁾.

Gamma-ray spectroscopy

For the analysis of terrestrial isotopes such as ^{226}Ra , ^{232}Th , and ^{40}K in soil samples, a p-type High Purity Germanium (HPGe) detector (CANBERRA Industries, USA) was utilised. This detector is characterised by a relative efficiency of 16.4% and a Full Width at Half Maximum (FWHM) of 1.63 keV at 1332.5 keV (^{60}Co). The detector's output was evaluated utilising a 1000 DSA system, which was connected to a personal computer. The GENIE 2000 software was utilised for assessing the spectra of every sample. To prevent X-ray interference with gamma rays, the detector was encased in a rectangular lead shield that was 4 inches (10 cm) thick, with an additional 2 mm copper layer inside. The disc type gamma sources ^{137}Cs (661.8 keV), ^{133}Ba (80.99 keV, 276.39 keV, 302.85 keV, 356.01 keV, 383.84 keV), ^{60}Co (1173 keV, 1332 keV), ^{57}Co (122 keV, 136 keV), and ^{22}Na (511 keV, 1274 keV) are used for energy calibration of a gamma spectrometer. These sources were manufactured by the Bhabha Atomic Research Centre (BARC), India⁽¹⁴⁻¹⁵⁾. The background spectrum was recorded for 24 h using an empty Petri dish. Similarly, the samples were examined for 24 h.

A comparative approach was used to ascertain the specific activities of individual radioisotopes. The activity concentration of ^{226}Ra was assessed using the average of the gamma photopeak energies: 295.22 keV (19.3%) from ^{214}Pb , 351.93 keV (37.6%) from ^{214}Pb , and 609.31 keV (46.1%) from ^{214}Bi . Similarly, the activity concentration of ^{232}Th was determined using the average of gamma photopeak energies: 338.32 keV (11.27%) from ^{228}Ac , 583.19 keV (84.5%) from ^{208}Tl , and 911.20 keV (25.8%) from ^{228}Ac . The activity concentration of potassium ^{40}K was calculated using the 1460.83 keV (11%) gamma photopeak^(10, 12). The activity concentration was calculated by deducting the background count from the overall photopeak area on the energy spectrum, which yielded the net area of the photopeaks. Equation (1) is used to compute the specific activity of ^{226}Ra , ^{232}Th , and ^{40}K radionuclides in the soil samples⁽¹⁶⁾:

$$A \text{ (Bq kg}^{-1}\text{)} = \frac{N}{\epsilon \cdot m \cdot t \cdot I_\gamma} \quad (1)$$

In this case, N denotes the net area under the relevant photopeak, t represents measurement time, m indicates sample mass, ϵ stands for detector absolute efficiency for specific gamma ray energy, and I_γ refers to the intensity of the gamma ray in a

radionuclide.

As each sample had a different mass, the formula for the unidentified specific activity will be provided by equation (2)⁽¹⁰⁾:

$$\frac{A_S}{A_{Std}} = \frac{N_S}{N_{Std}} \times \frac{m_{Std}}{m_S} \quad (2)$$

Where A_{Std} denotes the specific activity of the standard sample, A_S denotes the specific activity of the unknown sample, N_{Std} signifies the net area under the photo-peak for the standard sample, N_S represents the net area under the photo-peak for the unknown sample, m_{Std} indicates the mass of the standard sample, and m_S indicates the mass of the unknown sample.

Radium equivalent activity (R_{eq})

The radium equivalent activity (R_{eq}) is determined to evaluate the combined radioactivity from ^{226}Ra , ^{232}Th , and ^{40}K in soil samples. This calculation assumes that 7, 130, and 10 Bq kg^{-1} yield comparable radiation dose rates for ^{226}Ra , ^{232}Th , and ^{40}K , respectively. Equation (3) is used to evaluate the radium equivalent activity⁽¹⁷⁾:

$$R_{eq} = A_{Ra} + 1.43A_{Th} + 0.07A_K \quad (3)$$

A_{Ra} , A_{Th} , and A_K represent the distinct activities of ^{226}Ra , ^{232}Th and ^{40}K , respectively.

Internal radiation hazard index (H_{in})

This parameter helps assess the potential hazards from internal exposure to naturally occurring radioactive materials in soil, through inhalation and ingestion. The internal radiation hazard index is derived by the equation (4)⁽¹⁸⁾:

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (4)$$

External radiation hazard index (H_{ex})

An evaluation of external exposure from soil persistently emitting gamma radiation due to natural radionuclides is referred to as the external hazard index. Equation (5) determines the external hazard index⁽¹⁹⁾:

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

Alpha Index (I_α)

I_α is a radiological parameter utilised to evaluate potential health concerns associated with the use of soil as a building material containing alpha-emitting radionuclides, particularly ^{226}Ra . It is essential to assess the risks of inhaling or consuming radon gas and its by-products resulting from the decomposition of ^{226}Ra . Equation (6) was utilized to compute the alpha index⁽²⁰⁾:

$$I_\alpha = \frac{A_{Ra}}{200} \quad (6)$$

According to UNSCEAR (2000), the denominator (200 Bq kg^{-1}) represents the threshold activity

concentration above which radon emissions from the soil may pose significant health risks.

Gamma Index (I_γ)

The I_γ is a radiological hazard parameter used to assess the potential external gamma radiation exposure from naturally occurring radionuclides, such as ^{238}U , ^{232}Th , and ^{40}K , particularly in materials like soil when considered for use in construction. Equation (7) is used to evaluate the gamma index ⁽²¹⁾:

$$I_\gamma = \frac{A_{\text{Ra}}}{300} + \frac{A_{\text{Th}}}{200} + \frac{A_{\text{K}}}{3000} \quad (7)$$

Activity utilisation index (AUI)

AUI is a parameter used to assess whether soil is radiologically suitable for use in construction. It reflects the combined contribution of gamma radiation from naturally occurring radionuclides such as ^{226}Ra , ^{232}Th , and ^{40}K . This index helps to determine whether the use of soil in building materials poses any potential health risk to individuals occupying the structures, which is represented by equation (8) ⁽²²⁾:

$$\text{AUI} = 0.02(A_{\text{Ra}} \cdot f_{\text{Ra}} + A_{\text{Th}} \cdot f_{\text{Th}} + A_{\text{K}} \cdot f_{\text{K}}) \quad (8)$$

Where; $f_{\text{Ra}} = 0.462$, $f_{\text{Th}} = 0.604$ and $f_{\text{K}} = 0.0417$ indicate the fractional contributions of the actual activity of these radionuclides to the airborne gamma radiation dose rate ⁽²³⁾.

Absorbed Gamma Dose Rate (GD)

The gamma dose absorbed from terrestrial gamma radiation in the air at a height of 1 meter above the ground is determined by the activity concentration of ^{232}Th , ^{226}Ra and ^{40}K . The indoor and outdoor absorbed gamma dose rates were estimated using equations (9) and (10), respectively ⁽²⁴⁾:

$$\text{GD Indoor (nGy h}^{-1}\text{)} = 0.92A_{\text{Ra}} + 1.10A_{\text{Th}} + 0.082A_{\text{K}} \quad (9)$$

$$\text{GD Outdoor (nGy h}^{-1}\text{)} = 0.46A_{\text{Ra}} + 0.62A_{\text{Th}} + 0.041A_{\text{K}} \quad (10)$$

Annual effective dose equivalent (ED)

The annual effective dose equivalent measures a person's cumulative radiation exposure over a year, considering the different types of radiation and their biological effects. To assess the ED, the conversion coefficient and occupancy factor must be considered, and to convert the absorbed dose into an effective dose, a coefficient of 0.7 Sv Gy^{-1} is used. Outside, the occupancy level is 20%, whereas inside, it is 80% (UNSCEAR, 1993). The equations (11) and (12) are used to determine the ED for indoor and outdoor, respectively ⁽²⁵⁾:

$$\text{ED Indoor (mSv y}^{-1}\text{)} = \text{Indoor GD (nGy h}^{-1}\text{)} \times 8760 (\text{h}) \times 0.8 \times 0.7 (\text{Sv Gy}^{-1}) \times 10^{-6} \quad (11)$$

$$\text{ED Outdoor (mSv y}^{-1}\text{)} = \text{Outdoor GD (nGy h}^{-1}\text{)} \times 8760 (\text{h}) \times 0.2 \times 0.7 (\text{Sv Gy}^{-1}) \times 10^{-6} \quad (12)$$

ICRP has established that the total annual effective dose limit is 1 mSv for the general public and 20 mSv for radiation workers ⁽²⁶⁾.

Excess lifetime cancer risk (ELCR)

The ELCR signifies the likelihood of cancer occurrence in individuals exposed to radiation over an extended period. The indoor and outdoor ELCR values are determined by the equations (13) and (14), respectively ⁽²⁷⁾:

$$\text{ELCR Indoor} = \text{ED Indoor} \times T \times \text{RF} \quad (13)$$

$$\text{ELCR Outdoor} = \text{ED Outdoor} \times T \times \text{RF} \quad (14)$$

Where; ED is the annual effective dose equivalent, T is the life expectancy, assumed to be 70 years, and RF denotes the fatal cancer risk coefficient, assumed to be 0.05 Sv^{-1} for stochastic effects, suggested by the ICRP ⁽²⁶⁾.

Statistical analysis

The Pearson correlation test was used to analyse the correlation between the specific activities of ^{226}Ra , ^{232}Th , and ^{40}K using XLSTAT software.

RESULTS

The radionuclide activity concentrations were measured through their specific gamma-ray emissions. To enhance accuracy, the values for ^{226}Ra and ^{232}Th were calculated using the average of several gamma lines emitted by their decay products. Table 1 lists the mean, minimum, and maximum activity levels for the isotopes ^{226}Ra , ^{232}Th and ^{40}K . The mean activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K were 20.23 Bq kg^{-1} , 34.17 Bq kg^{-1} , and $335.09 \text{ Bq kg}^{-1}$, respectively. The lowest concentrations computed are 9.68 Bq kg^{-1} for ^{226}Ra in sample S8, 13.58 Bq kg^{-1} for ^{232}Th in sample S4, and $242.14 \text{ Bq kg}^{-1}$ for ^{40}K in sample S8, while the highest concentrations computed are 36.33 Bq kg^{-1} for ^{226}Ra in sample S5, 57.95 Bq kg^{-1} for ^{232}Th in sample S5, and $490.60 \text{ Bq kg}^{-1}$ for ^{40}K in sample S3. Sample S5 exhibited the highest specific activity among all the soil samples. The specific activity of ^{226}Ra in samples S3 (35.95 Bq kg^{-1}) and S5 (36.33 Bq kg^{-1}) exceeded the worldwide mean of 33 Bq kg^{-1} . Similarly, the specific activity of ^{232}Th in samples S1 (51.98 Bq kg^{-1}), S3 (45.08 Bq kg^{-1}) and S5 (57.95 Bq kg^{-1}) exceeded the worldwide mean of 45 Bq kg^{-1} . The specific activity of ^{40}K in S3 (490 Bq kg^{-1}) exceeded the worldwide average of 420 Bq kg^{-1} . The activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K differed across sampling locations due to variations in the soil's physical and geochemical characteristics within the study area. The application of chemical fertilizers and decomposed animal remains as soil enhancers can affect the concentration of ^{40}K , due to their considerable potassium content. Due to the

substantial variation in the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in soil, directly comparing their individual activity levels can be challenging. To overcome this, the radium equivalent activity (R_{eq}) is used. R_{eq} provides a single standardized value that expresses the combined radioactivity of these radionuclides in terms of an equivalent amount of ^{226}Ra . Table 1 also displays the computed R_{eq} values for the soil sample data, with an average of 84.91 Bq kg^{-1} ; the estimated R_{eq} levels vary from 44.27 to $138.19 \text{ Bq kg}^{-1}$. The R_{eq} levels in Samples S1 and S3 are higher than the global average of $129.59 \text{ Bq kg}^{-1}$, but lower than the recommended safety limit of 370 Bq kg^{-1} (29). Figure 2 presents the variation in their activity concentrations along with the associated measurement uncertainties.

Table 1. The determined specific activities of radionuclides ^{226}Ra , ^{232}Th , and ^{40}K , along with radium equivalent activity (R_{eq}) in different soil samples (S1–S10), include comparisons with global average values, as well as a statistical summary.

Sample code	Specific activity concentration (Bq kg^{-1})			R_{eq} (Bq kg^{-1})
	^{226}Ra	^{232}Th	^{40}K	
S1	21.47±0.63	51.98±1.34	382.31±51.34	125.23
S2	22.80±0.74	21.04±0.74	298.47±40.52	75.86
S3	35.95±1.15	45.08±1.42	490.60±67.01	138.19
S4	12.05±0.43	13.58±0.57	248.29±34.09	50.60
S5	36.33±1.13	57.95±1.70	325.46±45.08	44.27
S6	14.90±0.53	21.17±0.80	297.89±40.89	68.12
S7	18.11±0.65	42.80±1.32	391.44±53.63	109.46
S8	9.68±0.37	25.85±0.82	242.14±33.23	65.29
S9	13.10±0.46	37.00±1.10	323.21±43.88	90.90
S10	17.94±0.66	25.32±0.99	351.18±48.15	81.18
Minimum	9.68	13.58	242.14	44.27
Maximum	36.33	57.95	490.60	138.19
Mean	20.23	34.17	335.09	84.91
World average	33.0 ⁽⁶⁾	45.0 ⁽⁶⁾	420.0 ⁽⁶⁾	129.59 ⁽²⁸⁾

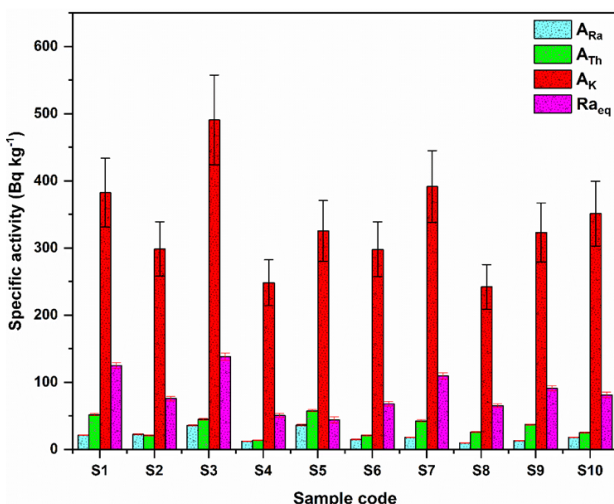


Figure 2. Variations in the specific activities of ^{226}Ra , ^{232}Th , ^{40}K , and radium equivalent activity (R_{eq}) in each soil sample, along with their respective errors.

The H_{in} , H_{ex} , I_{α} , I_{γ} and AUI calculated values are listed in Table 2. The estimated internal hazard (H_{in}) values have a mean of 0.33 and range from 0.17 to 0.49. The computed external hazard index (H_{ex})

levels range from 0.14 to 0.39, with a mean of 0.26. Every calculated H_{in} and H_{ex} level is below the upper limit of unity (30). Bricks made from locally sourced soil were extensively used in the construction of residential houses and dwellings in the investigated area, prompting the calculation of gamma and alpha indexes to evaluate the potential radiation risk from gamma and alpha radiation associated with the use of this soil. The computed alpha index (I_{α}) values range from 0.048 to 0.181, with an average of 0.101, which is nearly 9.9 times less than the permissible limit of unity (31). Gamma index (I_{γ}) values vary from 0.190 to 0.519 and have a mean of 0.350. All computed values of I_{γ} are safe and below the maximum permissible limit of unity. If the soil is used in bulk amounts as a building material, $I_{\gamma} \leq 0.5$ corresponds to the criteria of an annual effective dose value of 0.3 mSv y^{-1} , and $I_{\gamma} \leq 1$ corresponds to the criteria of an annual effective dose value of 1 mSv y^{-1} . $I_{\gamma} \leq 2$ corresponds to the criteria of an annual effective dose value of 0.3 mSv y^{-1} , while $I_{\gamma} \leq 6$ corresponds to the criteria of an annual effective dose value of 1 mSv y^{-1} , if the soil is used in superficial amounts as a building material (32). The estimated AUI exhibits a mean value of 0.874, ranging from 0.479 to 1.139. The AUI values of samples S1, S3, S5, and S7 exceed the permitted upper limit of 1 (23). Figure 3 shows the variation in H_{in} , H_{ex} , I_{α} , I_{γ} , and AUI levels across the soil samples with a maximum allowable limit of 1.

Table 2. Calculated values of radiological hazard indices (H_{in} , H_{ex}), α index (I_{α}), gamma index (I_{γ}) and activity utilization index (AUI) in soil samples include comparisons with global average values, as well as the mean, minimum, and maximum values.

Sample code	Hazard Indices		Alpha Index (I_{α})	Gamma index (I_{γ})	AUI
	H_{in}	H_{ex}			
S1	0.40	0.34	0.107	0.458	1.139
S2	0.27	0.21	0.114	0.280	0.709
S3	0.47	0.37	0.179	0.508	1.279
S4	0.17	0.14	0.060	0.190	0.479
S5	0.49	0.39	0.181	0.519	1.303
S6	0.22	0.18	0.074	0.254	0.638
S7	0.35	0.30	0.090	0.404	1.005
S8	0.20	0.18	0.048	0.242	0.600
S9	0.28	0.25	0.065	0.336	0.833
S10	0.27	0.22	0.089	0.303	0.759
Minimum	0.17	0.14	0.048	0.190	0.479
Maximum	0.49	0.39	0.181	0.519	1.139
Mean	0.33	0.26	0.101	0.350	0.874
Maximum permissible limit	1.0 ⁽³⁰⁾	1.0 ⁽³⁰⁾	1.0 ⁽³¹⁾	1.0 ⁽³²⁾	1 ⁽²³⁾

Table 3 shows the estimated absorbed gamma dose rate (GD), annual effective dose (ED), and excess lifetime cancer risk. Indoor GD rates range from 46.39 to $123.87 \text{ nGy h}^{-1}$ with an arithmetic mean value of 83.64 nGy h^{-1} , whereas outdoor GD rates range from 24.15 to 65.99 nGy h^{-1} with an arithmetic mean of 44.24 nGy h^{-1} . Total GD rates range from 70.55 to $189.86 \text{ nGy h}^{-1}$ with an arithmetic mean of $127.93 \text{ nGy h}^{-1}$. Some samples exhibit higher indoor and outdoor GD values than the recommended levels

of 84 and 60 nGy h⁻¹ (6), respectively. Derived from their respective GD levels, the computed indoor ED varies from 0.23 to 0.60, with an arithmetic mean value of 0.40, and the outdoor ED ranges from 0.03 to 0.08, with a mean value of 0.05. The indoor ED values for samples S1, S3, S5 and S7 exceed the recommended limits of 0.41 mSv y⁻¹, while outdoor ED levels for samples S3 and S5 surpassed the recommended level of 0.07 mSv y⁻¹ (6). To assess the potential impact of prolonged exposure to ionizing radiation, the excess lifetime cancer risk (ELCR) is estimated. The computed indoor ELCR levels vary from 0.79×10⁻³ to 2.12 ×10⁻³, with an arithmetic mean value of 1.44 ×10⁻³, and the computed outdoor ELCR levels vary from 0.10 ×10⁻³ to 0.28 ×10⁻³, with an arithmetic mean value of 1.63 ×10⁻³. Some indoor ELCR levels surpassed the recommended level of 1.19×10⁻³, whereas all values of outdoor ELCR are below the recommended level of 0.19×10⁻³ (33).

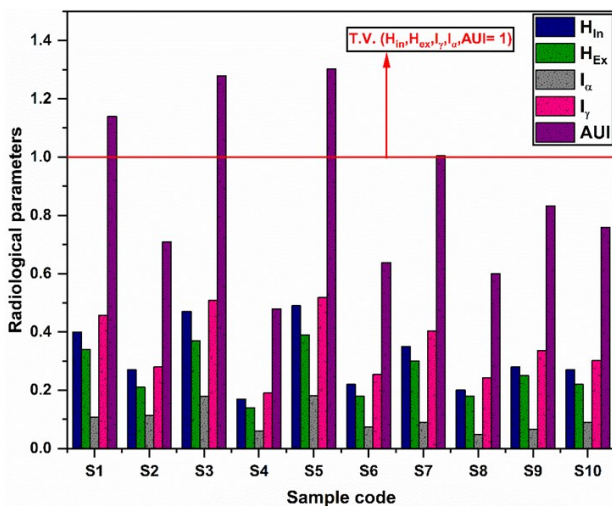


Figure 3. Variations in radiological parameters (H_{in}, H_{ex}, I_α, I_γ, and AUI) for each soil sample, along with their recommended safety threshold values (T.V).

Table 3. The determined values of the absorbed gamma dose rate (GD), annual effective dose equivalent (ED) and excess lifetime cancer risk (ELCR) in soil samples include comparisons with global average values, as well as the mean, minimum, and maximum values.

Sample code	GD (nGy h ⁻¹)			ED (mSv y ⁻¹)			ELCR×10 ⁻³		
	Indoor	Out-door	Total	In-door	Out-door	Total	In-door	Out-door	Total
	S1	108.28	57.78	166.06	0.53	0.07	0.60	1.85	0.24
S2	68.59	35.77	104.36	0.33	0.04	0.37	1.17	0.15	1.32
S3	122.89	64.60	187.49	0.60	0.08	0.68	2.11	0.27	2.38
S4	46.39	24.15	70.54	0.23	0.03	0.26	0.79	0.10	0.89
S5	123.87	65.99	189.86	0.60	0.08	0.68	2.12	0.28	2.40
S6	61.43	32.20	93.63	0.30	0.04	0.34	1.05	0.13	1.18
S7	95.84	50.92	146.76	0.47	0.06	0.53	1.64	0.21	1.85
S8	57.19	30.41	87.60	0.28	0.04	0.32	0.98	0.13	1.11
S9	79.25	42.22	121.47	0.38	0.05	0.43	1.36	0.18	1.54
S10	73.14	38.35	111.49	0.36	0.05	0.41	1.25	0.16	1.41
Minimum	46.39	24.15	70.55	0.23	0.03	0.26	0.79	0.10	0.89
Maximum	123.87	65.99	189.86	0.60	0.08	0.68	2.12	0.28	2.40
Mean	83.69	44.24	127.93	0.40	0.05	0.45	1.44	0.19	1.63
Recommended value	84 (6)	60 (6)	-	0.41 (6)	0.07 (6)	1 (26)	1.19 (33)	0.29 (33)	-

A bivariate statistical technique used to assess the interrelationships and intensity of associations between pairs of variables is Pearson’s correlation coefficient analysis. This study analysed the correlations among the specific activities of ²²⁶Ra, ²³²Th and ⁴⁰K, and the Pearson correlation coefficients along with their respective p-values are tabulated in Table 4. This table shows the strong positive correlation between the specific activities of ²²⁶Ra - ²³²Th, ²³²Th - ⁴⁰K, and ²²⁶Ra - ⁴⁰K.

Table 4. The correlation matrix components for the specific activities of ²²⁶Ra, ²³²Th, and ⁴⁰K are presented along with their P-values in soil samples.

		A _{Ra}	A _{Th}	A _K
A _{Ra}	Correlation coefficient	1	0.680	0.658
	P-value	0	0.030	0.039
A _{Th}	Correlation coefficient	0.680	1	0.621
	P-value	0.030	0	0.055
A _K	Correlation coefficient	0.658	0.621	1
	P-value	0.039	0.055	0

DISCUSSION

The mean values of specific activities of ²²⁶Ra, ²³²Th and ⁴⁰K in this study are well below the worldwide values of these radionuclides reported in the UNSCEAR, 2000 report. Table 5 presents a comparative analysis of natural radioactivity across various regions with the present study. The activity concentrations of radionuclides are higher than those reported in Turkey and Nigeria but lower than the significantly elevated levels found in Tamil Nadu, Karnataka, and Andhra Pradesh, India. Regions such as the Upper Himalayas and parts of Rajasthan show values comparable to the present study. The calculated Ra_{eq} in the present study is also lower than in high-background areas like Andhra Pradesh and Tamil Nadu, indicating a relatively low radiological hazard. Overall, the study area falls within internationally accepted safety limits.

Table 5. Comparison of the present work with previous studies from various countries, including India, for radionuclide activity concentrations of ²³⁸U/²²⁶Ra, ²³²Th, ⁴⁰K, and radium equivalent activity (Ra_{eq}) in soil samples.

Region	A _{Ra} /A _U (Bq kg ⁻¹)		A _{Th} (Bq kg ⁻¹)		A _K (Bq kg ⁻¹)		Ra _{eq} (Bq kg ⁻¹)	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Turkiye (34)	5-55	12	4-32	15	54-413	1623	-	-
Tanzania (35)	99-487	302	65-88	78	99-487	207	-	-
Nigeria (36)	BDL-31.53	20.32	BDL-37.15	22.55	20.90-127.15	91.63	33.62-81.66	59.62
China (23)	8.7-14.2	10.7	35.6-51.6	42	487.1-658.8	555.6	101.6-142.3	113.9
Tamil Nadu, India (37)	1.7-63.2	13	6.8-862	163	8.5-4052	453	22.4-1331	283
Karnataka, India (38)	13-64	39	19-185	58	197-1214	592	68-395	168
Upper Himalayas region, India (39)	9.7-40.6	19.9	15.5-55.2	33.5	124-542	335	41.3-144.4	93.6
Andhra Pradesh, India (40)	17-69	31	74-584	188	196-1114	471	141-941	337
Rajasthan, India (41)	37.67-70.25	50.28	16.54-55.94	34.16	541.29-632.33	587.45	110.53-194.8	144.36
Rajasthan, India (42)	9-34	18	16-89	36	115-761	310	43-187	94
Present study	9.68-36.33	20.23	13.58-57.95	34.17	242.14-490.60	335.09	44.27-138.19	84.91

Table 6 shows that the present study reports higher gamma dose rates, annual effective doses, and excess lifetime cancer risks compared to most other regions, except Pakistan, which exhibits greater values across these parameters. Regions like Egypt, Saudi Arabia, and China generally have lower radiation exposure and associated health risks. While some areas, such as Turkey and South Africa, show similar or slightly elevated gamma dose rates, their cancer risk remains lower than in the present study. These results emphasize the importance of ongoing radiation monitoring and implementing protective measures in the study area to reduce potential health impacts.

Table 6. Comparison of gamma dose rate (GD), Annual effective dose (ED), and Excess lifetime cancer risk (ELCR) across various regions.

Region	GD (nGy h ⁻¹)		ED (mSv y ⁻¹)		ELCR (×10 ⁻³)	
	Range	Mean	Range	Mean	Range	Mean
China ⁽²³⁾	47.4-63.6	53.5	0.058-0.078	0.065	0.2-0.3	0.2
Turkey ⁽⁴³⁾	76.38-170.73	110.69	0.093-0.209	0.136	0.33-0.73	0.73
Tamilnadu, India ⁽⁴⁴⁾	-	-	-	-	0.326-1.067	0.700
South Africa ⁽⁴⁵⁾	-	152.94	-	0.187	-	0.756
Saudi Arabia ⁽⁴⁶⁾	-	22.03	0.05-0.30	0.14	0.03-0.24	0.095
Pakistan ⁽⁴⁷⁾	-	252.86	-	0.92	1.39-6.41	3.21
Nigeria ⁽⁴⁸⁾	16.2-109	38.7	0.019-0.134	0.114	0.07-0.47	0.17
Macedonia ⁽⁴⁹⁾	55.3-79	68.1	72-96.8	83.5	0.26-0.37	0.33
Kenya ⁽⁵⁰⁾	16.06-29.35	23.87	0.11-0.18	0.14	0.34-0.65	0.50
Egypt ⁽⁵¹⁾	12.71-33.68	24.17	0.015-0.033	0.024	0.054-0.163	0.100
Present study	46.39-123.87	83.69	0.26-0.68	0.45	0.89-2.40	1.63

The study is limited by the relatively small number of soil samples, which may not fully represent the variability in radionuclide concentrations across the study area. The assessment of internal exposure is limited by the lack of radon exhalation measurements. In future studies, larger soil samples and measurements of radon and thoron exhalation rates will be included to better assess the risk.

CONCLUSION

In this study, the specific activities of ²²⁶Ra, ²³²Th, and ⁴⁰K, along with their radiological hazards, were assessed in soil samples from Shrimadhapur, Rajasthan. The results indicate that most samples show activity concentrations within the established world average limits, except for samples S1, S3, and S5, which display elevated concentrations, which may be due to geological or anthropogenic factors. The radiological parameters,

such as the internal hazard index, external hazard index, alpha index, and gamma index, were all below the permissible maximum limit of unity. The absorbed gamma dose rate, annual effective dose equivalent and activity utilisation index values were also within safe limits for the majority of samples. Furthermore, all samples' excess lifetime cancer risk values were below the maximum permissible limits, indicating minimal long-term risk. Therefore, most soil samples did not pose considerable radiological hazards to the public in the study area. Correlation analysis revealed a strong positive relationship among the specific activities of ²²⁶Ra, ²³²Th, and ⁴⁰K, suggesting that an increase in the activity of one radionuclide is likely associated with increases in the activities of the others.

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