Journal of Radioanalytical and Nuclear Chemistry (2024) 333:3185–3194
https://doi.org/10.1007/s10967-023-09301-9

Assessment of natural radioactivity in soil around Khetri copper belt of Rajasthan, India

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Received: 30 August 2023 / Accepted: 26 November 2023 / Published online: 4 January 2024

Abstract

The concentration of natural radionuclides (^{226}Ra, ^{232}Th, ^{40}K) in the fifty soil samples around the Khetri copper belt is measured using an HPGe detector. The values of ^{226}Ra, ^{232}Th, and ^{40}K are found to be lying in the range of 5.2 ± 0.3 to 27.5 ± 0.6 Bq kg^{-1}, 12.9 ± 0.4 to 38.8 ± 1.3 Bq kg^{-1}, and 113.3 ± 27.8 to 308.5 ± 31.2 Bq kg^{-1} respectively. The radium equivalent activity ranged from 38.63 to 93.35 Bq kg^{-1} with a mean value of 56.21 Bq kg^{-1}. The values of absorbed dose rate, annual effective dose, and annual gonadal dose rate are also estimated, which comes out to be less than their corresponding world average values. Hazard indices (internal and external) and level indices (alpha and gamma) are also observed to be less than unity. The soil of the study area can be considered safe for people living there because of its low radiological risk.

Keywords Natural radioactivity · Khetri copper belt · HPGe · Radium equivalent activity · Radiological hazards

Introduction

Natural radioactivity has existed since the beginning of the earth. Humans are subjected to natural radiation from inside and outside the Earth's atmosphere. Extraterritorial radiation is caused by cosmic radiation from space, whereas earth-based terrestrial radiation is caused mainly by ionising radiation emitting from the rocks, soil, and water around us. These radiations emanate naturally in the environment due to the presence of radioactive series such as the ^{238}U series, ^{232}Th series, and ^{40}K [1]. Humans are also exposed to man-made radioactivity due to human events such as nuclear fallout and medical applications [2]. According to the IAEA, natural radionuclides contribute 80% of the time to absorbed dosage in the environment, while cosmic rays contribute the remaining 20% [3].

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Natural radioactivity can be found in soil, water, rocks, and the atmosphere [4]. The soil is one of the major sources of human radiation exposure [5]. Radioactivity in the soil is caused mainly by primordial radionuclides and decay products in uranium, actinium, and thorium radioactive series [6–9]. As a result, most radioactivity measurement studies concentrate on natural background radiations from primordial radionuclides, which account for around 80% of an individual's annual radiation dose [10]. The radiation exposure varies in strength from region to region due to geological and radiochemical variations [11, 12]. Different types of rocks contain different amounts of radioactivity; for example, high amounts of radioactive radiation are found in volcanic and granitic rocks. In contrast, metamorphic rocks and sedimentary rocks are generally observed to have lower levels of radioactivity [13]. There has been an upsurge in the exploration of radioactivity in soils and parent rocks worldwide in the last ten to twenty years (both on an individual and organisational level) [13–15]. As soil transfers radionuclides to biological systems, it is an important component of radioactive pollution [16]. Thus, measuring the radioactivity (^{238}U, ^{232}Th, ^{40}K) levels in the soil becomes imperative. Radioactivity in the soil is also utilised to investigate radiation dangers, nuclear safety, and exploration [17].

The present study evaluates the level of naturally occurring radioactivity in the soil around the copper mining area

of Khetri, Rajasthan, India. The interest behind the selection of this region is due to the presence of a nearby mining area, which is having a significant impact on the soil of the surrounding area and the life of the people living nearby. The literature review reveals that several studies have been conducted around copper and uranium mines in India and worldwide. Nguyen et al. [18] measured the radioactivity around the copper mines region and found that the average values of ^{226}Ra, ^{232}Th, and ^{40}K are 254 Bq kg^{-1}, 54 Bq kg^{-1}, 560 Bq kg^{-1}, respectively. Similarly, Atibu et al. [19] discovered ^{226}Ra activity 5 to 10 times greater than the global average values in the vicinity of copper mining areas of the Democratic Republic of Congo. Patra et al. [20] reported the mean values of ^{226}Ra, ^{232}Th, and ^{40}K as 81 Bq kg^{-1}, 65 Bq kg^{-1}, and 517 Bq kg^{-1}, respectively, at the Singhbhum shear zone of Jharkhand, India. The natural radioactivity estimated in the artisanal mining sites of Anka in Nigeria is reported by Akpanowo et al. [21]. It was observed that the radioactivity of ^{226}Ra and ^{232}Th are higher than the world average values, while the ^{40}K values were lower than the world average values. However, there is no systematic radiation evaluation in and around the Khetri mining area of Rajasthan, India.

To measure the background radioactivity in the region, we collected an extensive set of soil and groundwater samples. The uranium concentration in groundwater samples has already been published [22]. A higher amount of uranium concentration in groundwater is observed in many of the measured samples in the studied region, indicating the presence of higher uranium content in the region's bedrock. However, the soil of this arid region is continuously shifting due to widespread saltation and suspension processes. Due to this, the soil radioactivity would represent only an average radioactivity value of the region and may not represent the bedrock properties. In this study, the amount of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides in the surface soil of the study area is estimated using a properly shielded HPGe detector system at IIT Ropar. The concentration of ^{226}Ra is measured instead of ^{238}U as most of the influence of the ^{238}U series is estimated by ^{226}Ra [23]. The observed data can be taken as baseline data to notice any future changes in the radioactivity levels of the soil due to man-made activities. The radiological impact of these radionuclides on the inhabitants and the environment is estimated by computing the absorbed dose rate, Raeq (radium equivalent activity), yearly effective absorbed amount, and gamma and alpha radiation hazard indices.

Study area

The sampling area is primarily located in the districts of Jhunjhunu and Sikar in Rajasthan, India, and the sampling locations are depicted in Fig. 1. The soil samples were taken from the area surrounding the Khetri copper belt. The Khetri copper belt (KBC), located in the Aravalli hills, stretches for around 100 km from Singhana (28°05′: 75°49′) in Jhunjhunu District to Sangarva (27°34′: 75°18′) which is located in Sikar District. Khetri Nagar is well-known for the Copper Project of Hindustan Copper Limited (HCL), a government-run public-sector enterprise that created and now operates the city. It has an average elevation of 485 m (1591 feet). There are primarily three mines in the Khetri copper belt: (a) the Madhan Kudhan mines, which are the largest underground metal mines in the country; (b) Chandmari, located 1 km northwest of Khetri town; and (c) Kolihan, located 10 km southwest of Nagar. The Khetri copper belt is divided in two by the Kantli Fault and a small seasonal river called Kantli. Khetri copper belt rocks are connected with mafic volcanic rocks derived from the Delhi Super Group. They are further classified into (1) the Alwar Group and (2) the Ajabgarh Group. The Ajabgarh group of the Delhi super-group covers most of the research region. The Ajabgarh group comprises phyllites, biotite schists, calc gneisses, and other pre-Delhi intrusives such as amphibolites, granites, pegmatites, and epidiorites. Diorite, epidiorites, amphibolite, and other basic intrusives are examples. The district's climate is mostly desert.

The region has three seasons: summer, winter, and monsoon. The temperature can drop below 0 °C in the winter and reach 50 °C in the summer. The soil in the examined area primarily comprises lithosols and regisols of the hill type. These gravels are located just beneath the.

surface and are light-textured, relatively well-drained, and range from reddish to greyish brown.

Material & measurement steps

Sample collection and preparation

A total of 50 soil samples were taken at various locations around the study area. Each soil sample carries approximately 1 kg weight and is taken from a depth of 15 cm of the surface to avoid any contamination from the surface soil. The soil samples are collected with GPS coordinates and sealed in polythene bags. Each soil sample was dried for 24 h in an oven at 110 °C to remove moisture. After proper grinding, these samples are passed through a sieve of 0.5 mm to make them homogeneous. Soil samples thus processed are sealed in air-tight taped 250 cc plastic containers. They are stored for 30 days to achieve secular equilibrium between the natural radionuclides and their respective radioactive progenies. The samples were properly coded according to the sampling location; these codes are listed in Table 1.

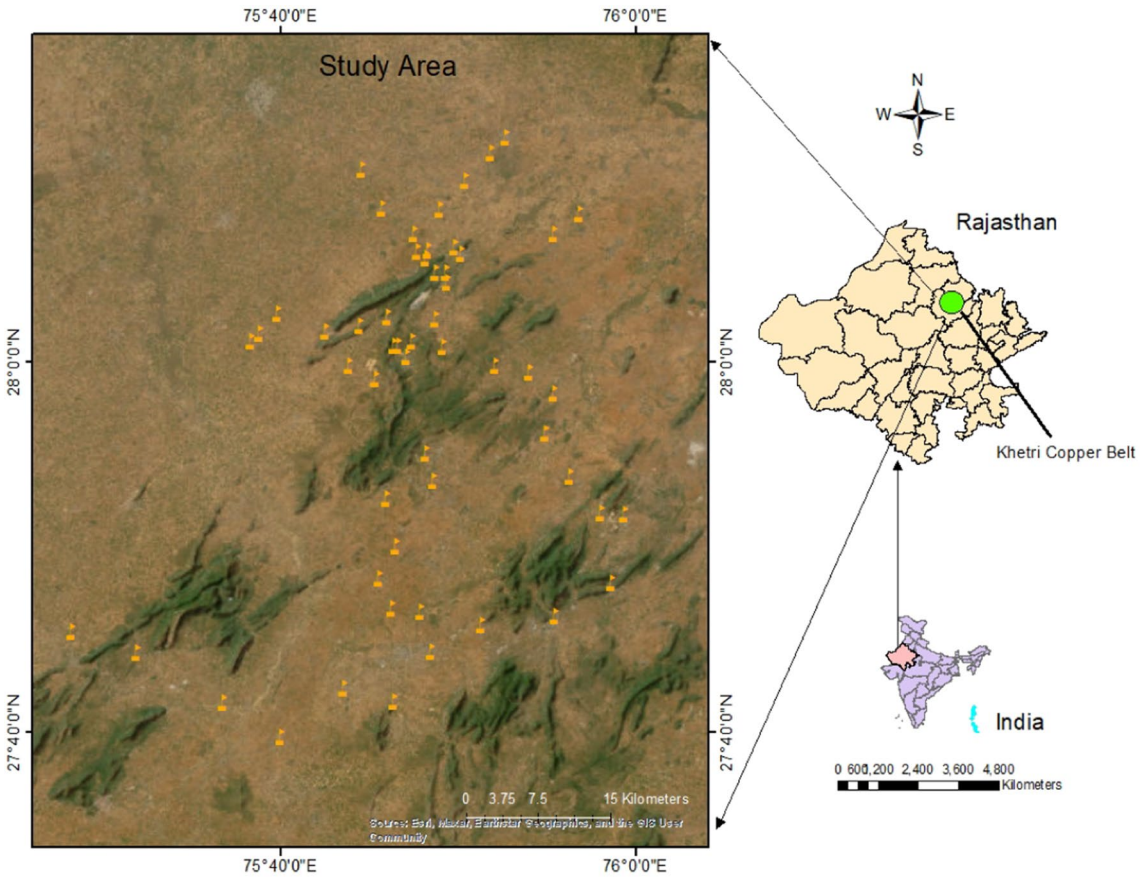

Fig. 1 Study Area Map along with sample locations

Calculation of activity concentration

The gamma spectroscopy of soil samples was carried out using an n-type coaxial HPGe detector (ORTEC, model GMX20) at IIT Ropar. For ^{60}Co at 1.33 MeV, the detector has a relative efficiency of 20% and an energy resolution of 1.8 keV. The minimum detection limit of the detector is 2.74 Bq kg^{-1} for ^{226}Ra, 1.17 Bq kg^{-1} for ^{234}Th, and 7.08 Bq kg^{-1} for ^{40}K. A 10 cm thick lead shielding around the detector and sample setup is utilised [24] to reduce the background radiation. The detector was linked to a PC-based MCA and ADC for data collecting. Since the decay of ^{226}Ra and ^{232}Th do not produce gamma rays, their activity values are determined by calculating the activities of their decay products.

The estimation of ^{226}Ra activity can be carried out using the gamma measurements of its subsequent decay products, namely, ^{214}Pb (295 keV), ^{214}Bi (609 keV), and ^{214}Bi (1120 keV). Similarly, the decay products of the ^{232}Th series, namely, ^{212}Pb (238 keV), ^{228}Ac (911 keV), and ^{228}Ac (968 keV), with the assumption of the decay series being in equilibrium [25], are used. The activity of ^{40}K is measured using the 1460 keV peak directly. The samples and the background were counted over a period of 43,200 s. The LAMPS software was used for spectrum analysis.

Calculation of activity (Bq kg^{-1})

The activity of radioisotopes was estimated using the relation [26]

$$\text{Activity}\left(\text{Bq kg}^{-1}\right) = \frac{cps}{W * \eta * P\gamma} \quad (1)$$

where cps is net counts per second after subtraction of background counts, η is the efficiency of the detector, W is the weight of the sample in kg, and Pγ is the photon emission probability for that energy.

Health risk assessment

Absorbed dose rate

Using the activity concentration of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in the soil, it is possible to determine the

Table 1 Radionuclides concentration, absorbed dose rate, and annual effective dose in the study area

S.no	Latitude	Longitude	^{226}Ra Bq kg^{-1}	^{232}Th Bq kg^{-1}	^{40}K Bq kg^{-1}	Ra_{eq}. Bq kg^{-1}	D_i nGy h^{-1}	D_o nGy h^{-1}	AED_i μSv y^{-1}	AED_o μSv y^{-1}
1	28.01583	75.77333	8.1 ± 0.7	17.9 ± 0.8	131.3 ± 25.0	43.82	37.66	20.04	0.185	0.025
2	28.01556	75.77667	13.9 ± 0.8	27.7 ± 1.0	138.2 ± 24.3	64.11	54.28	28.90	0.266	0.035
3	28.01917	75.78944	9.5 ± 0.7	19.6 ± 0.9	175.7 ± 26.0	51.16	44.44	23.60	0.218	0.029
4	28.03972	75.81222	12.9 ± 0.8	19.7 ± 0.9	161.9 ± 27.0	53.56	46.50	24.62	0.228	0.030
5	28.07222	75.82278	8.4 ± 0.7	19.1 ± 0.8	163.1 ± 26.1	48.21	41.74	22.19	0.205	0.027
6	28.08139	75.82194	10.7 ± 0.8	19.3 ± 1.0	113.3 ± 27.8	47.07	40.17	21.34	0.197	0.026
7	28.09889	75.83583	9.4 ± 0.7	17.6 ± 0.8	182.9 ± 25.3	48.55	42.56	22.56	0.209	0.028
8	28.10139	75.80500	9.4 ± 0.7	19.5 ± 0.8	172.1 ± 25.9	50.56	43.89	23.31	0.215	0.029
9	28.09500	75.80306	11.7 ± 0.8	24.9 ± 0.9	193.6 ± 27.7	62.17	53.60	28.50	0.263	0.035
10	28.10028	75.79528	10.0 ± 0.7	19.8 ± 0.9	167.6 ± 25.6	51.24	44.41	23.58	0.218	0.029
11	27.89389	75.81028	13.8 ± 0.8	29.6 ± 1.4	308.5 ± 31.2	79.86	69.92	37.11	0.343	0.046
12	27.91806	75.80306	10.7 ± 0.8	26.9 ± 0.9	258.9 ± 30.1	69.08	60.13	31.98	0.295	0.039
13	27.87750	75.76583	21.9 ± 0.9	26.0 ± 1.0	186.6 ± 28.0	73.54	63.75	33.64	0.313	0.041
14	27.83472	75.77528	12.5 ± 0.8	24.2 ± 0.9	200.9 ± 26.6	62.59	54.20	28.77	0.266	0.035
15	27.80556	75.75861	13.2 ± 0.9	25.8 ± 1.0	226.9 ± 27.9	67.62	58.72	31.17	0.288	0.038
16	27.77889	75.77111	12.5 ± 0.9	26.3 ± 1.0	226.9 ± 20.3	67.67	58.66	31.16	0.288	0.038
17	27.69472	75.77278	11.2 ± 0.8	21.8 ± 1.0	201.9 ± 29.1	57.96	50.47	26.78	0.248	0.033
18	27.70694	75.72639	12.5 ± 0.8	26.4 ± 1.0	187.6 ± 26.7	64.75	55.59	29.57	0.273	0.036
19	27.66250	75.66667	12.7 ± 0.8	25.7 ± 1.0	203.6 ± 30.2	65.14	56.25	29.89	0.276	0.037
20	27.69306	75.61278	12.7 ± 0.8	28.4 ± 1.0	183.5 ± 29.7	67.43	57.59	30.67	0.283	0.038
21	27.73833	75.53167	10.9 ± 0.8	29.4 ± 1.0	237.2 ± 31.1	71.17	61.31	32.67	0.301	0.040
22	27.98528	75.75556	6.2 ± 0.7	14.6 ± 0.9	179.4 ± 28.8	40.92	36.14	19.18	0.177	0.024
23	28.04194	75.76722	10.1 ± 0.8	25.1 ± 1.0	183.4 ± 29.7	60.05	51.52	27.45	0.253	0.034
24	28.13472	75.94722	10.4 ± 0.8	22.5 ± 0.9	198.0 ± 28.3	57.74	50.10	26.62	0.246	0.033
25	28.11611	75.92306	13.3 ± 0.9	27.3 ± 1.0	194.9 ± 28.8	67.29	57.81	30.73	0.284	0.038
26	28.21778	75.68222	8.9 ± 0.8	20.6 ± 1.0	186.3 ± 28.9	52.75	45.79	24.34	0.225	0.030
27	28.13944	75.76194	10.1 ± 0.8	21.3 ± 0.9	208.7 ± 29.7	56.52	49.33	26.19	0.242	0.032
28	28.10500	75.82944	6.7 ± 0.8	15.6 ± 0.8	177.7 ± 27.5	42.66	37.51	19.91	0.184	0.024
29	28.16472	75.84000	9.1 ± 0.8	20.1 ± 0.9	196.4 ± 29.3	52.95	46.19	24.53	0.227	0.030
30	28.20333	75.87833	7.5 ± 0.8	17.1 ± 0.9	209.7 ± 31.1	48.09	42.47	22.53	0.208	0.028
31	28.01444	75.81889	12.1 ± 0.9	25.9 ± 1.0	230.6 ± 29.7	66.89	58.06	30.84	0.285	0.038
32	28.99944	75.81806	17.2 ± 1.0	38.8 ± 1.3	268.7 ± 29.9	93.35	79.98	42.58	0.392	0.052
33	27.99722	75.86806	13.3 ± 0.9	27.6 ± 1.0	176.6 ± 28.0	66.42	56.77	30.20	0.278	0.037
34	27.99111	75.90000	11.3 ± 0.4	19.4 ± 0.5	169.4 ± 11.2	52.05	45.27	23.99	0.222	0.029
35	27.93611	75.91472	10.3 ± 0.3	19.6 ± 0.5	202.4 ± 13.1	53.89	47.21	25.03	0.232	0.031
36	27.89750	75.93778	11.1 ± 0.3	22.7 ± 0.5	183.5 ± 12.3	57.66	49.85	26.48	0.245	0.032

Table 1 (continued)

S.no	Latitude	Longitude	^{226}Ra Bq kg^{-1}	^{232}Th Bq kg^{-1}	^{40}K Bq kg^{-1}	Ra_{eq}, Bq kg^{-1}	D_i nGy h^{-1}	D_o nGy h^{-1}	AED_i µSv y^{-1}	AED_o µSv y^{-1}
37	27.86472	75.96722	8.4 ± 0.3	22.0 ± 0.5	209.2 ± 13.3	56.06	48.74	25.93	0.239	0.032
38	27.86361	75.98944	27.5 ± 0.6	24.9 ± 0.6	183.1 ± 12.1	77.21	67.34	35.38	0.330	0.043
39	27.80167	75.97722	8.2 ± 0.3	15.7 ± 0.4	174.6 ± 11.8	44.10	38.79	20.56	0.190	0.025
40	27.77194	75.92444	9.1 ± 0.3	18.4 ± 0.4	284.9 ± 18.3	57.45	51.49	27.24	0.253	0.033
41	27.76333	75.85528	8.9 ± 0.3	18.5 ± 0.5	174.6 ± 11.8	48.76	42.47	22.55	0.208	0.028
42	27.73944	75.80750	8.0 ± 0.3	17.3 ± 0.4	190.9 ± 12.4	47.45	41.68	22.11	0.204	0.027
43	27.77556	75.79833	10.6 ± 0.4	21.4 ± 0.4	187.4 ± 12.6	55.61	48.27	25.63	0.237	0.031
44	28.02861	75.70889	6.9 ± 0.3	14.4 ± 0.4	189.9 ± 12.3	42.13	37.41	19.82	0.184	0.024
45	28.02611	75.64694	6.5 ± 0.3	14.6 ± 0.4	195.4 ± 12.9	42.48	37.72	19.99	0.185	0.025
46	28.01944	75.63861	6.7 ± 0.3	14.5 ± 0.4	191.1 ± 12.7	42.08	37.34	19.79	0.183	0.024
47	27.99833	75.65722	5.5 ± 0.3	12.9 ± 0.4	191.1 ± 12.8	38.63	34.52	18.29	0.169	0.022
48	27.96806	75.70861	6.1 ± 0.3	13.4 ± 0.5	194.9 ± 12.9	40.28	35.95	19.04	0.176	0.023
49	27.94306	75.67528	5.2 ± 0.3	13.0 ± 0.3	192.1 ± 12.7	38.68	34.53	18.31	0.169	0.022
50	28.00556	75.78528	6.7 ± 0.3	14.9 ± 0.4	193.3 ± 12.8	42.89	38.02	20.15	0.186	0.025

air-absorbed gamma dose rates from gamma radiations at 1 m above the earth's surface. [27, 28]

$$\text{Indoor}\left(\text{nGyh}^{-1}\right) = 0.92A_{Ra} + 1.1A_{Th} + 0.08A_K \tag{2}$$

$$\text{Outdoor}\left(\text{nGyh}^{-1}\right) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \tag{3}$$

where equation no (2) and (3) are the indoor and outdoor absorbed dose rates, ^{226}Ra, ^{232}Th and ^{40}K activity concentration, respectively.

Annual effective dose (AED)

The annual effective dose can be estimated from the values of air-absorbed dose using the relation [27, 28]

$$\text{Indoor}\left(\text{mSvy}^{-1}\right) = \text{AD}\left(\text{nGyh}^{-1}\right) \times 8760\text{h} \times 0.8 \times 0.7\text{SvGy}^{-1} \times 10^{-6} \tag{4}$$

$$\text{Outdoor}\left(\text{mSvy}^{-1}\right) = \text{AD}\left(\text{nGyh}^{-1}\right) \times 8760\text{h} \times 0.2 \times 0.7\text{SvGy}^{-1} \times 10^{-6} \tag{5}$$

where AD stands for the absorbed dose. A conversion factor of 0.7 Sv Gy^{-1} is used, and 0.8 and 0.2 are considered indoor and outdoor occupancy factors, respectively.

Radiation hazards

Radium equivalent activity (Ra_{eq})

The distribution of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides in the soil is not homogeneous. To estimate the total effect of exposure from these radionuclides and for comparison of specific activity of the soils having different concentrations of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides, the Ra_{eq} (Bq kg.$^{-1}$) is calculated by using the following relation [29, 30]

$$Ra_{eq} = \left(\frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}\right) \times 370 \tag{6}$$

where A_{Ra}, A_K, and A_{Th} are the activity of ^{226}Ra, ^{40}K, and ^{232}Th in Bq kg^{-1}.

External and internal hazard indices (H_{ex} and H_{in})

For the risk assessment of the effect of these radiations on living beings, the Hazard Indices are calculated. The External Hazard Index is calculated for external exposures using the relation [27, 29]

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (7)$$

where A_{Ra}, A_{Th}, and A_K are the activity of ^{226}Ra, ^{232}Th, and ^{40}K in units of Bq kg^{-1}.

The internal hazard index is calculated for internal exposure to radiation through inhalation to humans and estimated using the relation [27, 29]

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (8)$$

where A_{Ra}, A_{Th}, and A_K are the activity of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in units of Bq kg^{-1}. The value of the external and internal hazard index is considered safe, having a value less than unity.

Gamma index (I_γ) and alpha index (I_α)

Gamma exposure from rocks and soils is measured using the gamma index. It considers how much radiation exposure is possible when soil and rocks are used as building materials. The relationship shown below can be used to estimate it. [28, 30]

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \quad (9)$$

The value of $I_\gamma \leq 0.5$ corresponds to 0.3 mSv y^{-1} dose rate, and for $I_\gamma \geq 0.5$, the value corresponds to 1 mSv y^{-1} dose rate.

The exposure induced by inhaling ^{222}Rn, a decay product of.^{226}Ra, can be assessed in terms of the alpha index, which is estimated by the relationship [30, 31]

$$I_\alpha = \frac{A_{Ra}}{200} \quad (10)$$

The value of I_α will be unity for 200 Bq kg^{-1} activity concentration of ^{226}Ra in the soil. The values of I_α exceeding unity signify the higher rates of radon exhalation from the soils.

The gonadal dose equivalent rate (AGDE)

The bone surface cells, bone marrow, and gonads are widely regarded as the most critical organs. AGDE was accomplished using the equation shown below [13].

$$AGDE\left(\mu Svy^{-1}\right) = 3.09 \times A_{Ra} + 4.18 \times A_{Th} + 0.314 \times A_K \quad (11)$$

The maximum safe value[13] of AGED is 300 mSv y^{-1}.

Cancer risk

The equation is used to calculate the excess lifetime cancer risk [32, 33].

$$ELCR = AEDE \times DL(65years) \times RF\left(ICRP60, 1990uses0.05Sv^{-1}\right) \quad (12)$$

Result and discussion

In this manuscript, the gamma radioactivity concentration in fifty soil samples is measured using an HPGe detector. The observed values of activity concentration of ^{226}Ra, ^{232}Th, ^{40}K, and $Ra_{eq.}$ along with the sample locations and radiological doses, are summarised in Table 1.

The radioactivity concentrations of ^{226}Ra in the study area vary from 5.2 ± 0.3 to 27.5 ± 0.6 Bq kg^{-1}. The average activity concentration of ^{226}Ra in soil is 10.6 ± 0.6 Bq kg^{-1} and is lower than the world average value for ^{226}Ra in soil (32 Bq kg^{-1}) [29]. The activity concentration of ^{232}Th varies between 12.9 ± 0.4 and 38.8 ± 1.3 Bq kg^{-1} with an average value of 21.4 ± 1.0 Bq kg^{-1}. The highest value is found for the village 'Tihara' and the minimum value for the village 'Nagli Saledhri'. The ^{232}Th concentration in all the soil samples is below the world average value of 45 Bq kg^{-1} [29]. The activity concentration of ^{40}K lies between 113.3 ± 27.8 and 308.5 ± 31.2 Bq kg^{-1}, having an average value of 194.8 ± 22.4 Bq kg^{-1}. It is observed that the concentration of ^{40}K lies below the world average value of 420 Bq kg^{-1} [29]. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K are comparable or lower than those reported in neighbouring states and other areas of Rajasthan [34–37]. The lower levels of natural radionuclide concentration (particularly ^{40}K) recorded in the research region can be linked to the geological and mineral composition of the Khetri copper belt. When compared to locations with different geological formations, the geology of the Khetri copper belt may not be conducive to the presence of higher concentrations of natural radionuclides. The region's soil is older alluvium, and the region's principal rock types are metamorphic and igneous, resulting in a low concentration of radionuclide ^{40}K [38]. This study is the first of its type in the studied region. The obtained data can be taken as baseline data for future reference. Spatial distribution maps of the region also indicate no region of higher radioactivity in the study area. The spatial distribution maps are shown in Fig. 2.

Radium equivalent activity ($Ra_{eq.}$)

Radium equivalent activity is lying between 38.63 and 93.35 Bq kg^{-1} with a mean value of 56.21 Bq kg^{-1}, as shown in Table 1. Maximum value of $Ra_{eq.}$ is found for the village

'Tihara', while the village 'Nagli Saledhri' has the minimum value of Ra_{eq}. It is observed that all the values of radium equivalent activity are found to be much lesser than the recommended limit of 370 Bq kg^{-1} prescribed by OECD [39]. The spatial distribution map of the area also shows no place having high radio equivalent activity (Fig. 2).

Indoor and outdoor absorbed dose rate

Indoor absorbed dose rate (D_i) for all the samples lies between 34.52 and 79.98 nGy h^{-1} with an average value of 48.89 nGy h^{-1}. The value for all the soil samples is less than the world average value of 84 nGy h^{-1} [29]. Outdoor absorbed dose rate (D_o) varied between 18.30 and 42.58 nGy h^{-1} with a mean value of 25.95 nGy h^{-1}. The world average value for outdoor absorbed dose rate is 58 nGy h^{-1} [29], and all samples exhibited values less than the recommended limit. The obtained values are displayed in Table 1.

Indoor and outdoor annual effective dose (AED) and Annual gonadal dose (AGDE)

The values of indoor and outdoor annual effective doses are tabulated in Table 1. The indoor annual effective dose is observed between 0.17 and 0.39 µSv y^{-1} with an average value of 0.24 µSv y^{-1}. The values of the indoor absorbed dose rate were found to be lying below the recommended limit of 0.48 µSv y^{-1} [29]. Outdoor annual effective dose is observed to be varying in between 0.02 and 0.05 µSv y^{-1}. The average value for outdoor AED value comes out to be 0.03 µSv y^{-1}. The outdoor AED value for all samples is lying well below the recommended limit of 0.07 µSv y^{-1} [29].

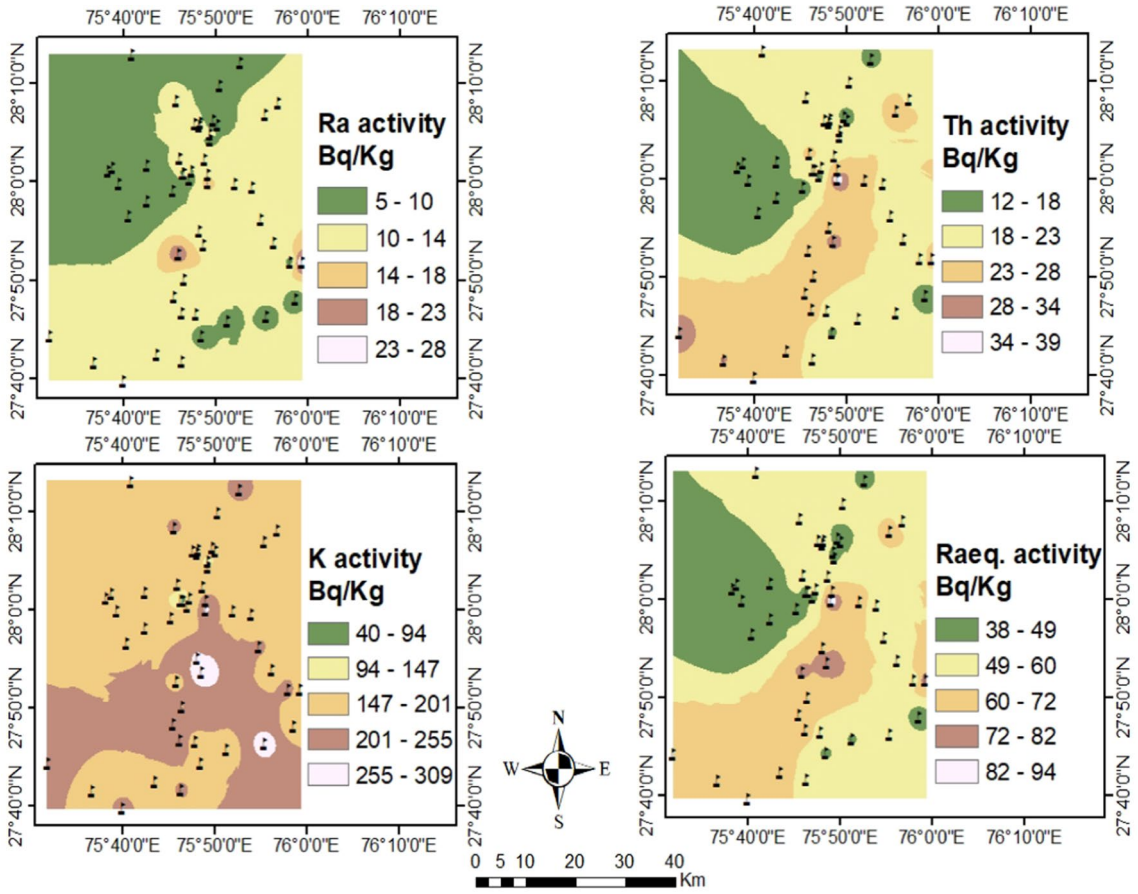

Fig. 2 Spatial Distribution map of radionuclides present in the soil of the study area

The yearly gonadal dose value (AGDE) ranges from 130.84 to 299.64 μSv y^{-1}, having an average value of 183.39 μSv y^{-1}, as shown in Table 2. However, the AGDE value for all samples lies below the prescribed limit of 300 μSv y^{-1} [29]. However, few samples indicated AGDE value very close to the recommended limit.

Hazards indices

The values of the internal hazard index (H_{in}) ranged from 0.12 to 0.30, with a mean value of 0.18. Similarly, the external hazard index (H_{ex}) values lie between 0.10 and 0.25, along with an average value of 0.15. The values of both internal and external hazard indices lie below the recommended limit of 1 [29], which indicates no radiological danger due to the radionuclides present in the soil of the study area. The values are presented in Table 2.

Level indices

The value of the alpha index (I_α) is found to be between 0.03 and 0.14. The average value of Iα is obtained as 0.05, which is very low from the prescribed limit of 1. The evaluated value of gamma index I_γ varies between 0.15 and 0.34 with an average value of 0.21, as shown in Table 2. The values of I_γ lie below the prescribed limit of 1 for all the soil samples, indicating no radiation hazards to the people living in the study area. The obtained values are shown in Fig. 3 in the form of the box plot.

Cancer risk

The possible cancer risk (CR) due to the presence of the radionuclide in the soil of the study area is also estimated. The value of the cancer risk area was found to be lying in the range of 0.07×10^{-3}–0.17×10^{-3} with a mean value of 0.10×10^{-3}, as shown in Table 2. The cancer risk value for all the soil samples is lying well below the prescribed limit of 0.29×10^{-3} [28], indicating low cancer risk in the soil of the study region.

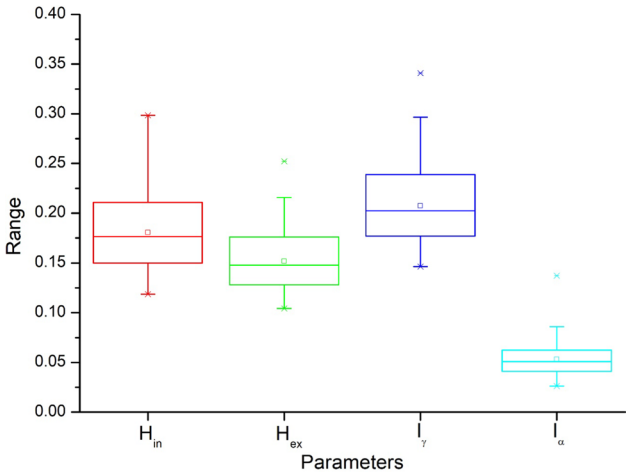

Fig. 3 Box plot for hazard indices and level indices in the studied region

Conclusion

In this study, the concentration of primordial radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) is measured in fifty soil samples collected from the region around the Khetri copper belt, Rajasthan, India. The radionuclides are estimated using the gamma spectroscopy technique using the HPGe detector setup. It is observed that the concentration of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) lies well within the corresponding world average values for all the soil samples. The mean values of ^{226}Ra, ^{232}Th, and ^{40}K are 10.6 ± 0.6 Bq Kg^{-1}, 21.4 ± 1.0 Bq kg^{-1}, and 194.8 ± 22.4 Bq kg^{-1} respectively. Radium equivalent activity is found to be lying between 38.63 and 93.35 Bq kg^{-1} with a mean value of 56.21 Bq kg^{-1}, which is far less than the recommended value of 370 Bq Kg^{-1}. The indoor and outdoor absorbed dose rate and annual effective dose values also lie below the world average values, indicating low radiological implications of the soil of the study area. Annual gonadal dose ranges from

Table 2 Statistical parameters for the Hazard indices, Level indices, gonadal dose, and cancer risk in the soil

	H_{in}	H_{ex}	I_γ	I_α	AGDE (μSv y^{-1})	CR × 10^{-3}
Minimum	0.12	0.10	0.15	0.03	130.84	0.07
Maximum	0.30	0.25	0.34	0.14	299.62	0.17
Mean	0.18	0.15	0.21	0.05	183.39	0.10
Median	0.18	0.15	0.20	0.05	179.11	0.10
Standard deviation	0.04	0.03	0.04	0.02	36.76	0.02
Variance	0.002	0.001	0.002	0.00	1351.56	0.00
Geometric mean	0.18	0.12	0.20	0.05	179.90	0.10

130.84 to 299.64 μSv y^{-1}, which is slightly less than the world average value of 300 μSv y^{-1}. The value of hazard indices (H_{in} and H_{ex}) and level indices (I_α and I_γ) are less than unity for all the samples, which indicates that the soil of the study region has no radiological hazards. The soil of the region also indicated no cancer risk. The findings of this study state that the soil around the Khetri copper belt has no significant radiological risk to the inhabitants living in the area.

Acknowledgements The research work of Naresh Kumar is supported by the research grant (Junior Research Fellowship) of the University Grant Commission (UGC) of India.

Declarations

Conflict of interest The authors declare that they do not have any potential conflict of interest which may influence the work reported in the present research paper. Most of the data from research work is included in the present paper, and any further information may be obtained from the corresponding author.

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