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ORIGINAL ARTICLE

Studies on Radon Exhalation Rate and Activity of Radioactive Elements in Soil Samples and their Radiological Hazards to the Population of Davanagere District, Karnataka, India

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ABSTRACT

Exhalation rate of ^{222}Rn from soil samples and the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were studied in soil samples of Davanagere district, Karnataka state, India. ^{222}Rn exhalation rate was measured using smart radon monitor (SRM). The mass exhalation rate of ^{222}Rn varies from 6.9 ± 1.7 to 38.5 ± 3.3 mBqkg^{-1}h^{-1} with a geometric mean of 20.1 ± 2.5 mBqkg^{-1}h^{-1}. The surface exhalation rate of ^{222}Rn varies from 0.39 ± 0.1 to 2.15 ± 0.18 Bqm^{-2}h^{-1} with a geometric mean of 1.12 ± 0.14 Bqm^{-2}h^{-1}. Activity concentrations of the radionuclide in soil samples were measured using HPGe detector. ^{226}Ra, ^{232}Th and ^{40}K concentration varied from 32.0 to 106.1 Bqkg^{-1}, from 19.6 to 78.8 Bqkg^{-1} and from 20.1 to 968.0 Bqkg^{-1} respectively. The average activity of ^{226}Ra in the soil samples was 63.2 Bqkg^{-1} which is higher than the global average and the Indian average value, whereas the activities of ^{232}Th and ^{40}K were found to be 34.9 Bqkg^{-1} and 458.8 Bqkg^{-1} respectively and are comparable to global average values. When the structural and physical properties of the soil samples were similar, radon exhalation rate from soil samples shows good correlation with its ^{226}Ra activity.

INTRODUCTION

^{222}Rn, a radioactive noble gas is produced by the radioactive decay of ^{226}Ra through the emission of an alpha particle. A fraction of ^{222}Rn produced in the earth's crust transports through the pores of the soil and enters the open atmosphere before decaying to its daughter nuclei. Each and every living being is open to the harmful radiation originating from naturally occurring radionuclides. The living system receives the energetic radiation from the radionuclides present in air, water, and food through inhalation and ingestion. According to UNSCEAR (1993), 87% of the radiation dose received by humans is from natural sources and the remaining is from anthropogenic activities. The rocks, sand and soil contains trace amounts of primordial radionuclides such as ^{238}U and ^{232}Th along with their daughter products and also a trace amount of ^{40}K. In the study area the soil is widely used as a construction material in the form of bricks and also as a filling material. Since soil is in direct contact with radionuclides, it has become a major source of radiation exposure to the public. ^{222}Rn and its daughter products can be used as a tracer for understanding different environmental processes using sophisticated analytical tools and detection systems.

The number of ^{222}Rn atoms escaping from the soil grains in to the pore space in a given interval of time is known as the ^{222}Rn emanation rate. The rate of emission of ^{222}Rn from any surface area is known as the ^{222}Rn exhalation rate. ^{222}Rn exhalation rate depends on the material parameters such as its ^{226}Ra concentration, porosity, density, diffusion coefficient and texture. It is also affected by the meteorological parameter such as atmospheric pressure, rainfall, humidity, temperature, and the geological parameters like rock formations, cracks in the rock and breaking of bedrocks (Mustonen 1984; Shweikani et al., 1995; Keller et al., 2001; Shashikumar et al., 2009).

Radionuclides in the building materials emit gamma rays and alpha particles which are the important sources of external and internal exposure to the population (Akerblom et al., 1984). Among the building materials, granites have a large amount of ^{238}U and are the major sources of indoor ^{222}Rn concentration. Also the soil formed from granitic rocks has a higher ^{222}Rn exhalation rate. On an average, in a year, a person spends nearly 7300 hours indoors. Short-lived daughter products of ^{222}Rn emitted from the soil and building materials into the indoor air contribute to the internal and external radiation exposure (Lubin and Boice 1997). Therefore bringing awareness about indoor ^{222}Rn concentration and its harmful effects to the people is important. The presence of natural radionuclide in the underlying soil contributes to the indoor ^{222}Rn concentration of a building. The indoor and outdoor ^{222}Rn levels in a locality can be estimated by the ^{222}Rn exhalation rate of the soil. ^{222}Rn exhalation rate from the building materials, ambient temperature, atmospheric pressure, and ventilation are the main factors that control the amount of indoor ^{222}Rn levels (Sannappa et al., 2006; Akbari et al., 2013).

^{222}Rn exhaled from the surface of the soil reaches the atmosphere and further decays to a series of short-lived radionuclides such as ^{218}Po, ^{210}Pb, and ^{214}Bi which are the most important radionuclides as far as the inhalation dose is concerned (Kai, 2016). The concentration of ^{226}Ra and the exhalation rate of ^{222}Rn from soil help in assessing possible radiological health hazards to humans (UNSCEAR 2000). The International Commission on Radiological Protection (ICRP) has mentioned a range of 200-300 Bqm^{-3} for indoor ^{222}Rn (Harrison and Marsh, 2020). The world average indoor effective dose due to gamma rays from building materials is estimated to be 0.4 mSvy^{-1} (UNSCEAR 2000). The dose to the population from the radiation causing cancers and tissue disorders depends on the concentration of natural radionuclide in the soil. Around 70% of ^{226}Ra entering the body, gets deposited in the bones because of its similar properties to that of calcium and remaining gets into the tissues (Andersson et al., 2014). If a building is constructed with a material having higher concentration of natural radionuclide, then its indoor radiation dose rate will also be higher, which is the main reason for human lung cancer (Lubin and Boice 1997). Thus the characterization of various locations with respect to ^{222}Rn concentration is essential for dose estimation.

The geological survey in the study area has revealed the presence of granite and granitic gneisses, which are known to contain higher activity of radionuclides viz. ^{238}U, ^{232}Th and ^{40}K in Davanagere district. Previous studies in the Davanagere district, indicate that at few locations the activity of ^{222}Rn and ^{226}Ra in ground water samples were higher than the safe limit of 100 Bql^{-1} given by WHO (Hidayath et al., 2022; WHO 2004). The data of the present investigation is expected to provide a clear comprehensive picture of radioactive elements present in the study area and the type of geology responsible for the observed level of radioactive elements in the environmental matrix. An attempt has been made to compare the results of radon exhalation rate measured using a Smart Radon Monitor and an alpha counting system in which alpha probe is directly coupled to the radon exhalation chamber.

STUDY AREA

The soil samples were collected from various locations of Davanagere district, covering all the 6 taluks. The study area lies between the geographical coordinates 13°45'00" N to 14°50'00" N latitude and 75°30'00" E to 76°30'00" E longitude and confined to a geographical area of 5976 km^2 consisting of 920 villages with a population of 1.7 million (Census handbook 2011). The area consists of major physiographic units, undulating plains, interspersed with sporadic ranges, isolated dusters of low ranges of rocky hills including an agricultural land of 4225 km^2. The major water-bearing formation in this area are weathered, fractured gneiss, granites, and schists. Lithology map of the study area is shown in Fig. 1 (CGWB 2012). The locations from which the soil samples were collected are also marked in the Fig. 1.

The geomorphology of the Davanagere district is characterized by heaved plains scattered with irregular ranges. Granites and granitic-gneisses, schists are present in Harihara, Honnali, and Channagiri taluks. Davanagere taluk is covered by fractured granitic-gneisses, gneisses, and hornblende schists. Harapanahalli taluk has gneisses and schists. Jagalur taluk contains granitic gneisses and schist types of rocks. The soil in the study area comprises of red loams, red sandy, sandy loams, and medium black. The black soil is found mostly in the north-eastern part of the district (CGWB 2012).

EXPERIMENTAL TECHNIQUES

^{222}Rn Exhalation Rate from Soil Samples

The soil samples were collected across Davanagere district, Karnataka state, India. At each location, 6-8 spots were identified which were separated from one another by at least 10-15m. At each spot, an area of about 0.25m^2 was marked out and the vegetation and roots of the top layers of each marked spot was cleared. The marked spot was

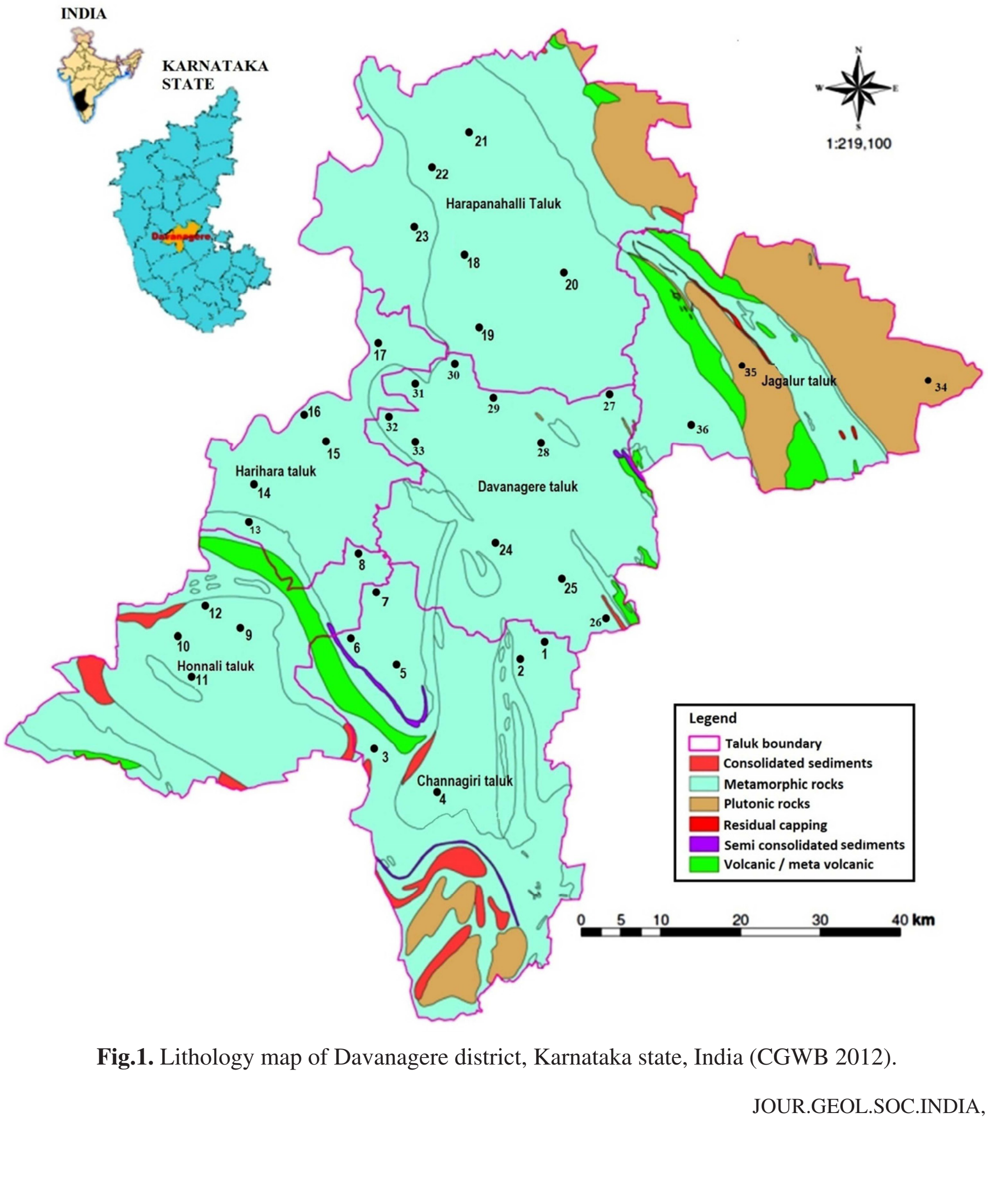

Fig.1. Lithology map of Davanagere district, Karnataka state, India (CGWB 2012).

dug to a depth of 50 cm and about 2kg of the soil was collected. Finally, all the samples were thoroughly mixed and a composite sample of about 2-3kg was taken for sample processing. The rocks, vegetation, and organic materials were removed and the sample was crushed into a fine powder. The powdered soil was dried in the oven at 110°C for 24 hours and sieved through a 150mm sieve, to obtain a fine quality sample. In the present study all the soil samples were powdered, sieved and uniformly dried in the oven to maintain similar structural and physical properties such as particle size, porosity and moisture content (Sahoo et al., 2007, Mahamood et al., 2020). About 400 grams of the sample was examined in the radon exhalation chamber.

$ZnSO_4$(Ag) scintillation-based smart radon monitor (SRM), developed by Bhabha Atomic Research Centre (BARC), Mumbai, India was used for determining the ^{222}Rn exhalation rate from the soil samples. The experimental set-up for measuring the ^{222}Rn exhalation rate using SRM is shown in Fig. 2. The instrument is calibrated regularly using a standard source. The powdered sample is filled in a cylindrical container, which is coupled to the scintillation cell. ^{222}Rn exhaled from the sample was transferred to the $ZnSO_4$(Ag) scintillation cell through diffusion. Alpha particles emitted by ^{222}Rn and its decay products in the scintillation cell were counted using the photomultiplier tube and associated electronics. It is implemented with an indigenous smart algorithm in the microprocessor that automatically compensates the background counts from residual decay products of ^{222}Rn which helps in continuous real-time measurement of ^{222}Rn activity (Ramola and Choubey 2003; Sahoo et al., 2007). Both surface exhalation rate and mass exhalation rate of ^{222}Rn were obtained using the measured value of ^{222}Rn activity at different time scales.

For some of the soil samples the ^{222}Rn exhalation rate was also measured using an alpha counting system with a similar indigenous experimental setup (Fig. 3). Radon exhalation chamber filled with soil sample was directly coupled to the alpha probe. Proper care was taken to minimize the leakage of ^{222}Rn gas from the exhalation chamber.

The ^{222}Rn emission potential for the powdered sample is governed by the ^{222}Rn mass exhalation rate (J_m). The build-up of ^{222}Rn concentration C_t in the container as a function of time is calculated using equation (1) (Sahoo et al., 2007).

$$C_t = (J_m M / V_{eff} \lambda_e)\, [1 - e^{-\lambda_e t}] + C_o e^{-\lambda_e t} \quad (1)$$

Where, C_t is the activity concentration of ^{222}Rn (Bqm^{-3}) at time t (s), J_m is the mass exhalation rate of ^{222}Rn ($Bqkg^{-1}s^{-1}$), M is the mass of the soil sample taken in the exhalation chamber (kg), V_{eff} is the effective volume available for the exhaled ^{222}Rn gas (volume of the exhalation chamber + internal volume of the scintillation cell and connectors – volume of the soil sample) (m^3), λ_e is the leakage rate of

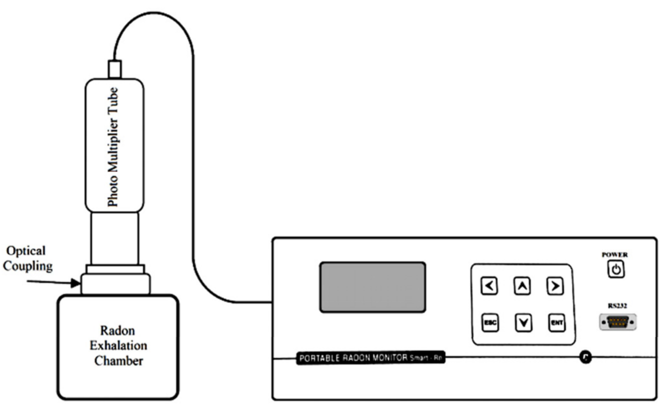

Fig.2. Experimental set-up for the measurement of ^{222}Rn exhalation rate from soil samples using SRM.

Fig.3. Measurement of ^{222}Rn exhalation rate from soil samples using alpha counting system.

^{222}Rn (if existing) + radioactive decay constant of ^{222}Rn (s^{-1}), C_o is the initial activity concentration of ^{222}Rn (Bqm^{-3}) at time t=0 (s) and t is the duration of the alpha counting (s)

For the smaller exhalation times of the order of 15-20 hours, the equation (1) can be approximated to equation (2) (Ramola and Choubey 2003; Sahoo et al., 2007).

$$C_t = (J_m M / V_{eff})\, t + C_o \quad (2)$$

^{222}Rn exhaled from the soil sample diffuses into the scintillation cell and its activity concentration gradually increases with time. For each soil sample ^{222}Rn concentration in the exhalation chamber was monitored at intervals of 30 min up to about 10 hours. The variation of ^{222}Rn activity in the scintillation cell with time was linear and can be fitted into a straight line using the linear regression method to determine the radon exhalation rate from the soil sample.

The mass exhalation rate of ^{222}Rn (J_m) and the surface exhalation rate of ^{222}Rn (J_s) were estimated using the equations (3) and (4).

$$J_m = [(C_t - C_o)\, V_{eff}\,] / M\, t \quad (3)$$

$$J_s = [(C_t - C_o)]\, V_{eff} / A\, t \quad (4)$$

Where, M is the mass of the soil sample taken for analysis (0.4kg), A is the internal area of the radon exhalation chamber ($7.16 \times 10^{-3}\ m^2$) and V_{eff} is the effective volume available for ^{222}Rn exhalation ($5.57 \times 10^{-4} m^3$).

Activity of ^{226}Ra, ^{232}Th and ^{40}K in Soil Samples

After the measurement of radon exhalation rate, a few samples were taken for analysis of ^{226}Ra, ^{232}Th and ^{40}K activity using p-type coaxial Hyper Pure Germanium (HPGe) detector to study a possible correlation between ^{222}Rn exhalation rate and activity of radionuclides. About 250 grams of soil samples were sealed in an air-tight PVC container and kept sealed for a month in order to obtain equilibrium between radionuclides and their respective progeny. The containers were properly sealed to prevent the escape of ^{222}Rn and ^{220}Rn gases from the samples. Proper lead shielding was done to the HPGe detector to minimize the background counts. The efficiency of the spectrometer for various gamma energies was estimated using standard sources which were taken in the containers of the same geometry and density as that of the soil samples under study. Gamma spectrum for each sample was accumulated for a period of about 1 hour to obtain good statistics (Volchok and Planque 1983).

Activity concentration of radionuclides was estimated using photo peaks of the gamma spectrum obtained by HPGe detector. ^{226}Ra has a photopeak of 609 keV (from ^{214}Bi (46.1%)and 186 keV (not used for counting as it interferes with the photopeak of ^{235}U (185.7 keV). ^{232}Th activity is measured using 583keV (86%) (Gamma transitions from ^{208}Tl) photopeak and ^{40}K activity from 1461 keV (10.7%). The photo peaks of 238.6 keV (^{212}Pb), 338.4 keV (^{208}Tl), 583.2 keV (^{214}Bi), 911 keV (^{228}Ac) and 2614 keV (^{208}Tl) were chosen for the equilibrium of ^{232}Th series. The activity of ^{226}Ra, ^{232}Th and ^{40}K were calculated using the relation (5) (Volchok and Planque, 1983).

$$C = (S \pm \sigma) / (E \times A \times M) \quad (5)$$

Where, C is the activity concentration of radionuclide (Bqkg^{-1}), S is the net counts under photo peak of interest (s^{-1}), σ is the standard deviation of the net counts (s^{-1}), E is the efficiency of the HPGe spectrometer, A is the fraction of the gamma abundance of radionuclide and M is the mass of the soil sample (kg).

ESTIMATION OF RADIOLOGICAL HAZARD INDICATORS

Radium Equivalent Activity

The ^{226}Ra equivalent activity (Ra_{eq}) is the weighted sum of activities of ^{226}Ra, ^{232}Th and ^{40}K and were estimated using the equation (6) (Beretka and Matthew 1985). This is based on the assumption that 1 Bqkg^{-1}of ^{226}Ra, 0.7 Bqkg^{-1} of ^{232}Th and 13 Bqkg^{-1} of ^{40}K give the same amount of gamma dose rate. The value of 370 Bqkg^{-1} of ^{226}Ra equivalent activity will produce an effective gamma dose of 1.5 mGyy^{-1}, which is equivalent to a dose value of 1.0 mSvy^{-1}. This is an alternative way to assess the construction materials for their suitability to use in the buildings.

$$Ra_{eq} = C_{Ra} + (C_{Th} / 0.7) + (C_K /13) \quad (6)$$

Where, C_{Ra}, C_{Th} and C_K are the measured activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K respectively.

Hazard Indices

External hazard index (H_{ex}) and internal hazard index (H_{in}) due to the activity of ^{226}Ra, ^{232}Th and ^{40}K in soil samples were estimated using equations (7) and (8) respectively (Beretka and Matthew 1985; ICRP 1990; EC 1999).

$$H_{ex} = (C_{Ra} /370) + (C_{Th} / 259) + (C_K /4810) \leq 1 \quad (7)$$

$$H_{in} = (C_{Ra} /185) + (C_{Th} / 259) + (C_K /4810) \leq 1 \quad (8)$$

Gamma Activity Concentration

Gamma activity concentration index I_g has been defined by the European Commission (EC 1999). This index is obtained to find whether the annual external gamma radiation dose due to radionuclides present in building material is exceeding 1 mSv. The gamma activity index is given by the equation (9).

$$I_Y = (C_{Ra} /300) + (C_{Th} / 200) + (C_K /3000) \leq 1 \quad (9)$$

Where, 300, 200 and 3000 are the activity concentration indexes for ^{226}Ra, ^{232}Th and ^{40}K activities respectively. These values were rounded to the nearest full 100 Bqkg^{-1} for ^{226}Ra, ^{232}Th and 1000 Bqkg^{-1} for ^{40}K.

Gamma Absorbed Dose Rate

Gamma absorbed dose rate (D) was computed using equation (10) (UNSCEAR 2000; ICRU 1994; Saito and Jacob 1995).

$$D = 0.462\, C_{Ra} + 0.604\, C_{Th} + 0.0417\, C_K \quad (10)$$

Where, 0.462nGyh^{-1}(Bqkg^{-1})$^{-1}$, 0.604nGyh^{-1}(Bqkg^{-1})$^{-1}$ and 0.0417nGyh^{-1}(Bqkg^{-1})$^{-1}$ are the gamma absorbed dose conversion factors of ^{226}Ra, ^{232}Th and ^{40}K respectively.

RESULTS AND DISCUSSION

The results of the ^{222}Rn exhalation rate from soil samples collected from different locations are given in Table 1. The mass exhalation rate of ^{222}Rn from soil varied from 6.9 ± 1.7 to 38.5 ± 3.3 mBqkg^{-1}h^{-1} with an average of 21.8 ± 2.6 mBqkg^{-1}h^{-1}. The surface exhalation rate of ^{222}Rn from soil samples varied from 0.39 ± 0.10 to 2.15 ± 0.18 Bqm^{-2}h^{-1} with an average of 1.22 ± 0.14 Bqm^{-2}h^{-1}. A typical variation of radon concentration with time in the radon exhalation chamber measured for a period of 40 hours with Smart Radon Monitor and with an Alpha Counting System is shown in Fig. 4. The concentration was linear with time in both the instruments and similar type of trend is observed in all soil samples.

The ^{222}Rn exhalation rate of soil samples was found to be higher at Jagalur, Somanahalli, Devarahatti, Machihalli, Sasevahalli, Kalledevapura, Harapanhalli villages. Several factors are responsible for the presence of higher concentration of radionuclide in the soil such as type of soil, geography, and geology of the region. Flood causes the movement of soil from one place to another and is responsible for varying concentrations of radionuclides in different locations hence floods and distribution of radionuclides in soil are interconnected. A higher exhalation rate of ^{222}Rn may be due to higher activity concentrations of ^{226}Ra in soil derived from granite rocks. Soil porosity also plays a crucial role in ^{222}Rn exhalation. Granitic rocks have higher levels of ^{226}Ra content whereas sedimentary rocks have a lower concentration. The Devarahatti region in Davanagere district has fractured granite, gneisses and hornblende schists that may be the possible reason for higher ^{222}Rn concentration. Davanagere district has large agricultural land, where farmers use more phosphate fertilizers that contain ^{232}Th and U. The fertilizers have a larger concentration of radioactive elements such as ^{226}Ra and its decay products.

Activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil samples of Davanagere taluk and their ^{222}Rn exhalation rate are shown in Table 2. ^{226}Ra concentration varied from 32.0 Bqkg^{-1} (Yaragunte) to 106.1 Bqkg^{-1} (Anagodu). ^{232}Th concentration ranges from 19.6

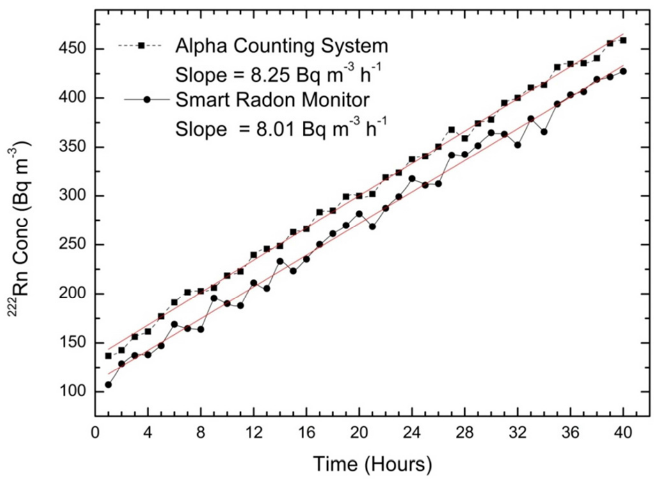

Fig.4. Typical variation of radon concentration with time in the radon exhalation chamber measured with Smart Radon Monitor and an with an Alpha Counting System.

Table 1. ^{222}Rn exhalation rate from soil samples of Davanagere district

Sl. No.	Location	Latitude	Longitude	Mass Exhalation rate of ^{222}Rn (mBqkg^{-1}h^{-1})	Surface Exhalation rate of ^{222}Rn (Bqm^{-2}h^{-1})
1	Doddabbigere	14°09'42.19" N	76°03'31.51" E	19.0 ± 2.6	1.06 ± 0.15
2	Santebennur	14°09'12.60" N	75°56'29.19" E	6.9 ± 1.7	0.39 ± 0.10
3	Mathikoppa	14°07'31.35" N	75°05'31.25" E	10.5 ± 1.9	0.59 ± 0.11
4	Billahalli	14°02'43.37" N	75°54'21.11" E	11.6 ± 2.1	0.65 ± 0.12
5	Kerebilchi	14°08'15.24" N	75°52'33.24" E	20.8 ± 2.7	1.16 ± 0.15
6	Basavapatna	14°11'053.5" N	75°49'21.94" E	16.2 ± 2.4	0.90 ± 0.13
7	Doddaghatta	14°13'16.71"N	75°52'54.18" E	20.4 ± 2.7	1.14 ± 0.15
8	Sasvehalli	14°09'01.62" N	75°43'008.9" E	33.5 ± 3.5	1.87 ± 0.19
9	Honnali	14°13'38.68" N	75°37'49.30" E	17.2 ± 1.1	0.96 ± 0.06
10	Soratur	14°12'46.40" N	75°35'29.68" E	20.1 ± 2.7	1.12 ± 0.15
11	Arundi	14°11'16.20" N	75°34'31.01" E	26.5 ± 3.1	1.48 ± 0.17
12	Guddada Madapura	14°18'07.16" N	75°34'23.55" E	23.6 ± 2.3	1.32 ± 0.13
13	Kumbaluru	14°22'43.28" N	75°45'06.83" E	26.1 ± 3.1	1.46 ± 0.17
14	Yalavatti	14°24'43.98" N	75°43'34.01" E	29.6 ± 3.2	1.66 ± 0.18
15	Belludi	14°26'45.27" N	75°47'08.05" E	20.4 ± 2.7	1.14 ± 0.15
16	Rajanahalli	14°30'15.14" N	75°46'23.73" E	21.1 ± 2.7	1.18 ± 0.15
17	Dheetur	14°34'04.53" N	75°49'49.93" E	22.6 ± 2.8	1.26 ± 0.16
18	Punabaghatta	14°36'05.75" N	76°01'33.86" E	19.7 ± 2.7	1.10 ± 0.15
19	Hucchangidurga	14°35'22.43" N	76°03'12.57" E	24.5 ± 3.3	1.37 ± 0.18
20	Gadi Dudal	14°36'27.54" N	76°07'33.29" E	25.0 ± 3.0	1.40 ± 0.17
21	Harapanhalli	14°46'41.41" N	75°57'53.92" E	31.5 ± 3.6	1.76 ± 0.20
22	Machihalli	14°44'42.97" N	75°55'03.55" E	34.6 ± 3.5	1.93 ± 0.20
23	Telagi	14°41'02.41" N	75°53'41.59" E	13.8 ± 2.5	0.77 ± 0.14
24	Vidyanagar	14°26'34.59" N	75°54'53.06" E	17.8 ± 1.9	0.99 ± 0.11
25	SG Halli Layout	14°25'50.73" N	75°55'11.49" E	15.6 ± 2.0	0.87 ± 0.11
26	Doddabathi	14°28'25.15" N	75°51'1.048" E	8.0 ± 1.4	0.45 ± 0.08
27	Taralabalu Layout	14°26'035.3" N	75°55'18.48" E	21.5 ± 2.0	1.20 ± 0.11
28	Yaragunte	14°29'22.92" N	75°53'45.29" E	9.0 ± 1.5	0.50 ± 0.08
29	Devarajnagar	14°28'50.63" N	75°55'54.06" E	21.4 ± 1.9	1.20 ± 0.11
30	Shamanur	14°26'03.36" N	75°52'52.49" E	12.5 ± 2.6	0.70 ± 0.14
31	Kundavada	14°27'08.86" N	75°51'55.54" E	17.2 ± 1.9	0.96 ± 0.11
32	Devarahatti	14°30'39.16" N	75°54'46.13" E	34.8 ± 3.5	1.94 ± 0.20
33	Aangodu	14°23'31.31" N	76°02'48.27" E	21.5 ± 2.6	1.20 ± 0.14
34	Kalledevapura	14°26'12.00" N	76°26'27.00" E	32.8 ± 2.8	1.83 ± 0.16
35	Jagalur	14°30'49.12"N	76°20'12.42" E	38.5 ± 3.3	2.15 ± 0.18
36	Somanahalli	14°27'36.97"N	76°15'47.37" E	37.6 ± 3.4	2.10 ± 0.19
	Minimum			6.9 ± 1.7	0.39 ± 0.10
	Maximum			38.5 ± 3.3	2.15 ± 0.18
	Median			20.9 ± 2.6	1.17 ± 0.15
	Arithmetic mean			21.8 ± 2.6	1.22 ± 0.14
	Geometric mean			20.1 ± 2.5	1.12 ± 0.14
	Standard deviation			8.4 ±0.6	0.47 ± 0.04

Table 2. Variation of ^{222}Rn mass exhalation rate, activity of ^{226}Ra, ^{232}Th and ^{40}K, hazard indexes and absorbed dose rate in soil samples from Davanagere taluk.

Sl. No.	Location	J_m (mBqkg^{-1}h^{-1})	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	Absorbed dose rate (nGyh^{-1})	H_{ex}	H_{in}	$I_{ã}$
			(Bq kg^{-1})							
1	SSM Nagara	13.95	62.7	28.3	385.5	133.1	62.25	0.36	0.53	0.48
2	DVG Industrial area	10.92	45.6	23.5	463.6	115.0	54.65	0.31	0.43	0.42
3	Doddabathi	8.02	48.7	25.6	20.1	86.9	38.84	0.23	0.37	0.30
4	Karur industrial area	14.67	56.0	26.8	272.4	115.4	53.42	0.31	0.46	0.41
5	Aanagodu	21.50	106.1	78.8	585.2	263.7	120.97	0.71	1.00	0.94
6	Avaragere	12.24	56.5	30.9	482.7	137.6	64.84	0.37	0.52	0.50
7	Shamanur	12.48	73.2	44.4	456.0	171.8	79.65	0.46	0.66	0.62
8	Yaragunte	9.03	32.0	19.6	415.3	92.0	43.94	0.25	0.33	0.34
9	Kundavada	17.16	67.6	25.7	968.0	178.7	87.06	0.48	0.67	0.68
10	KTJ Nagara	17.64	83.3	45.6	539.6	190.0	88.48	0.51	0.74	0.69
	Minimum	8.02	32.0	19.6	20.1	86.9	38.84	0.23	0.33	0.42
	Maximum	21.50	106.1	78.8	968.0	263.7	120.97	0.71	1.00	2.14
	Arithmetic mean	13.76	63.2	34.9	458.8	148.4	69.41	0.40	0.57	1.08
	Geometric mean	13.20	60.1	32.0	349.5	140.5	65.67	0.38	0.54	0.95
	Standard deviation	4.15	20.9	17.6	239.7	53.8	24.87	0.15	0.20	0.19
	Indian average(UNSCEAR 2000)	-	29	64	400	151.32	68.73	0.41	0.49	1.10
	World average (UNSCEAR 2000)	-	35	30	400	108.70	50.97	0.29	0.39	0.80

(Yaragunte) to 78.8 $Bqkg^{-1}$ (Aangodu) and ^{40}K concentration ranges from 20.1 $Bqkg^{-1}$ (Doddabathi) to 968.0 $Bqkg^{-1}$ (Kundavada). The variation in the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K can be attributed to the presence of fractured granitic-gneisses, gneisses and hornblende schists in the region. ^{40}K concentration in soil is directly proportional to the presence of silica contents in granites, which is directly related to the high activity of ^{40}K. Average values of the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in soil samples of the study area are 63.2 $Bqkg^{-1}$, 34.9 $Bqkg^{-1}$ and 458.8 $Bqkg^{-1}$ respectively. The world average concentrations of radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in soil were 35 $Bqkg^{-1}$, 30 $Bqkg^{-1}$ and 400 $Bqkg^{-1}$ respectively (UNSCEAR 2000). In India, the average value concentrations of these radionuclides were 29 $Bqkg^{-1}$, 64 $Bqkg^{-1}$ and 400 $Bqkg^{-1}$ (UNSCEAR 2000). The activity of ^{226}Ra in the soil samples of the study area was found to be higher than the global average and the Indian average value, whereas the activities of ^{232}Th and ^{40}K were comparable to global average values. The activity of ^{232}Th in soil samples of the study area is less than the Indian average value.

Activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in soil samples were used to estimate ^{226}Ra equivalent activity, internal hazard index, external hazard index and gamma activity concentration index (Beretka and Matthew 1985; ICRP 1990; EC 1999; UNSCEAR 2000; ICRU 1994; Saito and Jacob, 1995). The variation of activity concentration of radionuclides in the study area and hazard indices is shown in Table 2. The estimated ^{226}Ra equivalent activities Ra_{eq} varied from 86.9 to 263.7 $Bqkg^{-1}$ with a geometric mean of 140.5 $Bqkg^{-1}$. Ra_{eq} in soil samples of Anagodu, KTJ Nagara and Kundavada were found to be higher. The estimated values of H_{ex} range from 0.23 to 0.71 with a geometric mean of 0.38 and the estimated values of H_{in} range from 0.33 to 1.00 with a geometric mean of 0.54. Since the hazard index values of all the samples were <1, the soil of the study area may be considered as safe from the radiological point of view for the construction of residential buildings (Beretka and Matthew 1985). The measured gamma index I_g for soil samples range from 0.42 to 2.14 with a geometric mean of 0.95. The estimated absorbed gamma dose rates due to the activity of radionuclides in soil varied from 38.84 to 120.97 $nGyh^{-1}$ with a geometric mean of 65.67 $nGyh^{-1}$. The obtained values were slightly higher compared to the world average value of 50.97 $nGyh^{-1}$ (UNSCEAR 2000).

The mass and surface exhalation rate of ^{222}Rn was compared with Indian and world values taken from literature and is shown in Table 3. The researchers have used different experimental techniques and also samples of different dimensions for the measurement of mass and surface exhalation rate of ^{222}Rn. The surface exhalation rate of ^{222}Rn also depends on the thickness of the sample, which is not considered during calculation. Similarly the mass exhalation rate also depends on the surface area of the sample. Apart from this, the grain size, porosity and moisture content of the soil sample also affect the ^{222}Rn exhalation

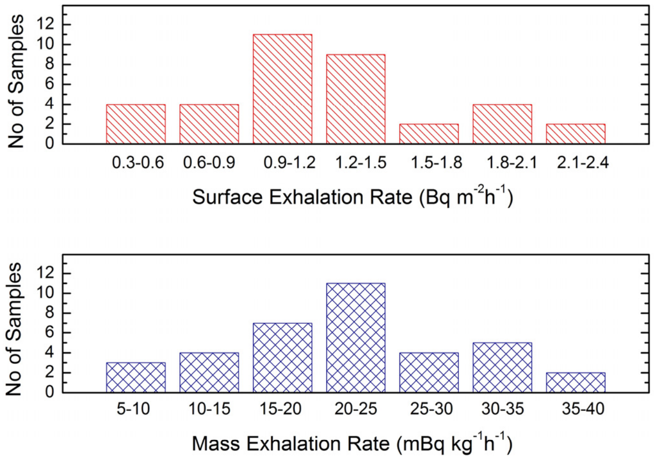

Fig.5. Frequency distribution of mass and surface exhalation rate of ^{222}Rn.

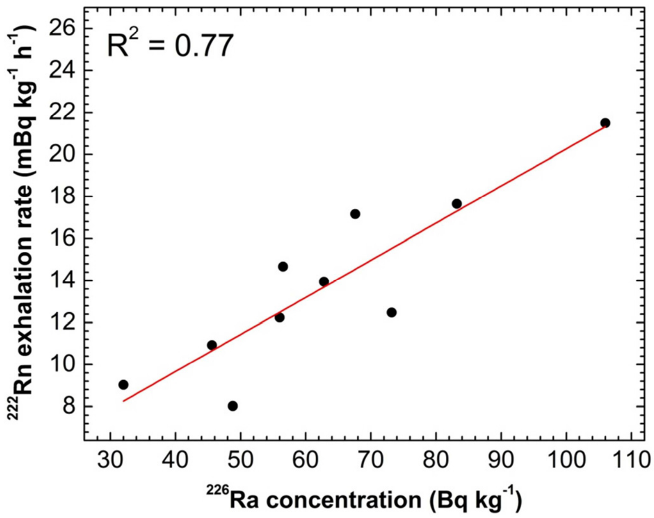

Fig.6. Correlation between ^{222}Rn exhalation rate and ^{226}Ra activity in soil samples.

Table 3. Comparison of mass and surface exhalation rate of ^{222}Rn with other literature values.

Sl. No.	Region	^{222}Rn Mass Exhalation Rate ($mBqkg^{-1}h^{-1}$)	^{222}Rn Surface Exhalation Rate ($Bqm^{-2}h^{-1}$)	Experimental methods followed	Reference
1	Southern Sakarya, Turkey	35.76 to 253.15	0.73 to 5.18	LR-115 type-II	Tabar et al., (2018)
2	Yeman	22.79 to 33.25	0.74 to 1.08	CR-39	Al Mugahed and Bentayeb (2018)
3	HalfaAljadid Area, Sudan	17.62 to 58.91	0.88 to 2.93	CR-39	Elzain et al., (2019)
4	Udhampur District, J & K State, India	11.57 to 65.62	–	SRM	Sharma et al., (2019)
5	Chamarajanagar district, Karnataka, India	10.0 to 31.4	0.142 to 0.918	LR-115 type-II	Nagaraju et al., (2013)
6	Roma, Italy	–	0.36 to 3.82	RAD7	Lucchetti et al., (2019)
7	Coastal region of Kerala, India	2.4 to 23.4	0.048 to 0.466	LR-115 type-II	Mahamood et al., (2020)
8	Tashkent City, Uzbekistan	–	11.2 to 26.0	CR-39	Vasidov and Vasidova (2020)
9	North Caucasus Region, Russia	–	0.08 to5.6	Open Charcoal Chamber Method	Miklyaev et al., (2020)
10	Hamirpur District, Himachal Pradesh, India	18.81 to 87.85	0.110 to 0.942	SRM	Thakur et al., (2021).
11	Southeastern Ireland	–	0.15 to 1.84	RAD7	Mousavi et al., (2021)
12	Davanagere, India	6.9 to 38.5	0.39 to 2.15	SRM	Present work

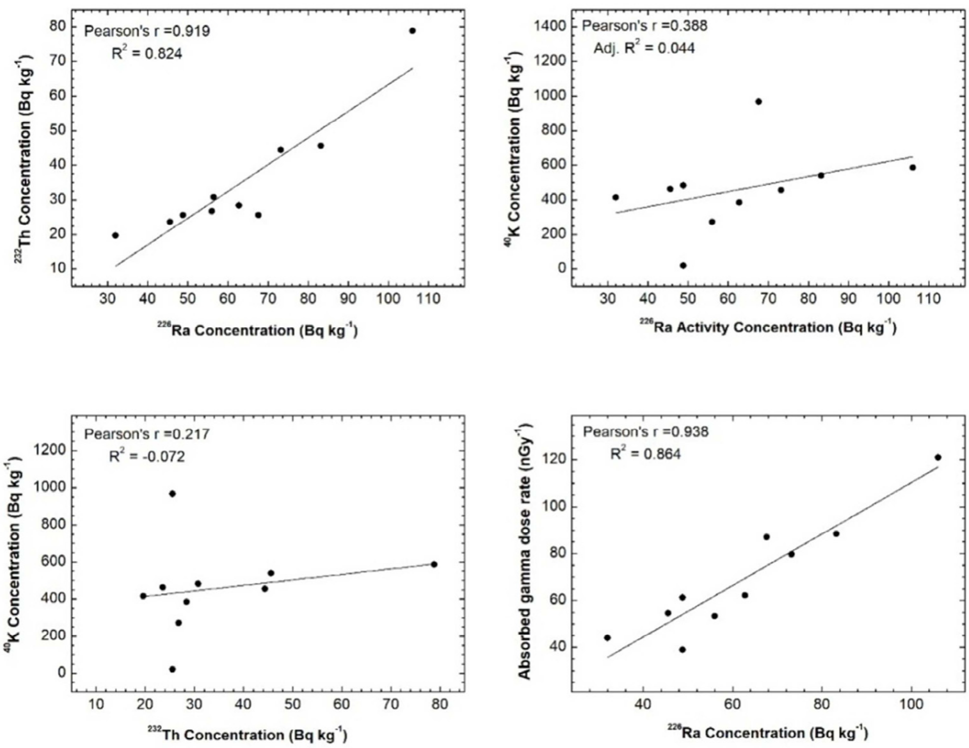

Fig.7. Correlation between activity of ^{226}Ra, ^{232}Th, ^{40}K and absorbed gamma dose rate.

rate. In the present investigation, all the soil samples were crushed, powdered and sieved to obtain uniform samples. The samples were dried in the oven to remove the moisture content. Because of similar structural and physical properties of the soil samples ^{222}Rn exhalation rate is expected to depend mainly on the radium content in the soil.

The frequency distribution of mass exhalation rate and surface exhalation rate of ^{222}Rn is shown in Fig. 5. Maximum numbers of samples were observed in the range of 0.9 to 1.2 Bqm^{-2}h^{-1} for surface exhalation rate and 20 to 25 mBqkg^{-1}h^{-1} for mass exhalation rate. The correlation between ^{222}Rn exhalation rate and ^{226}Ra concentration in soil samples of the study area is shown in Fig. 6. There is a good correlation between them with an adjusted R^2 value of 0.77. This shows that the exhalation rate of ^{222}Rn depends mainly on radium content in the samples.

The activity concentration of radionuclides such as ^{226}Ra, ^{232}Th and ^{40}K in the study area and their correlation studies were also carried out. There was a good correlation between ^{226}Ra and ^{232}Th activity with an adjusted R^2 value of 0.82 and no correlation was observed between ^{226}Ra and ^{40}K activity and also between^{40}K and ^{232}Th activity concentration. This would infer that the radionuclides ^{40}K and ^{232}Th in the study area were of different origins.^{226}Ra concentration and absorbed gamma dose rate showed a good correlation with an adjusted R^2 value of 0.86 (Fig. 7).

CONCLUSION

The mass exhalation rate of ^{222}Rn from soil samples of Davanagere district, Karnataka state, India varied from 6.9 ± 1.7 to 38.5 ± 3.3 mBqkg^{-1}h^{-1} with an average of 21.8 ± 2.6 mBqkg^{-1}h^{-1}. Whereas the surface exhalation rate of ^{222}Rn varied from 0.39 ± 0.10 to 2.15 ± 0.18 Bqm^{-2}h^{-1} with an average of 1.22 ± 0.14 Bqm^{-2}h^{-1}. The ^{222}Rn exhalation rate of the present study was comparable to the values published in literature.

Average values of the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in soil samples of the Davanagere taluk are 63.2 Bqkg^{-1}, 34.9 Bqkg^{-1} and 458.8 Bqkg^{-1} respectively. The activity of ^{226}Ra in the soil samples of the study area was found to be higher than the global average and the Indian average value. There was a good correlation between ^{226}Ra and ^{232}Th activity with an adjusted R^2 value of 0.82. The estimated absorbed gamma dose rate due to radionuclides in soil varies from 38.84 to 120.97 nGyh^{-1} with an average of 69.41 nGyh^{-1}, which is slightly higher than the world average value of 50.97 nGyh^{-1}.

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