CHAPTER: 5

RADON/THORON EXHALATION RATES IN SOIL SAMPLES AND THEIR CORRELATION WITH INDOOR CONCENTRATION

This chapter deals with the introduction, brief literature about radon/thoron in soil, methodology and standard formulae has been used to assess the radon mass/thoron surface exhalation rates in soil samples using a scintillation based Smart RnDuo. In the last detailed discussion about results along with final conclusion have been included.

5.1 INTRODUCTION

The existence of natural radioactivity everywhere on earth is mostly because of the presence of radioactive sources like uranium, thorium and potassium. It is important to understand the creation and migration process of radon from soil and building materials. The exhalation from soil and from building materials are the two essential sources of radon that contributes towards the indoor radon (Sahoo et al., 2011). Radon moves to the indoor air from matrix of soil and building materials by the two processes of exhalation and emanation from matrix (Figure 5.1). Exhalation is the process of transport of radon gas from air-filled pores to the atmosphere while emanation is the process by which radon escapes from the solid mineral grains to the air- filled pores. Although the whole processes responsible for radon emanation from grains is not completely perceived, but it is accepted that the main contribution to emanation comes from the recoil processes. Effect of temperature on radon emanation is too small but moisture has a large effect on it. This is because radon molecule entering a pore that is filled or half filled with water has a higher probability of being stopped in the pore volume without crossing the pore space and being breathed out in the environment. Transport of radon from pore space to atmosphere takes place mainly by diffusion and flow process. The emission rate of radon depends upon different factors like moisture, temperature, rain fall, pressure, soil fertility, activity concentration of radionuclide in soil and rocks (Mayya et al. 1998; UNSCEAR, 2000). The radon/thoron exhalation rates can be defined as emission of radon/thoron gas per unit mass surface area per unit time from compounds such as soil/building materials can be utilized for measurement of indoor radon concentration using numerous models (Sahoo et al. 2011). The greater part of homes in India have been developed utilizing blocks with combination of soil nearabout 80%, which contains exceptionally occurring natural radionuclides (Fardoas et al. 2007; Bhagotra et al. 2017).

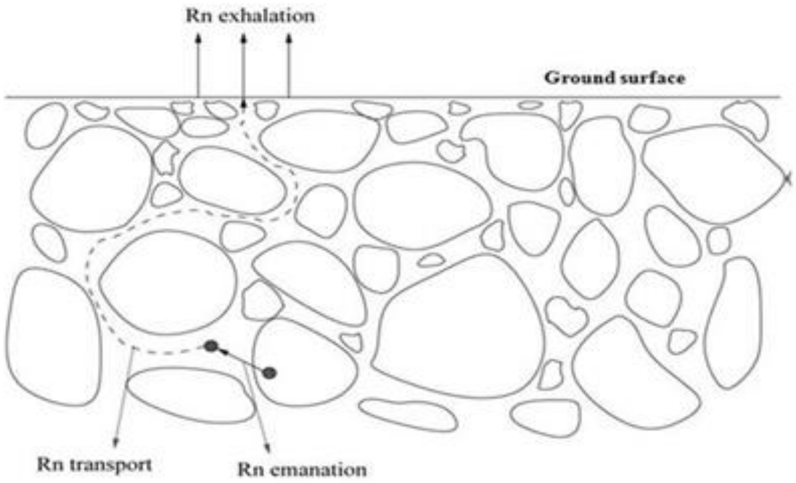

Figure 5.1: Process leading to radon release from the soil to the atmosphere (Sapra et al., 2016)

The primary source of radon/thoron is soil. Radon/thoron indoor level is influenced by underneath soil gas concentration and is enhanced with the use of materials having high source content for construction purposes (Kumar et al., 2014). Emanated radon/thoron from underneath reaches the indoor air by crossing the soil and building materials. Knowledge of the amount of natural radionuclide and radon/thoron exhalation rates in soil and construction materials is vital to assess the possible radiological risk and associated hazards index to human health and additionally to develop the standard for their use. As only radon contributes to 55% of the total radiation dose received by local public of the environment (UNSCEAR, 2000; Chauhan et al., 2014; Singla et al., 2021). When we breathe in the radon and its progenies Po-218 and Po-214 mainly, then these progenies get attached to aerosols which are available in air and constitutes a significant radiological health risk to respiratory system (Tanner et al. 1980: Kumar et al. 2014; Sahoo et al., 2007). Indoor radon exposure is connected with the risk of leukaemia and some different cancers such as melanoma, cancer of kidney and prostate cancer (Henshaw et al 1990; Kansal et al 2015). Radon is second driving cause of lung cancer in North America and the main source of lung cancer for individual who have never smoked (Mehra et al., 2015; BEIR VI, 1999; Sonkawde et al., 2003). USEPA has assessed that the 20000 of the lung cancer deaths expected every year can be portrayed to radon (USEPA, 2014). As per WHO, lung cancer is among the five primary kinds of cancer leading to overall cancer mortality (WHO, 2009). As per the United Nations Scientific Committee on the Effects of Atomic Radiation, average annual effective dose to an individual from naturally occurring sources of ionizing radiation has been assessed at 2.4 mSv, out of which 52% is because of inhalation exposure and 92% of this part is contributed by the radioactive component radon and its progenies (UNSCEAR, 2000; Kumar et al. 2018).

The motive of the study is to identify the radon inclined area and appropriate soil in constructing new buildings. Numerous researchers have studied the exhalation rate in soil samples worldwide. Radon and thoron exhalation rates are measured using Smart RnDuo for first time in the Hanumangarh, Sri Ganganagar and Churu districts of Northern Rajasthan and their comparison with similar investigations performed in other parts of India.

5.2 METHODOLOGY

5.2.1 Field Work

Soil samples were collected from different villages in such a way to cover the whole area of three districts. During sampling, the outdoor gamma level was measured using gamma survey meter (Polymaster PM/1405, Republic of Belarus) at one meter height from the surface as shown in Table 1. The polymaster PM-1405 has a gamma energy response from 0.05 to 3 MeV and can be used for dose rate measurement vary from 0.01 μSvh^{-1} to 130 μSvh^{-1}. The GPS coordinates along with longitude and latitude were noted using GPS map. An aggregate of 70 soil samples each weighing 1000 gm have been collected at the depth of about 20 cm beneath the soil profile to get pure soil samples from 70 villages of Hanumangarh (25 villages), Sri Ganganagar (25 villages) and Churu (20 villages) districts of Rajasthan, India. To preserve homogeneity, the obtained samples were crushed with a pestle and filtered. To remove moisture, the soil was dried in an oven. Smart RnDuo, a scintillation-based detector, was utilised to quantify radon/thoron exhalation rates. It works on the idea of detecting alpha particles that strike the detector and cause scintillations inside the cell due to the ZnS:Ag coating. The Photo Multiplier Tube counts the scintillations and converts them to radon/thoron activity using an integrated algorithm.

5.3 FORMULAE USED FOR CALCULATIONS

5.3.1 Calculation of Radon Mass Exhalation Rates

The data from the detector was utilised to create a graph between radon concentration (C) and time (t), and the slope of the graph was calculated using the least square fitting approach as described in equation 1. (Sahoo et al., 2013). The radon mass exhalation rate (J_{Rm}) was derived from the slope of the graph using equation 2 as follows:

$$C(t) = (\frac{J_{Rm}M}{V})t + C_o \qquad (1)$$

$$J_{Rm} = slope \times \frac{V}{M} \qquad (2)$$

Where J_{Rm} ($Bqkg^{-1}.h^{-1}$) is the radon mass exhalation rate,

C_0 is the radon concentration (Bqm^{-3}) present in the chamber volume (cm^3) at t = 0,

M is the total mass of the dry soil sample (kg) inside the chamber,

t is the measurement time (h),

and V is the effective volume (volume of detector + porous volume of sample ($Vp = Vs - \frac{M}{\rho_g}$)+ residual air volume of the mass exhalation chamber) (m^3)

where, ρ_g is the specific gravity of sample which can be taken as 2.7 gm/cc for clay type soil sample.

5.3.2 Calculation of Thoron Surface Exhalation Rates

At equilibrium, the thoron surface exhalation rate has been calculated by using equation (3) (Radon handbook, BARC).

$$J_{Ts} = \frac{C_T V_T \lambda}{A} \qquad (3)$$

Where, J_{Ts} is the thoron surface exhalation rate of soil sample ($Bqm^{-2}h^{-1}$),

A is the surface area of the chamber (m^2),

V_T is the effective volume (m^3) (i.e., residual volume of chamber + internal volume of detector + volume of cylindrical pipes + residual volume of lid over the chamber),

C_T is the thoron build up concentration inside the chamber (Bqm^{-3}), and λ ($0.0126 s^{-1}$ assuming half-life is 55s) is the decay constant of thoron.

5.4 RESULTS AND DISCUSSION

In Hanumangarh district, total 25 soil samples have been collected from 25 different villages at the depth of about 20 cm below the soil surface to get fresh sample to avoid the atmospheric deposition. The radon mass exhalation rate has been found to vary from 12.23 ± 0.62 $mBqKg^{-1}h^{-1}$ to 62.03 ± 3.49 $mBqKg^{-1}h^{-1}$ with an average value of 33.67 ±1.37 $mBqKg^{-1}h^{-1}$ and thoron surface exhalation rate varies from 3.34 ± 0.39 to 8.57 ± 0.62 kBq $m^{-2}h^{-1}$ with an average of 6.07 ± 0.62 $kBqm^{-2}h^{-1}$ as shown in Table 5.1.

The frequency distribution shows that the radon mass exhalation rate for 8% soil samples (2) lie between 0 -15 $mBqkg^{-1}h^{-1}$, for 24% soil samples (6) lie between 15-30 $mBqkg^{-1}h^{-1}$, for 56% soil samples (14) lies between 30-45 $mBqkg^{-1}h^{-1}$ and for the rest of 12% soil samples (3) lie in 45-60 $mBqkg^{-1}h^{-1}$ as shown in Figure 5.2. The frequency distribution shows that the thoron surface exhalation rate for 12% soil samples (3) lie between 0-4 $kBqm^{-2}h^{-1}$, for 80% soil samples (20) lie between 4-8 $kBqm^{-2}h^{-1}$ and for 8% soil samples (3) lie between 8-12 $kBqm^{-2}h^{-1}$ as shown in Fig 5.2. These values are lower than the worldwide average value of 57 $mBqKg^{-1}h^{-1}$ for radon mass exhalation rate and higher than the worldwide value of 3.6 $kBqm^{-2}h^{-1}$ for thoron surface exhalation rate (UNSCEAR, 2000).

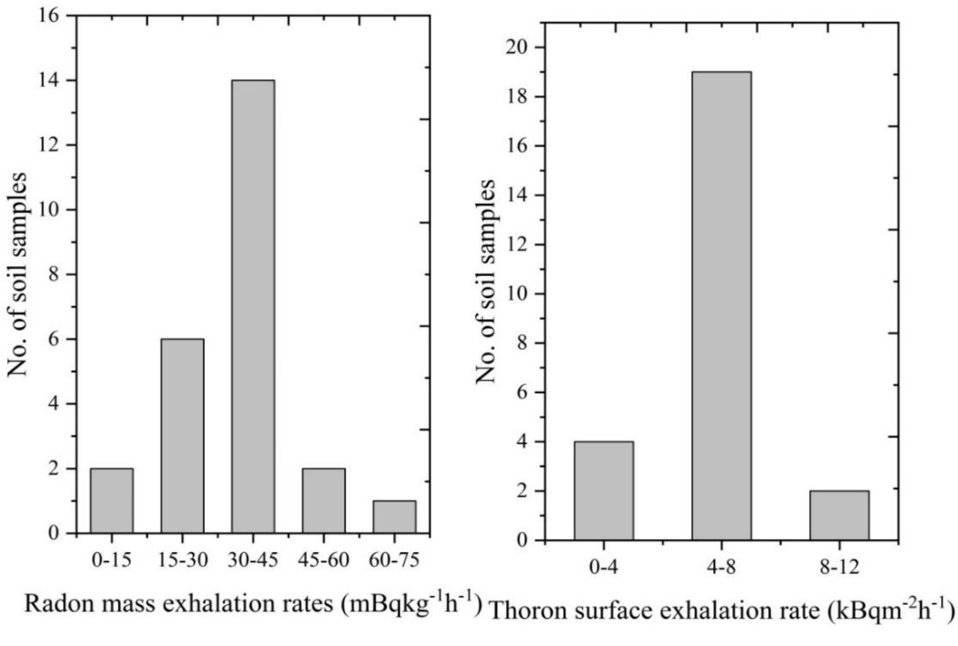

Figure 5.2: Frequency distribution for radon mass/thoron surface exhalation in soil samples of Hanumangarh district

In Sri Ganganagar district, total 25 soil samples have been collected from 25 different villages at the depth of about 20 cm below the soil surface to get fresh sample to avoid the atmospheric deposition. The radon mass exhalation rate has been found to vary from 1.56 ± 0.46 to 43.82 ± 2.20 $mBqKg^{-1}h^{-1}$ with an average value of 26.23 ± 1 $mBqKg^{-1}h^{-1}$ and thoron surface exhalation rate varies from and the thoron surface exhalation rates varies from 2.01 ± 0.31 to 6.66 ± 0.5 $kBqm^{-2}h^{-1}$ with an average of 4.54 ± 0.43 $kBqm^{-2}h^{-1}$ as shown in Table 5.1. The frequency distribution shows that the radon mass exhalation rate for 8% soil samples (2) lie between 0-15 $mBqKg^{-1}h^{-1}$, for 24% soil samples (6) lie between 15-30 $mBqKg^{-1}h^{-1}$, for 56% soil samples (14) lie between 30-45 $mBqKg^{-1}h^{-1}$ and for the rest of 12% soil samples (3) lie between 60-75 $mBqKg^{-1}h^{-1}$ as shown in Figure 5.3. The frequency distribution shows that the thoron surface exhalation rate for 8% soil samples (4) lie between 0-3 $kBqm^{-2}h^{-1}$, for 88% soil samples (19) lie between 3-6 $kBqm^{-2}h^{-1}$ and for 4% soil samples (2) lie between 6-9 $kBqm^{-2}h^{-1}$ as shown in Figure5.3. These values are lower than the worldwide average value of 57 $mBqKg^{-1}h^{-1}$ for radon mass exhalation rate and higher than the worldwide value of 3.6 $kBqm^{-2}h^{-1}$ for thoron surface exhalation rate (UNSCEAR, 2000).

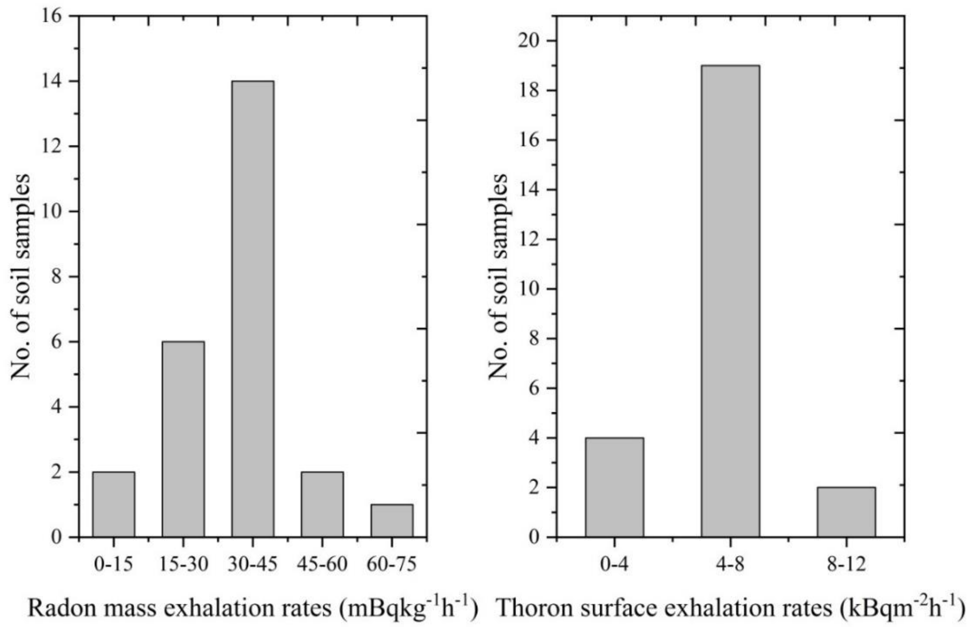

Figure 5.3: Frequency distribution for radon mass/thoron surface exhalation in soil samples of Sri Ganganagar district

In Churu district, total 20 soil samples have been collected from 20 different villages at the depth of about 20 cm below the soil surface to get fresh sample to avoid the atmospheric deposition. The radon mass exhalation rate has been found to vary from 12.06 ± 0.27 to 37.83 ± 0.94 $mBqKg^{-1}h^{-1}$ with an average value of 22.23 ± 0.65 $mBqKg^{-1}h^{-1}$ and the thoron surface exhalation rate varies from 0.03 ± 0.01 to 7.32 ± 0.08 $kBqm^{-2}h^{-1}$ with an average of 3.53 ± 0.04 $kBqm^{-2}h^{-1}$ as shown in table 5.1. The frequency distribution shows that the radon mass exhalation rate for 25% soil samples (4) lie between 0- 15 $mBqKg^{-1}h^{-1}$, for 70% soil samples (14) lie between 15-30 $mBqKg^{-1}h^{-1}$, for 5% soil samples (2) lie between 30-45 $mBqKg^{-1}h^{-1}$ as shown in Fig 5.4. The frequency distribution shows that the thoron surface exhalation rate for 10% soil samples (4) lie between 0-3 $kBqm^{-2}h^{-1}$, for 65% soil samples (11) lie between 3-6 $kBqm^{-2}h^{-1}$ and for 25% soil samples (5) lie between 6-9 $kBqm^{-2}h^{-1}$ as shown in Figure 5.4. These values are lower than the worldwide average value of 57 $mBqKg^{-1}h^{-1}$ for radon mass exhalation rate and higher than the worldwide value of 3.6 $kBqm^{-2}h^{-1}$ for thoron surface exhalation rate (UNSCEAR, 2000).

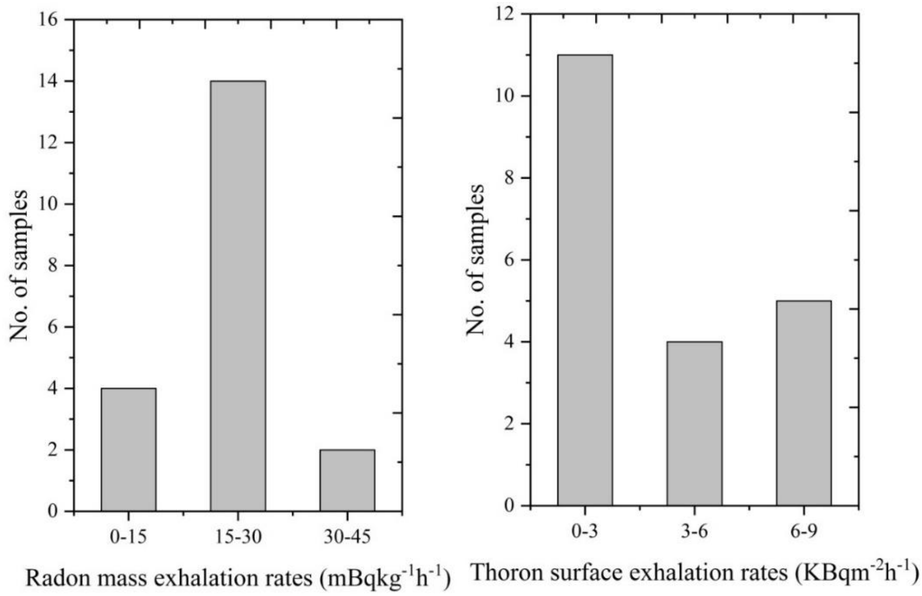

Figure 5.4: Frequency distribution for radon mass/thoron surface exhalation in soil samples of Churu district

5.4.1 CORRELATION BETWEEN INDOOR RADON/THORON CONCENTRATION WITH RADON/THORON EXHALATION RATES

In Hanumangarh district, analysis was done to find out the correlation between radon exhalation rates and indoor radon concentration. Figure 5.5a shows the linear fit having

R^2 value of 0.027 and Pearson's r value (which quantifies linear dependency) of -0.17, indicating very weak connection between the two quantities. Also, the analysis was done to study the correlation between thoron exhalation rates and indoor thoron concentration. Figure 5.5b shows that the linear fit having R^2 value of 0.006 and Pearson's r value (which quantifies linear dependency) of -0.002, indicating very weak connection between the two quantities.

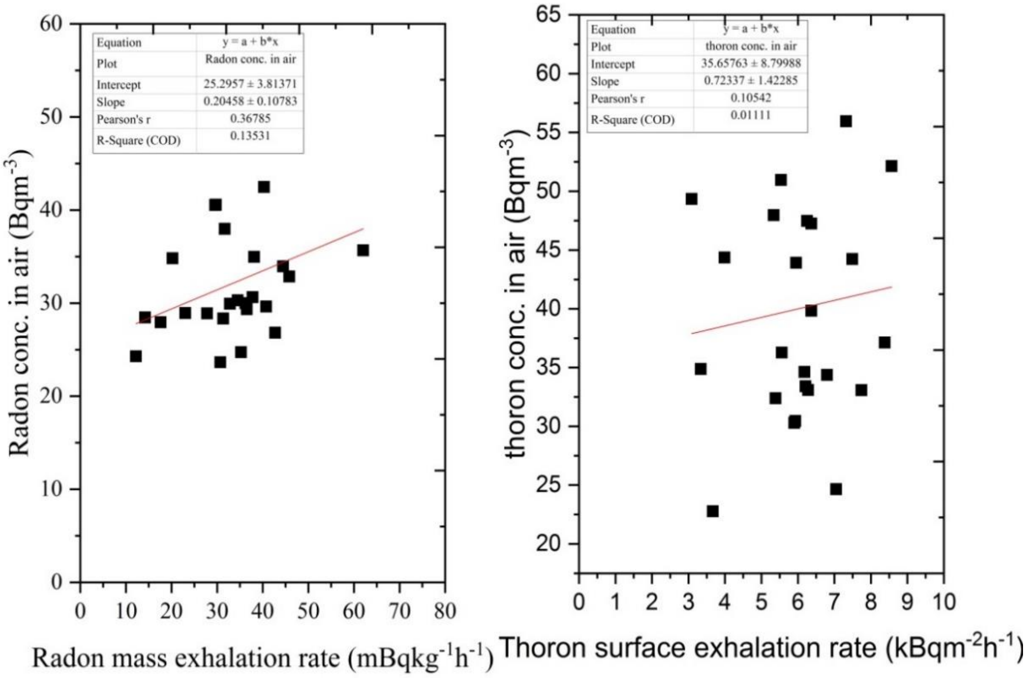

Figure 5.5: Correlation between a) radon concentration in indoor dwellings with radon mass exhalation rates in soil samples b) thoron concentration in indoor dwellings with thoron surface exhalation rates in soil samples in Hanumangarh district

In Sri Ganganagar district, Analysis was done to find out the correlation between radon exhalation rates and indoor radon concentration. Figure 5.6a shows the linear fit having R^2 value of 0.064 and Pearson's r value (which quantifies linear dependency) of -0.25, indicating very weak connection between the two quantities. Also, the analysis was done to study the correlation between thoron exhalation rates and indoor thoron concentration. Figure 5.6b shows that the linear fit having R^2 value of 0.018 and Pearson's r value (which quantifies linear dependency) of 0.13, indicating weak connection between the two quantities.

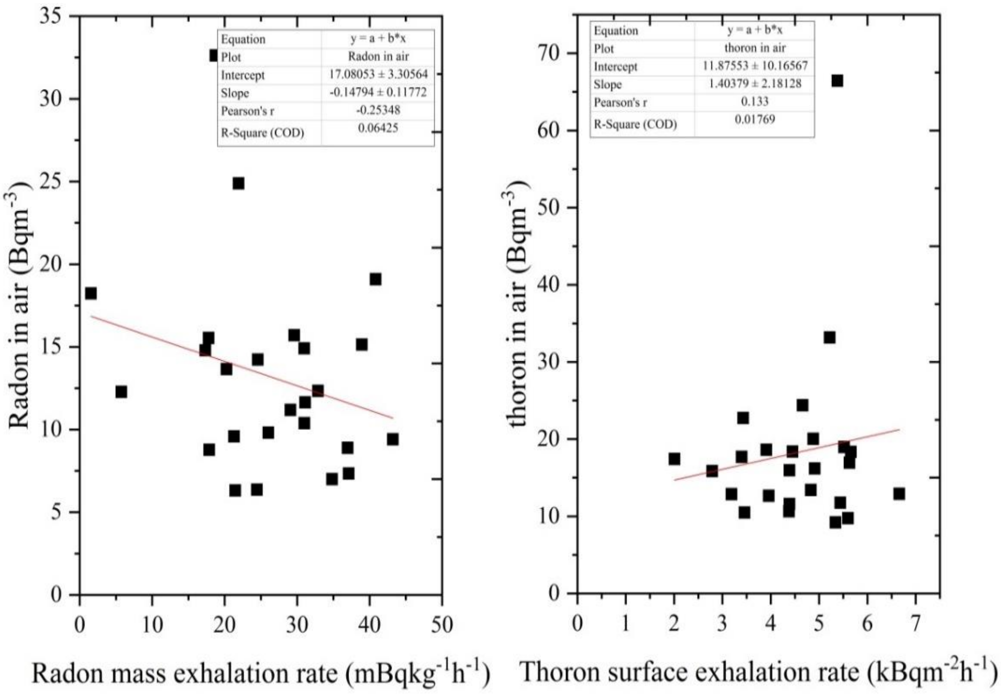

Figure 5.6: Correlation between a) radon concentration in indoor dwellings with radon mass exhalation rates in soil samples b) thoron concentration in indoor dwellings with thoron surface exhalation rates in soil samples in Sri Ganganagar district

In Churu district, Analysis was done to find out the correlation between radon exhalation rates and indoor radon concentration. Figure 5.7a shows the linear fit having R^2 value of 0.03 and Pearson's r value (which quantifies linear dependency) of 0.175, indicating weak connection between the two quantities. Also, the analysis was done to study the correlation between thoron exhalation rates and indoor thoron concentration. Figure 5.7b shows that the linear fit having R^2 value of 0.01 and Pearson's r value (which quantifies linear dependency) of 0.1, indicating weak connection between the two quantities.

The weak correlation between radon/thoron exhalation rates and indoor radon/thoron concentration in all the three districts may be due to the reason for the same may be that the soil may not be contributing to the concentration of radon/thoron in air and most of the time building materials may be more responsible for the concentration of radon in air.

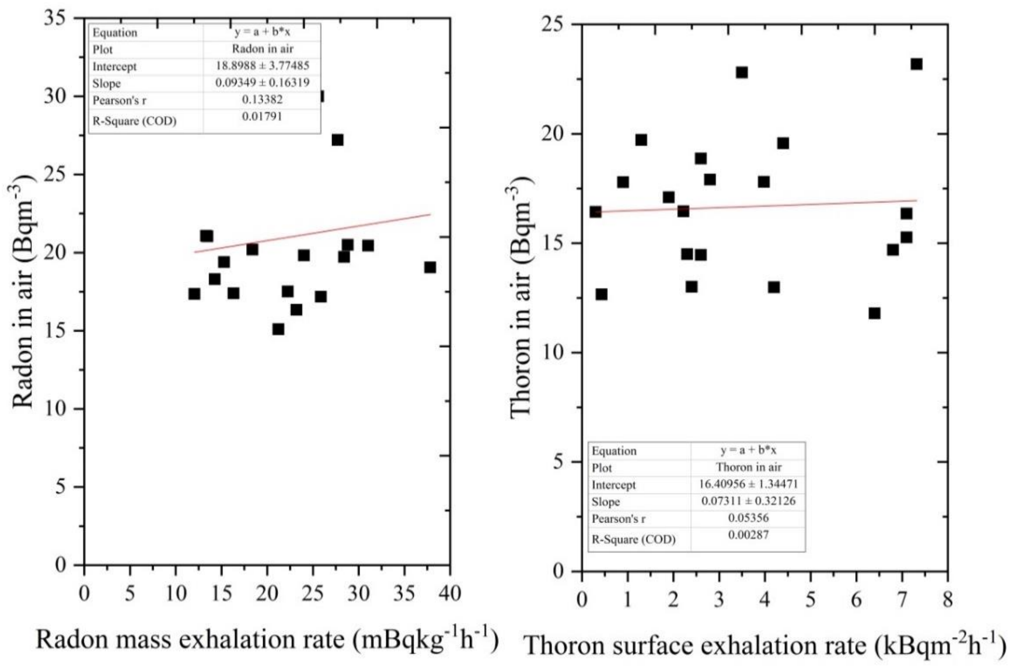

Figure 5.7: Correlation between a) radon concentration in indoor dwellings with radon mass exhalation rates in soil samples b) thoron concentration in indoor dwellings with thoron surface exhalation rates in soil samples in Churu district

The radon mass exhalation rates in soil samples have lower values than 57 $mBqkg^{-1}h^{-1}$ and thoron surface exhalation rates were higher than 3.6 $kBqm^{-2}h^{-1}$ as recommended by UNSCEAR (2000), respectively in all the three districts of Northern Rajasthan. The high level of thoron concentration and surface exhalation rate may be attributed to appreciably large thorium contents in this soil samples. It is in close agreement with the results of the higher thorium in the northern part of India which was shown in the radiation profile map of India (Prajith et al., 2019; Gussain et al., 2009; Ramchandran et al., 2009).

Comparison with Similar Investigations in Other Areas

The variation in exhalation rates may be due to certain factors like geology of study area, radon emanation factor and porosity of soil samples as reported by BK Sahoo et al., 2007. The outcomes in the study area have been compared with similar investigations performed in the other parts of India as shown in Table 3.3. These are slightly higher than the studied carried out in Tarantaran and Amritsar districts of Punjab (Kaur et al., 2018), Shiwalik Himalayas of Jammu and Kashmir (Kumar et al., 2018). These values are lower than uranium mineralization area Una and Hamirpur districts of Himachal Pradesh (Bala P et al., 2017), Aravali Hills (Chauhan 2014), Hemavathi river environment in Karnataka (Karthik et al., 2018), Cauvery river sediments (Kaliparshad et al., 2018), plain area Faridabad, Haryana (Singh et al., 2020), worldwide average value of 57 $mBqkg^{-1}$ h^{-1} (UNSCEAR, 2000).

The variation in exhalation of thoron due to topography and geological conditions of soil sample location. Accordingly, by and large consequences of more significant level of thoron is in close concurrence with the after effects of higher Th-232 in the northern part of India was appeared in radiation profile guide of India, because of higher thorium content in rocks since development of earth. The results of present study are comparable with the outcomes of investigations performed in other regions of India listed here. The thoron surface exhalation rates are higher than Taran Taran and Amritsar districts of Punjab (Kaur et al., 2018), Himalayas of Jammu and Kashmir (Kumar et al., 2018), Shiwalik Himalayas of Jammu and Kashmir (Kaur et al., 2018), Kalpakkam, Tamilnadu (Sunder et al., 2015), Bengaluru (Karthik et al., 2015) and worldwide average value of 5700 $Bqm^{-2}h^{-1}$ (UNSCEAR, 2000).

5.5 CONCLUSION

- Out of 70 samples, the radon exhalation rate in 1 sample (1.4%) has higher value (62.03 $mBqkg^{-1}h^{-1}$) and rest of samples have lower value than the world average value of 57 $mBqkg^{-1}h^{-1}$ (UNSCEAR, 2008).
- Out of 70 samples, the thoron exhalation rates in 51 soil samples (72.8%) have higher values (3.67 to 8.57 $kBqm^{-2}h^{-1}$) and rest of samples have lower values than recommended value of 3.60 $kBqm^{-2}h^{-1}$ (UNSCEAR, 2008).
- The variation in the exhalation rates may be because of varied geological locations of soil samples, topography, radon emanation factor and soil porosity.
- The higher thoron surface exhalation rates may be because of higher thorium rich contents in rocks in the Northern portion of India (Ramchandran et al., 2009; Prajith et al., 2019; Gusain et al., 2009).
- Weak correlation has been observed between radon mass/thoron surface exhalation rates with the indoor radon/thoron concentration. The reason for the

same may be that the soil may not be contributing to the concentration of radon/thoron in air and most of the time building materials may be more responsible for the concentration of radon in air. Hence, soil is suitable for construction of building materials.

- The areas where exhalation rates are higher may be explored further for radiological health effects to the residents of the area.
- The study will contribute towards the national pool for mapping and for further studies.

Table 5.1: Radon mass and thoron surface exhalation rates of soil samples in the studied area

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
Hanumangarh district						
1	Hanumangarh. Junction	74˚18’08.13” 29˚36’40.90”	165	0.121	30.72 ± 2.06	7.05 ± 0.55
2	Phephana	74˚54’58.94” 29˚20’00.11”	164	0.164	12.23 ± 1.62	6.18 ± 0.51
3	Padampura	74˚55’36.45” 29˚17’57.09”	163	0.175	32.83 ± 1.19	7.49 ± 0.59
4	Janania	74˚56’52.64” 29˚20’09.99”	171	0.116	36.23 ± 2.10	8.38 ± .62
5	Jandawali	74˚13’11.33” 29˚38’39.66”	170	0.138	40.76 ± 1.80	6.21 ± 0.56
6	Dabli Rathan	74˚11’27.56” 29˚32’54.03”	162	0.164	36.53 ± 1.12	5.95 ± 0.49
7	Sangria	74˚27’52.64” 29˚48’17.74”	165	0.157	29.59 ± 0.67	5.56 ± 0.48

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
8	Pirkamria	74°28’06.69” 29°36’17.76”	160	0.158	40.30 ± 1.64	7.74 ± 0.55
9	Dhaba	74°30’36.14” 29°52’35.15”	178	0.165	38.14 ± 1.99	5.34 ± 0.47
10	Bhagat Pura	74°27’14.68” 29°50’56.12”	169	0.172	42.73 ± 0.89	5.39 ± 0.46
11	Nagrana	74°25’29.39” 29°39’44.14”	166	0.110	62.03 ± 1.57	5.93 ± 0.50
12	Goluwala	74°07’22.19” 29°37’49.84”	167	0.171	46.05 ± 1	6.25 ± 0.52
13	Tibbi	74°30’07.41” 29°33’13.06”	166	0.123	29.75 ± 1.32	3.99 ± 0.41
14	Panniwala	74°25’50.47” 29°36’26.14”	175	0.124	45.84 ± 1.42	8.57 ± 0.58

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
15	Kharliya	73°59’47.54” 29°33’39.30”	169	0.138	44.48 ± 3.49	6 ± 0.21
16	Hansliya	74°02’39.49” 29°34’29.17”	164	0.78	37.81 ± 1.05	6.8 ± 0.53
17	25 DWD	74°19’41.40” 29°15’53.70”	169	0.174	20.25 ± 1.06	5.54 ± 0.49
18	Rawatsar	74°24’31.98” 29°15’51.57”	167	0.135	14.24 ± 0.62	3.34 ± 0.39
19	Hanumangarh. Town	74°53’60.13” 29°32’33.09”	175	0.161	27.80 ± 0.83	7.32 ± 0.53
20	Dholpalia	75°11’17.37” 29°02’51.45”	181	0.164	31.67 ± 0.91	6.37 ± 0.55
21	Bhadra	75°11’17.37” 29°06’57.24”	183	0.134	23.04 ± 0.78	3.09 ± 0.43

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
22	2 KBM	74°22'22.61" 29°15'02.06"	188	0.132	17.62 ± 0.90	3.67 ± 0.41
23	Jodkiyan	74°17'07.91" 29°39'30.05"	179	0.146	35.25 ± 1.46	6.28 ± 0.51
24	Jogiwala	75°16'21.07" 29°06'25.92"	167	0.144	34.54 ± 1.78	6.37 ± 0.51
25	Pillibanga	74°04'41.14" 29°39'09.41"	162	0.168	31.34 ± 0.88	5.9 ± 0.5
Sri Ganganagar district						
1	Jorawar	73°26'58.62" 29°41'36.75"	166	0.14	29.62 ± 0.80	5.52 ± 0.47
2	Roopnagar	73°29'03.51" 29°46'19.37"	168	0.159	17.81 ± 0.77	3.46 ± 0.39
3	Fojuwala	73°26'45.01" 29°34'46.32"	166	0.185	38.93 ± 2.07	4.66 ± 0.44

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
4	Sri Ganganagar	73°51'34.78" 29°54'52.79"	178	0.157	26.05 ± 0.46	3.96 ± 0.41
5	Ghumudwali	73°46'07.34" 29°40'40.33"	164	0.139	29.08 ± 1.06	3.19 ± 0.37
6	Gajsinghpur	73°26'15.27" 29°39'27.82"	169	0.111	43.22 ± 1.36	6.66 ± 0.50
7	70RB	73°26'34.74" 29°36'11.86"	166	0.164	37.12 ± 2.20	5.6 ± 0.49
8	Sawatsar	74°32'28.16" 29°23'01.12"	161	0.135	36.97 ± 0.80	2.01 ± 0.31
9	Sadulshehar	74°09'51.87" 29°54'14.43"	183	0.183	5.75 ± 0.68	5.34 ± 0.47
10	Khaliwala	74°55'48.06" 29°53'02.53"	178	0.183	18.74 ± 0.53	4.91 ± 0.44

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
11	Smeecha Kothi	74°41' 21.29" 29°13'03.21"	166	0.107	24.45 ± 1.20	3.91 ± 0.41
12	Lakhiyan	73°27'30.31" 29°50'12.13"	166	0.181	30.98 ± 0.84	5.44 ± 0.48
13	Rattewala	73°15'32.41" 29°62'42.23"	162	0.125	17.35 ± 0.79	2.79 ± 0.34
14	Sadhawali	73°54'34.71" 29°53'18.21"	178	0.174	24.58 ± 0.69	4.38 ± 0.43
15	Nathewala	73°52'31.30" 29°50'09.18"	167	0.164	20.26 ± 0.99	4.39 ± .7
16	58 F	73°27'73.27" 29°49'13.25"	168	0.98	17.88 ± 0.85	3.4 ± 0.37
17	Gulabewala	74°32'42.87" 29°45'54.43"	168	0.188	34.82 ± 1.21	5.66 ± 0.49

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
18	Kalwasia	74°53’35.02” 29°46’13.16”	183	0.121	21.30 ± 0.60	4.45 ± 0.43
19	Karanpur	73°27’29.41” 29°50’14.15”	185	0.162	32.88 ± 0.80	5.63 ± 0.47
20	Raisinghnagar	73°26’51.93” 29°31’30.20”	160	0.212	40.83 ± 0.81	5.38 ± 0.48
21	Banda Colony	74°13’33.94” 29°16’16.96”	156	0.139	21.93 ± 1.45	3.43 ± 0.37
22	Gharsana	74°04’18.49” 29°01’14.97”	152	0.158	1.56 ± 0.71	4.39 ± 0.43
23	Anoopgarh	73°12’19.06” 29°10’35.85”	155	0.148	31.11 ± 1.22	4.83 ± 0.49
24	Binjwala	73°47’12.19” 29°39’26.07”	167	0.143	21.48 ± 1.10	4.88 ± 0.48

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
25	47F	73°28'99.03" 29°48'12.63"	169	0.178	31.00 ± 0.90	5.22 ± 0.48
Churu district						
1	Sardarshehar	74°31'12.87" 28°29'50.29"	237	0.184	21.23 ± 0.68	0.3± 0.01
2	Jasrasar	74°41'01.07" 27°55'37.45"	313	0.178	13.32 ± 0.53	0.43 ± 0.01
3	Malsar	74°22'39.35" 28°35'08.06"	221	135	25.12 ± 0.72	0.9 ± 0.03
4	Salasar	74°43'07.00" 27°43'51.17"	320	0.112	24.03 ± 0.69	2.3 ± 0.02
5	Asalrsar	74 34'28.90" 28°19'39.56"	269	0.173	18.35 ± 0.58	1.3 ± 0.02
6	Churu	74°59'36.00" 28°17'01.17"	294	0.187	28.41 ± 0.84	2.4 ± 0.04

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
7	Ratangarh	74°58'03.05" 28°12'40.05"	297	0.168	31.04 ± 0.89	7.1 ± 0.12
8	Motisar	75°07'39.98" 28°24'69.87"	279	0.136	27.72 ± 0.78	4.2 ± 0.03
9	Dhadar	75°03'20.80" 28°19'46.97"	285	0.178	12.05 ± 0.48	6.4 ± 0.07
10	Bhojrasar	74°26'21.67" 28°32'59.70"	219	0.12	15.30 ± 0.49	3.5 ± 0.03
11	Bhanipur	74°22'21.07" 28°37'29.30"	207	0.143	14.28 ± 0.37	2.6 ± 0.03
12	Aspalsar	74°28'29.66" 28°32'53.51"	237	0.161	23.20 ± 0.82	1.9 ± 0.01
13	Bhaghsar Purvi	74°44'57.49" 28°46'13.86"	334	0.163	16.33 ± 0.47	2.8 ± 0.08

Sample No.	Village	Geographical coordinates	Elevation (metres)	Gamma Level (μRh^{-1})	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
14	Gudawadi	74˚43’27.27” 27˚44’55.37”	327	0.108	25.57 ± 0.77	6.8 ± .06
15	Nakrasar	74˚24’39.03” 28˚34’00.81”	222	0.133	22.26 ± 0.65	7.32 ± 0.06
16	Sujangarh	74˚52’31.19” 27˚52’39.92”	325	0.169	13.48 ± 0.62	2.22 ± 0.03
17	Rajgarh	75˚21’28.17” 28˚38’09.91”	234	0.132	28.82 ± 0.86	3.98 ± 0.03
18	Shobasar	74˚48’22.83” 28˚45’33.01”	325	0.161	18.39 ± 0.51	4.4 ± 0.05
19	loonch	74˚39’43.12” 27˚46’13.16”	318	0.108	25.88 ± 0.27	2.6 ± 0.03
20	Sawar	74˚32’11.60” 28˚22’47.95”	269	0.151	37.83 ± 0.94	7.1 ± 0.07

Table 5.2: Descriptive statistics of radon mass and thoron surface exhalation rates

S. No.	Statistics	Radon mass exhalation rate (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rate (J_{TS}) ($kBqm^{-2}h^{-1}$) ± σ
Hanumangarh District			
1.	Minimum	12.23 ± 0.62	3.34 ± 0.39
2.	Maximum	62.03 ± 3.49	8.57 ± 0.62
3.	Average	33.67 ± 1.37	6.07 ± 0.62
4.	Kurtosis	0.28 ± 2.66	0.059 ± -0.103
5.	Skewness	-0.52 ± 1.59	0.245 ± -0.20
Sri Ganganagar			
1.	Minimum	1.56 ± 0.46	2.01 ± 0.31
2.	Maximum	43.22 ± 2.20	6.66 ± 0.5
3.	Average	26.23 ± 1.00	4.54 ± 0.43
4.	Kurtosis	0.29 ± 2.72	0 ± -1.37
5.	Skewness	0.53 ± 1.62	-0.43 ± -0.67
Churu			
1.	Minimum	12.05 ± 0.27	0.03 ± 0.01
2.	Maximum	37.83 ± 0.94	7.32 ± 0.08
3.	Average	22.13 ± 0.65	3.53 ± 0.04
4.	Kurtosis	-0.32 ± -0.67	-1 ± -0.54
5.	Skewness	0.35 ± -0.28	0.48 ± 0.67

Table 5.3: Comparison of radon mass and thoron surface exhalation rates with similar investigations in other areas

S. No.	Place	Radon mass exhalation rates (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ	Thoron surface exhalation rates (J_{TS}) ($Bqm^{-2}s^{-1}$) ± σ	Reference
1.	Tarn Taran	23 ± 5	1531 ± 1503	Kaur et al., 2018
2.	Amritsar	20 ± 7	664 ± 237	Kaur et al., 2018
3.	Jammu and Kashmir	8 ± 1 to 62 ± 3	295 to 3628	Kumar et al., 2018
4.	Shiwalik Himalayas of Jammu and Kashmir	7 to 48	123 to 2606	Kaur et al., 2018
5.	Haryana and Delhi	6 to 10	-	Chauhan and Chakarvarti, 2012
6.	Aravali hills	23 to 50 with average of 35	-	Chauhan, 2014
7.	Una and Hamirpur Himachal Pradesh	39 to 91 with average of 60	-	Bala et al., 2017
8.	Hemavathi river in Karnataka	67± 12 to 547 ± 34	-	Karthik et al., 2018
9.	Cauvery river sediments	45 to 333	-	Kaliparshad et al., 2018
10.	Faridabad, Haryana	12 ± 1 to 62 ± 4 with average of 31 ± 12		Bhupinder et al., 2020
11.	Banguluru	-	4737 to 10,886	Karthik et al., 2015
12.	Kalpakkam, Tamilnadu	-	942 to 7720	Sunder et al., 2015

S. No.	**Place**	**Radon mass exhalation rates (J_{Rm}) ($mBqkg^{-1}h^{-1}$) ± σ**	**Thoron surface exhalation rates (J_{TS}) ($Bqm^{-2}s^{-1}$) ± σ**	**Reference**
13.	**Hanumangarh district**	12.23 ± 0.62 to 62.03 ± 3.49 with average of 33.67 ± 1.37	3.34 ± 0.39 to 8.57 ± 0.62 with average of 6.07 ± 0.62	Present study
14.	**Sri Ganganagar district**	1.56 ± 0.46 to 43.22 ± 2.2 with average of 26.23 ± 1	2.01 ± 0.31 to 6.66 ± 0.5 with average of 4.54 ± 0.43	
15.	**Churu district**	12.05 ± 0.51 to 37.83 ± 0.16 with average of 22.13 ± 0.12	0.03 ± 0.01 to 7.32 ± 0.08 with average of 3.53 ± 0.04	

SUMMARY OF CONCLUSION

Indoor radon/thoron, their progeny concentration and attached/unattached fractions:

In the studied area, out of 275 dwellings, 12 dwellings (4.36%) having higher indoor annual average radon concentration (40.22 to 99.86 Bqm^{-3}) than the recommended value of 40 Bqm^{-3} (UNSCEAR, 2008). 99% of dwellings having higher indoor annual average thoron concentration (10.65 to 100 Bqm^{-3}) than the world average value of 10 Bqm^{-3} (UNSCEAR, 2008). The concentration of thoron gas is higher in most of dwellings, this presumably due to use of thorium rich materials in construction of dwellings of this area. 4.36 % dwellings having higher indoor annual average radon progeny concentration (15.42 to 21.4 Bqm^{-3}) than the world average recommended value of 15 Bqm^{-3}, while 201 dwellings (73%) having higher indoor annual average thoron progeny concentration (0.5 to 8.7 Bqm^{-3}) than the world's average value of 0.5 Bqm^{-3} (UNSCEAR, 2008).The measured average values for indoor radon, thoron and their progeny concentration in the studied area is higher in winter season as compared to rainy and summer season which may be because of the poor ventilation conditions in winter due to less exchange of gases between indoor and outdoor environments, thereby leading to accumulation of radon gas during winters. The poor ventilation dwellings have higher concentration than the average and well ventilated dwellings. The calculated annual average equilibrium factor between radon and its progeny was 0.4 and for thoron and its progeny was 0.02, which are comparable to the values as recommended by UNSCEAR (2008). The annual average effective dose for inhalation lies below than recommended value of 14 μSvy^{-1} for the residential places (ICRP, 2018). The concentration of indoor radon/thoron in some areas like Pillibanga, Jandawali, Sangria, Bhagatpura, Dhaba, Kharliya, Bhadra, Rawatsar, and Panniwala of Hanumangarh District and Ratangarh of Churu District of Rajasthan with higher values may be explored further for radiological health effects to the residents of the area.

Radon in water:

The average concentration of radon in all the water samples have lower concentration than recommended value of 11 BqL^{-1} by USEPA (1991), 100 BqL^{-1} by WHO (2004) and 4-40 BqL^{-1} recommended by UNSCEAR (2008). The annual effective dose for various age groups like infants, children and adults lies below the safe 100 μSvy^{-1}

recommended by WHO (2008). For a given concentration of radon in drinking water, the dose was highest in case of infants and followed a decreasing trend with age. The concentration of radon in underground water have higher value than concentration in surface water which may be because of presence of granite, sands, gravel in the bedrock (Stojkovic et al., 2015) and also for the reason that underground water directly encounters U-238 rich rocks that releases radon in water and cannot escape to atmosphere, whereas in contrast radon in surface water samples can easily escape to atmosphere due to aeration and agitation in water (Voronov A.N. et al. 2004; Skeppstorm et al. 2007). Hence the water in the studied area is safe for drinking purposes from the radiological risk point of view.

Radon/thoron exhalation rates in soil:

Out of 70 samples, the radon exhalation rate in 1 sample has value (62.03 $mBqkg^{-1}h^{-1}$) higher than world average value of 57 $mBqkg^{-1}h^{-1}$ (UNSCEAR, 2008), and the thoron exhalation rates in 51 soil samples (72.8%) have values (3.67 to 8.57 $kBqm^{-2}h^{-1}$) higher than recommended value of 3.60 $kBqm^{-2}h^{-1}$ (UNSCEAR, 2008) in all the three districts. The variation in the exhalation rates may be because of varied geological locations of soil samples, topography, radon emanation factor and soil porosity. The higher thoron surface exhalation rates may be because of higher thorium rich contents in rocks in the Northern portion of India (Ramchandran TV et al., 2009; Prajith R et al., 2019; Gusain et al., 2009). Weak correlation has been observed between radon mass/thoron surface exhalation rates with the indoor radon/thoron concentration. The reason for the same may be that the soil may not be contributing to the concentration of radon/thoron in air and most of the time building materials may be more responsible for the concentration of radon in air. Hence, soil is suitable for construction of building materials.

The overall conclusion of this study is that in most of the studied area, the values have been found to be within the permissible recommended levels and hence may not pose any radiological health risk to the local population. The available data will further contribute for the radon mapping of the country and for carrying out further studies in the areas, where values have been found to be on higher side for radiation related risk assessment.

SCOPE OF FUTURE WORK

Future studies can be carried out in the areas where thoron and radon levels are high for associated health effects to the residents of the area. A diurnal and seasonal measurement of radon activities in groundwater and soil gas through online monitoring devices is essential in predicting earthquakes. Although the study lies in the low risk zone area that is Zone-4, but still for the prediction of earthquakes, radon geo-station may be established in this area. Countries like China, India, Japan, Russia, Turkey and the United States are located on plate boundaries of the earth and several such projects are going on in these countries.