CHAPTER 4

RADON/THORON EXHALATION RATES IN SOIL AND ITS CORRELATION WITH THEIR CONCENTRATION IN THE DWELLINGS

In this chapter, Radon mass exhalation and thoron surface exhalation rates have been measured in the studied area using Smart RnDuo indigenously developed by BARC, Mumbai. Further, correlation of radon/thoron exhalation rates with indoor radon/thoron concentration has also been discussed. The detailed introduction about the topic, measurement procedure, formulae used for calculations, results and discussion and conclusion have been discussed in this following section.

4.1 INTRODUCTION

Soil exhalation rates are important input parameters to estimate radon concentration in the atmosphere and indoor environment. Radon and thoron gases emerge from rocks and soil containing uranium and thorium and which are further concentrated in the confined spaces like underground mines or houses. Radon reaches the indoor atmosphere from the soil and building material by exhalation from the matrix and emanation from material (Figure 4.1) (Sahoo et al., 2011). The process of radon gas escaping from the grains of solid mineral to the air-filled pores is known as emanation, while the process of transfer of radon gas to atmosphere from air filled pores is called exhalation. Exhalation rate of soil basically depends upon various parameters like radium content in soil, diffusion coefficient of radon in the soil matrix, dry bulk density and porosity in matrix of soil, factor of radon emanation and its decay constant, along with this various external factor like rainfall, snowfall, expansion in pressure and temperature which can also impact the diffusivity (UNSCEAR, 2000; WHO, 2009).

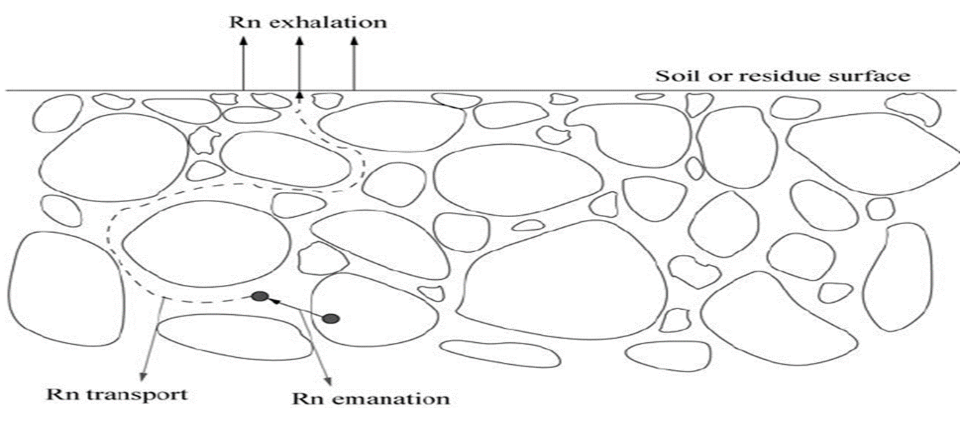

Figure 4.1: Process of release of radon gas to atmosphere from the soil (Ishmori et al., 2013)

In dry soil matrix the pores are filled with air only, while in the soil pores containing moisture, the radon atoms are partially distributed in air and water in the proportion to the water/air (partition coefficient of radon). The radon and thoron concentration in rocks or soil present around the dwellings is 10^3 to 10^4 times higher than indoor air (Jakhu et al., 2017). Radon enters buildings through cracks in the floors or at floor-wall junctions, gaps around pipes or cables, small pores in hollow block walls, cavity walls. Radon levels are usually higher in basements and living spaces in contact with the ground (Sahoo et al., 2007). The huge fraction of radon and thoron in the indoor atmosphere comes from the structural materials used in the construction of residential buildings (UNSCEAR, 2000).

For estimation of radon exhalation flux from soil and building materials, diffusion based analytical models have been broadly used by researchers (Mayya et al., 1998; Antonopoulos et al., 1998; Keller et al., 2001; Chen et al., 2010; Hassan et al., 2010). The radon in soil which escapes into the outdoor atmosphere have enough risk potential to the human health since it is exceptionally diluted by outdoor air (Deborah et al., 2020). The inhalation of attached radioactive radon and its progeny to the aerosols present in atmosphere poses greater radiological risk towards human lungs (Tanner et al., 1980; Kumar and Kaur 2014). While breathing, air containing radon/thoron enters the lungs and decays into their respective progeny (Po-214, Po-212 respectively) by emitting alpha radiations, these progenies may adhere to alveoli and may expose cells of the bronchial and pulmonary epithelium in the lungs to the radiation there by damaging the cells, DNA and perhaps causing lung cancer (ICRP, 2011; Chauhan et al., 2016). Pooled studies in Europe (Darby et al., 2005), North America (Krewski et al., 2005) and China (Lubin et al., 1995; 1997) have confirmed that even low concentrations of radon such as those commonly found in residential settings also pose health risks and contribute to the occurrence of lung cancers worldwide. Lung cancer risk rises 16% per 100 Bqm^{-3} increases in long time average radon exposure (Keller et al., 2001). Epidemiological studies have also demonstrated a significant relation between radon levels in homes and leukaemia in the inhabitants. 25% of children and adults of all ages may get affected by leukaemia due to radon at 50 Bqm^{-3} (Richardson et al., 1991). Radon is second driving cause of lung cancer in North America and is the main source of lung cancer for individual who have never smoked (Mehra et al., 2015). As per BEIR report (BEIR 1999), the exposure of radon and its progeny due to their higher activity concentration to the general public leaves long impact on respiratory system and may lead to lung cancer (BEIR (VI) 1999; ATSDR 1999).

Punjab being an agrarian state, soil is used for production of eatables via agriculture along with its use as basic raw materials in bricks for construction work. These bricks mixed with nearly 80% of soil may contain high concentration of natural radionuclide (Fardoas et al., 2007; Bhagotra et al., 2017). Therefore, it is of much importance to find out the exhalation rates of radon/thoron from the soil samples which will be helpful determine if the soil from the studied area can be used for agriculture and construction purpose without posing any radiological health risks. The research plan is to measure the radon mass exhalation rate for assessing the radon exhalation potential and measurement of the thoron surface exhalation rate from the powder samples of the soil and find their correlation with average indoor radon/thoron concentration in the dwellings. Hence this study has been carried out for the first time by following the standard protocol recommended by Bhabha Atomic Research Centre (BARC), Mumbai, India (Sapra et al., 2016).

4.2 METHODOLOGY

4.2.1 Collection of Samples and Lab Work

Total 50 soil samples (each weighing approximately 1000 gm) were collected from Barnala and Moga districts of Punjab based on grid pattern covering the whole of the studied area. Each soil sample is collected at depth of about 20 cm beneath the soil profile to get pure soil sample which is unaffected by atmospheric deposition. The collected samples were squashed by pestle and filtered to maintaining homogeneity. The soil was dried in an oven to remove moisture content. Scintillation based detector, Smart RnDuo has been used for the measurement of radon/thoron exhalation rates. The exhalation chamber with constant volume (540 cm^3) and height (approx 8.5 cm) has been used. It is based on the concept that the diffusion length of soil for radon is about 1 m while for thoron it is about 1 cm. Due to large difference of diffusion length between radon and thoron, it is expected that only top surface of soil will contribute for thoron exhalation while total mass of the sample will be responsible for radon exhalation. Also, the thickness of the soil sample does not affect the magnitude of thoron exhalation as this is a surface phenomenon (Tokonami et al., 2002). Hence, exhalation rates for both radon and thoron will be independent of the geometry of exhalation chamber.

4.3 FORMULAE USED

4.3.1 To Calculate Radon Mass Exhalation Rate (J_{rn})

The retrieved data from the detector was used to draw graph between radon concentration (C) and time (t) and then the slope of graph was measured by using least square fitting method as per equation 1 (Sahoo et al., 2013). From the slope of graph radon mass exhalation rate (J_{rn}) was calculated using equation 2 as given below:

$$C = (\frac{J_{rn}m}{v})t + C_o \quad (1)$$

$$J_{rn} = slope \times \frac{v}{m} \quad (2)$$

Where J_{rn} ($Bqkg^{-1}h^{-1}$) represents the rate of mass exhalation of radon,

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

m is the total mass of the dry soil sample (kg) in the mass exhalation chamber,

t is the time measurement (h),

and v is the effective volume (volume of detector + porous volume of sample ($v_{porus} = v_s - \frac{m}{\rho_g}$) + residual air volume of the mass exhalation chamber) (m^3)

where, ρ_g (2.7 $gm(cc)^{-1}$ for clay type soil sample) is the specific gravity.

4.3.2 To Calculate Thoron Surface Exhalation Rate (J_{th})

The surface exhalation rate for thoron has been calculated by using equation (3) given below (Sapra et al., 2016):

$$J_{th} = \frac{C_t V_t \lambda_\circ}{a} \quad (3)$$

Where, J_{th} represents the surface exhalation rate of thoron in soil sample ($kBqm^{-2}h^{-1}$),

a represents the surface area of the exhalation chamber (m^2),

V_t is the effective volume (m^3) (residual volume of chamber + detector volume + volume of rubber tubes + residual volume of lid used to cover the exhalation chamber),

C_t is the concentration of thoron build up inside the chamber (Bqm^{-3}),

and $\lambda_\circ$ ($0.0126s^{-1}$) is the thoron decay constant.

4.4 RESULTS AND DISCUSSION

4.4.1 Radon Mass/Thoron Surface Exhalation Rates

Table 4.1 shows the calculated values of radon/thoron exhalation rates in soil samples collected from 50 different locations of the Barnala and Moga districts of Punjab. **In Barnala district,** the measured radon mass exhalation rate in the soil samples have been found to vary from 11.48 ± 0.53 $mBqkg^{-1}h^{-1}$ (Mehta) to 39.19 ± 1.21 $mBqkg^{-1}h^{-1}$ (Tapa) with an average value 24.61 ± 1 $mBqkg^{-1}$ h^{-1} and the thoron surface exhalation rates varies from 1.50 ± 0.42 $kBqm^{-2}h^{-1}$ (Aspal Kalan) to 21.83 ± 1.46 $kBqm^{-2}h^{-1}$ (Diwana) with an average value 14.96 ± 1.21 $kBqm^{-2}h^{-1}$.

In Moga district, the measured radon mass exhalation rate in all the soil samples have been found to vary from 4.56 ± 0.53 $mBqkg^{-1}h^{-1}$ (Karyal) to 41.13 ± 1.21 $mBqkg^{-1}h^{-1}$ (Marhi) with an average value 24.97 ± 1 $mBqkg^{-1}h^{-1}$ and the thoron surface exhalation rates varies from 7.25 ± 0.63 $kBqm^{-2}h^{-1}$ (Smalsar) to 23.77 ± 1.52 $kBqm^{-2}h^{-1}$ (Marhi) with an average value 16.29 ± 1.24 $kBqm^{-2}h^{-1}$.

The measured values of radon mass exhalation are found to be lower than 57 $mBqkg^{-1}h^{-1}$ and thoron surface exhalation rates are found to be higher than 3.60 $kBqm^{-2}h^{-1}$ worldwide average values (UNSCEAR, 2000). The higher thoron exhalation rates may be because of the reason that Northern portion of India has higher thorium rich content in rocks since the origin of the world, which has already been revealed in the radiation profile map of India (Mishra 1972; Sankaran et al., 1986). Topography varied geological locations of soil sample, radon emanation factor and soil porosity may all play a role in the broad variance in exhalation rates from place to place (Sahoo et al., 2007; Prajith et al., 2019; Gusain et al., 2009).

From the exhalation rates skewness and kurtosis have been calculated as shown in table 4.1. The distribution of radon exhalation rates in the soil samples show negative skewness from their normal distribution towards left tail whereas for thoron exhalation rates it shows slightly positive skewness from their normal distribution towards right tail. The kurtosis value shows heavily tailed distribution for radon and thoron exhalation rates.

4.4.2 Frequency Distribution

Figure 4.2 shows the frequency distribution graph for radon mass exhalation rates in Barnala and Moga districts that 4% of samples lies between 0-9 $mBqkg^{-1}h^{-1}$, 18% of samples lies between 9-18 $mBqkg^{-1}h^{-1}$, 38% of samples lies between 18-24 $mBqkg^{-1}h^{-1}$ and the remaining 40% of samples lie between 24-45 $mBqkg^{-1}h^{-1}$.

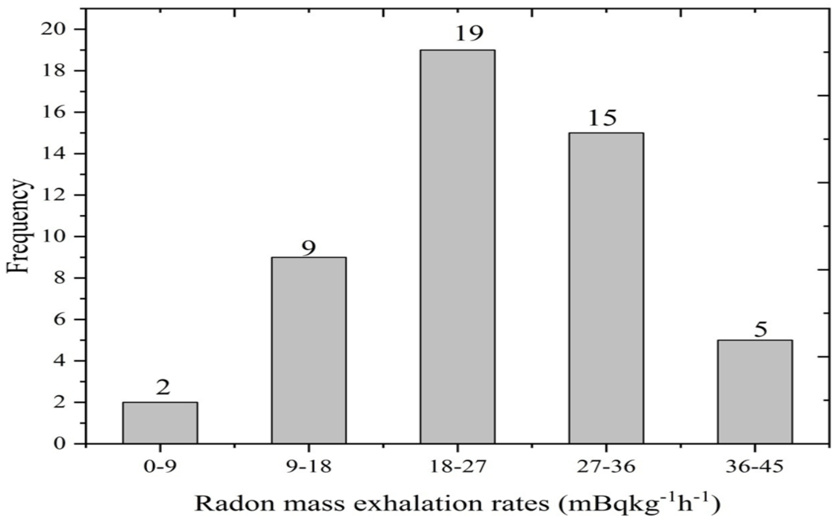

Figure 4.2: Frequency distribution of radon mass exhalation rates in studied area

The frequency distribution graph for thoron surface exhalation rates in Barnala and Moga districts that 4% of samples lies in the range of 0-8 $kBqm^{-2}h^{-1}$, 50% of samples lies from 8-16 $kBqm^{-2}h^{-1}$ and the remaining 46% of samples lies from 16-24 $kBqm^{-2}h^{-1}$ (Figure 4.3). The radon mass exhalation rates have been found to be in positive correlation with the indoor radon activity concentration in dwellings of same area.

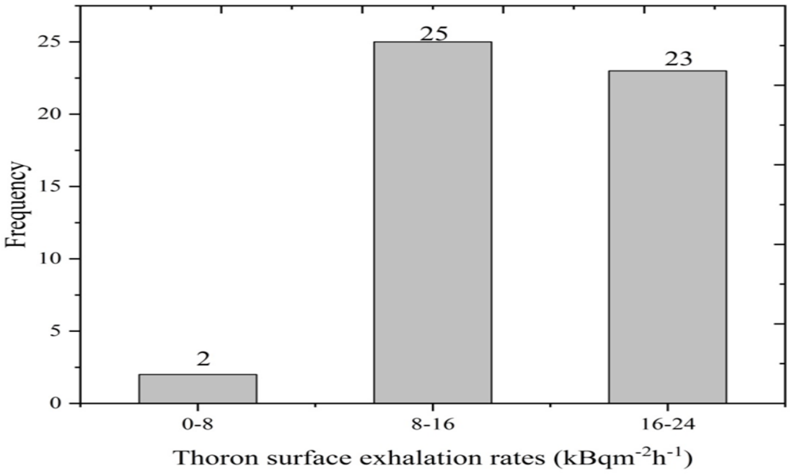

Figure 4.3: Frequency distribution of thoron surface exhalation rates in studied area

4.4.3 Correlation between Radon/Thoron Exhalation Rates with the Radon/Thoron Concentration in the Dwellings

Table 4.2 shows the measured average indoor radon/thoron concentration with respect to exhalation rates in soil samples of the studied area respectively. Analysis was done to find out the correlation between radon exhalation rates and indoor radon concentration. The plot between these two quantities, linear fitting using least square regression is shown in Figure 4.4.

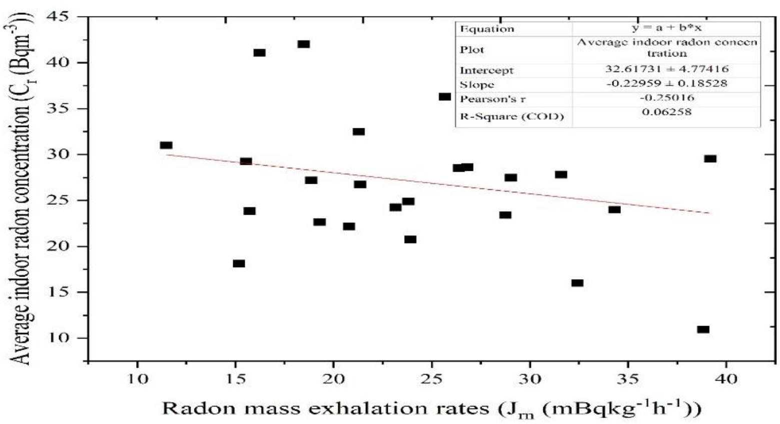

Figure 4.4: Correlation of radon mass exhalation rates with radon concentration in the dwellings of Barnala district

For **Barnala district,** the linear fit having R^2 value of 0.06 and Pearson's r value (which quantifies linear dependency) of -0.25, indicating weak connection between the two quantities.

Also, the analysis was done to study the correlation between thoron exhalation rates and indoor thoron concentration. Same correlation was done between thoron exhalation rates and indoor thoron concentration. Figure 4.5 shows that the linear fit having R^2 value of 0.03 and Pearson's r value (which quantifies linear dependency) of -0.16, indicating very weak connection between the two quantities.

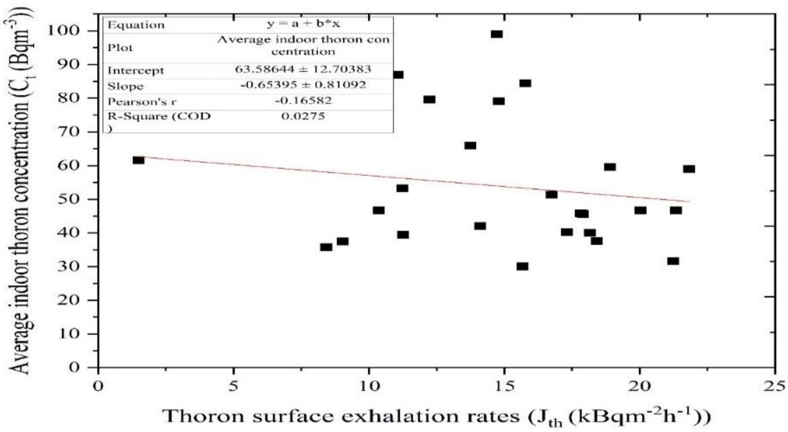

Figure 4.5: Correlation of thoron surface exhalation rates with thoron concentration in the dwellings of Barnala district

For Moga district, (as show in Figure 4.6) the linear fit having R^2 value of 0.23 and Pearson's r value (which quantifies linear dependency) of -0.48, indicating weak connection between the two quantities.

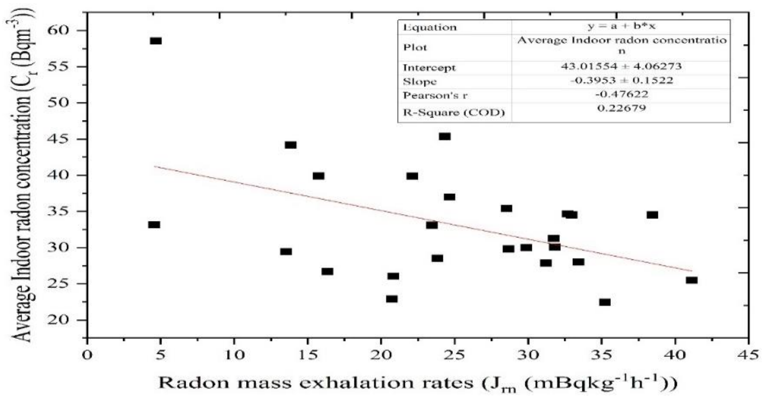

Figure 4.6: Correlation of radon mass exhalation rates with radon concentration in dwellings of Moga district

Also, the analysis was done to study the correlation between thoron exhalation rates and indoor thoron concentration. The plot between these two quantities, linear fitting using least square regression is shown in Figure 4.7. The linear fit having R^2 value of 0.21 and Pearson's r value (which quantifies linear dependency) of -0.46, indicating weak connection between the two quantities. Indoor radon/thoron concentration would not be affected by radon/thoron emitted from the soil surface beneath the concrete dwellings. In this study region, weak correlation was found between indoor radon/thoron and exhalation rates of soils.

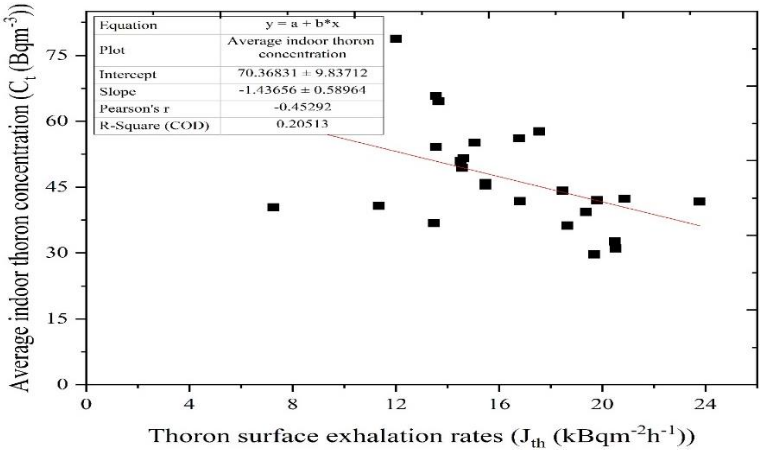

Figure 4.7: Correlation of thoron surface exhalation rates with thoron concentration in dwellings of Moga district

Table 4.3 shows the comparison of measured radon mass/thoron surface exhalation rates with similar investigations done by researchers in other parts of India. The measured radon mass exhalation rates (4.56 to 41.13 $mBqkg^{-1}h^{-1}$) in the studied area are lower than that of Himachal Pradesh (39.1 to 91.2 $mBqkg^{-1}h^{-1}$) (Bala et al., 2017), higher than Garhwal Himalaya (0.59×10^{-5} to 2.2×10^{-5} $Bqkg^{-1}h^{-1}$) (Yadav et al., 2016), Kapurthala district (2.96 to 5.74 $mBqkg^{-1}h^{-1}$) (Kumar A et a l., 2014) and almost comparable to that of Amritsar and Tarantaran districts (10 to 33 $mBqkg^{-1}h^{-1}$) (Kaur et al., 2018), Malwa region of Punjab (6.4 to 36.3 $mBqkg^{-1}h^{-1}$) (Mehra R et al., 2006), Haryana (6.32 to 14.25 $mBqkg^{-1}h^{-1}$) (Kansal et al., 2015), of Jaipur and Ajmer districts of Rajasthan (5.20 to 26.29 $mBqkg^{-1}h^{-1}$) (Jakhu et al., 2017) and of Charmarajanagar (10 to 31.4 $mBqkg^{-1}h^{-1}$) (Nagaraju et al., 2013).

The measured value for thoron surface exhalation rates (1.50 to 23.77 $kBqm^{-2}h^{-1}$) are higher than that of Amritsar and Tarantarn districts (0.25 to 1.22

$kBqm^{-2}h^{-1}$) (Kaur et al., 2018) and comparable to that of Faridabad district of Haryana (3.32 to 10.16 $kBqm^{-2}h^{-1}$) (Singh et al., 2020).

4.5 CONCLUSION

- The radon mass exhalation rates in all samples have lower value than the worldwide average of 57 $mBqkg^{-1}h^{-1}$.
- The thoron surface exhalation rates in 98% samples have higher values than worldwide average of 3.60 $kBqm^{-2}h^{-1}$. The higher thoron surface exhalation rates may be because of higher thorium rich contents in rocks in the Northern portion of India.
- The variation in the exhalation rates may be because of varied geological locations of soil samples, topography, radon emanation factor and soil porosity.
- Weak correlation has been found between average indoor radon/thoron concentration and exhalation rates in samples. Therefore, radon/thoron emitted from soil surface underneath the concrete and mud houses would not contribute to indoor radon/thoron concentrations.
- 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 4.1: Radon/thoron exhalation rates in the soil samples

S. No	Village	Longitude	Latitude	Radon mass exhalation rate (J_{rn}) ($mBqkg^{-1}h^{-1}$)	Thoron surface exhalation rate (J_{th}) ($kBqm^{-2}h^{-1}$)
Barnala District					
1	Dhanola	75°34’16.81”	30°16’ 55.62”	25.67 ±0.72	14.72 ± 1.24
2	Bhadaur	75°35’92.20”	30°28’ 27.37”	15.20 ± 0.61	9.03 ± 1.05
3	Jangaina	75°27’63.20”	30°4’78.37”	34.31 ± 1.96	16.76 ± 1.41
4	Channa	75°29’89.14”	30°43’03.01”	23.82 ± 0.71	12.24 ± 1.18
5	Nainewal	75°32’66.5”	30°44’51.60”	26.82 ± 088	10.37 ± 1.22
6	Tapa	75°36’88.49”	30°29’80.59”	39.19± 1.21	18.90 ± 1.56
7	Draj	75°34’26.87”	30°31’12.64”	32.43 ± 1.71	15.68 ± 1.24
8	Mehta	75°54’86.67”	30°37’44.74”	11.48 ± 0.53	14.11 ± 1.26
9	Dhurkot	75°46’20.64”	30°24’29.81”	18.48 ± 0.62	17.32 ± 1.36
10	Sanghere	75°56’54.68”	30°39’98.86”	16.24 ± 0.65	15.77 ± 1.10
11	Wazidke	75°57’31.59”	30°46’02.88”	21.3 ± 0.93	11.23 ± 1.16
12	Chuhanke	75°53’14.85”	30°47’38.75”	28.75 ± 1.33	17.90 ± 1.34
13	Sehjra	75°55’24.57”	30°49’28.81”	18.87 ± 0.97	11.05 ± 1.12
14	Bhadalwad	75°56’75.91”	30°42’40.86”	26.38 ± 0.54	13.75 ± 1.31
15	Barnala	75°48’10.74”	30°39’88.95”	19.3 ± 0.81	14.79 ± 1.25
16	MehalKalan	75°56’83.59”	30°52’70.74”	15.56 ± 068	8.43 ± 0.81
17	Kurar	75°64’25.82”	30°52’83.98”	38.83 ± 1.63	21.23 ± 1.25
18	AspalKalan	75°54’07.83”	30°20’66.75”	20.8 ± 0.61	1.50 ± 0.63
19	Dangarh	75°59’73.69”	30°29’97.76”	31.58 ± 1.42	18.17 ± 1.39
20	Harigarh	75°63’38.66”	30°26’50.72”	37.15± 1.5	21.35 ± 1.65
21	Bhaini Jassa	75°25’56.74”	30°25’24.79”	23.91 ± 0.82	11.26 ±1.08

S. No	Village	Longitude	Latitude	Radon mass exhalation rate (J_{rn}) ($mBqkg^{-1}h^{-1}$)	Thoron surface exhalation rate (J_{th}) ($kBqm^{-2}h^{-1}$)
22	Attar Singh Wala	75°57’07.75”	30°28’51.51”	15.74 ± 0.63	17.83 ± 1.51
23	Diwana	75°41’98.99”	30°57’49.84”	29.03 ± 0.86	21.83 ± 1.47
24	Kattu	75°63’38.78”	30°31’03.89”	23.17 ± 0.95	18.42 ± 1.42
25	Handiaya	75°51’01.97”	30°38’88.85”	21.35± 0.93	20.03 ± 1.55
Moga district					
26	Bhagapurana	75°09’39.88”	30°86’ 56.77”	22.12 ± 0.72	16.77 ± 1.42
27	Marhi	75°17’17.07”	30°87’ 64.60”	41.13 ± 1.62	23.77 ± 1.52
28	Rode	75°01’49.78”	30°68’00”	24.65 ± 0.98	13.55 ± 1.28
29	Khokhrana	74°98’07.91”	30°82’61.01”	28.69 ± 0.78	13.56 ± 1.28
30	Nathuwala	75°29’48.57”	30°80’06.04”	31.81 ± 0.95	15.48 ± 1.21
31	Smalsar	74°99’83.49”	30°63’73.45”	13.53 ± 0.51	7.25 ± 0.63
32	SmadhBhai	75°15’02.04”	30°59’27.77”	33.45 ± 1.13	20.51 ± 1.84
33	Charik	75°17’56.23”	30°72’06.34”	32.96 ± 1.76	18.46 ± 1.23
34	NihalSinghwala	75°28’01.01”	30°59’26.87”	4.67 ± 0.21	14.52 ± 1.16
35	Himatpura	75°36’16.07”	30°52’88.98”	13.84 ± 0.68	13.65 ± 1.74
36	Dharamkot	75°23’04.05”	30°93’80.98”	23.45 ± 0.85	15.06 ± 1.24
37	Chotiankalan	74°96’12.15”	30°86’11.75”	29.89 ± 1.04	19.69 ± 1.53
38	Badhni	75°29’16.56”	30°67’83.85”	16.35 ± 0.89	12.00 ± 1.16
39	Buttar	75°27’55.91”	30°72’57.89”	23.84 ± 0.86	14.56 ± 1.24
40	Moga	75°10’26.75”	30°48’56.96”	24.35 ± 0.94	16.80 ± 1.24
41	Baddowal	75°26’28.59”	30°51’68.34”	15.74 ± 0.79	13.47 ± 1.13
42	Mehna	75°27’0”	30°80’23.98”	35.23 ± 1.32	20.48 ± 1.26
43	Ajitwal	75°33’83.08”	30°81’34.75”	20.82 ± 0.53	17.55 ± 1.50

S. No	Village	Longitude	Latitude	Radon mass exhalation rate (J_{rn}) ($mBqkg^{-1}h^{-1}$)	Thoron surface exhalation rate (J_{th}) ($kBqm^{-2}h^{-1}$)
44	Dina	75°23’48.11”	30°54’86.15”	31.74 ± 1.8	20.87 ± 1.36
45	Kokri Kalan	75°33’24.76”	30°84’61.12”	38.45 ± 1.27	19.37 ± 1.42
46	Rajeana	75°06’55.24”	30°66’20.19”	20.74 ± 0.94	11.35 ± 1.32
47	Karyal	75°17’22.15”	30°82’68.21”	4.56 ± 0.15	14.62 ± 1.05
48	BabihaBhaike	75°53’18.99”	30°24’48.84”	31.21 ± 1.13	15.47 ± 1.35
49	Gill	75°10’04.78”	30°71’94.89”	28.54 ± 0.88	18.65 ± 1.37
50	Ludhaike	75°21’01.98”	30°28’87.15”	32.7 ± 1.24	19.79 ± 1.65
Minimum				4.56 ± 0.15	1.50 ± 0.63
Maximum				41.13 ± 1.62	23.77 ± 1.52
Average				24.8 ± 1	15.62 ± 1.24
Standard Deviation				8.65	4.28
Skewness				-0.33	1.16
Kurtosis				-0.21	-.073

Table 4.2: Average indoor radon/thoron concentration in dwellings and radon/thoron exhalation rates in the soil samples

S. No.	Village/ Town	Average indoor radon concentration (Bqm^{-3})	Radon mass exhalation rates ($mBqkg^{-1}h^{-1}$)	Average indoor thoron concentration (Bqm^{-3})	Thoron surface exhalation rates ($kBqm^{-2}h^{-1}$)
1	Dhanola	36.29	25.67	98.98	14.72
2	Bhadaur	18.13	15.2	37.48	9.03
3	Jangiana	23.98	34.31	51.36	16.76
4	Channa	24.91	23.82	79.58	12.24
5	Nainewal	28.62	26.82	46.66	10.37
6	Tapa	29.51	39.19	59.50	18.9
7	Draj	16.01	32.43	30.04	15.68
8	Mehta	30.99	11.48	42.01	14.11
9	Dhurkot	42.02	18.48	40.28	17.32
10	Sanghere	41.08	16.24	84.36	15.77
11	Wajid Ke	32.48	21.3	53.27	11.23
12	Chahuan Ke	23.40	28.75	45.67	17.9
13	Sehjra	27.19	18.87	86.94	11.05
14	Bhadalwad	28.53	26.38	65.94	13.75
15	Barnala	22.64	19.3	79.04	14.79
16	Mehal Kalan	29.25	15.56	35.79	8.43
17	Kurar	10.96	38.83	31.58	21.23
18	Aspal Kalan	22.16	20.8	61.53	1.5
19	Dangarh	27.83	31.58	40.03	18.17
20	Harigarh	35.16	37.15	46.71	21.35
21	Bheni Dessa	20.74	23.91	39.51	11.26

S. No.	Village/ Town	Average indoor radon concentration (Bqm^{-3})	Radon mass exhalation rates ($mBqkg^{-1}h^{-1}$)	Average indoor thoron concentration (Bqm^{-3})	Thoron surface exhalation rates ($kBqm^{-2}h^{-1}$)
22	Attar Singh Wala	23.83	15.74	45.76	17.83
23	Diwana	27.46	29.03	59.02	21.83
24	Kattu	24.25	23.17	37.57	18.42
25	Handiaya	26.73	21.35	46.69	20.03
26	Bhagapurana	39.86	22.12	56.10	16.77
27	Marhi	25.47	41.13	41.72	23.77
28	Rode	36.99	24.65	54.18	13.55
29	Khokhrana	29.80	28.69	65.71	13.56
30	Nathuwala	30.09	31.81	45.35	15.48
31	Samalsar	29.45	13.53	40.42	7.25
32	Smadh Bhai	27.98	33.45	31.04	20.51
33	Chrik	34.50	32.96	44.17	18.46
34	Nihal Singhwala	58.55	4.67	50.92	14.52
35	Himatpura	44.17	13.84	64.52	13.65
36	Dharamkot	33.08	23.45	55.11	15.06
37	Chotian Kalan	30.01	29.89	29.64	19.69
38	Badhni	26.70	16.35	78.78	12
39	Buttar	28.49	23.84	49.39	14.56
40	Moga	45.34	24.35	41.83	16.8
41	Badoowal	39.89	15.74	36.78	13.47
42	Mahna	22.43	35.23	32.59	20.48
43	Ajitwal	26.04	20.82	57.67	17.55

S. No.	Village/ Town	Average indoor radon concentration (Bqm^{-3})	Radon mass exhalation rates ($mBqkg^{-1}h^{-1}$)	Average indoor thoron concentration (Bqm^{-3})	Thoron surface exhalation rates ($kBqm^{-2}h^{-1}$)
44	Dina	31.26	31.74	42.31	20.87
45	Kokri kokri	34.51	38.45	39.37	19.37
46	Rajiana	22.88	20.74	40.75	11.35
47	Karyal	33.15	4.56	51.58	14.62
48	Babiha Bhaike	27.86	31.21	45.96	15.47
49	Gill	35.40	28.54	36.23	18.65
50	Ludhai Ke	34.64	32.7	42.05	19.79

Table 4.3: Comparison of radon mass/thoron surface exhalation rates with other similar investigations in India

S. No.	Studied area	Radon mass exhalation rate (J_{rn}) ($mBqkg^{-1}h^{-1}$)	Thoron surface exhalation rate (J_{th}) ($kBqm^{-2}h^{-1}$)	Reference
1.	Jaipur and Ajmer districts of Rajasthan	5.20 - 26.29	-	Jakhu et al., 2017
2.	Kapurthala, Punjab	2.96- 5.74	-	Kumar and Kaur, 2014
3.	Malwa region of Punjab	6.4 - 36.3	-	Mehra et al., 2006
4.	Himachal Pradesh, India	39.1 - 91.2	-	Bala et al., 2017
5.	Garhwal Himalya	$(0.8 - 3.2) \times 10^{-2}$	-	Yadav et al., 2016
6.	Amritsar and Tarantaran	10-33	0.25 - 10.16	Kaur et al., 2018
7.	Western Haryana	6.32 - 14.25	-	Kansal et al., 2015
8.	Chamarajanagar	10 - 31.4	-	Nagaraju et al., 2013
9.	Faridabad Southern Haryana	12 ± 1 – 62 ± 4	3.32 ± 0.37 – 10.16 ± 0.60	Singh et al., 2020
10.	Uttar Pradesh	2.1 - 10.6	-	Choudhary, 2014
11.	Barnala and Moga district of Punjab	4.56 - 41.13	1.50 – 23.77	**Present study**