Journal of Radioanalytical and Nuclear Chemistry (2020) 326:831–843
https://doi.org/10.1007/s10967-020-07365-5

Quantification of radon/thoron exhalation rates of soil samples collected from district Faridabad of Southern Haryana, India

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Received: 24 February 2020 / Published online: 14 September 2020

Abstract

This paper describes radon mass exhalation rate (J_m) and thoron surface exhalation rate (J_s) of 46 soil samples of district Faridabad, Southern Haryana, India. Scintillation detector based SMART RnDuo (AQTEK System, India) coupled with exhalation chamber was used. Outdoor gamma exposure rate was measured by GM counter based survey meter. J_m of one sample and J_s of 95% samples were found higher than world average values of 57 mBq kg^{-1} h^{-1} and 3600 Bq m^{-2} h^{-1} for J_m and J_s respectively reported by UNSCEAR 2000. No significant correlation was observed between radon/thoron exhalation rates with outdoor gamma exposure rate.

Keywords Radon/thoron · Gamma · Mass/surface exhalation · Alpha scintillometry

Introduction

Exposure from radon isotopes and their progeny received significant recognition by world community because of their dangerous health effects [1]. Natural radioactivity depends primarily on geological and geographical conditions of the region [2, 3]. Radon is a naturally occurring radioactive gas and is produced continuously in rocks and soils grain due to radioactive decay of ^{226}Ra, originating from the primordial radionuclide—^{238}U present in the rock and soil. There are two fundamental processes by which Radon migrates from rocks and soil grains to environment. The first stage is emanation from the material grain and the second is exhalation from the matrix through different transport processes [4–6]. *Emanation* is the process by which radon atom escape from the solid mineral grains to the air-filled pores. *Exhalation* is the process of transport of radon gas from air-filled pores to the atmosphere. Radon transport in soil pore is mainly governed by (1) diffusion brought out by concentration gradient and (2) advection brought out by pressure driven flow of soil gas [5, 7]. Radon being eight times heavier than air travels near to ground and can deposit its progeny in form of solid radioactive fallout on soil surface, vegetation and water. Radon can migrate due to Brownian motion if it finds way to diffuse. The permeability, medium porosity, pressure difference, moisture and temperature have large impact on concentration of radon in soil [8, 9]. Along with natural radioactivity, anthropogenic activities like industrial wastes and extensive use of phosphate fertilizers are also responsible for soil radioactivity. Based on the experimental observations and studies involving the models for radon entry, it is now understood that soil is predominant source for indoor radon concentration [4, 10]. Soil and rocks of northern part of India are mainly rich in granites, phosphates, sandstones and siltstones which are disintegrated from rock to soil by rain and water flow [11]. In India, soil is used as basic raw material in construction of bricks. Thus, it is of much importance to find out the concentration and exhalation rate of radon & thoron from the soil samples. The purpose of the present study is to identify radon prone region and suitable building material in constructing new buildings. Investigations were also performed for radon/thoron concentrations in indoor environment, underground and surface water samples in present study region [12, 13]. Also, results will specify the regions of higher (or lower) level of radon/thoron. This study is a part of project of radon mapping at national level

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sponsored by Board of Research in Nuclear Science, Department of Atomic Energy, Government of India.

Measurement of exhalation rate of radon and thoron can be carried out by using active and passive techniques. The active technique includes measurements by Alpha GUARD, RAD 7, SMART RnDuo etc. and the passive technique includes Canister technique, Solid state alpha spectroscopy technique etc. [14–18]. It was reported that radon measurements by Alpha GUARD, SMART RnDuo and RAD7 are very much comparable with each other [18]. In the present investigations, SMART RnDuo monitor coupled with exhalation chamber has been used for the online measurement of radon/thoron concentration of soil samples collected from different villages of district Faridabad, Haryana, India. SMART RnDuo has a portable monitor and it has advantage that measurements with scintillation detector are unaffected by humidity and traces of different gases present in samples. SMART RnDuo monitor has been used for the first time in the present study region for the measurement of radon and thoron concentration. This instrument has been calibrated against standard Radon–Thoron sources (Model RN-1025 & TH-1025) acquired from Pylon Electronics Inc., Ottawa, Canada in a 0.5 m^3 calibration chamber available at Bhabha Atomic Research Centre (BARC), Mumbai, India [19]. This calibration chamber has the facilities of controlling the relative humidity from 10 to 99% and temperature from 20 to 50 °C. For study of radon level in soil samples, measurement of mass exhalation rate of radon has been carried out. The magnitude of radon mass exhalation rate depends on the bulk thickness of the sample. In case of thoron, measurement of surface exhalation rate in soil samples has been carried out. The magnitude of the thoron exhalation is not affected by thickness of source as it is surface phenomena [14]. Diffusion length of radon in soil is about 1 m while for thoron, it is about 1 cm. We have used an accumulation chamber which has a height of about 10 cm. Due to large difference in diffusion length between radon and thoron, it is expected that only top surface of soil sample in the chamber will contribute thoron while entire mass of the sample will contribute radon. If we normalize the thoron exhalation with respect to top surface area of the sample and radon exhalation with respect to mass of sample, the parameters will be independent of geometry of accumulation chamber, otherwise it will dependent upon geometry of chamber which is not the right way. Hence, we have calculated radon mass exhalation rate but thoron surface exhalation rate.

Also, outdoor gamma level was measured during sampling. Gamma dose at 1 m from ground is not affected by airborne decay products. The gamma dose is mainly due to gamma rays emitted from daughter products of radon (^{214}Pb, ^{214}Bi & ^{210}Pb) and thoron (^{212}Pb, ^{212}Bi & ^{208}Tl) present in the soil matrix. Thus, measurement of outdoor gamma level was performed to explore any correlation between them.

About the study area

Faridabad district is extended from 28° 13′ 16.4″ N to 28° 28′ 08.3″ N latitude and from 077° 26′ 51.4″ E to 077° 19′ 36.6″ E longitude and elevation varies from 185 to 203 m above the sea level. It is bordered by national capital New Delhi in north, by state Uttar Pradesh in east, by district Palwal of state Haryana in south and by Gurugram district of state Haryana in the west as shown in Fig. 1. District Faridabad includes 149 villages, town Ballabgarh and City Faridabad. Soil of Faridabad district is classified as tropical and brown soil, existing in major parts of the district. Most of the area is covered by alluvium soil. The average conductivity of the soil is around of 0.80 μmho cm^{-1} and average pH of the soil is between 6.5 and 8.7 [20].

Aravali range is also located in this region of Southern Haryana. It is an eroded stub of ancient mountains. It consists of two main sequences formed in Proterozoic eon, metasedimentary rock (sedimentary rocks metamorphised under pressure and heat without melting) and metavolcanic rock (metamorphosed volcanic rocks). It contains commercially viable quantities of minerals [12, 13, 20].

Methodology

Sample collection and preparation

Soil samples were collected from different villages of district Faridabad, Haryana, India from field area. The sampling sites were selected in such a way that it covers the entire districts. During sampling, the outdoor gamma level was measured by using gamma survey meter (Polimaster PM/1405, Republic of Belarus) at one metre height from the earth surface. Survey meter incorporates a large energy compensated Geiger Muller tube for precise measurement of the ambient equivalent dose rate of the gamma radiation in the range from background level to 100 mSv h^{-1} (10 R h^{-1}). The Polimaster PM1405 has a gamma energy response from 0.05 to 3 MeV and can be used for dose rate measurement vary from 0.01 μSv h^{-1} to 130 mSv h^{-1} suggesting suitability for environmental gamma survey. It has a calibration accuracy of ± (20 + 1/H) % where H is dose rate in μSv h^{-1}. The more technical information about PM1405 can be found in catalogue [21]. The GPS coordinates (longitude & latitude), elevation above sea level of the sampling location were noted using GPS map. The physical appearance (powder/crystalline etc.), material (soil/rock pieces/mixture etc.), colour of sample and sampling date were also noted. The samples were taken after removing 5 cm soil from surface

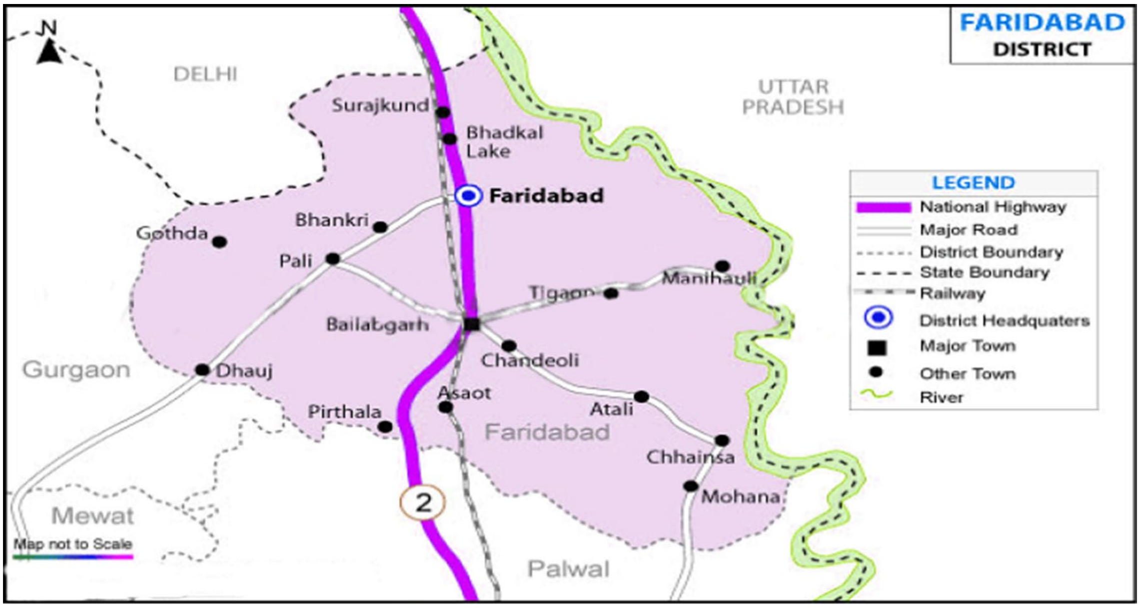


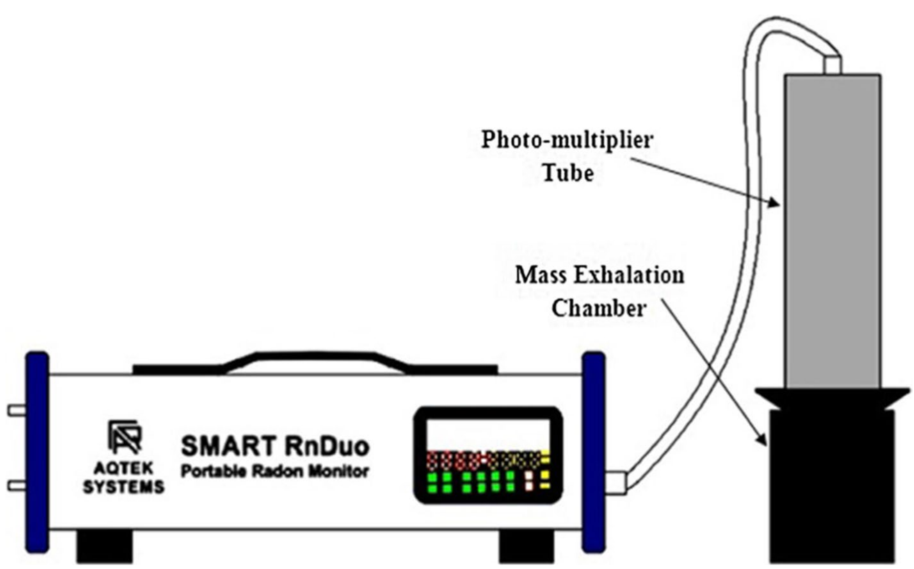
Fig. 1 Geographical map of study area district Faridabad, Haryana, India

to collect fresh sample so that any atmospheric deposition will not affect the samples and collected into thick polythene bags. Samples were crushed by Pestle and filtered to maintain the homogeneity so that comparative study can be made among the samples collected from different locations. The moisture was dried in an oven at 110 °C for 12 h to reduce the effect of water content in measurement. The bulk density of samples was also measured.

Measurement of radon concentration and mass exhalation rate

Radon and thoron exhalation from soil samples were measured by following growth curve analysis to radon build up data in an accumulation chamber connected to a continuous radon–thoron monitor (SMART RnDuo, (AQTEK System, India)). Soil samples were filled into cylindrical accumulation chamber and connected to the setup as shown in Fig. 2. Accumulated radon in the chamber diffuse through a progeny filter and enters into a scintillation cell of volume 153 cm^3 which is internally coated with ZnS:Ag scintillating

Fig. 2 Set up of measurement of radon mass exhalation rate from soil sample using SMART RnDuo in diffusion mode



materials and having a transparent glass window for photon measurements [22, 23]. Scintillation photon emitted due to interaction of alpha particles emitted from radon and its decay products is counted by a Photo Multiplier Tube attached with the glass window of the scintillation cell and converted to radon and thoron activity concentration using inbuilt algorithm in the micro-controller of the monitor. Alpha detection efficiency of the scintillation cell is about 75% and the device has a radon sensitivity of 1.2 CPH Bq^{-1} m^{-3} [24]. The build-up of radon concentration with time was measured up to 12 h with a cycle period of 1 h. The build-up data were retrieved from the monitor and used later for least square fitting of the growth curve model [25, 26] to estimate fitting parameters and radon mass exhalation rate of the sample.

Measurement of thoron concentration and surface exhalation rate

Thoron measurement was carried out in flow mode as shown in Fig. 3. Equipment has an in-built micro pump of flow capacity 0.7 l min^{-1} which was used for re-circulation of air in the accumulation chamber with the scintillation cell of the monitor. Monitor was operated in 15 min cycle. In this 15 min cycle, the micro-controller of the monitor make the pump on for initial 5 min and kept off in remaining 10 min. When the pump is on, both radon and thoron gases in the chamber enters the scintillation cell through the progeny filter. Hence, the counts during the initial 5 min give a measure of thoron and radon along with long lived background. Later 5 min is used for delay to ensure nearly complete decay of thoron (half life 55.6 s). The remaining 5 min gives a measure of radon and long-lived background. Thoron concentration is estimated by the micro-controller by taking difference of counts measured during initial 5 min and last 5 min and using appropriate calibration factor. To find the equilibrium value of thoron concentration in the accumulation chamber, the measurements were carried out for 1 h having 15 min cycle period.

Calculation of radon mass exhalation and thoron surface exhalation rate

The radon concentration (Bq m^{-3}) at time t is estimated by least square fitting method and then the radon mass exhalation rate is obtained by using Eq. (1a) [11, 27]

$$C_R(t) = \frac{J_m M}{V\lambda}\left(1 - e^{-\lambda t}\right) + c_o e^{-\lambda t} \tag{1a}$$

where J_m (mBq kg^{-1} h^{-1}) represents radon mass exhalation, V (m^3) is effective volume, M (kg) is mass of dried soil sample, λ is disintegration constant for radon, c_o is initial radon concentration in chamber.

The uncertainty error in the measurement of radon mass exhalation rate (E_m) is given by Eq. (1b)

$$E_R(t) = \frac{E_m M}{V\lambda}\left(1 - e^{-\lambda t}\right) + c_o e^{-\lambda t} \tag{1b}$$

where E_R is the measurement error in reading reported by equipment.

The thoron surface exhalation rate J_s (Bq m^{-2} h^{-1}) is calculated using Eq. (2a) [25, 27]

$$J_s = \frac{C_{eq} \times V \times \lambda}{A} \tag{2a}$$

where C_{eq} (Bq m^{-3}) is average of readings of thoron gas concentration, V (m^3) is effective volume, A is surface area through which thoron emitted, λ is thoron decay constant (0.0126 s^{-1} or 45.36 h^{-1}).

The uncertainty error in the measurement of thoron surface exhalation rate (E_{eq}) is given by Eq. (2b)

$$E_s = \frac{E_{eq} \times V \times \lambda}{A} \tag{2b}$$

where E_{eq} is the average of measurement error in readings reported by the equipment.

Graphical representation of data viz. bar graphs, linear fit and correlation coefficient were determined with help of Microsoft Excel and ORIGIN software.

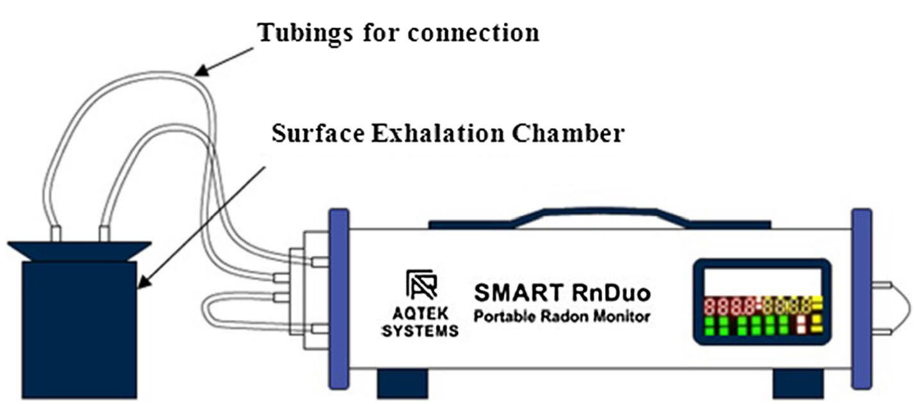


Fig. 3 Set up of the measurement of thoron surface exhalation rate from soil sample using SMART RnDuo in flow mode

Results and discussion

Gamma dose at 1 m from ground is not affected by airborne decay products. The gamma dose is mainly due to gamma rays emitted from daughter products of radon (^{214}Pb, ^{214}Bi & ^{210}Pb) and thoron (^{212}Pb, ^{212}Bi & ^{208}Tl) present in the soil matrix. The outdoor gamma level was measured at 1 m height above the earth surface. The measured gamma level varies from 9 to 20 μR h^{-1}.

^{222}Rn mass exhalation from soil samples

The measured gamma level, radon mass exhalation rate of soil samples collected from different villages of district Faridabad, Haryana are shown in Table 1. The measured radon mass exhalation rate varies from 12 ± 1 to 62 ± 4 mBq kg^{-1} h^{-1} with an average of 31 ± 12 mBq kg^{-1} h^{-1}.

The linear fit of radon activity concentration versus time of sample code SG03 is shown in Fig. 4 and the same trends of graph observed for other soil samples.

It is observed that, there is a wide variation in radon mass exhalation rate. It might be due to topography, different geological locations of soil samples, radon emanation factor and porosity of soil samples [28, 29]. The collected samples representing diverse locations have dissimilar geometries and soil composition that affect the ^{222}Rn exhalation rate from the soil. The highest radon mass exhalation rate was found in sample SG03 (62 ± 4 mBq kg^{-1} h^{-1}) of village Machgarh. The higher level of radon mass exhalation rate might be due to appreciably enriched radium contents in this soil and underlying bed rocks [30]. The lowest level was found in sample SG43 (12 ± 1 mBq kg^{-1} h^{-1}) of village Alampur as shown in Fig. 5.

The results of this study were comparable with results of investigations performed in other regions of India. Kaur et al. [31] reported an average radon mass exhalation rate in soil samples of Amritsar and Tan Taran districts of Punjab 20 ± 7 mBq kg^{-1} h^{-1} and 23 ± 5 mBq kg^{-1} h^{-1} respectively. Singh et al. [11] reported that radon mass exhalation rate in soil samples of district Hamirpur, Himachal Pradesh varies from 10 ± 1 to 54 ± 5 mBq kg^{-1} h^{-1} with an average of 22 ± 2 mBq kg^{-1} h^{-1}. Kumar et al. [32] reported that radon mass exhalation rate in Jammu and Kashmir varies from 8 ± 1 to 62 ± 3 mBq kg^{-1} h^{-1}. Kaur et al. [33] reported that radon mass exhalation rate in soil samples of region of Siwalik Himalayas of Jammu and Kashmir varies in the range of 7 to 48 mBq kg^{-1} h^{-1}. Rajkumari et al. [30] in an investigation reported that radon mass exhalation rate of soil samples of district Faridabad, Haryana varies from 13 to 29 mBq kg^{-1} h^{-1}. Chauhan and Chakarvarti [15] reported that radon mass exhalation in soil samples of Haryana and Delhi region varies from 6 to 10 mBq kg^{-1} h^{-1}. Chauhan et al. [16] reported that radon mass exhalation rate in soil samples of Aravali hills varies from 23 to 50 mBq kg^{-1} h^{-1} with an average of 35 ± 6 mBq kg^{-1} h^{-1}. Bala et al. [34] reported that radon mass exhalation rate of soil samples of Una and Hamirpur districts of Himachal Pradesh varies from 39 to 91 mBq kg^{-1} h^{-1} with an average of 60 mBq kg^{-1} h^{-1}. Kaliprasad et al. [35] in an investigation reported that this variation in soil samples of Hemavathi river environments in Karnataka varies from 67 ± 12 to 547 ± 34 mBq kg^{-1} h^{-1}. Kaliprasad et al. [36] reported radon mass exhalation varies from 45 to 333 mBq kg^{-1} h^{-1} in Cauvery river sediment samples. Thus, it indicates that the results of present study are comparable with results of other investigations of nearby regions of India.

^{220}Rn surface exhalation from soil samples

The measured gamma level, thoron concentration, thoron surface exhalation rate of soil samples collected from different villages of district Faridabad, Haryana are shown in Table 2. Thoron concentration varies from 1425 ± 162 to 4365 ± 260 Bq m^{-3} with an average of 2510 ± 611 Bq m^{-3} and thoron surface exhalation rate varies from 3319 ± 377 to $10{,}167 \pm 606$ Bq m^{-2} h^{-1} with an average of 5846 ± 1424 Bq m^{-2} h^{-1}.

It is observed that, there is a wide variation in thoron concentration and thoron surface exhalation rate due topography and different geological location of soil samples. The collected samples representing diverse locations have dissimilar geometries and soil composition that affect the ^{220}Rn exhalation rate from the soil. The highest thoron concentration and surface exhalation rate was found to be 4365 ± 260 Bq m^{-3} & $10{,}167 \pm 606$ Bq m^{-2} h^{-1} from soil sample (SG02) collected from village Chandawali. The high level of thoron might be due to appreciably large thorium contents in the soil of this region. The lowest level was 1425 ± 162 Bq m^{-3} & 3319 ± 377 Bq m^{-2} h^{-1} found in soil sample (SG27) of village Narhawali as shown in Fig. 6. Thus, overall results of higher level of thoron is in close agreement with the results of the higher ^{232}Th in the northern part of India which was shown in the radiation profile map of India due to higher thorium content in rocks since formation of earth [13, 37–39].

The results of the present study are comparable with the results of investigations performed in other regions of India listed here. Kaur et al. [31] reported that an average thoron surface exhalation rate in soil samples of Amritsar and Tarn Taran districts of Punjab were 664 ± 237 and 1531 ± 1503 Bq m^{-2} h^{-1} respectively. Kumar et al. [32] in an investigation reported that the thoron surface exhalation rate in soil samples of Himalayas of Jammu and Kashmir

Table 1 The measured gamma level, bulk density and mass exhalation rate of soil samples collected from different villages of district Faridabad, Haryana, India

Sample code	Village/town	Latitude N Longitude E	Elevation (m)	Gamma level ($\mu R\ h^{-1}$)	Bulk density ($g\ cm^{-3}$)	Radon mass exhalation rate (J_m) ($mBq\ kg^{-1}\ h^{-1}$)
SG01	Aggarwal College	28° 17′ 13.07″ N 077° 21′ 28.1″ E	189	14	1.1	25 ± 2
SG02	Chandawali	28° 19′ 20.3″ N 077° 20′ 49.1″ E	191	14	1.3	52 ± 4
SG03	Machgarh	28° 18′ 49.07″ N 077° 22′ 01.1″ E	195	13	1.1	62 ± 4
SG04	Imt, Faridabad	28° 19′ 23.07″ N 077° 21′ 20.1″ E	187	12	1.2	53 ± 4
SY05	Aterna	28° 13′ 35.07″ N 077° 24′ 25.1″ E	190	14	1.4	24 ± 2
SG06	Sahapur	28° 18′ 07.07″ N 077° 20′ 08.1″ E	195	10	1.1	48 ± 4
SG07	Deegh	28° 15′ 39.4″ N 077° 20′ 18.9″ E	190	9	1.1	34 ± 3
SG08	Sunper	28° 20′ 21.2″ N 077° 19′ 23.1″ E	188	9	1.1	33 ± 3
SG09	Dayalpur	28° 24′ 45.9″ N 077° 18′ 21.4″ E	186	11	1.1	29 ± 2
SG10	Mandhawali	28° 21′ 10.2″ N 077° 25′ 12.4″ E	193	11	1.0	38 ± 3
SG11	Atali	28° 17′ 19.8″ N 077° 25′ 34.1″ E	196	10	1.1	36 ± 3
SG12	Mojpur	28° 17′ 16.1″ N 077° 25′ 44.3″ E	205	11	1.1	28 ± 2
SY13	Mothuka	28° 17′ 11.6″ N 077° 27′ 15.0″ E	201	11	1.2	44 ± 4
SY14	Fajjipur	28° 18′ 27.6″ N 077° 27′ 35.5″ E	203	11	1.2	18 ± 1
SY15	Chandpur	28° 19′ 49.2″ N 077° 27′ 46.9″ E	187	11	1.1	24 ± 2
SG16	Ghorasan-Bela	28° 20′ 49.9″ N 077° 27′ 25.5″ E	196	11	1.1	26 ± 2
SY17	Gharora	28° 21′ 12.5″ N 077° 26′ 46.0″ E	194	11	1.1	23 ± 2
SG18	Jm Chhainsa	28° 16′ 23.7″ N 077° 26′ 45.0″ E	193	11	1.2	23 ± 2
SY19	Ahamadpur	28° 15′ 22.8″ N 077° 25′ 17.2″ E	193	12	1.3	22 ± 2
SG20	Hirapur	28° 14′ 01.5″ N 077° 26′ 03.2″ E	191	9	1.2	44 ± 4
SG21	Fatehpur Billoch	28° 15′ 07.1″ N 077° 22′ 33.6″ E	190	16	1.1	35 ± 2
SG22	Ladholi	28° 15′ 51.4″ N 077° 24′ 17.3″ E	189	12	1.2	36 ± 2
SY23	Jawan	28° 14′ 03.8″ N 077° 23′ 38.7″ E	195	20	1.3	21 ± 2
SG24	Mohna	28° 14′ 01.9″ N 077° 26′ 38.8″ E	189	11	1.2	39 ± 3
SG25	Chhainsa	28° 15′ 20.8″ N 077° 27′ 24.4″ E	193	11	1.2	23 ± 2
SY26	Naryala	28° 15′ 24.0″ N 077° 25′ 03.5″ E	201	12	1.2	28 ± 2

Table 1 (continued)

Sample code	Village/town	Latitude N Longitude E	Elevation (m)	Gamma level (μR h^{-1})	Bulk density (g cm^{-3})	Radon mass exhalation rate (J_m) (mBq kg^{-1} h^{-1})
SG27	Narhawali	28° 16′ 12.9″ N 077° 25′ 13.5″ E	195	12	1.2	12 ± 1
SG28	Sikri	28° 16′ 27.9″ N 077° 16′ 54.5″ E	196	11	1.2	30 ± 2
SG29	Sahupura	28° 16′ 40.0″ N 077° 17′ 46.4″ E	199	11	1.0	31 ± 2
SG30	Jajru	28° 17′ 28.7″ N 077° 18′ 57.9″ E	186	10	1.1	35 ± 3
SG31	Fajupur Neemka	28° 22′ 24.6″ N 077° 21′ 54.4″ E	192	13	1.1	46 ± 4
SB32	Mirjapur	28° 21′ 44.3″ N 077° 20′ 46.6″ E	192	16	0.9	41 ± 4
SG33	Neemka	28° 21′ 33.5″ N 077° 21′ 48.1″ E	192	11	1.1	32 ± 2
SG34	Kheri Kalan	28° 23′ 41.8″ N 077° 22′ 35.7″ E	193	11	1.0	21 ± 2
SG35	Prhladpur	28° 23′ 08.8″ N 077° 20′ 32.8″ E	188	10	1.2	24 ± 2
SG36	Bhatola	28° 23′ 37.5″ N 077° 21′ 52.1″ E	199	11	1.1	18 ± 2
SG37	Faridpur	28° 25′ 59.5″ N 077° 22′ 33.3″ E	193	11	1.0	44 ± 3
SG38	Samaypur	28° 19′ 07.6″ N 077° 17′ 01.01″ E	192	14	1.1	48 ± 4
SG39	Karnera	28° 18′ 570.5″ N 077° 16′ 02.3″ E	203	16	1.3	13 ± 1
SB40	Pawta	28° 22′ 36.8″ N 077° 12′ 18.4″ E	219	12	1.3	19 ± 2
SG41	Sirohi	28° 10′ 3.0″ N 077° 10′ 44.4″ E	190	13	1.2	17 ± 1
SY42	Kabulpur Banger	28° 17′ 33.8″ N 077° 14′ 24.1″ E	192	15	1.2	36 ± 3
SG43	Alampur	28° 19′ 37.4″ N 077° 11′ 13.9″ E	200	13	1.4	12 ± 1
SG44	Pali	28° 22′ 27.3″ N 077° 14′ 10.04″ E	197	12	1.3	34 ± 2
SG45	Pakhal	28° 21′ 57.6″ N 077° 13′ 5.0″ E	202	12	1.2	26 ± 2
SY46	Jakopur	28° 18′ 22.7″ N 077° 12′ 03.8″ E	196	14	1.1	20 ± 2

SG clayey (gray) soil sample, *SB* black soil sample, *SY* yellow soil sample

varies from 295 to 3628 Bq m^{-2} h^{-1}. Kaur et al. [33] reported that thoron surface exhalation in Siwalik Himalayas of Jammu and Kashmir varies from 123 to 2606 Bq m^{-2} h^{-1}. Sunder et al. [40] reported that thoron surface exhalation rate in soil samples of Kalpakkam, Tamilnadu varies from 942 to 7720 Bq m^{-2} h^{-1}. Karthik Kumar et al. [41] reported that level of thoron surface exhalation rates in soil samples of Bengaluru varies from 4737 to 10,886 Bq m^{-2} h^{-1}. Thus, it indicates that the results of present study for thoron concentration are comparable with results of other investigations of nearby regions of India.

Correlation of ^{222}Rn/^{220}Rn exhalation with outdoor gamma exposure rate

The distribution of radon mass exhalation rate of soil samples and outdoor gamma exposure rate is shown in Fig. 7a and distribution of thoron surface exhalation rate in soil samples and outdoor gamma exposure rate is shown in

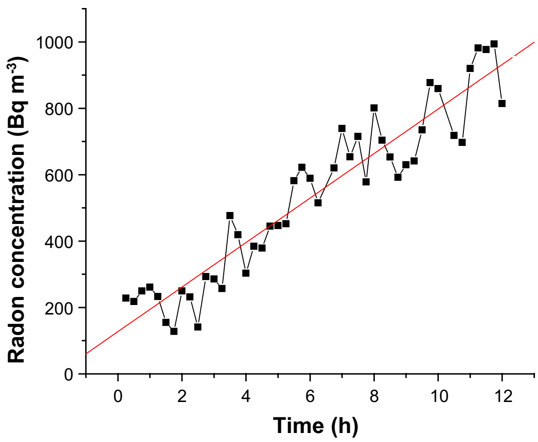


Fig. 4 Typical graph between the radon activity concentration and time of soil sample code SG03 of district Faridabad, Haryana, India

Fig. 7b. A poor positive correlation was observed between the outdoor gamma level and radon exhalation rate with correlation coefficient R = 0.1 and with correlation coefficient R = 0.1 between outdoor gamma exposure and thoron exhalation rate. Thus, there is no significant correlation was found between the gamma exposure from decay products and radon/thoron level.

Inter-comparison of $^{222}Rn/^{220}Rn$ exhalation rate of different colour soil samples

The radon mass exhalation rate in different colour soil samples of district Faridabad, Haryana, India varies from 18 ± 1 to 44 ± 4 mBq kg^{-1} h^{-1} with an average of 26 ± 2 mBq kg^{-1} h^{-1} in yellow soil, from 19 ± 2 to 41 ± 4 mBq kg^{-1} h^{-1} with an average of 30 ± 16 mBq kg^{-1} h^{-1} in black soil and from 12 ± 2 to 62 ± 4 mBq kg^{-1} h^{-1} with an average of 32 ± 2 mBq kg^{-1} h^{-1} in clayey (Gray) soil. The thoron surface exhalation rate is varies in different colour soil samples from 4206 ± 395 to 6523 ± 484 Bq m^{-2} h^{-1} with an average of 5440 ± 679 Bq m^{-2} h^{-1} in yellow soil samples, from 3720 ± 388 to 6948 ± 500 Bq m^{-2} h^{-1} with an average of 5334 ± 2282 Bq m^{-2} h^{-1} in black soil samples and from 3319 ± 377 to 10,167 ± 606 Bq m^{-2} h^{-1} with an average of 5941 ± 1559 Bq m^{-2} h^{-1} in gray soil samples. The radon mass exhalation rate and thoron surface exhalation rate is maximum in clayey (gray) soil as shown in Fig. 8.

Results of present investigation indicate that radon mass exhalation rate of one sample and thoron surface exhalation rate of 95% samples were found higher than world average values of 57 mBq kg^{-1} h^{-1} and 3600 Bq m^{-2} h^{-1} respectively reported by UNSCEAR 2000 [42, 43]. The level of radon/thoron in dwellings, in underground and surface water sources of district Faridabad, Haryana were found within the recommended limits of various agencies [12, 13]. Thus, radon and thoron have no serious concern in water bodies and dwellings of the present study region. Thoron has very small half life (55 s) thus its level in soil samples may not much harmful to public as outdoor exposure but may be harmful in indoor dwellings as its short lived decay products have nearly 98% contribution in annual effective dose due to inhalation of thoron and its progeny. The higher thoron level in soil indicates the possibility of high indoor thoron concentration which also close agreements with the indoor thoron results of the present study region [12].

Conclusions

A wide variation is observed in radon mass exhalation rate and thoron surface exhalation rate of soil samples collected from villages of district Faridabad. This may be attributed to topography, different geological location of soil samples, dependency on underlying bed rocks etc.

The measured radon mass exhalation rate varies from 12 ± 1 to 62 ± 4 mBq kg^{-1} h^{-1} with an average of 31 ± 12 mBq kg^{-1} h^{-1} and thoron surface exhalation rate varies from 3319 ± 377 to 10,167 ± 606 Bq m^{-2} h^{-1} with an average of 5846 ± 1424 Bq m^{-2} h^{-1}.

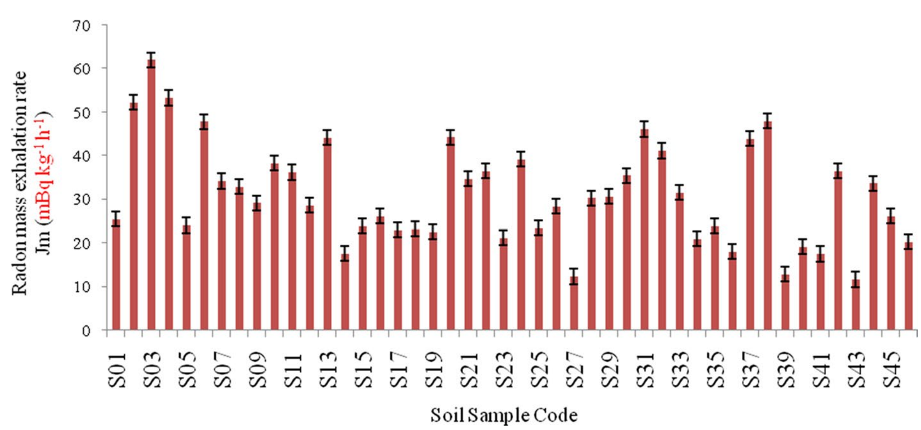


Fig. 5 Graphical representation of variation in radon mass exhalation rate in soil samples of district Faridabad, Haryana, India

Table 2 The measured gamma level, bulk density, thoron concentration and surface exhalation rate of soil samples collected from different villages of district Faridabad, Haryana, India

Sample code	Village/town	GPS coordinates Latitude N Longitude E	Elevation (m)	Gamma level (μR h^{-1})	Bulk density (g cm^{-3})	Average thoron concentration (Bq m^{-3}) × 10^3	Thoron surface exhalation rate J_s (Bq m^{-2} h^{-1}) × 10^3
SG01	Aggarwal College	28° 17′ 13.07″ N 077° 21′ 28.1″ E	189	14	1.08	2.6 ± 0.2	6.0 ± 0.5
SG02	Chandawali	28° 19′ 20.3″ N 077° 20′ 49.1″ E	191	13.6	1.34	4.4 ± 0.3	10.1 ± 0.6
SG03	Machgarh	28° 18′ 49.07″ N 077° 22′ 01.1″ E	195	13.3	1.11	4.2 ± 0.2	9.8 ± 0.6
SG04	Imt, Faridabad	28° 19′ 23.07″ N 077° 21′ 20.1″ E	187	12	1.23	3.3 ± 0.2	7.6 ± 0.5
SY05	Aterna	28° 13′ 35.07″ N 077° 24′ 25.1″ E	190	14	1.38	2.3 ± 0.2	5.5 ± 0.5
SG06	Sahapur	28° 18′ 07.07″ N 077° 20′ 08.1″ E	195	9.8	1.07	3.1 ± 0.1	7.2 ± 0.4
SG07	Deegh	28° 15′ 39.4″ N 077° 20′ 18.9″ E	190	9.5	1.09	2.3 ± 0.2	5.5 ± 0.4
SG08	Sunper	28° 20′ 21.2″ N 077° 19′ 23.1″ E	188	9.1	1.1	2.5 ± 0.2	5.9 ± 0.5
SG09	Dayalpur	28° 24′ 45.9″ N 077° 18′ 21.4″ E	186	11.3	1.13	2.5 ± 0.2	5.8 ± 0.5
SG10	Mandhawali	28° 21′ 10.2″ N 077° 25′ 12.4″ E	193	10.7	1.01	2.7 ± 0.2	6.3 ± 0.5
SG11	Atali	28° 17′ 19.8″ N 077° 25′ 34.1″ E	196	10.5	1.11	2.6 ± 0.2	6.1 ± 0.4
SG12	Mojpur	28° 17′ 16.1″ N 077° 25′ 44.3″ E	205	10.7	1.06	2.1 ± 0.2	4.8 ± 0.4
SY13	Mothuka	28° 17′ 11.6″ N 077° 27′ 15.0″ E	201	10.6	1.21	2.8 ± 0.2	6.5 ± 0.4
SY14	Fajjipur	28° 18′ 27.6″ N 077° 27′ 35.5″ E	203	10.6	1.19	2.3 ± 0.2	5.5 ± 0.4
SY15	Chandpur	28° 19′ 49.2″ N 077° 27′ 46.9″ E	187	11.1	1.07	2.1 ± 0.2	4.9 ± 0.4
SG16	Ghorasan-Bela	28° 20′ 49.9″ N 077° 27′ 25.5″ E	196	10.9	1.1	1.8 ± 0.2	4.2 ± 0.4
SY17	Gharora	28° 21′ 12.5″ N 077° 26′ 46.0″ E	194	10.9	1.08	1.8 ± 0.2	4.2 ± 0.3
SG18	Jm Chhainsa	28° 16′ 23.7″ N 077° 26′ 45.0″ E	193	10.7	1.19	2.0 ± 0.2	4.7 ± 0.4
SY19	Ahamadpur	28° 15′ 22.8″ N 077° 25′ 17.2″ E	193	11.6	1.31	2.5 ± 0.2	5.9 ± 0.4
SG20	Hirapur	28° 14′ 01.5″ N 077° 26′ 03.2″ E	191	9.5	1.17	3.2 ± 0.2	7.4 ± 0.5
SG21	Fatehpur Billoch	28° 15′ 07.1″ N 077° 22′ 33.6″ E	190	16	1.12	2.8 ± 0.2	6.5 ± 0.5
SG22	Ladholi	28° 15′ 51.4″ N 077° 24′ 17.3″ E	189	12.2	1.24	2.3 ± 0.2	5.4 ± 0.4
SY23	Jawan	28° 14′ 03.8″ N 077° 23′ 38.7″ E	195	19.8	1.26	2.4 ± 0.2	5.7 ± 0.4
SG24	Mohna	28° 14′ 01.9″ N 077° 26′ 38.8″ E	189	11.3	1.19	2.7 ± 0.2	6.4 ± 0.5
SG25	Chhainsa	28° 15′ 20.8″ N 077° 27′ 24.4″ E	193	11.5	1.23	1.8 ± 0.2	4.1 ± 0.4
SY26	Naryala	28° 15′ 24.0″ N 077° 25′ 03.5″ E	201	11.9	1.24	2.3 ± 0.2	5.4 ± 0.4

Table 2 (continued)

Sample code	Village/town	GPS coordinates Latitude N Longitude E	Elevation (m)	Gamma level (μR h^{-1})	Bulk density (g cm^{-3})	Average thoron concentration (Bq m^{-3}) × 10^3	Thoron surface exhalation rate J_s (Bq m^{-2} h^{-1}) × 10^3
SG27	Narhawali	28° 16′ 12.9″ N 077° 25′ 13.5″ E	195	12	1.23	1.4 ± 0.2	3.3 ± 0.4
SG28	Sikri	28° 16′ 27.9″ N 077° 16′ 54.5″ E	196	11.4	1.16	1.9 ± 0.2	4.4 ± 0.4
SG29	Sahupura	28° 16′ 40.0″ N 077° 17′ 46.4″ E	199	11.5	1.04	3.6 ± 0.2	8.3 ± 0.5
SG30	Jajru	28° 17′ 28.7″ N 077° 18′ 57.9″ E	186	9.8	1.06	2.5 ± 0.2	5.9 ± 0.5
SG31	Fajupur Neemka	28° 22′ 24.6″ N 077° 21′ 54.4″ E	192	12.9	1.06	3.1 ± 0.2	7.2 ± 0.5
SB32	Mirjapur	28° 21′ 44.3″ N 077° 20′ 46.6″ E	192	16	0.9	2.9 ± 0.2	6.9 ± 0.5
SG33	Neemka	28° 21′ 33.5″ N 077° 21′ 48.1″ E	192	11.3	1.13	2.1 ± 0.2	4.8 ± 0.4
SG34	Kheri Kalan	28° 23′ 41.8″ N 077° 22′ 35.7″ E	193	11.1	1.02	2.1 ± 0.2	4.8 ± 0.4
SG35	Prhladpur	28° 23′ 08.8″ N 077° 20′ 32.8″ E	188	10.4	1.22	2.2 ± 0.2	5.1 ± 0.4
SG36	Bhatola	28° 23′ 37.5″ N 077° 21′ 52.1″ E	199	10.9	1.13	1.5 ± 0.2	3.5 ± 0.4
SG37	Faridpur	28° 25′ 59.5″ N 077° 22′ 33.3″ E	193	11.2	1.02	2.5 ± 0.2	5.9 ± 0.5
SG38	Samaypur	28° 19′ 07.6″ N 077° 17′ 01.01″ E	192	13.6	1.11	2.4 ± 0.2	5.5 ± 0.5
SG39	Karnera	28° 18′ 570.5″ N 077° 16′ 02.3″ E	203	16.3	1.3	1.9 ± 0.2	4.4 ± 0.4
SB40	Pawta	28° 22′ 36.8″ N 077° 12′ 18.4″ E	219	12.2	1.31	1.5 ± 0.2	3.5 ± 0.4
SG41	Sirohi	28° 10′ 3.0″ N 077° 10′ 44.4″ E	190	13.1	1.24	2.0 ± 0.2	4.7 ± 0.4
SY42	Kabulpur Banger	28° 17′ 33.8″ N 077° 14′ 24.1″ E	192	15.2	1.23	2.8 ± 0.2	6.5 ± 0.4
SG43	Aalampur	28° 19′ 37.4″ N 077° 11′ 13.9″ E	200	13	1.39	2.4 ± 0.2	5.6 ± 0.5
SG44	Pali	28° 22′ 27.3″ N 077° 14′ 10.04″ E	197	11.9	1.3	3.0 ± 0.2	7.0 ± 0.5
SG45	Pakhal	28° 21′ 57.6″ N 077° 13′ 5.0″ E	202	12.2	1.2	2.7 ± 0.2	6.4 ± 0.5
SY46	Jakopur	28° 18′ 22.7″ N 077° 12′ 03.8″ E	196	13.7	1.13	2.0 ± 0.2	4.7 ± 0.5

SG clayey (gray) soil sample, *SB* black soil sample, *SY* yellow soil sample

The highest radon mass exhalation rate was found in sample SG03 (62 ± 4 mBq kg^{-1} h^{-1}) of village Machgarh. The higher level of radon mass exhalation rate might be due to appreciably enriched radium contents in soil of this region. The highest thoron surface exhalation rate was found to be 10,167 ± 606 Bq m^{-2} h^{-1} from soil sample (SG02) collected from village Chandawali.

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 ^{232}Th in the northern part of India which was shown in the radiation profile map of India.

A poor positive correlation was observed between the outdoor gamma level and radon exhalation rate with correlation coefficient R = 0.1 and with correlation coefficient R = 0.1 between outdoor gamma exposure and thoron exhalation rate.

The radon mass exhalation rate and thoron surface exhalation rate in different colour soil samples is found maximum in clayey (gray) and minimum in yellow soil samples.

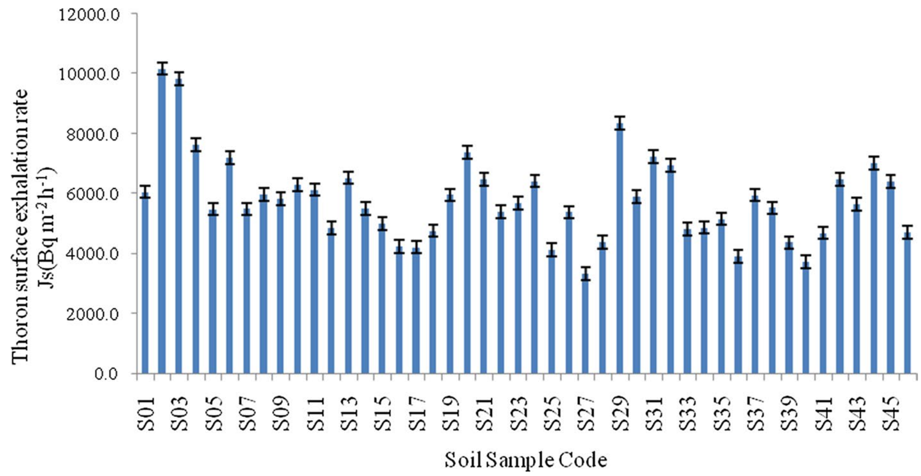


Fig. 6 Graphical representation of variation in thoron surface exhalation rate in soil samples of district Faridabad, Haryana, India

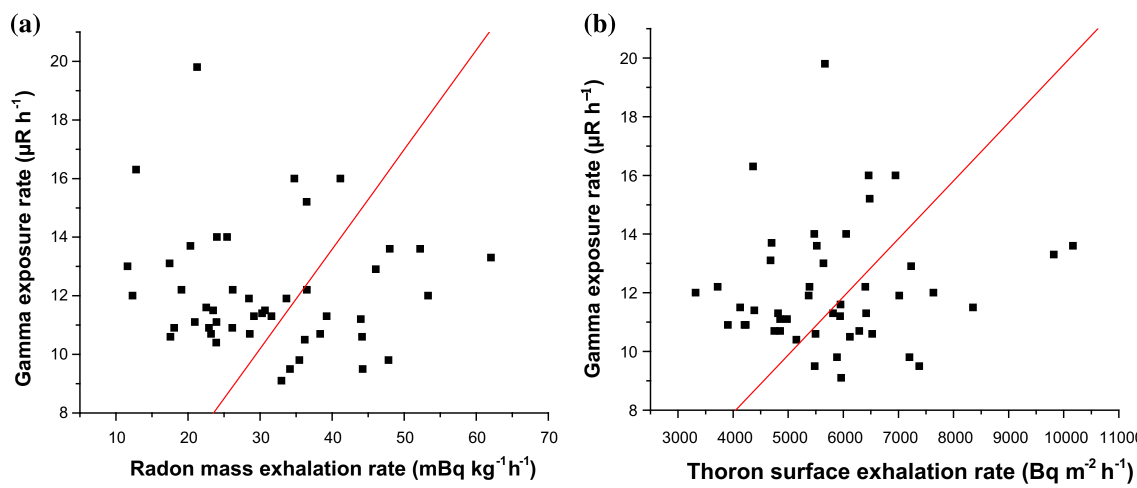


Fig. 7 **a** Distribution of gamma exposure rate with radon mass exhalation rate and **b** distribution of gamma exposure rate with thoron surface exhalation rate in different soil samples of district Faridabad, Haryana, India

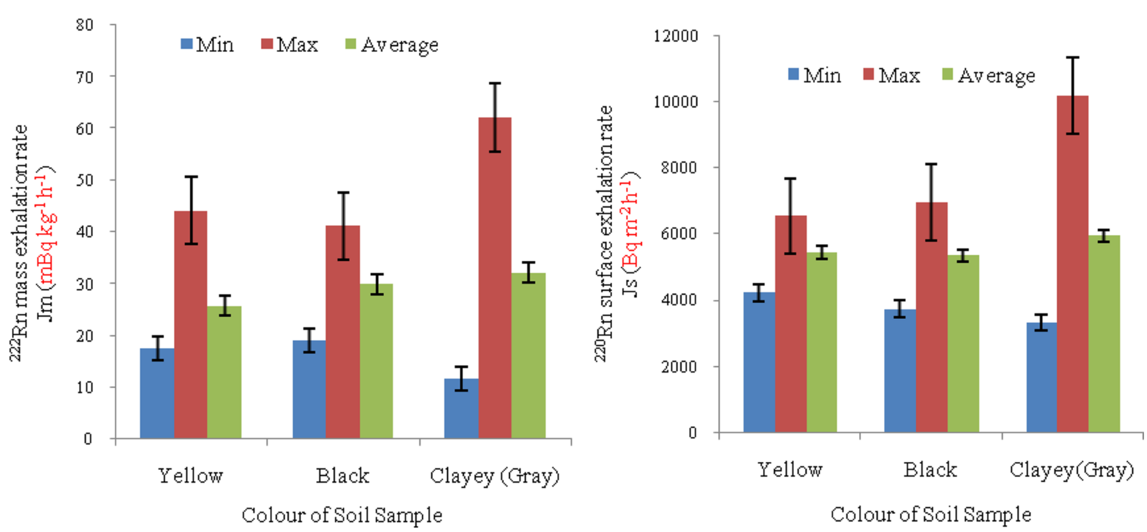


Fig. 8 Graphical representation. **a** Variation of radon mass exhalation rate in different colour soil samples and **b** variation of thoron surface exhalation rate in different colour soil samples of district Faridabad, Haryana, India

The data of this investigation can be use as standard data for radionuclide mapping. It is realized that the soil from the various geological locations can be used for construction material.

Acknowledgements The authors are thankful to Board of Research in Nuclear Sciences (BRNS), Department of Atomic Energy (DAE), Government of India, for extending financial assistance vide Project No.(36(4)/14/2014-BRNS/36018) dated 26/02/2016 for carrying out this work.

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