Indian Journal of Pure & Applied Physics
Vol. 62, January 2024, pp. 58-64
DOI: 10.56042/ijpap.v62i1.2599

The Study on Effect of Meteorological Parameter and Influence of Forest on Atmospheric Radon Concentration in the Shankaraghatta Forest Environment

Sandeep Dongre[a], Madhura R[a], Sunilkumar[a,b] & Sannappa J[a*]

[a]Department of PG Studies and Research in Physics, Kuvempu University, Shankaraghatta, Jnana Sahayadri 577 451, India

[b]Department of Physics, S.S Arts College and T.P. Science Institute, Sankeshwar 591 313, India

Received 13 June 2023; accepted 4 October 2023

The spatial and temporal variations of radon concentration and meteorological parameters were measured in and around the Kuvempu University campus, situated in the Western Ghats of Shankaraghatta forest environment is measured by active technique using Scintillation cell and the meteorological parameters measured using Automatic Weather System (AWS. The activity concentration of radium in soil is determined by Gamma-ray spectrometer with NaI (Tl) detector. The measured data of the present study shows that the built-up environment and forest ecosystem have enhanced the natural radiation level. The variation of atmospheric radon concentration is depends on meteorological parameters, geographical and geophysical parameters. The diurnal variation shows the maximum concentrations were noticed in the early morning and minimum during afternoon. The seasonal variation shows maximum concentration during winter season and minimum during the summer season. These variations were mainly depending on meteorological parameters. The correlation between the radon concentration and the meteorological are discussed and presented in this paper. The present study was aimed to establish a base-line data of Annual effective dose equivalent (AED). The diurnal, seasonal variations in different environmental conditions were discussed and presented in this paper.

Keywords: Atmospheric radon concentration; Metrological parameters; Diurnal and seasonal variation; Built-up environment and forest ecosystem; Annual effective dose equivalent (AEDE)

1 Introduction

Radon is a radioactive inert gas produced by disintegration of ^{226}Ra, it's a decay product of ^{238}U decay series. It is present in varying amount in soil, rock, air water and building materials[1,2]. Its concentration mainly depends on meteorological parameters, geographical, geophysical parameters and exhalation rate of soil and building materials[3,4]. The half life of radon is 3.82 days decays into short lived and long lived progeny which are the most significant for health hazard from the natural sources[5]. The international organizations such as USEPA, ICRP, UNSCEAR, IARCWHO and several studies have reported radon is carcinogenic and is second leading cause for lung cancer[6]. Radon is listed as the sixth environmental risk factor for human health in 2019 by a special Lancet journal research[7]. Apart from the negative health effect, it has useful applications in various fields such as Earth science, exploration of uranium, atmospheric air mixing, atmospheric electricity, rock burst, and volcanic, underground water discharge global warming[8]. During the rainfall radon gas present in soil is dissolved in water and percolates into different layers and collected as high concentration in ground water[9]. The trees and vegetations in the forest ecosystem absorbs the radon gas present in groundwater, pores of the soil, voids, fractures and joints of the earth crust along with the green house gases(CO_2, methane (CH_4) and (N_2O) nitrous oxide) through the roots and later released the radon gas, oxygen and water vapours through the stems and leaves[10,11,12,13]. The Kuvempu University was established in this forest area and it consists of different types of buildings, including departmental blocks, hostels, banks, guest houses, and Teachers quarters, as well as well-constructed roads and interlocks footpaths. The roads and footpath interlocks covers 30% to 40% of campus land. The total number of students, workers and faculty members reside in the campus are about 3500[14]. The material used for the construction of buildings and roads mainly consists of gray granitic rocks, M-sand, Cement and tar. These materials contain higher activity of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K)[14]. Therefore this area is well suitable for understanding the influence of built-up environment and forest

*Corresponding author: (E-mail: sannappaj2012@gmail.com)

ecosystem on radon concentration therefore due to this importance this area is selected for the study. This study is useful to understand the prevention and remedial action to reduce the radon concentration by the artificially human construction of roads buildings and interlocks of footpaths and also to identify the contaminants and relative parameters for influence of enhanced the radon concentration.

This is the first systematic study in this area no such type of study was carried out; it will be certainly a baseline data for future studies. Therefore to understand the effect of man-made construction of footpath interlock roads and buildings are influence on atmospheric radon concentration. In view of this importance the study area is selected.

The study area Shankaraghatta forest environment including the Kuvempu University lies in south- west part of Karnataka between75°39’ 30’’ East longitude and 13°45’30’’ North latitude as shown Fig. 1 (a-c) and the details of the study area was already published by Dongre S *et al*. 2022(14).

2 Methodology

To understand the variation of radon concentration for each location, to measure the radon concentration near the building covered by interlocks, thick trees and tar roads. Some of the villages are selected for the study around this university campus for the measurement of atmospheric radon concentration because of the different environmental conditions. Some villages are covered by thick forest and areca nut plantation and other villages are less trees without areca nut plantation. For the accurate estimation of radon concentration, and its variation, to measure the radon concentration at different time intervals in early in the morning, afternoon, evening and mid-night of a day. The average value of different intervals of time is taken and this was repeated for once in a week and four days within a month throughout the year, so that the pattern of its variation can be studied well. The active technique is used to measure the atmospheric radon concentration and this method involves scintillation cell and it is as shown in the Fig. 2.

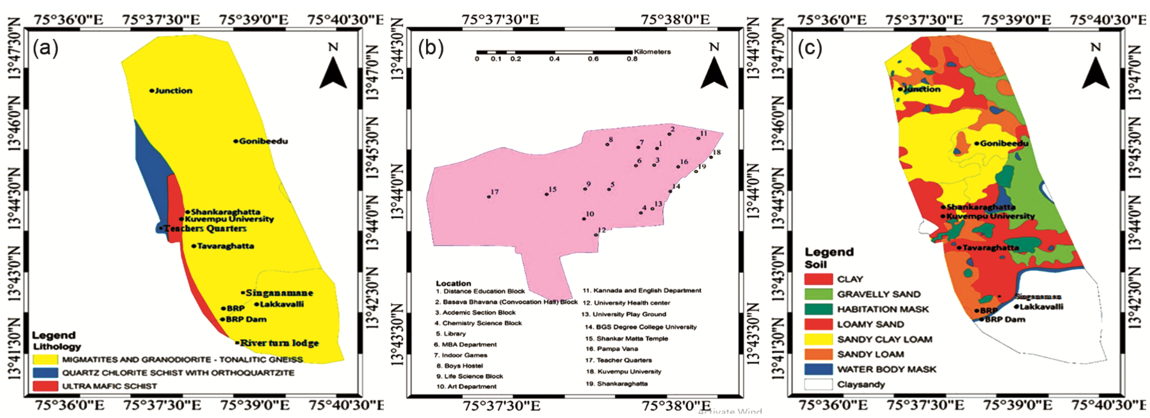

Fig. 1 — Geological map of Shankaraghatta forest environment.

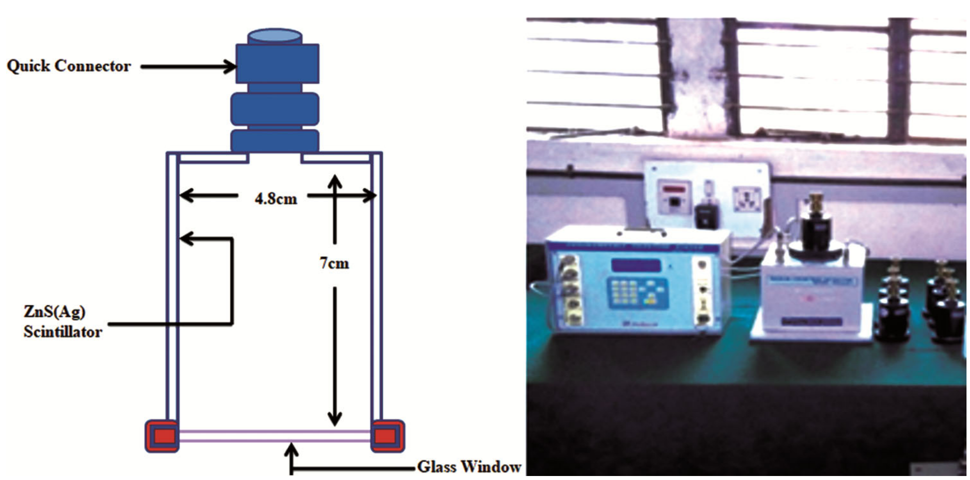

Fig. 2 — Schematic diagram of Scintillation cell and PMT assembly.

2.1 Scintillation Cell and Photomultiplier tube assembly

A portable device called Scintillation Cell, which is used for collecting and also for estimating the Radon (^{222}Rn) concentration, was used elsewhere[16]. The schematic diagram is as shown in Fig. 2. It consists of cylindrical chamber made up of aluminium and is coated with the ZnS(Ag) phosphor, as the alpha particles interact with this coating flashes of light is produced called scintillation and are detected and amplified with by the Photomultiplier mounted next to the glass window[17]. The sample is collected by evacuating the Lucas cell in the laboratory and the opening of the quick connector valve for sampling air at the site. Once the radon gas is filled in the Lucas cell, it is kept as such in a sealed cell to attain equilibrium with its daughters in about 3 hours after the collection time and then it is mounted to a photomultiplier. The entire counting system is made to determine the concentration of radon in the atmospheric air. The alpha counts obtained is coined as X; radon concentration Rn_C and is calculated as follows[16];

$$\mathrm{Rn_C(Bq.m^{-3})} = \frac{X}{3\times E\times t\times V\times e^{-\lambda\theta}} \quad \text{... (1)}$$

Where; $\mathrm{Rn_C}$ Radon concentration expressed in $(\mathrm{Bq.m^{-3}})$, X →Alpha counts obtained, E → is the counting efficiency= 0.74,t → is the counting period=17min,v → is the volume of the cell= $60(\mathrm{m^3})$, θ → is the delay time between sampling counting =10800 (sec), λ → is the decay constant of radon= $2.08\times10^{-6}(\mathrm{sec^{-1}})$.

The annual equivalent effective dose rate can be calculated by using equation provided in IARC1988, UNSCEARreports[1,18, 19].

$$\mathrm{AEDE_{Indoor}\,(mSv\,y^{-1}) = Rn_c\times I_f\times Eq_f\times C_f\times 24h\times 365\times 10^{-6}}$$
$$\mathrm{AEDE_{Outdoor}(mSvy^{-1}) = Rn_c\times O_f\times Eq_f\times C_f\times 24h\times 365\times 10^{-6}} \quad \text{... (2)}$$

Where; AED → Annual Effective Equivalent dose rate of radon, Rn_c→ Radon concentration expressed in$(\mathrm{Bq.m^{-3}})$, I_f → Indoor occupancy factor equal to 0.8, O_f →Outdoor occupancy factor equal to 0.2, Eq_f → Equilibrium factor *i.e.* 0.4, C_f → Conversion factor 9 nSv h^{-1} per Bqm^{-3}.

The meteorological parameters were recorded by A typical weather station that operates automatically is known as an automated weather station. AWS Plant was installed in the Kuvempu University campus, sponsored by the Bhabha Atomic Research Centre (BARC) Mumbai, India.

2.2 Soil Sample collection

Initially about 2 kg soil collected from each location of the study area, the soil samples are collected over a $0.5\mathrm{m}^2$ surface area, and once plants and roots have been removed, a location is marked. The marked spot was dug up to the depth of 15 cm, the sample extracted was crushed into the finest powdered form possible before being sieved through 500um (0.5mm) to remove the undesired debris and to remove the moisture content in the sample about 300g of samples are subjected to air dry for several days in it. The cleansed and sieved samples were then dried in an electric oven at temperature of 110 °C for 12 h make sure it has became moisture free and to achieve constant weight, thus formed powdered samples transferred to plastic containers and are stored in it, meanwhile care has taken that it is air tightened and are sealed externally using adhesive tapes. These homogenized samples were kept identical to that of reference materials as to their geometrical shapes, size and weight. Then kept aside for about a month (more than 7 times the half-lives of ^{222}Rn, and ^{224}Ra) at room temperature for to ensure that there exists an equilibrium between radium and its daughter products further more; before it is taken to analysis using gamma ray spectrometry[14]. The measurement of activity concentration of radium was carried out using the 3x3 NaI (Tl) gamma ray spectrometry and is studied elsewhere[14].

3 Results and Discussion

3.1 Effect of built-up environment

The radon concentration along with meteorological parameters was measured during the period of July 2021 to July2022 as given in the Table 1. The data from Table 1 shows that higher values of atmospheric radon concentration were found at the tar roads and interlocks locations very near to the buildings (Table 1). Slightly less radon concentration was found at interlock locations are away from the buildings (Table 1). This may be due to the fact that the materials used for the manufacturing of interlocks and for construction of roads such as grey granite rocks, cement and M-sands. Basically these constructive materials consist of higher activity of radionuclides[14,21]. Interlocks are porous materials; exhalation rate of radon is more[1,22,23]. And also the Activity of radium in the soil of these locations is also found to be slightly higher (Table 1). Higher radon concentration were found at the locations of the villages around the Kuvempu university but when the

Table 1 — Average radon concentration, activity of radium, meteorological parameters and annual effective dose in different locations of Shankaraghatta forest
(TRNB= tar road near building, TRAB= Tar road away from the building, INB= Interlocks near the buildings, IAB=Interlocks away from the building *L=3, 4, 5, 6- Number of Locations, SG= Sports Ground, TF= Thick Forest, LTF = Less Thick Forest, CR= Cement Road, MR= Mud Road, WFAP= With forest and areca nut plantation, WOF= Without Forest, MVM = more vehicle movement, LVM=Less Vehicle Movement)

SL. No	Locations with different environmental conditions	Average Outdoor Radon Concentration Bq m^{-3}	Activity of ^{226}Ra $Bqkg^{-1}$	Average Temperature in °C	Average Pressure (kPa)	Average Humidity in %	Average Wind Speed in m/s	Average Rain fall in cm	Average AEDE ($mSvy^{-1}$)
	Shankaraghatta Forest environment								
1	TRNB(L=5)	150.5 ± 10.5	16.7 ±2.4	32.8	939.9	85	1.7	1.8	0.95
2	TRAB(L=3)	112.5 ± 5.2	16.7 ±2.4	32.8	939.9	85	1.7	1.8	0.70
3	INB(L=5)	133.1 ± 6.2	15.4 ±1.5	26.2	939.7	80	1.7	1.8	0.84
4	IAB(L=2)	105.7 ± 4.6	15.4 ±1.5	26.2	939.7	80	1.7	1.8	0.66
5	SG(L=2)	50.4 ± 8.5	9.5 ± 1.6	24.0	934.2	65	2.6	1.8	0.32
6	TF(L=6)	117.7 ± 6.7	13.2 ±1.5	22.0	937.4	78	0.6	1.8	0.74
7	LTF(Open Place)(L=3)	72.5 ± 4.5	12.3± 2.0	23.6	936.6	72	0.9	1.8	0.45
	Villages around Shankaraghatta Forest environment								
8	TRNB	144.8 ± 8.8	15.5 ± 2.5	32.8	939.9	85	2.0	1.8	0.91
9	TRAB	110.4 ± 6.7	15.5 ± 2.5	32.8	939.9	85	2.0	1.8	0.69
10	CR	124.4 ± 9.2	10.6 ±2.4	29.0	938.8	75	2.0	1.8	0.78
11	MR	70.5 ± 7.4	08.2± 2.0	23.6	936.6	72	0.8	1.8	0.44
12	WFAP(L=4)	115.4 ± 7.1	10.3± 1.5	24.0	934.2	65	0.7	1.8	0.73
13	WOF(L=3)	68.7 ± 5.8	11.1 ±1.5	22.0	937.4	78	1.6	1.8	0.43
14	MVM	77.7 ± 6.5	10.7 ±0.5	25.2	936.4	65	0.7	--	0.49
15	LVM	143.1 ± 9.2	10.7 ±0.5	25.0	936.8	66	0.7	--	0.82
	Shankaramata Temple Hillock								
16	At the foot	82.50 ± 12.30	14.3±2.0	19.6	937.4	83	0.3	---	0.52
17	At the middle	105.50 ±15.05	14.3 ±2.0	19.8	937.4	83	0.5	---	0.67
18	At the top	62.80 ± 4.25	14.3 ±2.0	19.6	937.4	83	2.1	---	0.40

frequency of vehicle movement is very less but when the frequency of vehicle movement is more, the lower radon concentration was observed (Table 1). The vehicle movement dilutes the radon concentration. Slightly less radon concentration was observed at the locations consisting of cement road because the cement road is compactly packed compared to the tar road. Therefore the man made constructions enhanced the radon concentration.

3.2 Effect of forest environment

The forest ecosystem has influenced the radon concentration. The data from the Table 1 shows that the thick forest locations in the Kuvempu University campus and the villages around the university campus surrounded by the thick forest and areca nut plantations shown higher values of radon concentration. But slightly less compared to the tar road locations. The higher concentration is may be due to, the trees and the vegetation in the forest ecosystem absorbs the radon gas dissolved in underground water and also present in the soil porous, fractures, joints faults of the earth crust gets absorbed through the roots along with the green house gases and later release the radon gas, oxygen and water vapour through the stems and leaves[24,25,26]. Hence slightly high radon concentration was observed at these locations compared to less thick forest locations.

The lower concentration of radon was found in the university campus at the Sports Ground. These locations are covered with less trees and vegetation and the wind speed is recorded more at this locations. Also villages around Shankaraghatta without forest have shown lower radon concentration compared to the villages with forest. Moreover the geology of this area consists of rock system quarts chlorite schist and orthoquartzite, these rocks consists of mineral compositions such as quartz and epizoite, which contains lower activity concentration of radionuclides[14]. Hence it shows lower radon concentration.

There is a wide variation in radon concentration were observed at the different locations of the Shankaramata temple hillock (Table 1). The lower radon concentration was found at top of the hill Shankaramata temple. The temple is situated at the top of the hillock. The rock systems of this hill are comprised of gnesis, these rocks contains lower activity of radionuclides[14,19] and another reason is that at the top, the wind speed is higher compared to the bottom of the hills. At the middle of the hill, where the Ganesh temple was built and the space around the temple is covered by interlocks. The materials used for the construction of interlocks are granitic rocks and M-sand and cement, these materials consist of higher activity of radionuclides and the porosity of these materials may be high[14]. The bottom and middle of these locations are covered with thick trees and vegetations and hence they enhanced the radon concentration. In these places, the speed of the wind is low compared to top of the hillock (Table 1). Hence higher radon concentration is observed at the bottom and middle of the hill compared to top of the hill.

3.4 Diurnal variation of radon concentration along with the meteorological parameters

The diurnal variation of radon concentration with respect to different meteorological parameters at the different locations of Kuvempu University campus such as; tar road, interlocks, Thick forest, AWS near soil, Sports ground as given in Fig. 3. It is noted that air temperature, relative humidity, and atmospheric pressure all had a significant impact on radon concentration (Table 1). From the graph it can be seen that radon concentration was found to be maximum during early morning (4 to 6 hours) and decreases gradually, reaches its minimum value at afternoon (15hours). The radon concentration is found to decline at day time (10 to 15 hours) and then gradually increases, again reaches its maximum value during. This may be due to the fact that temperature

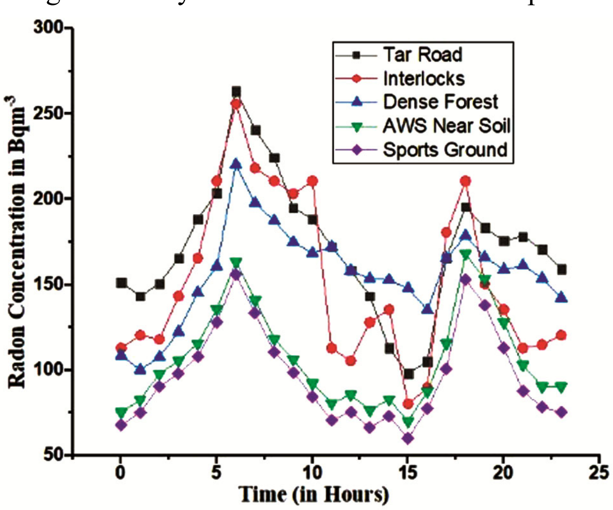

Fig. 3 — Diurnal variation of Radon concentration with respect to different time intervals of day.

inversion and change in atmospheric pressure will takes place in this period, due to the heating up of ground surface and low pressure during mid-night. Hence decrease in atmospheric radon concentration was noticed. Similar diurnal variation trend is observed at different locations of the study area.

Radon is a heavier gas and is unstable in atmospheric condition, it accumulates close to the ground surface during night time and early morning as the temperature, wind speed and humidity favours their concentration in the atmosphere[27,28]. During day time radon emitted from the ground can be diluted by turbulent eddy diffusion in the atmosphere caused by solar heating[29,30]. Furthermore, the atmospheric pressure will also changes during day and night (min during 7 to 15 hours and 20 to 23 hours , maximum during 1 to 6 hours and 16 to 19 hours), this will leads to a significant diurnal fluctuations of outdoor radon concentration. From the Fig. 3 it clearly shows that the radon concentration dependent on the meteorological parameters (Table 1). In all the five different locations similar pattern of variations in the radon concentration was observed except for the thick forest location during day time (10 to 15 hours). During this period, it will not reach to minimum but decreases and is higher than the other different conditions of the locations, it is almost stable and then later gradually increases, again reaches maximum concentration by evening (16 to 18 hours) (Fig. 3). This is may be due to less turbulence in the forest environment and due to the lack of solar radiation atmospheric air is not heated. The maximum radon concentration found at tar road locations, this may be due to the materials used to construction of the tar road consists of granite rocks and these rocks contains more radionuclides compared to other two location's soil. Clay shrinks and cracks when it dries, making dried clay soils porous[14,31]. But in the thick forest location slightly higher and almost stable radon concentration was observed during afternoon time (11 to 16 hours). Because in the thick forest location wind blows slowly and the temperature of this location is also less compared to the other locations (Table 1). Hence slightly higher concentration was observed during afternoon. The diurnal variation of radon concentration was observed less in the sport ground; this is because in the sport ground location the wind speed is higher than the other location (Table 1). Therefore man made construction plays prominent role in increase of radon concentration in the atmosphere.

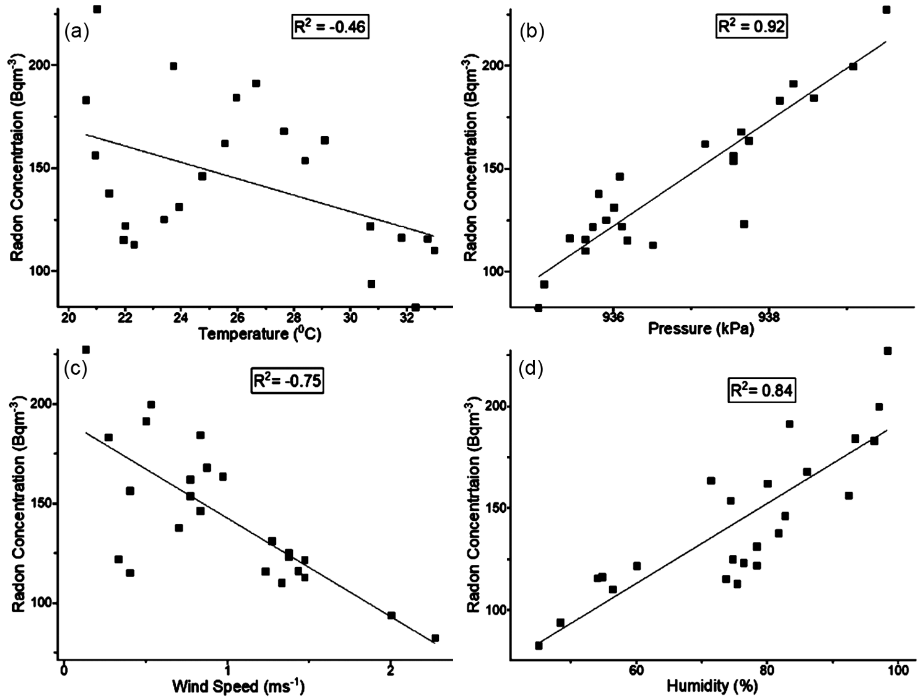

Fig. 4 — (a) Temperatiure v/s Radon Concentration (b) Pressure v/s Radon Concentration (c) Wind Speed v/s Radon Concentration (d) Humidity v/s Radon Concentration.

3.5 Correlations between atmospheric radon concentrations and meteorological parameters

Atmospheric radon concentration is influenced by temperature, this variation is as shown in Fig. 4(a) and as the ambient temperature increases, the radon concentration decreases hence weak and negative correlation is observed with a correlation coefficient of R^2 = -0.46. This was observed elsewhere Moses *et al*., (1960), Israel son *et al*., (1972), Pereira (1990), Butterweck *et al*. (1994), Nishikawa *et al*. (1995), and Dueˇnas *et al*. (1996).[32] Fig 4(a). Atmospheric pressure also shows good influence on the outdoor radon concentration. Radon concentration increases with increase in the atmospheric pressure, it has shown strong and positive correlation with correlation coefficient R^2 = 0.92 (Fig. 4(b)). Atmospheric radon concentration strongly influenced by the wind speed, as the wind speed increases the outdoor radon concentration decreases and also it shows a negative correlation with correlation coefficient of R^2= -0.75 and is as shown in Fig. 4(c). Humidity is one the major factor which greatly influence the atmospheric radon concentration from the graph (Fig. 4(d)) it is clearly that, atmospheric radon concentration increases with increase in the atmospheric humidity and it has shown strong and positive correlation with a correlation coefficient of R^2 = 0.84. Similar variations were noticed at all the locations of study area.

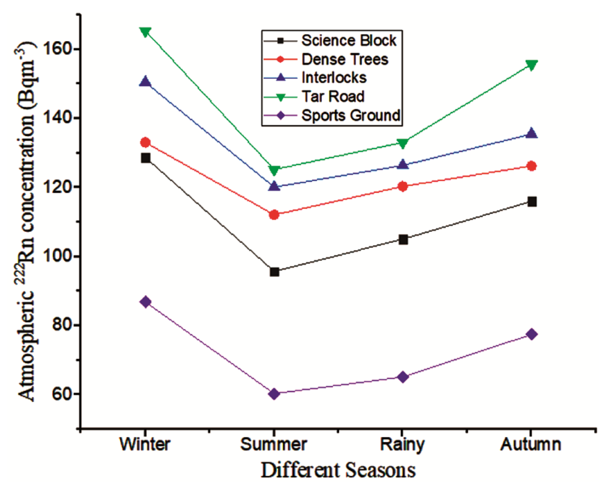

Fig. 5 — Seasonal variation of average atmospheric radon concentration at different environmental conditions.

3.6 Seasonal variation of atmospheric radon concentration at different locations

The seasonal variations of atmospheric radon concentration and meteorological parameters at the Chemical Science Block inside the campus are as shown in Fig. 5. The atmospheric radon concentrations were observed at different environmental conditions. From the graph it is observed that among the seasons; decrease in atmospheric radon concentration was observed in summer season. This may be due to turbulence and low moisture content in the atmosphere[33]. And in summer low transpiration of radon to atmosphere due to shading of leaves. Increase in atmospheric radon concentration during the winter and autumn was observed (Fig. 5). This is due to the fact that there is an increase in atmospheric pressure; it is essentially due to temperature inversions that occur during in these seasons (Fig. 5). During these seasons the transpiration of radon from soil by trees to atmosphere is more. And remain at a moderate level during the rainy season. During rainy season there is continuous rain fall and during this period emanation of radon is less and transpiration is more. Hence there slightly low atmospheric concentration compared to rainy season. Similar variations were observed in all locations of the study area.

4 Conclusions

The main conclusions of this research can be summarized as follows:

- The built-up environment such as man-made constructions, well planned roads, and interlocks has enhanced the atmospheric radon concentration.
- Forest ecosystem has shown a significant contribution in increasing the atmospheric radon concentration.
- The average atmospheric radon concentration of the study area found to be 103.21± 6.43$\mathrm{Bqm^{-3}}$, which is higher than the world average value 10$\mathrm{Bqm^{-3}}$[UNSCEAR][1].
- The average annual effective dose equivalent for atmospheric radon concentration is found to 0.64$\mathrm{mSv\ y^{-1}}$,which is higher than the global average value of (3-10 mSv) recommended by ICRP[34].
- Meteorological parameters and their correlation studies shown that the atmospheric radon concentration is influenced by them.

References

1 UNSCEAR 2019 report United Nations Scientific Committee on the Effects of Atomic Radiation. https://www.unscear.org/unscear/en/publications/2019.html.
2 Srinivasa E, Rangaswamy D R & Sannappa J, *J Geol Soc India*, 94 (2019) 100.
3 Sukanya S, Jacob N, & Sabu J, *Chemosphere*, (2022) 135141.
4 Sahu P, Panigrahi D C & Mishra D P, *Environ Earth Sci*, 75 (2016) 1.
5 Ćujić, Mirjana, *et al. Int J Biometeorol*, 65 (2021) 69.
6 Ponciano-Rodríguez G, *et al. Environ Geochem Health*, 43 (2021) 221.
7 Murray C J, Aravkin A Y, Zheng P, Abbafati C, Abbas K M, Abbasi-Kangevari M & Borzouei S, *The Lancet*, 396 (2020) 1223.
8 Das R & Mukherjee M, Earth Science in Environmental Management. In *Environmental Management: Issues and Concerns in Developing Countries*, Springer, Cham, (2021) 23.
9 Donelan J E, *Groundwater-Surface Water Interaction in the Kern River: Estimates of Baseflow from Dissolved Radon Analysis and Hydrograph Separation Techniques*. California State University, Long Beach.https://www.proquest.com/openview/2a3c23a0e416360d5f9d22967db54e00/1?pq-origsite=gscholar&cbl=18750, (2018).
10 Preston B L & Jones R N, *Climate change impacts on Australia and the benefits of early action to reduce global greenhouse gas emissions*, Canberra: CSIRO, (2006) 41.
11 Ye Y J, Xia X Q, Dai X T, Huang C H & Guo Q, *J Radioanal Nucl Chem*, 320 (2019) 369.
12 Sanjon E P, Maier A, Hinrichs A, Kraft G, Drossel B & Fournier C, *Sci Rep*, 9 (2019) 1.
13 Gavrilescu M, *Water*, 13 (2021) 2746.
14 Dongre S, Kumar S, Suresh S, Rangaswamy D R & Sannappa J, Assessment of natural radiation levels in the forest ecosystem of Shankaraghatta-Shivamogga District, (2022).
15 Fuente, Marta, *et al. Sci The Total Environ*, 695 (2019) 133746.
16 Raghavayya M, Iyengar M A R & Markose P M, Estimation of radium-226 by emanometry, (1980).
17 Sethy N K, *et al*. *J Radiat Res Appl Sci* 7 (2014) 475.
18 IARC International Agency for Research on Cancer, Summaries & Evaluations, 43 (1988).
19 Rangaswamy D R, Srinivasa E, Srilatha M C & Sannappa J, *Radiat Prot Environ*, 38 (2015) 154.
20 Ujjinappa B S, *et al*. *Environ Earth Sci*, 80 (2021) 1.
21 Reddy K U, Ningappa C & Sannappa J, *J Radioanal Nuclear Chem* 314 (2017) 2037.
22 Porter S W, Planning for and Management of Radiation Accidents. In *Handbook of Management of Radiation Protection Programs*, CRC Press, (2020) 193.
23 Gillieson D S, *Caves: processes, development, and management*. John Wiley & Sons, (2021).
24 Miklyaev P S, Petrova T B, Shchitov D V, Sidyakin P A, Murzabekov M A, Marennyy A M & Sapozhnikov Y A, *Appl Radiat Isot*, 167 (2021) 109460.
25 Vroom R J E, van den Berg M, Pangala S R, van der Scheer O E & Sorrell B K, *Aquatic Botany*, (2022) 103547.
26 Le Mer J & Roger P, *Eur J Soil Biol*, 37 (2001) 25.
27 Afreen S, Victor N J, Bashir G, Chandra S, Ahmed N, Siingh D & Singh R P, *J Atmos Sol-TerrestrPhysics*, 211 (2020) 105481.
28 Griffiths A D, Chambers S D, Williams A G & Werczynski S, *Atmospher Meas Tech*, 9 (2016) 2689.
29 Čeliković I, Pantelić G, Vukanac I, Krneta Nikolić J, Živanović M, Cinelli G & Rabago D, *Int J Environ Res Public Health*, 19 (2022) 662.
30 Jayaratne E R, Ling X & Morawska L, *Environ Sci Technol*, 45 (2011) 6350.
31 Ojovan M I, Lee W E & Kalmykov S N, *An introduction to nuclear waste immobilisation*, Elsevier, (2019).
32 Tchorz-Trzeciakiewicz D E & Solecki A T, *Geochem J* 45 (2011) 455.
33 Sannappa J, Paramesh L & Venkataramaiah P, *Indian J Phys* (1999).
34 International recommendation on radiological protection (ICRP ref 4836-9756-8598January 26, 2018https://www.icrp.org/.