



A Comprehensive Review of Radon Exhalation from Soil, Atmospheric Radon Concentration, Influencing Parameters, and Measurement Anomalies

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Abstract

Radon exhalation from soil and the ground surface has been extensively investigated worldwide using both active and passive measurement techniques. However, published studies report considerable variations in radon exhalation rates because of differences in measurement methods, environmental conditions, and geological characteristics. The present study critically compares these measurement techniques to identify the most reliable approach for estimating radon exhalation. An accumulation chamber coupled with the Lucas scintillation cell technique was employed to determine the radon exhalation rate from the ground surface and the corresponding outdoor atmospheric radon concentration. Simultaneously, meteorological parameters were continuously monitored using an Automatic Weather Station (AWS). The measured radon exhalation rate from the study area ranged from **1.06 to 5.80 mBq m⁻² s⁻¹**, with an average value of **3.86 mBq m⁻² s⁻¹**, which is considerably lower than the global average value of **26.2 mBq m⁻² s⁻¹** reported by UNSCEAR (2000). In contrast, the outdoor atmospheric radon concentration varied between **60.30 ± 2.50 Bq m⁻³** and **173.20 ± 15.50 Bq m⁻³**, with a mean value of **123.07 ± 6.77 Bq m⁻³**, exceeding the global average of **10 Bq m⁻³** recommended by UNSCEAR. The average activity concentration of ²²⁶Ra in soil was **11.52 ± 1.619 Bq kg⁻¹**, which is below the worldwide average, whereas local building materials exhibited an average ²²⁶Ra activity concentration of **48.53 ± 1.99 Bq kg⁻¹**, exceeding the corresponding global reference value.

The influence of meteorological variables on radon exhalation and atmospheric concentration was evaluated through detailed analyses of diurnal and seasonal variations. The results further demonstrate that both forest vegetation and built-up environments significantly affect radon release from the ground and its accumulation in the surrounding atmosphere.

Keywords: Radon exhalation rate; Accumulation chamber; Lucas scintillation cell; Gamma-ray spectrometry; Meteorological parameters; Diurnal variation; Forest ecosystem.

Introduction

Radon (²²²Rn) is a naturally occurring radioactive noble gas generated during the decay of uranium and thorium series radionuclides, primarily ²³⁸U, ²³⁵U, and ²³²Th, which are widely distributed in rocks, soils, and building materials [1,2]. Since its discovery by **F. E. Dorn** in 1900, radon and its short-lived decay products have attracted considerable scientific attention because of their environmental and health significance [3]. Exposure to radon constitutes the largest component of natural background radiation received by humans. According to reports published by UNSCEAR, USEPA, BEIR, ICRP, WHO, and several other research organizations, radon is classified as a human carcinogen and is recognized as the second leading cause of lung cancer after tobacco smoking [4]. Accurate estimation of radon exhalation from the ground and its concentration in the atmosphere is essential for evaluating environmental radiation exposure and associated health risks. Radon originates from the radioactive decay of ²²⁶Ra present in soil, rocks, and construction materials. During

alpha decay, recoil energy enables newly formed radon atoms to escape from mineral grains into pore spaces and fractures within the soil [5]. These atoms subsequently migrate to the atmosphere through diffusion and advection, a process referred to as **radon exhalation**. The exhalation rate is governed by several factors, including the activity concentration of ^{226}Ra , soil characteristics, geological conditions, and prevailing meteorological parameters [6].

Environmental characteristics such as vegetation cover and urban development can also influence radon transport and accumulation. The present investigation was conducted in the **Shankaraghatta forest ecosystem**, where **Kuvempu University** is located. The campus comprises numerous academic buildings, residential quarters, paved roads, and interlocking footpaths occupying nearly **30–40%** of the land area. Approximately **3,500** students, faculty members, and staff reside within the campus. Construction materials used throughout the campus, including granite, manufactured sand (M-sand), cement, and bituminous road materials, contain measurable concentrations of naturally occurring radionuclides such as ^{226}Ra , ^{232}Th , and ^{40}K [7]. Consequently, the combined influence of natural geological formations and anthropogenic construction creates a distinctive built-up environment that may alter radon exhalation and outdoor radon concentration. The coexistence of dense forest vegetation and extensive infrastructure within the study area provides an ideal setting for investigating the effects of both natural and human-induced environmental conditions on radon behavior. Understanding these influences is important for identifying the factors responsible for elevated radon levels and for developing appropriate mitigation strategies to minimize radiation exposure. To the best of our knowledge, no comprehensive investigation has previously examined radon exhalation rates and atmospheric radon concentrations in the Shankaraghatta forest ecosystem. Therefore, the present study establishes baseline radiological data that will support future environmental monitoring and radiation protection studies in this region.

Study Area

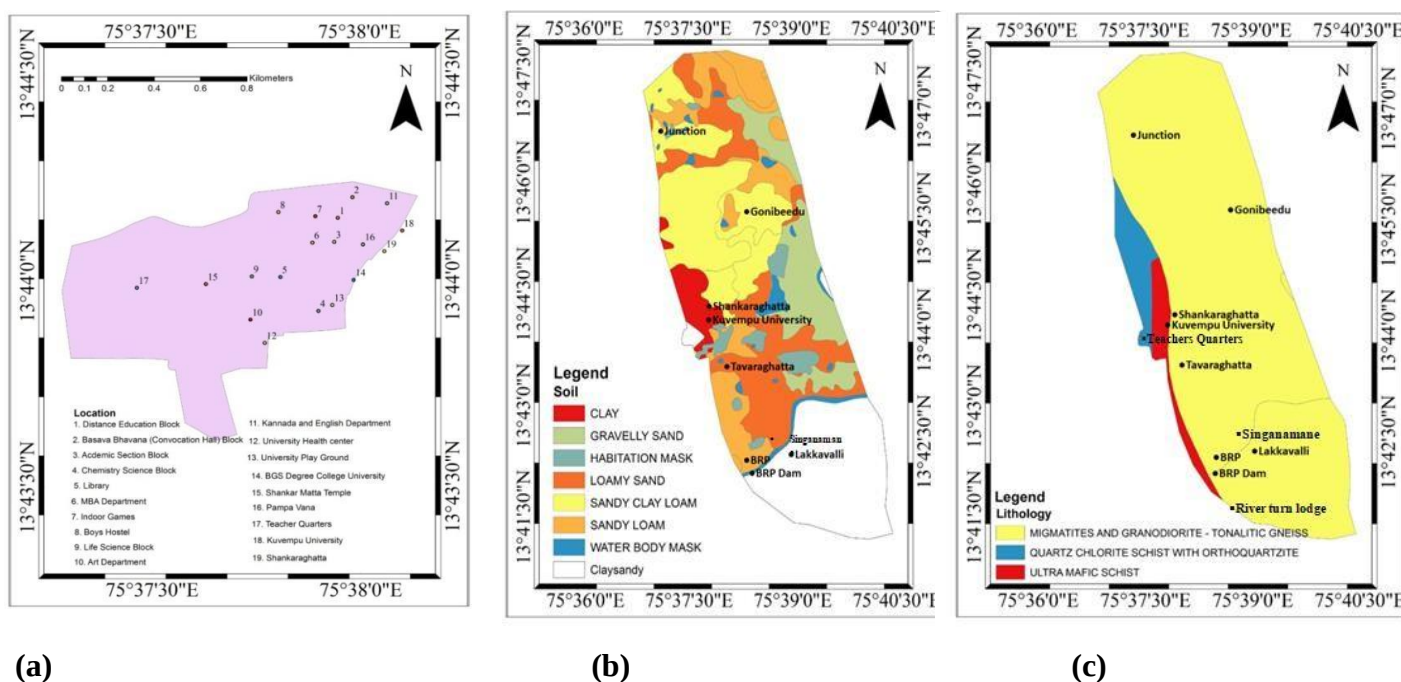


Fig (a,b&c). Geological map of the Shankaraghatta forest ecosystem

The present investigation was carried out in the **Shankaraghatta forest ecosystem**, which includes the **Kuvempu University** campus, situated in the south-western part of Karnataka, India, between **75°39'30" E longitude** and **13°45'30" N latitude**. The geographical location of the study area is illustrated in **Fig. 1(a–c)**. The region is characterized by undulating hills, rich natural heritage, and remarkable biodiversity, making it one of the ecologically important landscapes of the Western Ghats. Its elevated terrain, grassy hillocks, and extensive forest cover provide a favourable habitat for numerous endemic plant and animal species.

Administratively, the study area extends across the **Shivamogga** and **Chikkamagaluru** districts. It encompasses the densely forested high-altitude Malnad region in the west and the comparatively less forested semi-Malnad tablelands in the east. To investigate the spatial variation of radon exhalation and outdoor radon

concentration, the study region was divided into three distinct zones based on geological characteristics, vegetation density, land cover, and the degree of urban development.

The first zone is predominantly underlain by **migmatite** and **granodiorite** rock formations. The second zone mainly consists of **ultramafic schist**, surrounded by dense forest and hilly terrain ^[7]. The third zone comprises **quartz, dolerite, schist, and orthoquartzite** formations and is also characterized by extensive forest cover and elevated topography. The dominant soil types identified in the region include **clay, brown clay loam, and red sandy clay loam** ^[7]. These geological and soil characteristics are expected to favour relatively higher radon release from the subsurface and may also contribute to elevated radon concentrations in groundwater. The Shankaraghatta region falls within **Bhadravathi Taluk** and supports a population of approximately **13,000**. It serves as an important educational centre, with Kuvempu University accommodating nearly **3,500 students** and about **600 teaching and non-teaching staff members** ^[7]. The coexistence of natural forest ecosystems and modern infrastructure makes this area particularly suitable for studying the influence of geological, environmental, and anthropogenic factors on radon exhalation and atmospheric radon concentration.

1. Methodology

Radon exhalation from the ground and its atmospheric concentration can be measured using both **active** and **passive** techniques ^[8]. Passive methods, commonly referred to as the **can technique**, employ **Solid State Nuclear Track Detectors (SSNTDs)** for measuring radon concentration and exhalation from soil samples ^[9]. Although this technique is widely used, it has certain limitations. Back diffusion of radon within the chamber and the limited interaction of emitted alpha particles with the detector may lead to underestimation of the actual exhalation rate.

In the present investigation, an **active accumulation chamber method coupled with the Lucas scintillation cell technique** was adopted to determine radon exhalation from the ground surface and soil, as well as the corresponding atmospheric radon concentration. This method permits continuous and time-dependent measurements while simultaneously recording meteorological parameters, which is difficult to achieve using passive techniques.

A major advantage of the accumulation chamber method is that measurements can be performed directly on the ground surface and building materials without disturbing their original physical characteristics. In contrast, passive methods generally require soil samples to be collected, crushed, and sieved before analysis, thereby altering their natural structure and potentially affecting the measured exhalation rate. Consequently, the accumulation chamber technique provides a more realistic estimation of radon release under natural field conditions and is considered more suitable for environmental radon investigations.

1.1 Measurement of Atmospheric Radon Concentration

Atmospheric radon concentration was determined using a portable **Lucas scintillation cell**, a well-established instrument for collecting and measuring ²²²Rn activity ^[10]. A schematic representation of the experimental arrangement is shown in **Figure 1**. The detector consists of a cylindrical aluminium chamber internally coated with **ZnS(Ag)** scintillation phosphor. When alpha particles emitted by radon and its short-lived progeny strike the phosphor coating, scintillation flashes are produced. These light pulses are detected and amplified by a **photomultiplier tube** mounted adjacent to the optical window ^[10].

Prior to field sampling, the Lucas cell was evacuated in the laboratory to remove residual gases. At the sampling site, atmospheric air was drawn into the evacuated cell through a quick-connect valve. Following sample collection, the cell was sealed and stored for approximately **three hours** to allow radioactive equilibrium to be established between radon and its decay products. Subsequently, the scintillation cell was connected to the photomultiplier-based counting system, where alpha emissions were recorded.

The measured alpha counts, represented by **X**, were used to calculate the atmospheric radon concentration (**RnC**) according to the following relationship:

$$\text{RnC(Bqm-1)} = \frac{X}{3 X E X t X V X e^{-\lambda \theta}} \dots\dots\dots(1)$$

where:

- **RnC** = Atmospheric radon concentration (Bq m⁻³)
- **X** = Recorded alpha counts
- **E** = Counting efficiency (0.74)
- **t** = Counting duration (17 min)
- **V** = Volume of the Lucas cell (60 mL)

- θ = Delay time between sample collection and counting (10,800 s)
- λ = Decay constant of radon ($2.08 \times 10^{-6} \text{ s}^{-1}$)

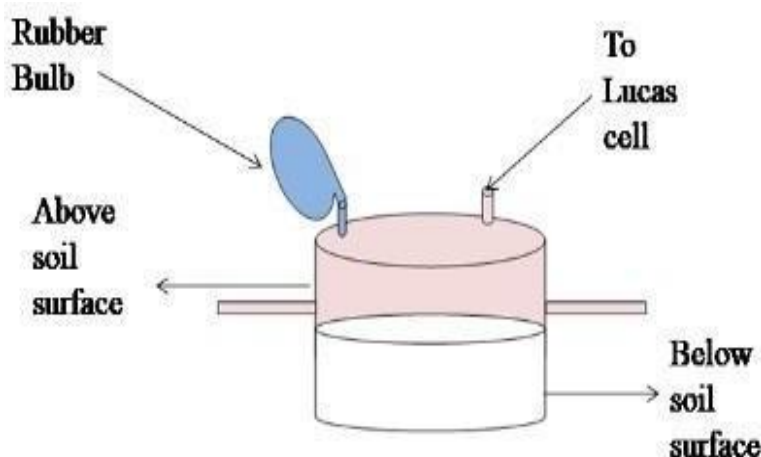
This procedure enables accurate determination of outdoor radon concentration while accounting for radioactive decay occurring during the interval between sample collection and measurement.

1.2 Measurement of Radon Exhalation Rate

The radon exhalation rate from the ground surface was determined using the **accumulation chamber method** coupled with a **Lucas scintillation cell** ^[12]. The measurement procedure consisted of four sequential stages:

1. Collection of radon gas released from the ground surface inside an accumulation chamber.
2. Transfer of the accumulated radon gas from the chamber to the Lucas scintillation cell.
3. Measurement of radon concentration in the Lucas cell.
4. Determination of the radon exhalation rate using the measured radon concentration.

The experimental arrangement used for radon collection is illustrated in **Figure 1a**.



1a. Accumulation Chamber

The accumulation chamber was fabricated from a cylindrical metallic vessel having a diameter of **30 cm** and a height of **30 cm**. During field measurements, the open end of the chamber was inserted approximately **15 cm** into the ground to obtain an airtight seal and prevent leakage of radon gas.

The upper surface of the chamber contained two ports. One port was connected to a rubber bulb, which was periodically operated to ensure uniform mixing of the accumulated air within the chamber. The second port served as the outlet for transferring the collected radon gas into the evacuated Lucas scintillation cell for subsequent measurement.

To optimize the experimental conditions, preliminary investigations were carried out using accumulation chambers of different volumes. The objective was to identify a chamber volume that would maximize radon accumulation within a fixed sampling period while minimizing back diffusion. The variation of radon concentration with chamber volume is presented in **Figure 1a**.

Back diffusion becomes negligible when the radon concentration inside the chamber remains lower than that in the soil pore air. To satisfy this condition, the chamber volume was selected to be at least **eight times greater** than the volume of the Lucas scintillation cell, following the recommendation reported by Eappen et al. ^[13]. This configuration minimizes radon loss during sampling and improves measurement accuracy.

Figure 1a. Variation of Radon Concentration with Chamber Volume

The influence of accumulation time on radon concentration was also investigated through a series of preliminary experiments. Radon released from the soil was allowed to accumulate inside the chamber for different collection periods before being transferred to the Lucas cell. The corresponding variation of radon concentration with collection time is shown in **Figure 1b**.

Figure 1b. Variation of Radon Concentration with Collection Time

The experimental results indicated that radon concentration increased with accumulation time and reached its maximum at approximately **30 minutes**. Beyond this duration, a slight decline in concentration was observed, which has also been reported in earlier studies ^[13]. The reduction is mainly attributed to the onset of back diffusion. Therefore, an accumulation period of **30 minutes** was selected as the optimum sampling duration for all subsequent measurements.

After the 30-minute accumulation period, the collected air sample was transferred from the chamber to the Lucas scintillation cell, and the radon concentration was determined using the procedure described in Section 1.1.

The surface radon exhalation rate (J) was calculated from the measured radon concentration using the following equation ^[12]:

$$(\text{mBq m}^{-2} \text{s}^{-1}) = \text{RnC} \frac{X(V+v)}{A(1 - e^{(-\lambda t)})} \quad \dots\dots\dots(2)$$

where

- J = Radon exhalation rate ($\text{mBq m}^{-2} \text{s}^{-1}$)
- RnC = Radon concentration measured in the Lucas cell (Bq m^{-3})
- V = Volume of the accumulation chamber (m^3)
- v = Volume of the Lucas scintillation cell (60 mL)
- A = Area enclosed by the accumulation chamber (m^2)
- λ = Decay constant of radon ($2.08 \times 10^{-6} \text{s}^{-1}$)
- t = Radon accumulation time (s)

1.3 Annual Effective Dose Estimation

The **Annual Effective Dose Equivalent (AEDE)** due to radon exposure was calculated using the equations recommended by **UNSCEAR** and **IARC (1988)** ^[1,14].

For indoor exposure,

$$\text{AEDE Indoor (mSv y}^{-1}) = \text{RnC} \times \text{If} \times \text{Eqf} \times \text{Cf} \times 24\text{h} \times 365 \times 10^{-6} \dots\dots\dots(2a)$$

For outdoor exposure,

$$\text{AEDE Outdoor (mSv y}^{-1}) = \text{RnC} \times \text{Of} \times \text{Eqf} \times \text{Cf} \times 24\text{h} \times 365 \times 10^{-6} \dots\dots\dots (2b)$$

where

- **AEDE** = Annual Effective Dose Equivalent (mSv y^{-1})
- **RnC** = Radon concentration (Bq m^{-3})
- **IF** = Indoor occupancy factor (0.8)
- **OF** = Outdoor occupancy factor (0.2)
- **EqF** = Radon equilibrium factor (0.4)
- **CF** = Dose conversion factor (9nSv h^{-1} per Bq m^{-3})

These equations were used to estimate the annual radiation dose received by individuals due to exposure to atmospheric radon under both indoor and outdoor conditions.

2.0 Results and Discussion

2.1 Comparison of Different Techniques for Measuring Radon Exhalation Rate

Table 1 summarizes the radon exhalation rates reported from ground surfaces and soil samples in different parts of the world using a variety of active and passive measurement techniques. A comparison of these published results reveals considerable variation in the reported exhalation rates, indicating that the choice of measurement technique has a significant influence on the estimated values.

Studies employing the accumulation chamber method have reported radon exhalation rates ranging from **0.9 to 69.2 $\text{mBq m}^{-2} \text{s}^{-1}$** , with an average value of **18.83 $\text{mBq m}^{-2} \text{s}^{-1}$** . These measurements are generally consistent with the theoretical and experimental values recommended by **UNSCEAR**, suggesting that the accumulation method provides reliable estimates of radon release from the ground surface ^[15]. In contrast, studies based on the passive can technique have reported substantially lower exhalation rates, varying from **0.12×10^{-5} to 16.50 $\text{mBq m}^{-2} \text{s}^{-1}$** , with a mean value of only **1.62 $\text{mBq m}^{-2} \text{s}^{-1}$** . This average is considerably lower than the corresponding **UNSCEAR** reference values, indicating that the passive technique may underestimate the actual radon exhalation rate.

One of the primary reasons for this discrepancy is the occurrence of **back diffusion** during passive measurements. In the can technique, the detector remains sealed inside the chamber for an extended exposure period, typically about **three months**. As radon accumulates within the chamber, its concentration may eventually exceed that of the surrounding soil pore air, creating a concentration gradient that promotes the diffusion of radon back into the soil. This process reduces the amount of radon available for detection and consequently lowers the measured exhalation rate ^[16].

Another factor contributing to the underestimation is the detector geometry. Alpha particles emitted by radon possess energies between **4 and 10 MeV**, corresponding to an effective range of approximately **5–11 cm** in air ^[17]. If the separation between the detector and the soil sample exceeds this range, only a fraction of the emitted alpha particles will reach the detector surface, resulting in incomplete detection and an artificially low estimate of radon exhalation.

The combined effects of back diffusion and improper detector placement largely explain the lower exhalation rates reported using passive techniques. In comparison, the accumulation chamber method minimizes these limitations by optimizing chamber volume and sampling duration, thereby providing more representative measurements of radon released under natural field conditions.

Based on the comparative analysis presented in Table 1, the accumulation chamber method coupled with the Lucas scintillation cell is considered more appropriate for determining radon exhalation from both ground surfaces and soil samples. To obtain accurate measurements, particular attention should be given to minimizing back diffusion and maintaining an appropriate distance between the detector and the sample during experimental measurements.

2.2 Variation of Radon Exhalation Rate under Different Environmental Conditions in the Forest Ecosystem

2.2.1 Influence of the Built-up Environment on Radon Exhalation Rate and Atmospheric Radon Concentration

The Shankaraghatta study area is predominantly covered by dense forest; however, a considerable portion of this landscape has been developed as the Kuvempu University campus, comprising academic buildings, residential structures, paved roads, and interlocking footpaths. This combination of natural vegetation and man-made infrastructure forms a distinctive built-up environment within the forest ecosystem. The measured radon exhalation rate, atmospheric radon concentration, and associated meteorological parameters at different sampling locations in and around the university campus are summarized in **Table 2**.

The measured radon exhalation rate from the ground surface varied between **1.06 and 5.80 mBq m⁻² s⁻¹**, with an average value of **3.86 mBq m⁻² s⁻¹**. This average is considerably lower than the worldwide mean value of **26.2 mBq m⁻² s⁻¹** reported by **UNSCEAR (2000)**. In contrast, the outdoor atmospheric radon concentration ranged from **60.30 ± 2.50 Bq m⁻³** to **173.20 ± 15.50 Bq m⁻³**, with a mean concentration of **123.07 ± 6.77 Bq m⁻³**, which is substantially higher than the global average value of **10 Bq m⁻³** recommended by UNSCEAR.

The observations presented in **Table 2** indicate that the highest average radon exhalation rates and atmospheric radon concentrations were recorded over tar roads and interlocking footpaths. This behaviour can be attributed primarily to the construction materials used in these surfaces, including cement, crushed stone aggregate (jelly), and manufactured sand (M-sand). Since M-sand is produced by crushing granite rocks, these materials generally contain relatively higher concentrations of naturally occurring radionuclides, particularly ²²⁶Ra, ²³²Th, and ⁴⁰K, which act as sources of radon generation ^[18, 19].

The physical properties of these construction materials also influence radon release. Reduction in grain size increases the surface area available for radon escape, thereby enhancing the exhalation rate ^[20]. Furthermore, the porosity of the surface layer plays an important role in radon transport. Tar roads generally possess greater pore space than interlocking pavements and cement-concrete roads, where the materials are more densely compacted. The higher porosity facilitates radon migration through the surface, resulting in comparatively greater exhalation rates from tar roads. In addition, the thickness of the pavement has been reported to influence radon release, with thicker tar layers exhibiting relatively higher exhalation rates than thinner road surfaces ^[21].

A slightly lower radon exhalation rate was observed over interlocking footpaths located adjacent to buildings compared with similar interlocking surfaces situated farther from buildings (Table 2). Nevertheless, atmospheric radon concentration in these locations remained relatively high because construction materials themselves contribute additional radon to the surrounding environment. The magnitude of radon release from buildings depends on both the radionuclide content of the construction materials and their physical characteristics, particularly porosity and permeability.

Within the university campus, the principal construction materials include **granite, cement, cement bricks, stabilized soil bricks**, and **locally available sand**. These materials contain measurable amounts of naturally occurring radionuclides and therefore serve as supplementary sources of radon. Consequently, the built-up environment not only modifies the natural pathways of radon migration but also contributes additional radon from construction materials, leading to enhanced radon exhalation and elevated atmospheric radon concentrations compared with undisturbed ground surfaces.

2.3 Influence of Dense Forest Cover on Radon Exhalation and Atmospheric Radon Concentration

The results presented in Table 2 indicate that sampling locations situated within dense forest exhibited radon exhalation rates and atmospheric radon concentrations that were lower than those measured over tar roads and interlocking pavements, but higher than those recorded at locations with sparse vegetation within the university campus.

Radon exhalation is primarily controlled by the physical characteristics of the soil, particularly its porosity, permeability, and the activity concentration of ^{226}Ra . In densely forested regions, continuous interaction between tree roots, microorganisms, and soil particles alters the soil structure by increasing pore connectivity and permeability [22-24]. These modifications facilitate the migration of radon from subsurface layers to the ground surface, resulting in comparatively higher exhalation rates than those observed in open areas with limited vegetation.

The elevated atmospheric radon concentration in dense forest locations may also be associated with increased radon levels in groundwater and soil gas reported at greater soil depths [25]. Radon dissolved in groundwater or trapped within soil pores, fractures, joints, and geological faults can be absorbed by plant root systems. During physiological processes such as transpiration and gas exchange, vegetation may contribute to the release of radon together with water vapour and oxygen through stems and leaves. Consequently, the forest ecosystem appears to enhance both radon exhalation from the soil and its concentration in the surrounding atmosphere.

2.4 Radon Behaviour in Areas with Sparse Vegetation

Lower radon exhalation rates and outdoor radon concentrations were observed at locations such as the Automatic Weather Station (AWS) site, the playground, and the BGS sports ground, where vegetation cover is relatively sparse. The limited root activity in these areas produces minimal changes in soil porosity and permeability. Furthermore, the radionuclide content of the soil does not vary significantly across these locations [7]. These conditions restrict radon migration from the subsurface and therefore result in comparatively lower exhalation rates.

The lowest values of radon exhalation and atmospheric concentration were measured at Lakkavalli village and in the vicinity of the Bhadra Dam. These sites are characterized by irrigated agricultural land with a shallow groundwater table. Because the soil remains highly saturated with water, pore spaces become filled, reducing the diffusion of radon towards the ground surface [26]. The high soil moisture content therefore acts as an effective barrier to radon transport, resulting in the minimum exhalation rates recorded during the study.

2.5 Diurnal Variation of Radon Exhalation Rate

The diurnal variations of radon exhalation rate, atmospheric radon concentration, and associated meteorological parameters under different environmental conditions are presented in Figures 2, 3, and 4(a-c). In most locations, radon exhalation and atmospheric concentration increased during the late night (22:00–00:00 h) and early morning (04:00–07:00 h), while the lowest values were generally observed between 10:00 and 14:00 h. These fluctuations are mainly governed by temperature gradients that develop between the soil profile and the overlying atmosphere due to solar radiation.

During the night and early morning, deeper soil layers retain more heat than the surface, creating an upward thermal gradient that promotes convective movement of soil gas. This process enhances the upward transport of radon, leading to higher exhalation rates and increased atmospheric concentration. In contrast, during daytime the surface soil becomes warmer than the deeper layers because of solar heating [27]. Under these conditions, atmospheric mixing and turbulence increase, promoting dilution of radon near the ground surface and reducing the measured exhalation rate.

Soil moisture also plays a significant role in radon release [28]. Moisture surrounding soil particles increases the probability that recoiling radon atoms escape into pore spaces, thereby enhancing radon emanation. The final amount of radon available for exhalation depends on the balance between adsorption and desorption processes. As soil temperature rises, desorption becomes more pronounced, increasing the quantity of radon available for transport [29]. Consequently, radon exhalation is generally higher when deeper soil layers remain warmer than the surface and when soil moisture is within a favourable range.

Most sampling sites exhibited similar diurnal trends, with the exception of tar road and dense forest locations.

At tar road locations, the maximum radon exhalation rate occurred during the afternoon (approximately 14:00–16:00 h). Bituminous road surfaces absorb substantial solar radiation, producing elevated temperatures within the pavement layers. Combined with the relatively high porosity of the road material, low moisture content, fine particle size, and comparatively higher radionuclide activity of construction materials, these conditions favour enhanced radon release during daytime. During the night, however, increased atmospheric pressure and lower pavement temperatures resulted in a slight reduction in radon exhalation.

A different diurnal pattern was observed in dense forest areas (**Figure 4a**). Here, radon exhalation gradually increased from approximately 10:00 to 15:00 h, reaching its maximum during daytime. The dense tree canopy shades the ground surface, maintaining lower surface temperatures while deeper soil layers remain relatively warmer. This reversed temperature gradient promotes upward movement of soil gas and consequently increases radon exhalation during daylight hours. Thereafter, radon exhalation gradually decreased, reaching minimum values between 18:00 and 22:00 h, a trend opposite to that observed in open environments.

2.6 Influence of Meteorological Parameters

Meteorological variables significantly affect radon transport from the ground to the atmosphere and have been extensively investigated in previous studies ^[30].

Correlation analysis presented in **Figures 5a, 6a, and 7a** shows a **positive relationship** between ground temperature and radon exhalation rate, with coefficients of determination (R^2) equal to **0.54, 0.28, and 0.32**, respectively. These results indicate that increasing ground temperature generally promotes radon release.

Atmospheric pressure exhibited a **weak negative correlation** with radon exhalation (**Figures 5b, 6b, and 7b**), with R^2 values of **−0.20, −0.30, and −0.56**. Higher atmospheric pressure suppresses the upward movement of soil gases, thereby reducing radon exhalation, a phenomenon consistent with earlier investigations ^[31].

Relative humidity showed the strongest influence among the meteorological parameters studied. As illustrated in **Figures 5c, 6c, and 7c** and summarized in **Tables 3–5**, radon exhalation decreased with increasing atmospheric humidity, yielding strong negative correlations with R^2 values of **−0.79, −0.75, and −0.80**. Similar observations have been reported by earlier investigators, who found that radon exhalation decreases significantly when soil moisture exceeds approximately **8.3%** ^[31, 32].

2.7 Effect of Rainfall

The influence of rainfall on radon exhalation was investigated during **June and July 2022** at the **Chemical Sciences Block**, and the results are presented in **Table 3** and **Figure 8**.

The measurements clearly indicate that radon exhalation decreases immediately after rainfall because the upper soil layer becomes saturated with water ^[12]. Water occupying soil pores restricts radon diffusion and consequently reduces the amount of radon reaching the ground surface. As the soil gradually dries through evaporation, radon that had accumulated beneath the saturated layer is released, producing a temporary increase in exhalation. Eventually, radon exhalation returns to its normal level as soil moisture approaches equilibrium.

Rainfall also modifies atmospheric pressure and increases soil density, both of which further impede the migration of soil gases, including radon, toward the atmosphere (WHO, 2009). During the rainy season, continuous precipitation maintains high soil moisture, thereby reducing radon emanation from the ground. In addition, enhanced transpiration by vegetation contributes to lower atmospheric radon concentrations ^[17]. Similar seasonal behaviour was consistently observed at all sampling locations throughout the study area.

SL. No	Sample type	Method used	Originally measured unit of Surface Exhalation	Surface Exhalation in $\text{mBqm}^{-2}\text{s}^{-1}$	Country of origin	Reference
1	Ground Surface	Accumulation Method	51.6 to 69.2	51.6 to 69.2	Daegu, Korea	(34)
2	Ground Surface	Accumulation Chamber	80.7 $\text{Bqm}^{-2}\text{d}^{-1}$	0.9	Canada	(35)
3	Uranium ore	Static accumulation method (cumulative leaching)	0.95 $\text{Bqm}^{-2}\text{s}^{-1}$	950	China	(36)
4	Ground Surface	Accumulation (ZnS)	10.4 $\text{Bqm}^{-2}\text{s}^{-1}$	10.4	Japan	(37)

5	Ground Surface	Accumulation (ZnS)LLRDS	$7.37 \text{ mBqm}^{-2} \text{ s}^{-1}$	7.37	Mysore, India	(12)
6	Ground Surface	Accumulation	12 to 17	12 to 17	Japan	(38)
7	Ground Surface	Accumulation	$4 \text{ to } 37 \text{ mBqm}^{-2} \text{ s}^{-1}$	4 to 37	Japan	(39)
8	Ground Surface	Accumulation Alpha Guard	$9.16 \text{ to } 16.18 \text{ Bqm}^{-2} \text{ h}^{-1}$	2.54 to 4.66	Egypt	(40)
9	Ground sample	Different Methods	$16 \text{ mBqm}^{-2} \text{ s}^{-1}$	16	UNSCEAR 2010	(41)
10	Slab	Accumulation	0.05 to 1.5	0.05 to 1.5	Italy	(33)
11	Slab	Accumulation RAD-7	$0.018 \text{ to } 0.95 \text{ mBqm}^{-2} \text{ s}^{-1}$	0.018 to 0.95	Italy	(33)
12	Slab	Accumulation	$1.1 \text{ to } 8.8 \text{ mBqm}^{-2} \text{ s}^{-1}$	1.1 to 8.8	Japan	(42)
13	Soil Sample	Alpha Guard	8.7 to 19.6	8.7 to 19.6	Slovak Republic	(43)
14	Soil Sample	Can Technique CR-39	$52.2 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.015	Palestine	(44)
15	Soil Sample	SSNTD	$24.3 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.0067	Punjab, India	(45)
16	Soil Sample	Can Technique	$10.93 \times 10^{-5} \text{ Bqm}^{-2} \text{ day}^{-1}$	0.12×10^{-5}	Uttar Pradesh, India	(46)
17	Soil Sample	Can Technique	$464 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.12	Pakistan	(47)
18	Soil Sample	Can Technique	$257 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.071	Pakistan	(47)
19	Soil Sample	Can Technique	$495 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.137	Rajasthan India	(48)
20	Soil Sample	Can Technique	$114\text{-}416 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.031 to 0.115	Pakistan	(49)
21	Soil Sample	Can Technique	$28\text{-}1892 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.0077 to 0.52	Panipat, Haryana, India	(50)
22	Soil Sample	Can Technique	$338\text{-}1426 \text{ Bqm}^{-2} \text{ day}^{-1}$	3.91- 16.50	Egypt	(51)
23	Soil Sample	Can Technique	$38.7 \text{ mBqm}^{-2} \text{ h}^{-1}$	10.75	Iraq	(52)
24	Soil Sample	Can Technique	$1.32 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.36	Dharamsha la Himachal Pradesh	(53)
25	Soil Sample	Can Technique	$32.2 \text{ mBqm}^{-2} \text{ h}^{-1}$	-6 8.9×10	Ghana	(54)
26	Soil	CR-39 plastic	$4580 \text{ to } 8400 \text{ mBqm}^{-2} \text{ h}^{-1}$	1.27 to 2.33	Saudi Arab	(55)
27	Soil Sample	Sealed Can Technique	45.5×10^{-3}	-3 45.5×10	Mangalore, India	(55)
28	Soil Sample	Can Technique	$610 \text{ mBqm}^{-2} \text{ h}^{-1}$	0.16	Iraq (Baghdad)	(56)

29	Soil Sample	Can Technique	4860 $\text{mBqm}^{-2}\text{h}^{-1}$	1.35	Sudan (El-Hosh)	(57)
30	Soil Sample	Can Technique	288 to 936 $\text{mBqm}^{-2}\text{h}^{-1}$	0.08 to 0.26	Egypt (West)	(58)
31	Soil Sample	Can Technique	521.08 $\text{mBqm}^{-2}\text{h}^{-1}$	0.144	Mangalore, India	(59)
32	Soil Sample	Sealed Can Technique	-6 5.75×10	-6 1.59×10	Cairo, Egypt	(60)

Table 1. The radon exhalation rate in soil of the ground surface and soil samples studied all over the globe and reported by many researchers using various techniques

Location	Average Temperature in $^{\circ}\text{C}$	Average Pressure in Hecto Pascal	Average Humidity in %	Average Rain Fall in cm	Activity of ^{226}Ra Bqkg^{-1}	Average Radon Concentration in Bq m^{-3}	Radon Exhalation in $\text{mBqm}^{-2}\text{s}^{-1}$	AEDE mSv y^{-1}
Thick Tar Road	21.3	938.5	85	0.1	90.12 ± 2.15	155.75 ± 0.5	5.00 ± 1.75	6.26
Thin tar Road	21.4	938.6	84	0.1	90.12 ± 2.15	145.10 ± 2.10	3.90 ± 1.50	4.91
Thick Cement road	20.8	938.5	85	0.1	25.53 ± 0.50	133.45 ± 1.29	4.15 ± 0.89	5.22
Thin Cement road	21.0	939.0	84	0.1	25.53 ± 0.50	126.88 ± 0.89	3.76 ± 1.10	4.73
Chemical Science Block(Inter locks)	21.2	938.5	85	0.1	47.05 ± 0.57	143.10 ± 0.25	4.64 ± 1.25	5.83
Away from Buildings (Interlocks)	21.2	938.4	86	0.1	47.05 ± 0.57	135.25 ± 1.10	3.92	4.91
Near AWS Soil	21.0	938.5	85	0.1	7.45 ± 0.40	95.3 ± 1.2	2.65 ± 1.15	3.3
Playground	21.2	938.5	85	0.1	6.52 ± 0.40	80.5 ± 1.5	2.33 ± 1.55	2.93
Near Bhadra River Dam	19	938.5	85	0.1	10.20 ± 0.89	90.57 ± 0.75	0.47 ± 1.10	0.59
Lakkavalli	22	938.6	86	0.1	8.50 ± 0.81	115.5 ± 0.50	0.90 ± 0.57	1.13
Shanthinagara	21	939.2	88	0.1	9.10 ± 1.29	125.50 ± 1.29	2.30 ± 0.89	2.88
Shankarag hatta	21	940.0	86	0.1	9.50 ± 0.50	126.45 ± 1.5	2.40 ± 0.5	3.01
Dense Forest near (a)Tr. Quarters	20.2	938.5	85	0.1	9.50 ± 0.50	135.5 ± 0.6	3.93 ± 1.29	4.94
(b) Boys Hostel	20.6	938.6	86	0.1	10.55 ± 0.80	134.2 ± 0.25	3.84 ± 0.75	4.83
(c) Basava Bhavana opposite less tress	21	938.5	85	0.1	14.25 ± 2.40	112.9 ± 0.5	3.43 ± 0.57	4.32
(d) Dense trees Nudi loka	21	938.6	86	0.1	15.54 ± 1.10	130.10 ± 0.6	3.60 ± 0.25	4.47

Table 2. Radon Exhalation rate at different locations of study area in environmental conditions (June 2021-July 2022)

The diurnal variation of radon exhalation rate along with the meteorological parameters at the Sports ground are given in figure2 (a, b&c) (Moisture content in the

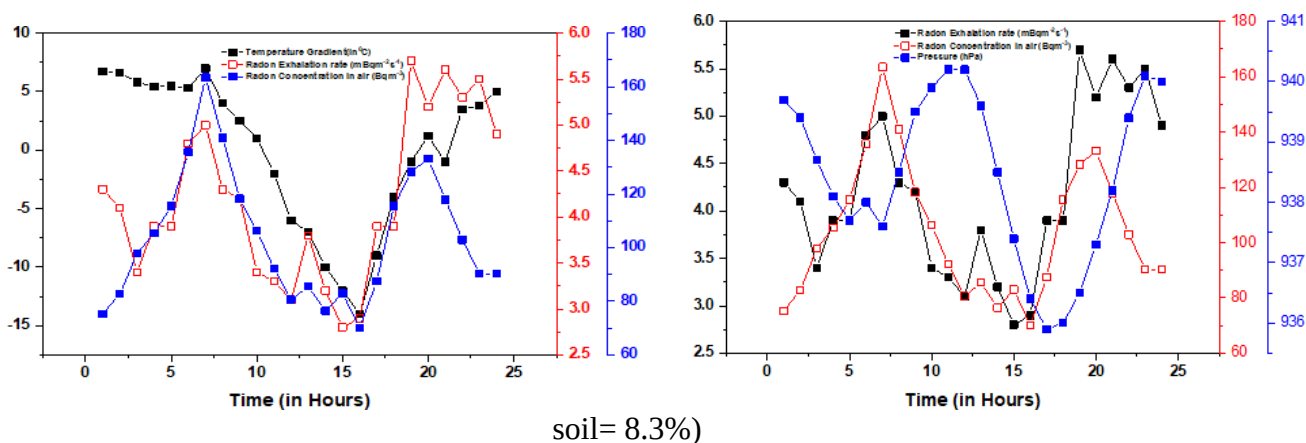


Fig2a. Radon exhalation rate v/s Temperature Gradient

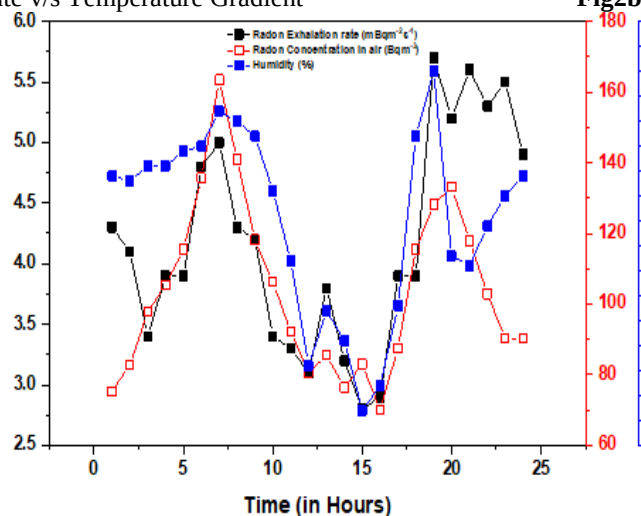


Fig2b. Radon exhalation rate v/s Pressure

Fig.2c. Radon Exhalation Rate v/s with humidity

The diurnal variation of radon exhalation rate and its concentration along with the meteorological parameters at Tar road of Kuvempu University are give in Figure 3(a,b&c).

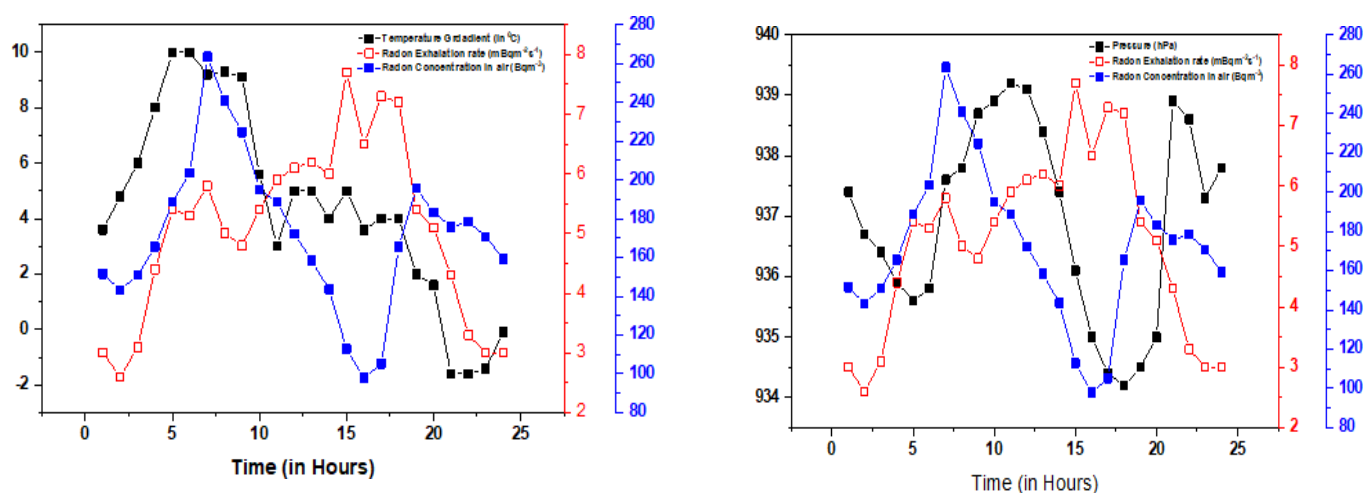


Fig 3a. Radon Exhalation rate v/s temperature Gradient

Fig 3b. Radon Exhalation rate v/s Pressure

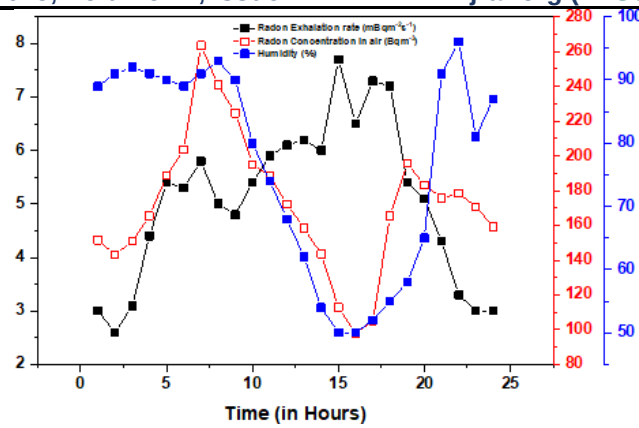


Fig3c. Radon Exhalation rate with Humidity

The diurnal variation of radon exhalation rate and its concentration in air at dense forest, Kuvempu university campus are given in **Figure 4(a,b&c)**

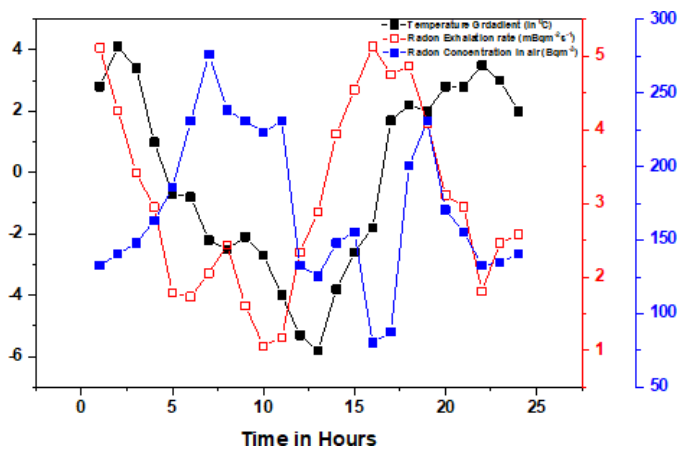


Fig4a. Radon Exhalation rate v/s Temperature Gradient

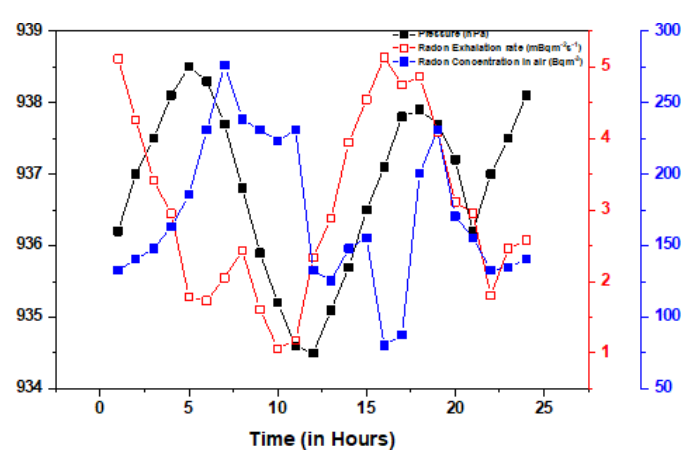


Fig4b. Radon exhalation rate v/s pressure

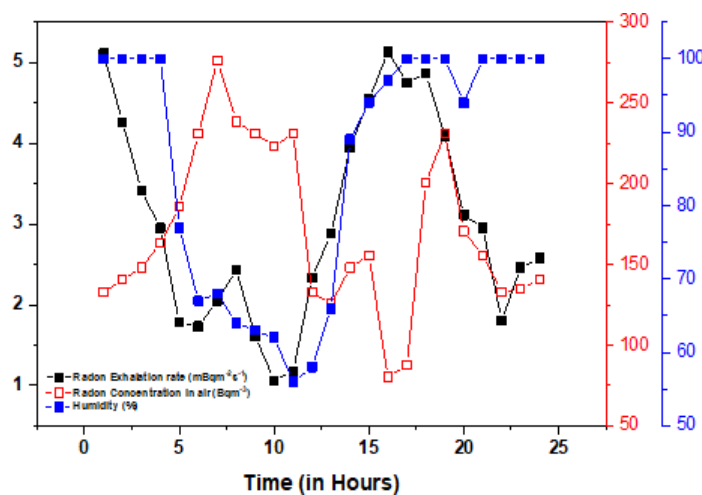


Fig4c. Radon exhalation rate v/s humidity

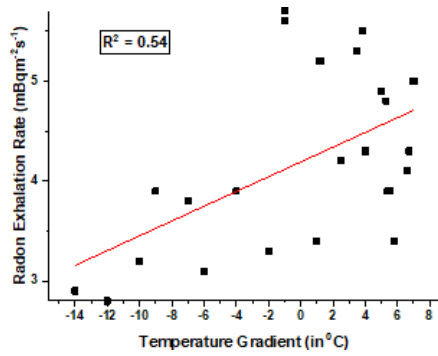


Fig 5a Temperature V/s Radon exhalation

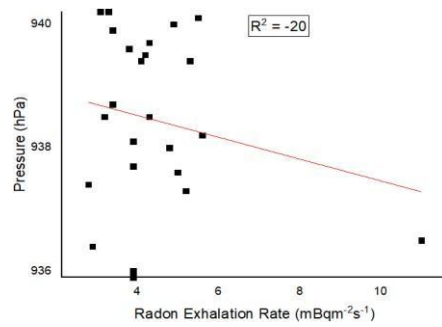


Fig 5b Pressure V/s Radon exhalation

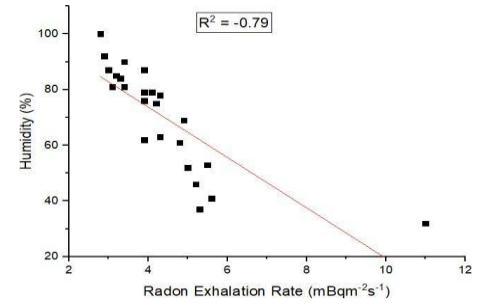


Fig 5c Humidity V/s Radon

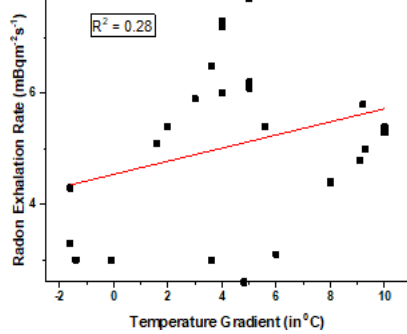
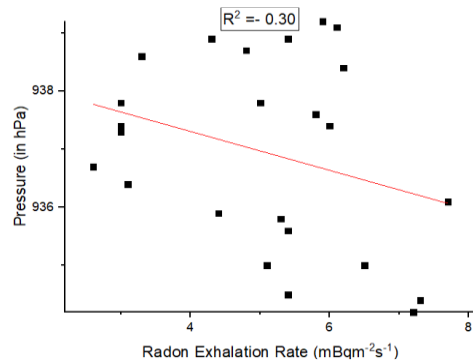
Fig 6a Temperature V/s Radon exhalation
Radon exhalation

Fig 6b Pressure V/s Radon exhalation

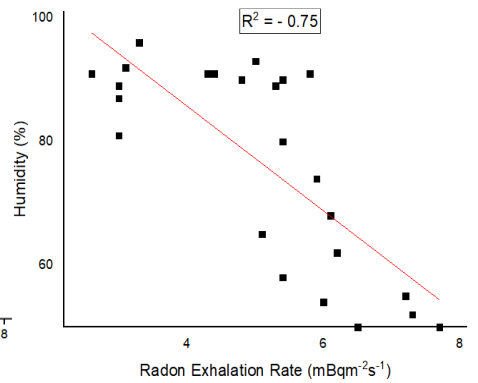


Fig 6c Humidity V/s

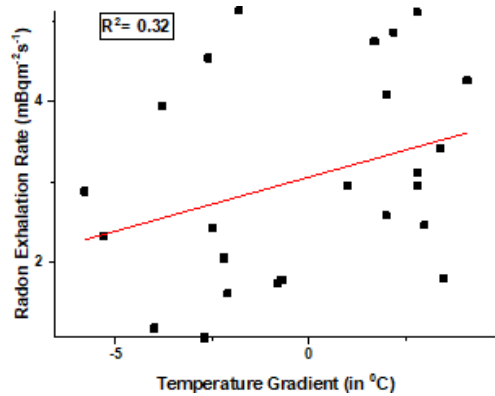
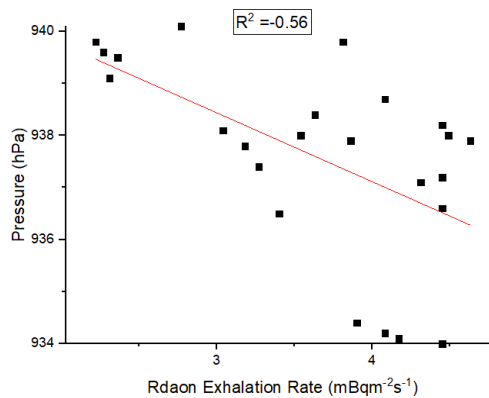
Fig 7a Temperature V/s Radon exhalation
exhalation

Fig 7b Pressure V/s Radon exhalation

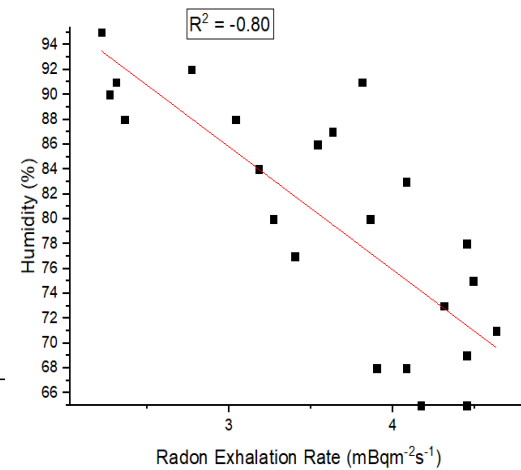


Fig 7c Humidity V/s Radon

Date	Radon concentration in air	Radon Exhalation in mBqm ⁻² s ⁻¹	Rainfall in cm
05-6-2022	240.88± 0.6	8.36	---
11-6-2022	180.60± 0.50	5.5	1.3
20-6-2022	218.29± 1.10	8.66	----
28-6-2022	105.38± 1.29	2.33	3.5

06-7-2022	255.93± 1.70	8.1	----
10-7-2022	225.82± 0.5	7.9	0.1
13-7-2022	127.96± 0.25	4.6	1.6
18-7-2022	233.35± 0.55	7.96	----
25-7-2022	229.58± 0.95	8.03	----

Table 3. Effect of Rainfall on radon Exhalation and its concentration in air

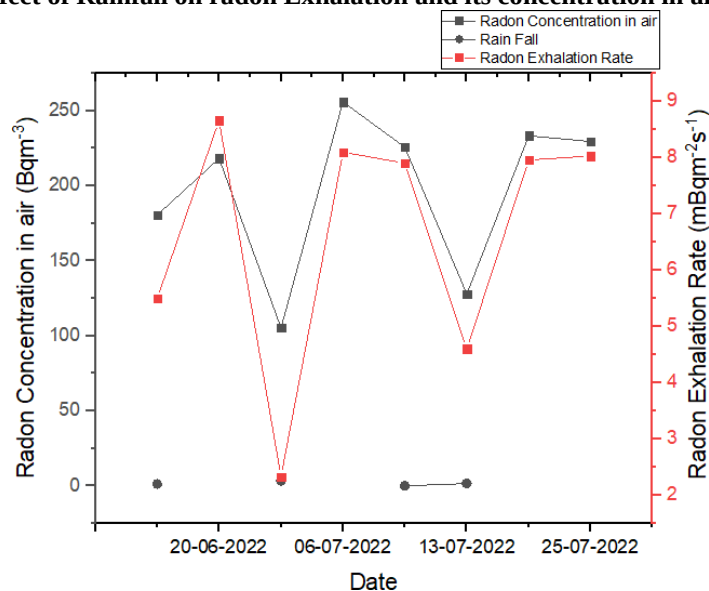


Fig 8. Effect of rain fall on radon exhalation rate and its concentration in air

CONCLUSIONS:

The present investigation provides a comprehensive assessment of radon exhalation from the ground surface and its atmospheric concentration under different environmental conditions in the Shankaraghatta forest ecosystem. Based on the experimental observations and data analysis, the following conclusions can be drawn:

- The built-up environment, including buildings, paved roads, and interlocking footpaths, significantly influences radon release by increasing both the radon exhalation rate and outdoor atmospheric radon concentration. Construction materials containing naturally occurring radionuclides act as additional sources of radon and contribute to the observed enhancement.
- Dense forest vegetation also plays an important role in regulating radon transport. Changes in soil porosity and permeability caused by root systems, together with soil–plant interactions, promote radon migration from the subsurface, resulting in relatively higher radon exhalation and atmospheric concentration compared with sparsely vegetated areas.
- The average radon exhalation rate measured in the study area was **3.86 mBq m⁻² s⁻¹**, which is considerably lower than the worldwide average value of **26.2 mBq m⁻² s⁻¹** recommended by **UNSCEAR (2000)**.
- The estimated average **Annual Effective Dose Equivalent (AEDE)** due to atmospheric radon exposure was **4.87 mSv y⁻¹**, which exceeds the global reference value recommended by the **International Commission on Radiological Protection (ICRP)**, indicating the need for continued environmental monitoring and appropriate mitigation strategies in regions with elevated outdoor radon concentrations.
- Diurnal and seasonal analyses demonstrated that radon exhalation and atmospheric radon concentration are strongly influenced by meteorological parameters. Temperature exhibited a positive correlation with radon exhalation, whereas atmospheric pressure and relative humidity showed negative correlations. Rainfall also reduced radon release by increasing soil moisture and restricting gas transport through soil pores.

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. Algattawi, Abdu Assalam A., and Ali M. Elmansuri. "Radon Concentration Due To Alpha Contribution Effects Of Soil And Rock Samples In Different West And Midlibyan Regions." (2022).
3. Zhang, Wei, et al. "Radon release from underground strata to the surface and uniaxial compressive test of rock samples." *Acta Geodyn. Geomater* 13 (2016): 407-416.
4. Becker, Klaus. "Health effects of high radon environments in central Europe: another test for the LNT hypothesis?." *Nonlinearity in biology, toxicology, medicine* 1.1 (2003): 15401420390844447.
5. Sukanya, S., Jacob Noble, and Sabu Joseph. "Factors controlling the distribution of radon (^{222}Rn) in groundwater of a tropical mountainous river basin in southwest India." *Chemosphere* 263 (2021): 128096.
6. Kumari, Punam, et al. "Mathematical Modelling to estimate Radon exhalation rates: A study on soil samples from Pangi valley of Chamba district, Himachal Pradesh, India." *Journal of Physics: Conference Series*. Vol. 2267. No.1. IOP Publishing, 2022.
7. Dongre, S., Kumar, S., Suresh, S., Rangaswamy, D. R., & Sannappa, J. (2022). Assessment of natural radiation levels in the forest ecosystem of Shankaraghatta-Shivamogga District.
8. Salih, Najeba F. "Determine the contaminations of radon in the drinking water using NTDs (CR-39) and RAD7 detectors." *Arabian Journal for Science and Engineering* 46.6 (2021): 6061-6074.
9. Rabi, R., and L. Oufni. "Study of radon dispersion in typical dwelling using CFD modeling combined with passive-active measurements." *Radiation Physics and Chemistry* 139 (2017): 40-48.
10. Raghavayya, M., M. A. R. Iyengar, and P. M. Markose. "Estimation of radium-226 by emanometry." (1980)
11. Sethy, N. K., et al. "A simple method for calibration of Lucas scintillation cell counting system for measurement of ^{226}Ra and ^{222}Rn ." *Journal of Radiation Research and Applied Sciences* 7.4 (2014): 475-477.
12. Sannappa, J., L. Paramesh, and P. Venkataramaiah. "Study of radon exhalation in soil and air concentrations at Mysore." *Indian Journal of Physics* (1999).
13. Eappen, K. P., J. Gaware, and Y. S. Mayya. "Real time radon-thoron monitors for environmental monitoring." *Proceedings of DAE-BRNS theme meeting: advances in the methods of assessment of exposure due to radon, thoron and their decay products*. 2008.
14. IARC International Agency for Research on Cancer. Summaries & Evaluations (1988). Vol. 43 Radon
15. Schery, S. D., and M. A. Wasiolek. "Modeling radon flux from the earth's surface." *Radon and Thoron in the human environment* (1998): 207-217.
16. Nikezic, D., and K. N. Yu. "Formation and growth of tracks in nuclear track materials." *Materials Science and Engineering: R: Reports* 46.3-5 (2004): 51-123.
17. El-Ghossain, M. O. "Calculations of stopping power, and range of ions radiation (alpha particles) interaction with different materials and human body parts." *International Journal of Physics* 5.3 (2017): 92-98.
18. Srilatha, M. C., and J. Sannappa. "A study on activity concentration of primordial radionuclide of building materials in Ramanagar and Tumkur Districts." *Proceedings of the twentieth national conference on solid state nuclear track detectors and their applications: abstracts*. 2017.
19. Ningappa, C., et al. "Studies on radon/thoron and their decay products in granite quarries around Bangalore city, India." *Indian Journal of Physics* 83.8 (2009): 1201-1207.
20. Saad, A. F., R. M. Abdallah, and N. A. Hussein. "Physical and geometrical parameters controlling measurements of radon emanation and exhalation from soil." *Applied Radiation and Isotopes* 137 (2018): 273-279.
21. Campos, M. P., et al. "Phosphogypsum recycling in the building materials industry: assessment of the radon exhalation rate." *Journal of Environmental Radioactivity* 172 (2017): 232-236.

22. Miklyaev, P. S., Petrova, T. B., Shchitov, D. V., Sidiyakin, P. A., Murzabekov, M. A., Marennyy, A. M., ... & Sapozhnikov, Y. A. (2021). The results of long-term simultaneous measurements of radon exhalation rate, radon concentrations in soil gas and groundwater in the fault zone. *Applied Radiation and Isotopes*, 167, 109460.
23. Vroom, R. J. E., van den Berg, M., Pangala, S. R., van der Scheer, O. E., & Sorrell, B. K. (2022). Physiological processes affecting methane transport by wetland vegetation-a review. *Aquatic Botany*, 103547. <https://doi.org/10.1016/j.aquabot.2022.103547>.
24. Le Mer, J., & Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: a review. *European journal of soil biology*, 37(1), 25-50.
25. Kumar, Amit, and R. P. Chauhan. "Measurement of indoor radon–thoron concentration and radon soil gas in some North Indian dwellings." *Journal of Geochemical Exploration* 143 (2014): 155-162.
26. Malakootian, M., and Y. Soltani Nejhad. "Determination of radon concentration in drinking water of Bam villages and evaluation of the annual effective dose." *International Journal of Radiation Research* 15.1 (2017): 81.
27. Ragini, N., et al. "Temporal and vertical variations of atmospheric electrical conductivity related to radon and its progeny concentrations at Mysore." (2008).
28. Miklyaev, Petr S., et al. "Radon transport in permeable geological environments." *Science of The Total Environment* 852 (2022): 158382.
29. Cinelli, Giorgia, et al. "Radon-Chapter 5." *European Atlas of Natural Radiation*. Publication Office of the European Union, 2019.
30. Barkat, Adnan, et al. "Time series analysis of soil radon in Northern Pakistan: Implications for earthquake forecasting." *Applied Geochemistry* 97 (2018): 197-208.
31. Sahu, Patitapaban, Durga Charan Panigrahi, and Devi Prasad Mishra. "A comprehensive review on sources of radon and factors affecting radon concentration in underground uranium mines." *Environmental Earth Sciences* 75.7 (2016): 1-19.
32. Jiang, Fuliang, et al. "Numerical simulation study on the relationship between thickness of the overburden and radon exhalation rate of a uranium tailings reservoir beach based on fluent software." *The Proceedings of the International Conference on Nuclear Engineering (ICONE) 2019*. 27. The Japan Society of Mechanical Engineers, 2019.