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Original Article

Radon Transport & Analysis of Radon Level in Existing Buildings Structures in India

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***Abstract* - *Due to the harmful consequences of radiation, there has been a growing interest in quantifying natural background gamma radiation levels indoors during the last few decades. Indoor radiation levels depend on various aspects, such as geology and building materials. However, there is a lack of information on the levels of radon in various Indian building types that are now in use. Hence, the study of Radon transport & analysis of Radon levels in existing building structures is conducted across various regions of India over a year, covering all three seasons. The study's main aim is to analyze the total indoor intensity of radon gas and investigate the exhalation rate of 222Rn from concrete and mortar. Monitoring was carried out utilizing LR-115-type Solid State Nuclear Track Detector (SSNTD) films, which accurately observed indoor radon levels. Previous mathematical models missed key variables such as soil flow density and ventilation rates, which led to inadequate predictions of indoor radon concentrations. To overcome this, the mathematical model Integrated Radon Transport and Exhalation Modeling is used, which incorporates various factors such as soil flux density, building material exhalation, ventilation rate, and outdoor radon levels. This inclusive approach enables a more accurate calculation of indoor radon concentrations by capturing the interactions between these factors over time. The study highlights seasonal variations in radon levels, with higher concentrations observed during winter compared to summer and rainy seasons, and also that radon levels are higher at ground level and decrease with elevation.*

Keywords* - *Radon concentration. Exhalation, Mathematical model, Indoor concentration, Solid state nuclear track detector.

1. Introduction

These days, concrete is the most extensively used and consumed building material due to its many useful qualities, including simplicity of manufacture, capacity to provide the appropriate durability and strength values, flexibility in construction, and total compatibility with steel [1]. Food, air, and water commonly include radioactive chemicals that enter the body through inhalation and digestion and eventually build up in the organs [2]. Under certain conditions, radon is a radioactive gas that occurs in rocks, soil, and building materials. Exhalation leads to its accumulation in indoor environments, where levels might approach those that are very hazardous to the health of anyone in contact. In addition to being colorless, odorless, water-soluble, and denser than air, radon is a costly inert gas. ^{222}Rn and ^{22}0Rn are the two main components. The biggest health danger when breathing in radon comes from its breakdown products [3, 4]. The solid chemical components produced by products of radon decay attach themselves to lung tissue after inhalation in the form of aerosols. The byproducts of radon decay, alpha and beta radiation, have a greater propensity to ionize than gamma radiation and can thus directly affect biological cells. This interaction directly damages cells' DNA and increases the generation of dangerous free radicals, both of which have significant negative effects on human health [5, 6]. Due to these characteristics, radon gas is second only to smoking as the primary cause of lung cancer [7].

Globally, there were predicted to be 1.7 million cancer-related deaths and 2 million new cancer diagnoses in 2018. Lung cancer affects 4,500 women and 23,000 men in Turkey on average each year. Although indoor radon gas consumption has been related to lung cancer, residential buildings only contain moderate quantities of the gas [8]. Because of variations in the atmosphere outside of buildings, radon gas concentrations are usually modest. The ^{226}Ra isotope in the soil is responsible for radon gas quantities seen inside [9]. Building materials, home water, and gaps and fractures in buildings can all contribute to potentially dangerously high levels of radon gas in the atmosphere [10, 11]. The kind of soil, nearby rocks, building materials, water supply, temperature and pressure variations, usage of fossil fuels, and lifestyle choices all affect indoor radon concentrations. Examining the seasonal variation in indoor radon concentration is necessary to reduce the health hazards associated with radon and its offspring. Numerous research findings show that there are seasonal variations in the amount of radon and its decay products in dwellings. The most significant factors affecting the amount of radon in indoor air are the kind of building structure, geology, building materials, ventilation levels in cramped spaces, and meteorological conditions [12]. A variety of factors, including temperature, pressure, humidity, ventilation, wind direction, and speed, cause variations in indoor radon concentration throughout the year.

Many studies on the application of ^{222}Rn as an environmental indicator and the hazards associated with its indoor concentration in human living situations have been carried out throughout the last few decades. In the constructed environment, the primary sources of radon are ground fissures and advection, then building materials, and trace quantities from water and air. Radon emissions may increase if building materials include naturally occurring radioactive materials or NORMs. Those who work inside and those who lead sedentary lives are more at risk of having radon pollution in their houses [13, 14]. The risk of radon in buildings and radiation in building materials were included in the EU Basic Safety Standards by the 2013/59/EURATOM directive. The benchmark levels of radon in indoor air are 300 Bq/m^3. Buildings are being forced to obtain radon certificates to guarantee appropriate levels. As radon's hazards become more well-known to scientists and the public, new active methods are being developed to lower levels in buildings. Seasonal differences in external and inside temperatures impact home ventilation rates. Seasonal variations in indoor radon concentrations mean that dwellings need to be regularly inspected [15].

In India, there is a notable lack of comprehensive data on radon levels in various building types currently in use. Despite extensive studies over the last few decades on radon as an environmental indicator and the hazards of indoor radon concentrations, there is inadequate data on radon levels in various types of Indian buildings. Many previous studies have limitations, such as assuming steady-state conditions, focusing only on specific building materials, not considering geological influences, failing to capture short-term variations, or not addressing factors like building materials and airflow rates. These limitations highlight the need for more holistic and contextually sensitive approaches to indoor radon research. Given the health risks associated with radon exposure and the gaps in existing research, it is essential to develop a more accurate and comprehensive model for predicting indoor radon levels. This study aims to address this gap by analyzing indoor radon concentrations and the exhalation rate of ^{222}Rn from concrete and mortar in various Indian buildings over different seasons using LR-115-type Solid State Nuclear Track Detector (SSNTD) films. This study's primary contribution is as follows:

- To effectively find the Radon concentration in indoor dwellings, the present study is introduced, in which the indoor Radon radiation concentration of existing building structures was measured in various regions of India during winter, rainy, and summer seasons.
- To overcome inadequate estimates of indoor radon concentrations, an integrated radon transport and exhalation modeling is utilized, which includes various factors influencing indoor radon levels, such as soil flux density, building material exhalation, ventilation rate, and outdoor radon levels, thereby accurately representing indoor radon levels.

Five components make up the paper. The introduction of the paper is given in Section 1. Section 2 provides an overview of the literature, Section 3 details the materials and techniques, and Section 4 talks about the experimental findings. The article is finally concluded in Section 5.

2. Literature Survey

Sabbarese et al. [16] assessed the amount of radon activity present on various building levels while taking into account the kind of building, the makeup of the underlying soil, and the materials used in construction. The concentration of indoor radon was determined using the Finite Differences Technique (FDM), which involved numerically solving relevant transport equations.

To model radon entry from soils and measure its concentration at various floors, many boundary conditions were applied. The lowest floor's proximity to the ground differed throughout the examined home designs. Unfortunately, the steady-state conditions and uniform distribution of radon sources used in this study do not adequately represent the variability found in the actual world.

Soniya et al. [17] investigated the exhalation rates of radon and radium in some commonly used building materials, such as brick, white cement, grey cement, gypsum, gravel, granite, and marble. It was determined how active radium was by scintillation gamma-ray spectroscopy. Surface exhalation levels from slab-type construction materials and radon mass exhalation rates employing powder building materials were calculated.

According to the study, different building materials have different rates of radon exhalation, which significantly affects indoor radon concentrations. Of all the samples evaluated, grey cement had the highest rate of radon mass exhalation, whereas gravel had the lowest. Because brick samples are more porous than other materials including granite, marble, and vitrified tile, and release the highest amounts of radioactive dust. The study did not consider the effect of building design on indoor radon concentrations, rather than focusing fully on the role of building materials.

Sajwan et al. [18] examined the amounts of ^{222}Rn, ^{220}Rn, and their offspring in the Ghuttu area of Uttarakhand, India's Tehri Garhwal district. An examination of how ventilation and home type impact seasonal fluctuations in radiation exposure. Wintertime radon concentrations were greater because of inadequate ventilation. However, lower amounts were discovered in the summer due to greater ventilation. Indoor radon concentrations are greater in mud constructions than in cemented dwellings because of radiation produced from interior surfaces and building components. Insufficient ventilation caused radon concentrations in buildings to rise, whereas sufficient ventilation caused levels to fall. Furthermore, not enough studies have been done on other factors that affect indoor radon levels, such as building materials and geological conditions.

Suman et al. [19] examined the levels of radon and thoron in homes' interiors in Buddonithanda, a town close to a potential site for uranium mining. It tried to clarify seasonal and daily differences in radon and thoron levels, as well as their regional variance. Radioactive isotope levels were measured over one year using pin-hole dosimeters (SSNTDs). The concentrations of radon and thoron in homes close to the planned mining location varied significantly. Radon levels vary depending on air circulation rates, which were highest throughout the day and night and were lowest at dawn and twilight. Compared to other types of dwellings, mud-built homes have somewhat higher airborne radiation levels. However, dosimeter readings fail to catch short-term variations in radon and thorium levels.

Kamalakar et al. [20] carried out a study to investigate seasonal fluctuations in indoor radon, thoron, and its progeny levels in the Belagavi District of Karnataka, India. The levels of thorium and radon were measured using LR-115 type II dosimeters in cups that had a single-entry pinhole. Measurements were performed all over the monsoon, autumn, winter, and summer seasons. The study examined the annual fluctuations in radon and thoron levels as well as the effects of building materials and ventilation. The results highlight the importance indoor radon and thoron exposure had on population health, especially during the autumn and winter. However, to reduce the risk of indoor radon and thoron exposure, better ventilation systems are required in future dwellings.

Semwal et al. [21] calculated the concentrations of ^{222}Rn, ^{220}Rn, and related decay products in the Kumaun Himalayan region of Uttarakhand, India's Nainital District, inside. It looked at how these concentrations change with the seasons (rainy, summer, and winter) and with the construction materials (cement, stone, and mud). Compared to stone or cement constructions, mud dwellings had greater concentrations of ^{222}Rn, ^{220}Rn, and associated decay products, especially in the winter. Winter concentrations were frequently higher than summer and wet season values. The annual range of inhalation doses was 0.85 to 3.93 mSv, with the majority coming from ^{220}Rn and its offspring. The 80-home sample size is too small to extrapolate the results to the entire population adequately.

Satyanarayana et al. [22] concentrated on measuring the levels of ^{222}Rn concentration inside homes during the winter, rainy season, and summer in the Visakhapatnam region of Andhra Pradesh. Using Rn-duo survey meters, indoor radon concentrations were measured in 42 residences during the winter, rainy, and summer seasons. In winter, the average radon concentration was 28.26 Bq.m^{-3}; in the rainy season, it was 23.47 Bq.m^{-3}; and in summer, it was 21.21 Bq.m^{-3}. Because of lower ventilation rates in the winter and higher ventilation rates in the summer, radon levels were highest in the former and lowest in the latter. The rainy season's radon levels fell between those of winter and summer. Radon concentrations in almost 80% of homes were between 20 and 35 Bq.m^{3}, which is less than the average for the world. However, tenant behavior and lifestyle choices impact indoor radon levels but are not fully explored in the study.

Rangaswamy et al. [23] investigated the ^{222}Rn, ^{220}Rn, and their offspring concentrations in the Shivamogga region. SSNTD-based pinhole dosimeters and deposition-based progeny sensors were used to monitor these concentrations. According to the study, normal indoor concentrations of ^{222}Rn and ^{220}Rn, and their offspring were found to be lower than the safe levels recommended by the WHO and ICRP. Wintertime brought with it higher levels of radon and thorium. Since the study seems to be cross-sectional, it is unable to look at long-term trends or any temporal variations in radon levels.

Miklyaev et al. [24] examined three years of long-term variations in soil radon levels and climate variables in the Mount Beshtau fault zone in the North Caucasus. The investigation focused on convective air circulation resulting from temperature differences between the surrounding environment and the mountain air as the mechanism of radon transfer. Strong seasonal variations were observed in radon levels, with summer maxima and winter minima in the fault zone and close to adit mouths. Because of anomalous radon emissions during mine air discharge, which produce dose rates of up to 19 mSv h^{-1}, abandoned adit mouths provide a greater risk of radiation exposure. The radiation exposure estimate is not representative of the wider environment; rather, it is based on local data.

Narasimhamurthy et al. [25] determined the ^{222}Rn and ^{220}Rn concentrations in the air of residences in and around Mandya City, Karnataka. Additionally, an attempt was made to calculate the annual effective dosage that the general public was exposed to due to radon and thorium. The effect of flooring, roofing, and building age on radon levels was examined. The study also discovered that an established model based on the mass balance equation may be used to anticipate indoor radon levels. Radon concentrations in around 89% of the buildings were lower than the 40 Bq m^3 national average for India. The mean efficacious inhalation dosages fall below the ICRP's recommended action level. There has been no discussion of elements like building materials and airflow rates that influence radon and thoron levels.

The study of the literature reveals several significant flaws in earlier studies on indoor radon levels. However, each research has several limitations and drawbacks: in [16], various building parameters assume steady-state conditions and uniform radon sources, limiting their real-world applicability. [17] Focus on building materials overlooks the broader impact of building design on radon levels. [18] Lacks a thorough investigation of geological conditions influencing indoor radon. [19] Fails to capture short-term variations in radon and thoron levels. [20] Seasonal variations overlook the influence of building materials and ventilation on long-term exposure. [21] Suffering from a small sample size that does not represent the population adequately, in [22], seasonal analysis neglects the role of tenant behavior. [23] The cross-sectional approach limits insights into long-term trends in radon levels. [24] A specific fault zone does not generalize to broader environmental contexts, and in [25], Factors that affect radon and thoron levels, such as airflow rates and constructing materials, have not been addressed. The reliability of studies in real-world scenarios is limited because the analyses have frequently assumed steady-state circumstances and uniform radon sources. In addition, much research neglected broader design and environmental considerations in favor of a restricted focus on construction materials. Sample sizes were typically too small to yield accurate results, and seasonal variations and brief swings in radon levels were routinely disregarded. These gaps underscore the need for a more holistic approach to studying indoor radon concentrations.

3. Material and Methods

A variety of toxins are known to affect indoor air quality, thereby affecting the health of the inhabitants of that region. Radon is a naturally occurring radioactive gas found in groundwater, rocks, and soil. The health of building occupants is at risk when radon gas leaks in through foundational fractures or gaps and builds up to dangerous levels. Like many other nations, India is beginning to understand how critical it is to measure indoor radon levels to protect the health and safety of residents. However, there is inadequate data on radon concentrations in existing building structures in various parts of India. Geological variances, construction materials, and construction procedures all have an impact on indoor radon levels, emphasizing the importance of region-specific research better to understand the degree of radon exposure in Indian houses. Hence, in this study, Radon Transport & Analysis of Radon Levels in Existing Buildings Structures in India is introduced. The primary objective of this study is to determine the overall indoor radon level and explore the exhalation rate of ^{222}Rn from concrete and mortar materials typically used in building construction. The analysis is conducted in various parts of India, including Lunglei, Serchhip, and Mamit in Mizoram, also Needkara, Chavara, and Maruthady in Kerala, and Mumbai in Maharashtra over one year, covering all three seasons as winter, rainy, and summer. Monitoring is carried out using LR-115-type Solid State Nuclear Track Detector (SSNTD) films, which allows for precise monitoring of radon concentrations indoors. The main sources of radon gas in dwellings were identified as structure materials and the subsoil below the foundation. Furthermore, existing mathematical models for estimating indoor radon concentrations do not fully account for all the factors influencing radon transport and accumulation indoors. These mathematical models have focused on specific elements of radon transport, such as diffusion through building materials, while neglecting additional significant variables, such as soil flux density and ventilation rates, resulting in inadequate estimates of indoor radon concentrations. Therefore, a novel mathematical model of Integrated Radon Transport and Exhalation Modeling is presented. This modeling approach overcomes limitations in existing models by combining various factors influencing indoor radon concentrations, such as soil flux density, building material exhalation, ventilation rate, and outdoor radon levels. Additionally, it considers the interaction between these factors and their impact on indoor radon concentrations over time. By integrating these complex dynamics, this model provides a more accurate representation of indoor radon levels and aids in the development of effective mitigation strategies for ensuring indoor air quality and occupant health.

3.1. Geology of Study Area

The study focuses on analyzing radon levels in existing building structures across three distinct states in India: Mizoram in the northeast, Kerala in the south, and Mumbai on the western coast. The geographical image of the study-focused area is illustrated in the following Figure 1.

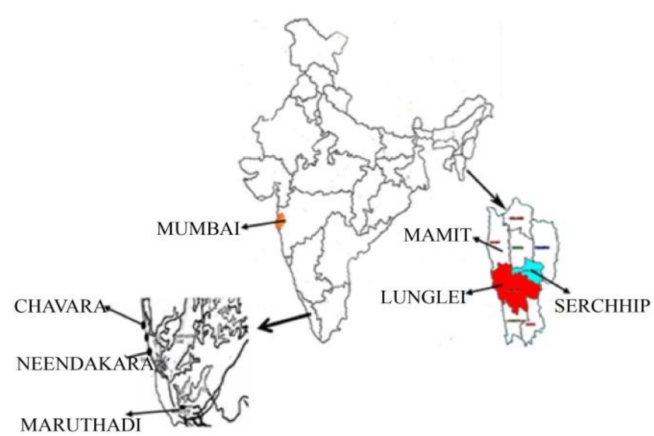

Fig. 1 Geology of study area

3.1.1. Northeastern State of Mizoram

Three districts of Mizoram, which are in north-eastern India, Lunglei, Serchhip, and Mamit, are compared geographically. Mizoram, positioned at latitudes 21° 58' to 24° 35' N and longitudes 92° 15' to 93° 29' E, experiences an annual rainfall ranging from 2500 to 3000 mm. The terrain is rugged, with elevations varying between 50 to over 2000 meters above sea level. The soil composition spans from clayey loam to sandy loam, and it is notably acidic with low base saturation. These geological features influence radon transport dynamics, potentially affecting radon levels within buildings.

3.1.2. Southern State of Kerala

In Kerala, specifically the regions of Chavara, Neendakara, and Maruthadi in Kollam District, the geography is characterized by a coastal setting, with coordinates 8.99690 N latitude and 76.87210 E longitude. This area is renowned for its monazite-rich sands, which contribute to high background radiation doses. The soil makeup here ranges from sandy clay loam to clay, which can impact radon infiltration into buildings.

3.1.3. Western Coast State of Mumbai

Moving to Mumbai, located on the western coast of India with coordinates 19.07600 N latitude and 72.87770 E longitude, the climate is moderately hot with elevated humidity levels. The soil type predominantly consists of sandy composition. These environmental factors, including climate and soil characteristics, play a crucial role in radon transport and accumulation within buildings.

3.2. Building Attributes

The architectural characteristics of the studied locations, especially Mizoram and Kerala, indicate a traditional architectural style adapted to the local climate and geography. Residences are mostly single-story constructions built using partially ventilated cemented materials, including bricks, mortar, concrete, sand, and cement. This building style is consistent with the region's historical architecture and environmental concerns. Mumbai, on the other hand, has a very different pattern of building growth because of its high population and restricted space available. The need to maximize land utilization efficiently has resulted in the multistory structures that define the urban environment. Mumbai's skyline is dotted by tall structures that represent the city's quick urbanization and high population density, as well as a shift away from conventional architectural designs and towards vertical growth to accommodate the growing population.

3.3. Indoor Radon Study

This study used twin cup dosimeters created at the Bhabha Atomic Research Centre (BARC) in Mumbai, India, to assess indoor ^{222}Rn concentration. Figure 2 shows the schematic diagram of the twin cup ^{222}Rn dosimeter. These dosimeters are made up of two cylindrical cups of equal capacity. Each cup has a diameter of 3.1 cm and a height of 4.1 cm. These cups are designed to store Solid-State Nuclear Track Detector (SSNTD) films inside, with an extra film inserted outside for progeny measurement. SSNTD is commonly used to measure indoor radon concentrations [26]. These detectors are frequently used for passive measurements because of their great endurance and stability. The SSNTD films utilized in the dosimeter are their cellulose nitrate films, also known as LR-115. Films measuring 3cm×3cm are attached to the bottom of each cup and the exterior surface of the dosimeter. One cup, referred to as the "filter cup," contains a glass fiber filter paper-covered aperture that lets in ^{220}Rn and ^{222}Rn gases. The other cup, called the "membrane cup," features two glass fiber filter sheets between semi-permeable membrane coatings.

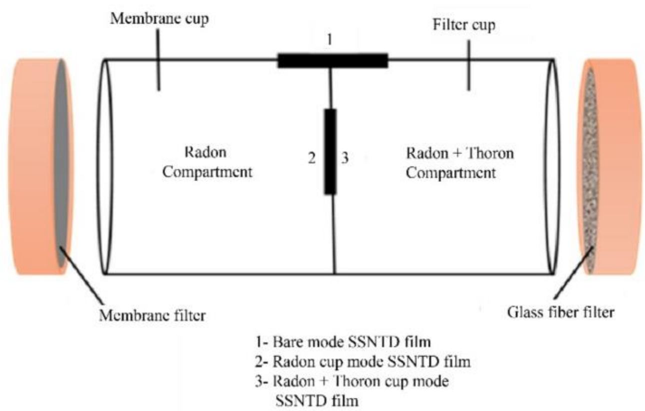

Fig. 2 Schematic diagram of twin cup 222Rn dosimeter

These membranes feature diffusion coefficients that enable 95% of ^{222}Rn gas to get through while blocking more than 99% of ^{220}Rn gas. The filter film captures tracks from both the ^{222}Rn and ^{220}Rn gases, whereas the SSNTD films within the membrane cup only store tracks related to the ^{222}Rn gas. When the third film is exposed in naked mode, it finds the alpha tracks that gases and their offspring leave behind. The determination of total alpha activity, which offers crucial information about the overall radiation levels in the examined region, is made possible by this bare mode exposure. To improve accuracy and reduce uncertainty from deposited activity on the film surface, 12 µm thick LR-115 films are used for bare mode exposure. This thickness promises that only alpha particles with energies larger than 5 MeV are recorded, thereby removing indications of deposit activity and increasing test reliability. To minimize irritation to people, the dosimeters are located roughly 1.5 m above ground. The active surface of the SSNTD film used in bare mode exposure was kept at least 10 cm away from any surface to minimize interference from attenuated alphas reaching these surfaces. Measurements are taken in each home throughout the year, covering all three seasons: rainy, winter, and summer. The SSNTD films are etched and the dosimeters are eliminated following exposure. The films are etched for ninety minutes at 60°C in a 10% NaOH solution. Ultimately, tracks captured on LR-115 films are totaled using a spark counter, which makes precise measurement of radon levels possible [27]. SSNTDs additionally provide reliable information for determining the exhalation rate of radon from building materials such as concrete and mortar, which contributes to a better understanding of indoor radon dynamics.

3.4. Integrated Radon Transport and Exhalation Modeling

This study focuses on examining transport systems using a mathematical model to better understand the transportation of radon gas through building materials and its influence on indoor radon concentrations. The objective of the model is to evaluate the relative contributions of many sources to the indoor radon concentration while taking into account variables, including soil flux density, exhalation of building materials, ventilation rate, outside radon levels, and room characteristics. One of the many sources of radon inside a structure is its interior surfaces' radon motion thickness. For a room that resembles an enclosed area inside a building, a theoretical relationship between radon concentration and radon intake from different sources is constructed. The following harmonization criterion for the different source commitments to the rate of rise of indoor radon concentration is necessary for the connection to exist. The rate at which the concentration of radon inside changes concerning time is zero under stable conditions when the source parameters are constant. This condition indicates a stable indoor radon concentration, which is expressed in the following Equation (1):

$$\frac{dC_i}{dt} = 0 \tag{1}$$

This formula, which was taken from a draft of the updated UNSCEAR report [UN 80], has been modified slightly to suit this present purpose. The steady-state radon concentration (C_i) in a room is given by the Equation (2),

$$C_1 = \frac{J * {}^{S}/_{V} + C_o \lambda_v}{\lambda + \lambda_v} \tag{2}$$

The radon flux density from the room's unit surface is denoted by J, while the radon concentration in the space is represented by C_1. The room's exhaling surface area is denoted by S. V is the room's volume. The radon decay constant, λ, is used to express the ventilation rate, or air changes per unit of time, as λ_v. The "reference house" (200 m3 volume, 350 m^2 interior surface area, and 0.5 h^{-1} airflow rate) mentioned in the draft UNSCEAR report [UN 80] is used to illustrate the relative relevance of indoor radon sources. With 80% of the entire contribution coming from building materials, these seem to be the most important sources. Outside air follows at 10%, suggesting that radon has infiltrated the environment. Water, including toilets and showers, accounts for 5%, while natural gas and liquefied petroleum gas make up 4% and less than 1%, respectively. These proportions demonstrate the significant impact of building materials and outside air on indoor radon levels.

Assume that a precious gas is mixed with the air in the building room, that it has no influence on any other object, and that it disappears naturally through decay and ventilation. Equation (3) demonstrates that the intensity of indoor radon gas concentration increases with surface area, room volume, ventilation rate, outside radon levels, and soil flux density. The following equations were used to determine the intensity of in-house gases, which are mostly influenced by radon gas in the soil and building materials.

$$\frac{dC_I(t)}{dt} = J * \frac{S_g}{V} - \lambda C_i \tag{3}$$

After soil, BM is the second leading source of radon in the structure. Particularly in high-rise structures, BM constitutes a more substantial source of radon penetration than soil. The difference in radon concentrations between the BM and indoor areas suggests that radon enters the BM by diffusion. Equation (4) can be used to represent the variation in indoor radon concentration caused by BM over a very short period.

$$Kd_{bm}(C_{bm} - C_1)\frac{S_{bm}}{V} \tag{4}$$

Kd_{bm} is the diffusion transfer coefficient of soil, C_{bm} represents radon concentration in building materials and S_{bm}denotes the indoor surface area of radon containing BM. Then from Equations (3) and (4),

$$\frac{dC_I(t)}{dt} = J * \frac{S_g}{V} + Kd_{bm}(C_{bm} - C_1)\frac{S_{bm}}{V} - \lambda C_i \tag{5}$$

The integrated equation, expressed in Equation (6), takes into account variations in indoor and outdoor levels as well as radon exchange carried on by airflow.

$$\frac{d}{dt}C_I = J * \frac{Sg}{V} + Kd_{bm}\,(C_{bm} - C_i)\frac{S_{bm}}{V} - \lambda C_i - \lambda_v\,(C_i - C_o) \tag{6}$$

The effects of ventilation and the difference in radon levels between indoor and outdoor spaces need to be considered in the integrated equation for radon concentration.

In particular, it is necessary to take the radon exchange between indoor and outdoor air $\lambda_v\,(C_i - C_o)$. The decay constant, denoted by the parameter λ, is significantly lower than the ventilation rate, denoted by λ_v.

$$\frac{d}{dt}C_I = J * \frac{Sg}{V} + Kd_{bm}\,(C_{bm} - C_i)\frac{S_{bm}}{V} + \lambda_v\,C_o - C_i(\lambda + \lambda_v) \tag{7}$$

According to Equation (7), ventilation has a far bigger impact on radon levels than decay does.

3.5. Radon Exhalation Rate Equation per Time

Emission and transport are the variables that influence radon respiration rate. "The expiration rate is radon moving out from concrete and mixing with the environment with time, which can be measured either per unit area or unit mass and exhalation rate is the rate of transfer of radon atoms N(t) per unit time". Where $N(t)$ is forthwith relative to the surface quantity of room and lifetime of noble gas particles,

$$\frac{d}{dt}N(t) = AT \tag{8}$$

Equation (8) illustrates the derivative of the radon atom count with time, expressed as which is proportionate to the room's floor space and the radon atoms' lifetime. The exhalation rate of indoor radon concentration, denoted as J, is determined by Equation (9),

$$J = \frac{C_1 \lambda_v}{AT} \tag{9}$$

Where, the typical radon density flux from the ground is given as 0.43 pCi m^{-2} s^{-1}. The diffusion transfer coefficient for concrete, which indicates the rate of radon diffusion through the material, ranges from.69×10^{-5} cm^2/s to 3.1×10–53.1×10^{-5} cm^2/s for concrete thicknesses ranging from 5 cm to 20 cm. The porosity of concrete, ranging from 0.05 to 0.25, influences its ability to facilitate radon transmission. The decay constant (λ_v) of radon is 2.1×10–62.1×10^{-6} s^{-1}. The ventilation rate of radon is 0.5 h^{-1}. t represents the time, which is given as 30 seconds in this study. The exhalation rate equation explains the speed at which radon released from concrete enters into the indoor atmosphere. More precisely, the model took account of the relation of soil flux density and ventilation rates on radon transfer, which was previously ignored in some models. The model provides more accurate estimations of interior radon concentrations by taking these variables into account, as well as other aspects, including building material exhalation and outside radon levels. This extensive approach makes it possible to understand better the relative importance of different radon sources and transport pathways, which leads to important insights for lowering the risks associated with indoor radon exposure.

4. Results and Discussion

Indoor radon concentrations were monitored across various dwellings in different regions of India, including Lunglei, Serchhip, and Mamit in Mizoram, as well as Needkara, Chavara, and Maruthady in Kerala, and Mumbai in Maharashtra.

4.1. Radon Concentrations and Influencing Factors in Needakara, Kerala

4.1.1. Seasonal Variations in Radon Concentrations in Needakara, Kerala

Needakara, located at approximately 8.60° N and 76.95° E, with an average elevation of 12 meters above sea level, exhibits significant seasonal fluctuations in indoor radon concentrations across various buildings. The proximity to the Arabian Sea and the presence of coastal alluvial soils may influence these radon levels.

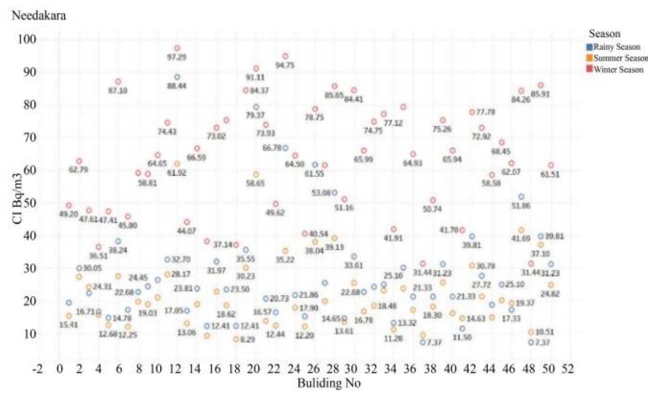

Fig. 3 Integrated radon output in different seasons at Needakara (Kerala)

Figure 3 has been observed that integrated radon concentrations differ across Needakara where there were several buildings. In this study, Variables like soil flux density, indoor room volume, exhalation surface area, decay constant, and ventilation rate will be taken into consideration.

Rainy Season

During the rainy season, radon concentrations ranged from 7 Bq/m³ to 100 Bq/m³. Building No. 12 recorded the highest concentration at 100 Bq/m³, which is 13.08% above the calculated average of 88.44 Bq/m³. This increase is attributed to its large exhalation surface area and room volume. Conversely, Building No. 5 had the lowest concentration at 14 Bq/m³, indicating better ventilation, as it was 5.27% below the calculated value.

Winter Season

The winter season showed the highest radon concentrations, ranging from 30 Bq/m³ to 110 Bq/m³. Building No. 12 again had the highest concentration at 110 Bq/m³, which is 13.07% above the calculated average of 97.29 Bq/m³, likely due to reduced ventilation. Building No. 13 recorded an average level of 44 Bq/m³, closely matching the calculated value of 44.07 Bq/m³, indicating consistent ventilation practices.

Summer Season

In the summer season, radon levels were lower, ranging from 7 Bq/m³ to 70 Bq/m³, reflecting improved ventilation. Building No. 12 had the highest concentration at 70 Bq/m³, which is 13.04% above the calculated average of 61.92 Bq/m³. Building No. 5 recorded a low concentration of 12 Bq/m³, below the calculated value of 12.68 Bq/m³.

From this analysis, it is obvious that seasonal fluctuations have an impact on radon concentrations within the Needakara area. The reason why winter shows mild cases per unit volume is that there is less supply of fresh air within rooms, whereas, during summers, lower concentrations occur since temperature increases the rate of air movement. Meanwhile, there are medium levels during rainy seasons which are a subsequent outcome of environmental conditions besides other building attributes. It is necessary to have good designs for both houses and adequate ventilation at all times throughout the year to manage indoor radon levels.

4.1.2. Building-Specific Variants

There were huge variations in the radon concentration levels in different buildings found in Needakara, Kerala, thus demonstrating varied changes which were confined within each specific structure due to airflow routes connected to the external environment by windows and doors near floor level. Each season throughout its testing year was experiencing different levels of underground gas emissions, with no two buildings being the same, let alone close together on their radon levels during any given season; house number 12 always showed greater levels of radon than others during all four seasons, reaching 100 Bq/m³ in Rainy season, 110 Bq/m³ come Winter and 70 Bq/m³ at Summertime. That can be explained by the fact that it has a large exhalation area, which is 227 m² and an equally wide room volume of 122 m³. All these atmospheric coordination between rainy/wintery summer seasons within these latter entered into much higher radiation dosage amounts when compared against atmospheric fractional short-lived nuclide major concentrations whose radon-related amounts are otherwise almost ever constant. Building number six also had heightened radon levels, especially over the winter season, where it reached 98 Bq/m³ with a remarkable 12.52% difference. The building's radon levels are determined significantly by the large exhalation surface area (172 m²) and the volume of the room (92 m³). On the other hand, building thirty seven took a dip as far as radon is concerned compared to other such structures, registering 9 Bq/m³ during summer time up to 30 Bq/m³ during winter. Lower radon levels in this house may refer to its well-designed ventilation system.

4.1.3. Exhalation Surface Area and Room Volume

Indoor parameters, including exhalation surface area and room volume form crucial factors that influence indoor radon levels. In Needakara: Bigger exhalation surface areas in buildings usually attract large amounts of radon gas. For example, Building No. 12, with a 227 m² exhalation surface area, consistently registers relatively high radon levels throughout the year as compared to the other buildings. This means that more radon would have been released into the air had the surface area been larger. Moreover, buildings with larger room volumes, such as Building No. 12 (122 m³), usually contain higher radon levels. Such room volumes do not allow the ventilation of radon especially when it is too much.

High Radon Levels in Specific Buildings

During winter, radon concentrations were significantly greater in selected buildings; as a result of restriction in terms of intake, the Concentration of the radioactive gas reached its peak at 110 Bq/m³ for Building No. 12, which is 13.07 % higher than the calculated value. This was due to its big surface area and volume and it had reduced ventilation. Building No. 6 also showed high radon levels at 98 Bq/m³, attributing to a 12.52 % increase from the calculated value.

Radon accumulation takes another dimension in winter months when a building's exhalation surface is massive while minute venting happens. The winter conditions exacerbate radon levels through reduced ventilation, thus increasing radon gas concentration indoors.

Impact of Reduced Ventilation in Summer

In the summertime, and despite increased ventilation, some buildings still register high radon levels: The amount of radon gas in building seven was 70 Bq/m³, which is 13.04% above the calculated value.

However, despite improvements made to its airflow situation during hot weather conditions, this structure would remain significant for radiation poisoning. Building No. 6 had a concentration of 31 Bq/m³, indicating a 12.38% difference. This implies that even with better summer ventilation, the building's characteristics contribute to elevated radon levels.

Likely, reduced ventilation is not an effective measure to reduce radon concentration during summer in a number of buildings where other factors are significantly present including exhalation surface area and room volume.

Radon Concentrations in Needakara, Kerala, reveal, generally, large exhalation surface areas and room volumes in buildings like Building No. 12 usually have increased radon levels throughout the entire year. The presence of low ventilation during winter causes high radon levels.

On the contrary, it is often found that the summer may see some decrease in radon levels in most places. Even so, there are specific buildings that still show high levels of radon gas in summer because ventilation alone cannot take care of everything. However, effective ventilation does not always suffice in buildings characterized by high exhalation surface areas or volumes.

Thus, comprehensive radon mitigation strategies should consider both the ventilation and the specifics of the building to control radon effectively. Mitigation measures directed at lowering indoor radon levels must be adopted in relation to individual needs, which include ventilation improvement and addressing structural issues within such buildings thus ensuring quality air indoors.

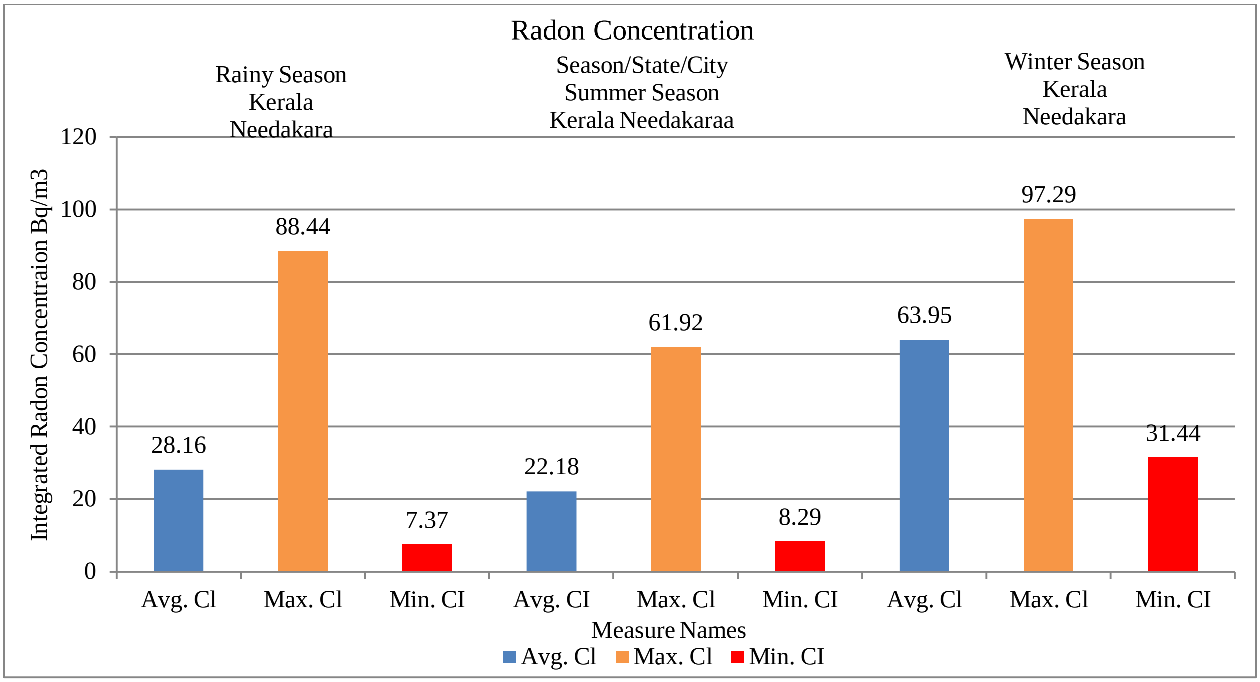

Fig. 4 Qualitative analysis of CI in Needakara

Figure 4 shows the quotative analysis of CI in Needakara. There were great seasonal variations in the degree of radon present in the atmosphere of Needakara, Kerala according to a study. Specifically, the amounts of this radioactive gas ranged from 8.29 Bq/m³ to 61.92 Bq/m³ during the hot season and from 7.37 Bq/m³ to 88.44 Bq/m³ in the wet season, with an average amount being 22.18 Bq/m³ and 28.16 Bq/m³ respectively. So, it can be seen that during winter months more radiation is experienced as opposed to summer when the least amounts are observed. With winter approaching, people tend to close their houses, thereby decreasing air circulation and leading to high levels of radon whilst they open them up during rainy seasons so that it becomes less. This trend also shows us that when there is a temperature rise there will surely be a fall and vice versa because peak seasons for radon are not the same as those when it decreases. The explanation for why increased amounts of radon are found in homes during cold weather could be attributed to the reduced number of open windows, which could remove it from buildings, while its accumulation is reduced during the rainy season due to more air that flows out of a home because of rainwater. Therefore, this alternation necessitates 24/7 watch for its presence and ability to mitigate these changes effectively at any moment of the year.

4.2. Radon Concentrations and Influencing Factors in Chavara, Kerala

4.2.1. Seasonal Variations in Radon Concentrations in Chavara, Kerala

Chavara is located at approximately 8.95° N latitude and 76.55° E longitude. It is 10 meters above sea level. Chavara is characterized by land which is mostly plain sloping gently in other parts close to the sea. The closeness to the ocean has a great influence on its physical relief. Moreover, how fast air moves over this region is related to its capacity for receiving water from the sea.

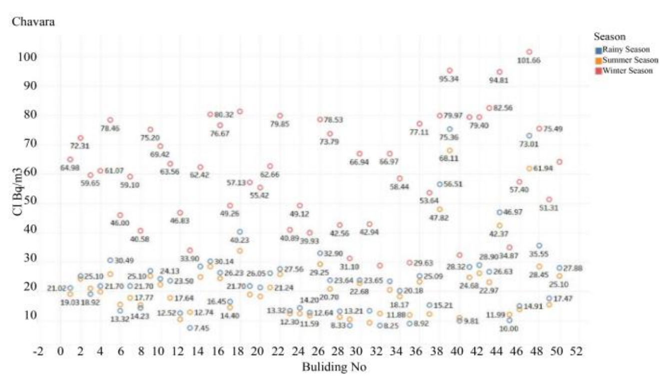

Fig. 5 Integrated radon output in different seasons at Chavara (Kerala)

Figure 5 exhibits the result, a detailed study in Chavara, Kerala offers a comprehensive insight into seasonal radon concentration variations inside different buildings. Using various factors like soil flux density, room volume, exhalation surface area, decay constant, and ventilation rate it gives an insight into how these variables affect radon levels.

Rainy Season Analysis

This means that the rainless periods range from a minimum level of 7 Bq/m³ to a maximum of 88 Bq/m³ within different buildings in the region of interest. During this period, there is significantly lower radon when compared with other times in years. There are many reasons for this.

The Rainy Season is a Time with Low Radon Levels: For instance, in Building No. 5, it was 33 Bq/m³, 7.77% more than the calculated 30.62 Bq/m³ concentration, while building No. 13 had 7 Bq/m³ concentration which is approximately 6.39% below 7.48 Bq/m³ calculated value.

Exhalation Parameters (Surface Area and Room Volume): In general, larger-surfaced and larger-volume buildings were found to have higher radon levels (Naddafi et al., 201). This can be portrayed with building number 38 having a radon concentration of 65 Bq/m³ because its exhalation surface area was as much as 192 m² and room volume was 105 m³, which is much higher than the calculated 56.78 Bq/m³. These adaptations show how environmental conditions in buildings are influenced by building characteristics during the rainy season to raise indoor radon levels.

Winter Season Analysis

Each winter season is largely characterized by high levels of radon that range between 31 Bq/m³ and 97 Bq/m³, averaging 63.95 Bq/m³. This is mainly associated with poor ventilation during the cold months, allowing for more indoor radon infiltration:

High Radon Levels in Some Buildings: For instance, building number five registered 85 Bq/m³ during winter time, which was approximately 7.85% more than the 78.81 Bq/m³ calculated value, but in comparison with the thirteen it was lower by about 5.98% when seventy-eight eighty-three 3 was calculated.

Impact of Lack of Ventilation: Reductions on winter's days inflate radon figures because there are no spaces allowing outside to come into these premises. This forms article goes in-depth by highlighting how ventilation controls indoor concentration during winters using Building No.44, whose figure of 103 Bq/m³ is eight-point seventeen percent (8.17) above the calculated value of 95.24 Bq/m³. Winter needs proper ventilation to avoid high radon levels.

Summer Season Analysis

In the summer period, radon ranged between 8 Bq/m³-62 Bq/m³ with an average dose of 22.18 Bq/m³. Less radon can accumulate indoors when it is hot because ventilation is usually higher. There are always higher radon levels during the summer season, maybe because more and more windows are opened for air circulation within the rooms, especially during the night time (Moridi et al., 2014).

On the contrary, building number 13 recorded its level at 12 Bq/m3 which is about 6.18% less than 12.79 Bq/m3 that was obtained by calculations. The large exhalation area and volume mean that Building No.38 had much more radon at 55 Bq/m³ than 48.05 Bq/m³ that were calculated for it.

In this analysis, the integrated analysis of Chavara radon concentration reveals that there are seasonal differences in indoor radon levels throughout the year- high levels during winter due to low ventilation rates, whereas summer has low levels due to high ventilation rates. On the other hand, it was found that there were moderate levels of radon during the rainy season falling in between these seasons. Therefore, specific mitigation measures against radon during the various seasons must be put in place to properly handle indoor concentrations inside buildings, such as enhancing winter ventilation which proves to reduce radon significantly.

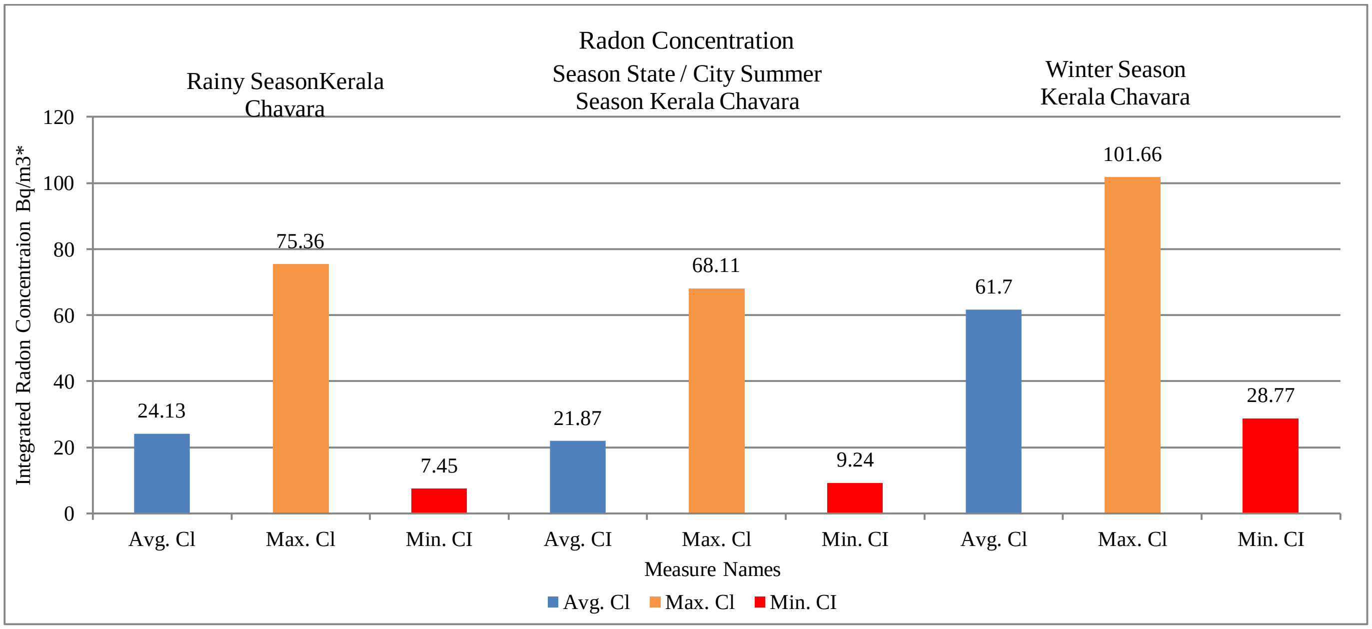

Fig. 6 Qualitative analysis of CI In Chavara

Figure 6 illustrates the result as, in the town of Chavara, the radon intensity changes greatly between seasons. During the period of rain, it may amount to between 7.45 Bq/m³ to 75.36 Bq/m³; winter season, it varies from 28.77Bq/m³ up to 101.66Bq/m³; summer period, the value changes from 9.24 Bq/m³ to 68.11 Bq/m³. The comparison shows that its maximum occurrence is in winter, while minimum levels are reached during periods of rainfall. For an average rainy season, radon gas was measured at 24.13 Bq/m³ and during winter 61.70 Bq/m³ as well as 21.87B q/m³ for a typical summer indicating well-pronounced seasonal variations from higher levels in winter to lower ones in rain.

4.3. Radon Concentrations and Influencing Factors in Maruthady, Kerala

4.3.1. Seasonal Variations in Radon Concentrations in Maruthady, Kerala

It is high at coordinates 9.00° N by 76.55° E, with about 15 meters above sea level. There are coastal plains as well as a small amount of raised places in the region which is almost flat or gently sloping. This location because sandy type soil acts as a major transporter for radon, making their health effects more severe in case they get exposed to the public. Figure 7 shows the result for Maruthady, a city in Kerala that had various levels of integrated radon concentrations depending on the season; for example, in the rainy season, there were 6 Bq/m³ to 60 Bq/m³ while during that period, 24.13 Bq/m³ was noted as an average value. Nevertheless, it was found that even though there were larger areas from which the gas could escape, as well as higher room volumes, there still were higher concentrations of radon, although there was a relatively low percentage difference from the expected values.

It is seen that in winter seasons, there is an increase ranging between 25- 110 Bq/m³ in radon concentrations (average-61.70 Bq/m³), while the percentage differences are more pronounced during this period, thus pointing out that reduced ventilation has a bigger impact compared to other factors such as low outdoor radon levels. The increased radon concentrations were likely to be due to the larger volume of indoor spaces and a seasonal decrease in ventilation.

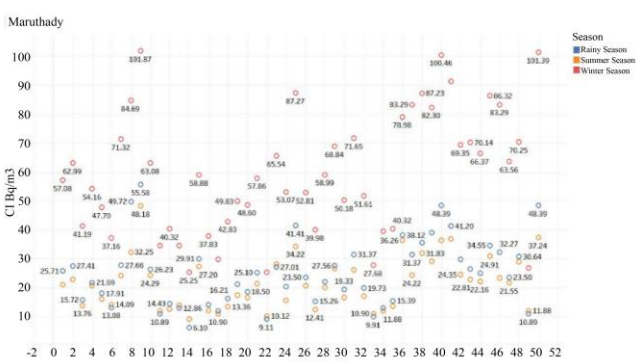

Fig. 7 Integrated radon output in different seasons at Maruthady (Kerala)

In this regard, during the summer season, radon concentrations were 9 Bq/m³ to 52 Bq/m³, with an average of 21.87 Bq/m³. Even when they were less than the amounts experienced in winter there were still significant radon concentrations recorded in some buildings because of the different rates of ventilation and soil flux densities. Nonetheless, the percentage differences were somehow higher, showing how much ventilation and soil composition affect the levels of radon gas. Data generally suggests that in Maruthady town, seasonal variability, building-specific variables, and environment are the main drivers of radon levels. This is why ventilation decline during winter leads to much higher radon accumulation indoors. Building 9 in Maruthady, Kerala, exhibited the highest quantity of radon during the rainy season, while in winter, it had the highest quantity of radon as follows:

Rainy Season

Building 9 exhibited the highest radon concentration at 60 Bq/m³. A significant exhalation surface area and room volume in this building were observed to have contributed much to its high radon levels even though, on a general note, they appeared low in the season.

Winter Season

The other time when Building 9 had a peak radon concentration was during the winter season when it reached 110 Bq/m³. Among reasons that may explain this could be lowered ventilation rates and greater size of indoor spaces within which radon would accumulate more during cold periods (winters).

Summer Season

Also, building 9 displayed the highest amount of radon at 52 Bq/m³. The building's susceptibility to soil types and ventilation aspect are evident in this aspect hence making it prone to continuous high radon levels over time.

In the final analysis, building 9 consistently had the highest levels of radon over all seasons due to its specific structural and environmental conditions which made it more exposed than any other buildings.

Figure 8 shows the qualitative analysis of CI in Maruthady. In Maruthady, Kerala, radon concentrations fluctuate depending on the season, with readings varying between 6.10 and 55.58 Bq/m³ during rainy seasons but shooting up to 25.23–108.87 Bq/m³ in winters and reducing to some 9.12 up to 48.18Bq/m³ in summertime. Winter always records the highest intensity of radon but with the lowest funny enough for the rainy season when compared with the three being studied. Hospitals also have more concentrations here, though not too high, like those found at homes located in this area. The rainy season, however, shows the lowest radon levels, while winter remains its peak period.

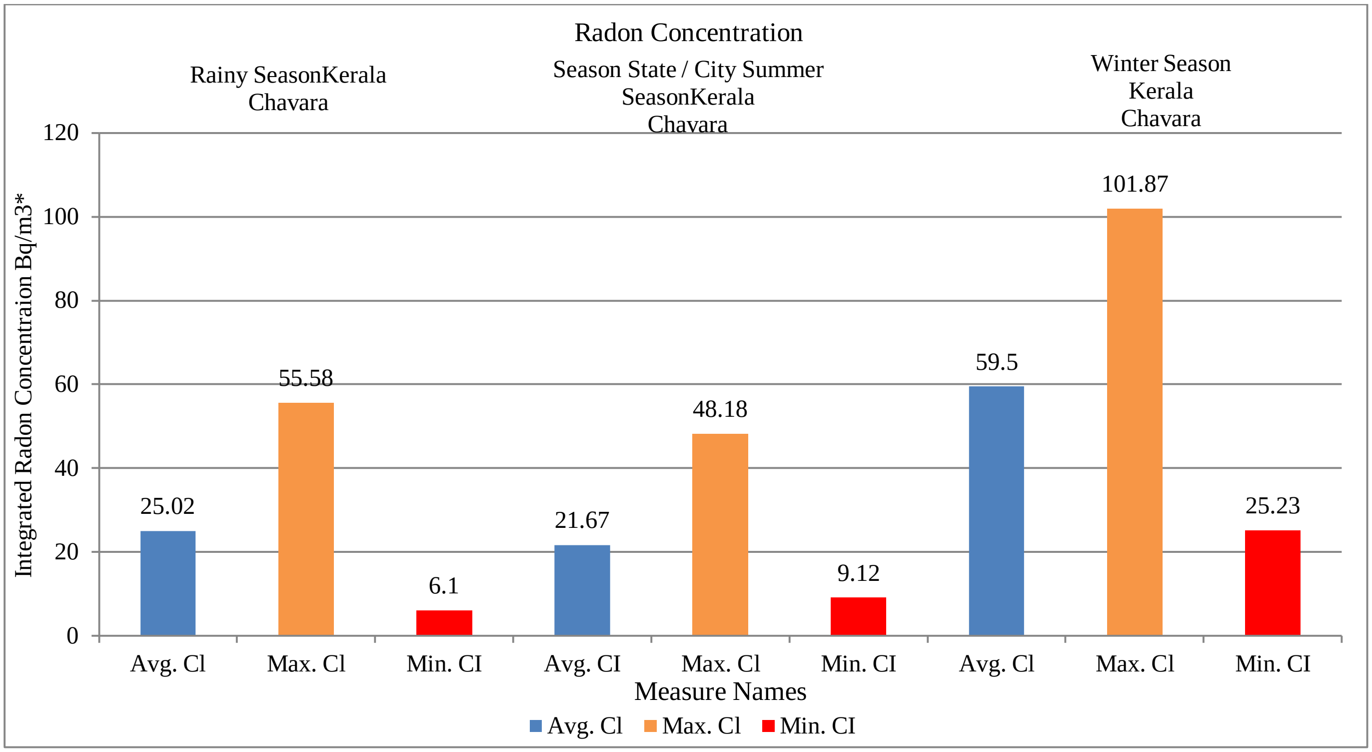

Fig. 8 Qualitative analysis of CI in Maruthady

The average radon levels are 25.02 Bq/m³, 59.5 Bq/m³, and 21.67 Bq/m³ for their respective seasons, which also include the rainy season, winter, and summer. The comparative analysis reveals that Chavara records the highest combined radon intensity across all three sites in Maruthady, Chavara, and Neendakara, owing to more favorable geologic, environmental, and climatic factors that promote this gas build-up.

4.4. Radon Concentrations and Influencing Factors in Mumbai (Maharashtra)

4.4.1. Seasonal Variations in Radon Concentrations in Mumbai (Maharashtra)

At the floor building, G+20 tower in Chembur, Mumbai, radon was aggregated for twelve months to cover all key seasons: Winter, Rainy, and Summer. Chembur is situated approximately at latitude 19° 03′ 04″ N and longitude 72° 53′ 38″ E, with an average height of fourteen meters above sea level. It is mostly lowlands interrupted occasionally by shallow hills from which emerge columnar basalt formations in the south along with a generally flat topography. Generally, this locality is flat with low hills and may not experience mold formation due to high altitude; however, its specific areas have radon accumulation because of underlying rocks made up mainly of basalt.

Figure 9 shows the data of integrated Radon concentration from a G+20 building in Chembur, Mumbai, showing that there is a clear change between dry and wet seasons. For instance, in the rainy season, it fluctuated between 18 Bq/m³ going up to 60 Bq/m³, with the highest point being on the first floor while the bottom most floor had it as low as 20Bq/m³. The average Radon concentration level was much higher, 58.58 Bq/m³ for the floors near the ground, implying that accumulation might occur due to poor ventilation rates and high soil flux density.

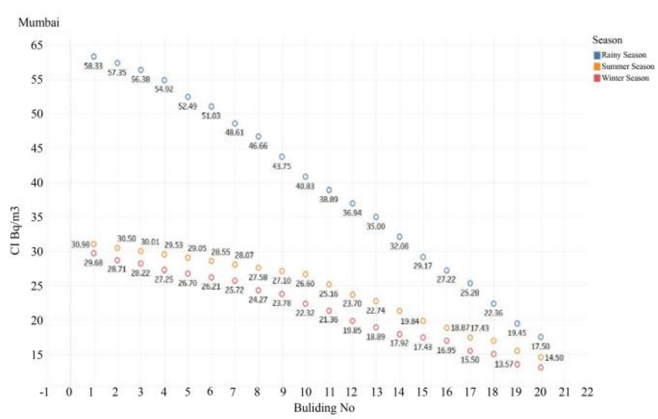

Fig. 9 Integrated radon output in different seasons at Mumbai (Maharashtra)

During winter time, Radon concentrations ranged between 13.5 Bq/m³ to 30.5 Bq/m³, in which case the upper floors registered lower values on average. The mean concentration for this season was measured at 29.80 Bq/m³, which indicated a fall compared with previous periods owing to reduced room ventilation and lower soil fluxes. According to the information above, it can be noted that during summer, levels were recorded to be ranging from 15 Bq/m³ going up to 32 Bq/m³ while the mean was at 31.37 Bq/m³. Radon levels were slightly lower in summer than rainy season but higher than in winter. This could be because higher temperatures increase radon emission from the ground, hence less effective ventilation. Before wrapping up the findings, some general insights can be drawn out here; as regards rainier periods, they are at their peak while they are at moderate levels during summer, then lowest in winter within the Mumbai area. Soil flux density, room volume, ventilation rates, and variations in seasonal external and internal environmental conditions control these variances.

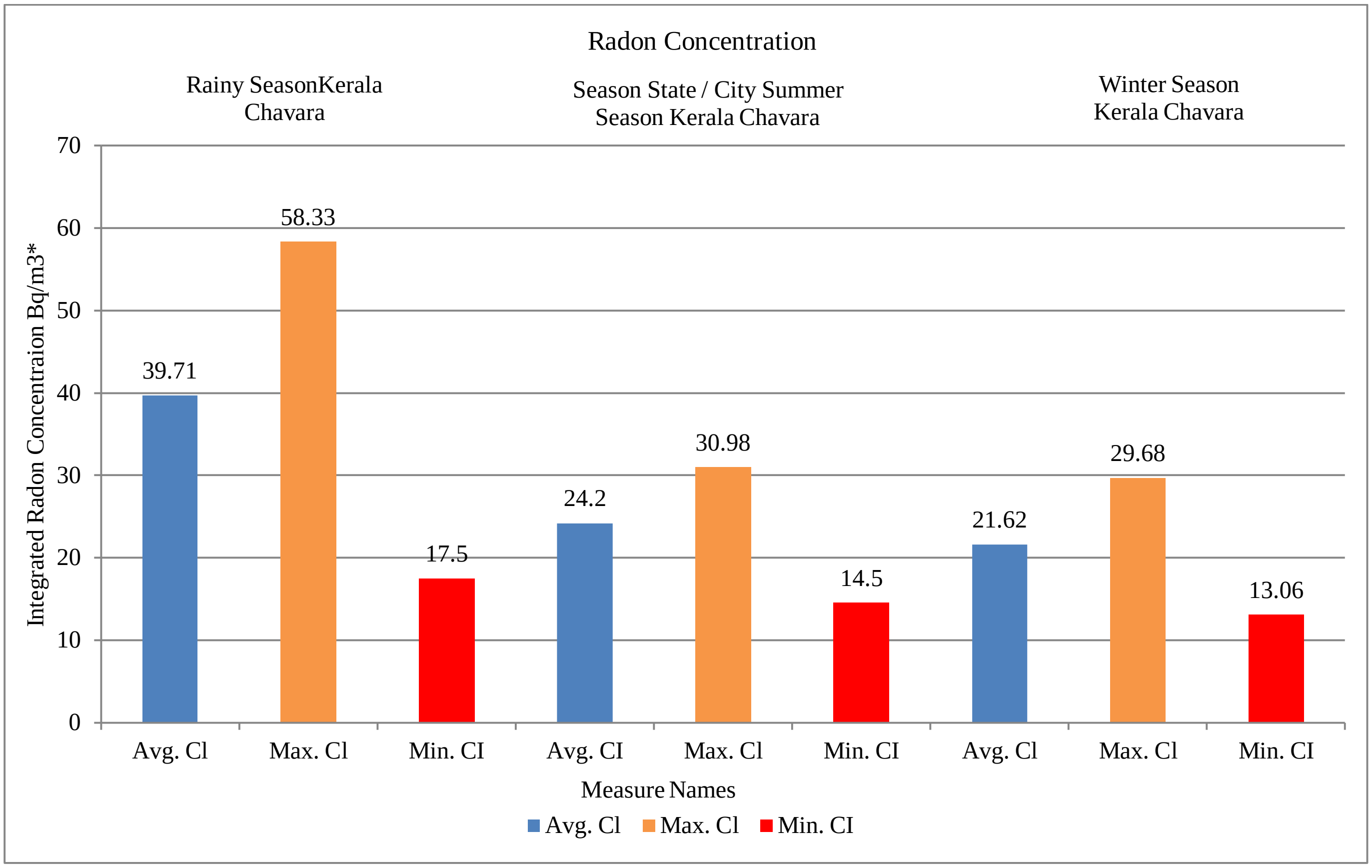

Fig. 10 Qualitative analysis of CI in Mumbai

Figure 10 depicts the qualitative analysis of CI in Mumbai. The rainy season had the highest radon levels because the rate of water infiltration reduced soil permeability; hence, water filled up the gaps and voids. This increased its accumulation since it is easily trapped and does not move freely due to water in that layer.

On the other hand, during winter, it had the least amounts since there was increased soil aeration and less radon emission. Therefore, seasonal radon occurrence patterns in a given area are related to the local geology, the nature of its soils, and the type of structures situated there, from which it can be deduced that control and prevention measures dealing with radon should target these aspects, especially radon intensity, Mumbai, Maharashtra-based investigations indicate that there is a noticeable change in the soil gas (radon) during rainy, winter and summer seasons. Radon measurements ranging between 17.5Bq/m³ and 58.33Bq/m³ have been recorded in the rainy season, 13.06Bq/m³ to 21.62Bq/m³ in winter, while 14.50Bq/m³ amounts to 30.98Bq/m³ during summer. The average radon concentrations were 39.71Bq/m³ for the rainy season, 21.62Bq/m³ for winter, and 24.20Bq/m³ for summer.

It was observed that the highest levels of radon gas are found during the rainy season because when raining, less water goes in than what comes out, making it difficult for rainwater to penetrate soils, reducing their permeability. This leads to higher radon accumulation as the gas is trapped and cannot escape easily.

Conversely, radon levels were lowest in winter, likely due to increased soil aeration and lower radon emission. Seasonal trends in radon intensity are influenced by local geology, soil conditions, and specific building characteristics, underscoring the importance of these factors in radon management and mitigation strategies.

Table 1. Concentration rate of radon from different buildings and different seasons for different places in india

Different places in India	Different Season	Calculated Reading (CI)		Experimental Reading		Difference	
		Max	Min	Max	Min	Max	Min
Lunglei – Mizoram	Rainy season	56.67	17.44	62.54	16.05	17.50	-7.98
	Winter season	125.27	24.59	133.17	27.18	17.51	-7.82
	Summer season	86.54	25.25	93.38	27.79	17.36	-7.72
Serchhip – Mizoram	Rainy season	66.02	14.65	73.58	15.45	11.44557	3.96568
	Winter season	112.23	24.74	118.61	26.12	11.42503	4.243831
	Summer season	63.89	23.79	68.54	25.66	11.3928	4.211443
Mamit - Mizoram	Rainy season	91.58	24.18	102.58	25.44	12.53939	-8.22137
	Winter season	133.93	32.94	148.64	35.37	12.45026	-8.18341
	Summer season	62.35	23.76	64.48	24.99	12.46323	-8.17987
Needkara - Kerala	Rainy season	88.44	7.37	100	7	13.07595	-5.27266
	Winter season	97.29	31.44	110	30	13.06724	-5.07641
	Summer season	61.92	8.29	70	8	13.04096	-5.35715
Chavara - Kerala	Rainy season	75.71	7.48	83	7	14.4844	-6.47557
	Winter season	102.12	28.88	110	28	14.4937	-6.2836
	Summer season	68.42	9.28	75	9	14.4577	-6.52557
Maruthady - Kerala	Rainy season	55.58	6.10	60	6	12.06733	-1.57283
	Winter season	101.87	25.23	110	25	12.17187	-1.00444
	Summer season	48.18	9.12	52	9	12.01796	-1.34806
Mumbai –Maharashtra	Rainy season	58.58	17.57	60	18	2.436644	1.95582
	Winter season	30.50	13.22	30.5	13.5	2.346378	1.95582
	Summer season	32.00	14.68	32	15	2.178307	1.987855

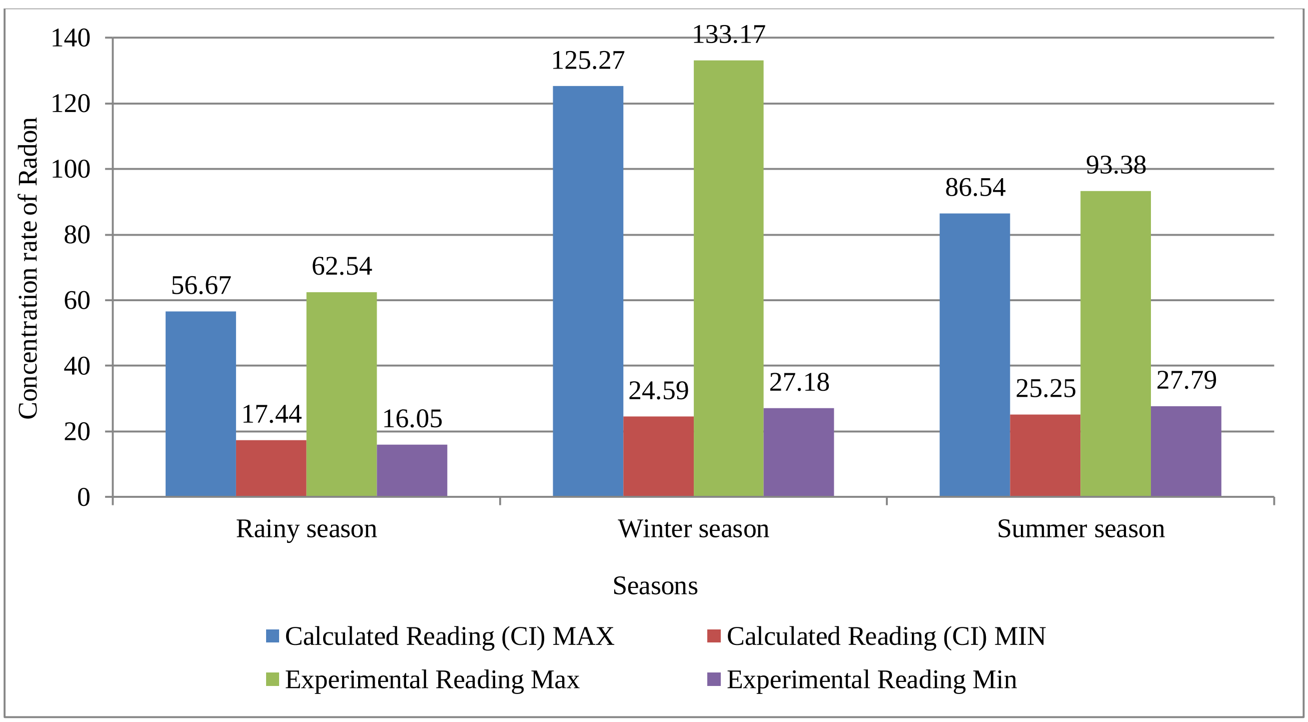

Fig. 11 Concentration rate of radon from different buildings in different seasons for Lunglei– Mizoram

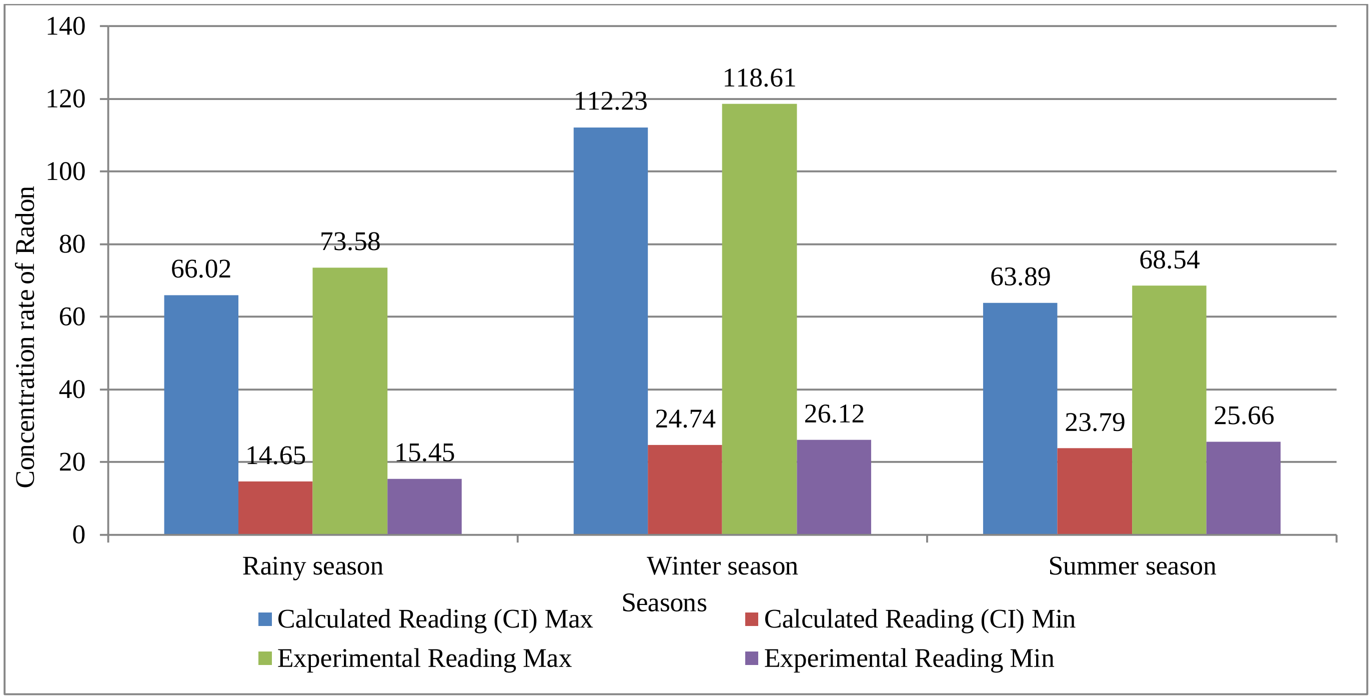

Fig. 12 Concentration rate of radon from different buildings and different seasons for Serchhip– Mizoram

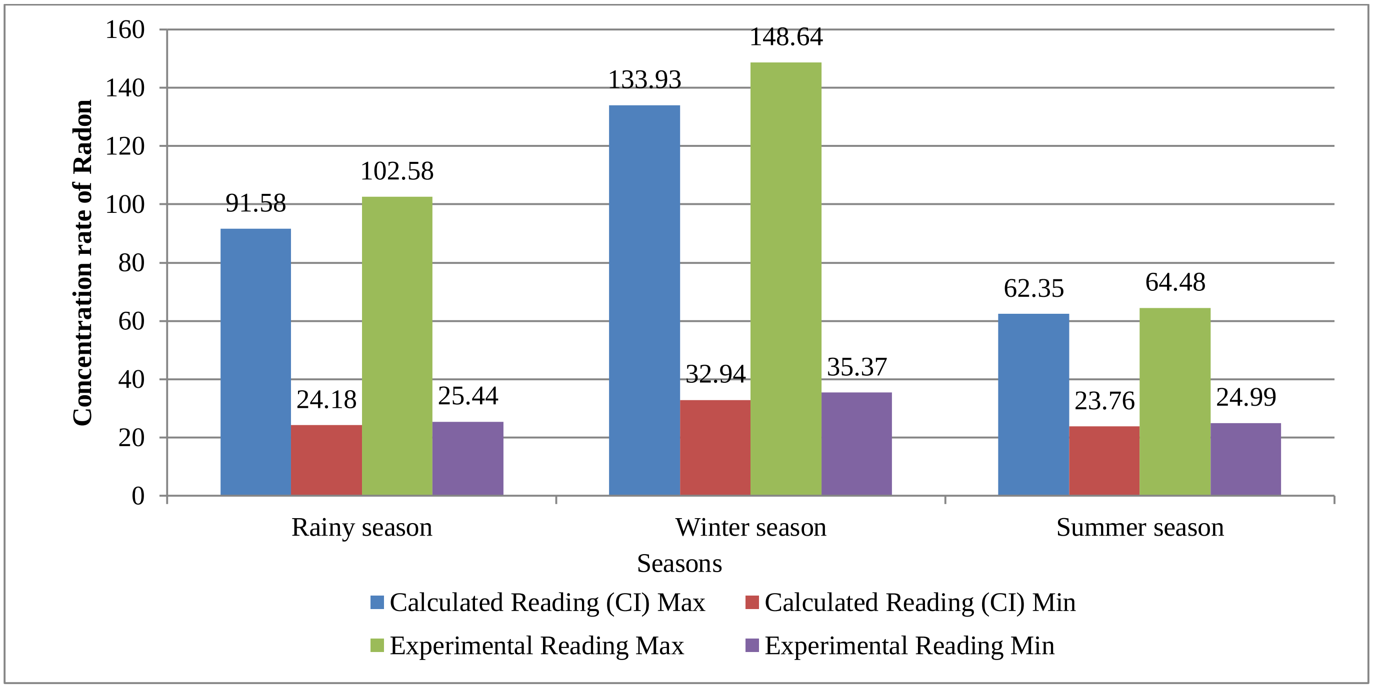

Fig. 13 Concentration rate of radon from different buildings and different Seasons for Mamit - Mizoram

The information gathered and shown in Table 1 helps to explain how indoor radon levels vary across these various locations.

The table contains calculated and experimental radon (CI) readings for various locations in India across different seasons. It demonstrates the fluctuation in radon levels, with maximum and minimum values recorded for each season.

Figure 11 illustrates that the concentration rate of radon varies across different buildings and seasons in Lunglei, Mizoram. During the rainy season, the highest calculated concentration is 56.67 Bq/m³, while the lowest is 17.44 Bq/m³. The experimental data indicate a similar pattern, with maximum and minimum values of 62.54 Bq/m³ and 16.05 Bq/m³, respectively. Winter provides higher concentration rates, with maximum and minimum values of 125.27 Bq/m³ and 24.59 Bq/m³, respectively. Experimental results support this pattern, with maximum and lowest values of 133.17 and 27.18 Bq/m³, respectively. Concentrations remain increased in the summer compared to the wet season but lower than in the winter. Summer concentrations are estimated at 86.54 Bq/m³ and 25.25 Bq/m³, whereas experimental observations show 93.38 Bq/m³ and 27.79 Bq/m³, respectively.

In Serchhip, Mizoram, the concentration rates of radon vary across different buildings and seasons illustrated in Figure 12. The experimental values for radon all over the rainy season varied from 15.45 to 73.58 Bq/m³, whereas the reported concentrations ranged from 14.65 to 66.02 Bq/m³. In winter, concentrations increased to levels between 24.74 and 112.23 Bq/m³, with experimental readings spanning 26.12 to 118.61 Bq/m³. Conversely, the summer season saw concentrations ranging from 23.79 to 63.89 Bq/m³ and experimental readings from 25.66 to 68.54 Bq/m³. The higher levels observed during the winter months have been related to factors such as reduced ventilation and the stack effect, in which warm air rises and flees through the building's upper floors, resulting in a greater influx of radon from the soil and building substances into the building's interior.

Figure 13 shows that the concentration rates of radon vary across different buildings and seasons in Mamit, Mizoram, reflecting the diverse construction materials and climatic conditions prevalent in the region. During the rainy season, radon concentrations range from 25.44 Bq/m³ to 102.58 Bq/m³, indicating a substantial variation influenced by factors such as increased moisture levels and potential changes in ventilation patterns due to weather conditions.

In contrast, the winter season sees higher concentrations, with readings ranging from 35.37 Bq/m³ to 148.64 Bq/m³, possibly due to reduced ventilation and tighter sealing of buildings to conserve heat. The summer season has lower radon concentrations, ranging from 24.99 Bq/m³ to 64.48 Bq/m³. Improved ventilation during the summer months, occasionally due to open doors and windows, improves air movement and radon gas dispersion, resulting in lower indoor radon concentrations.

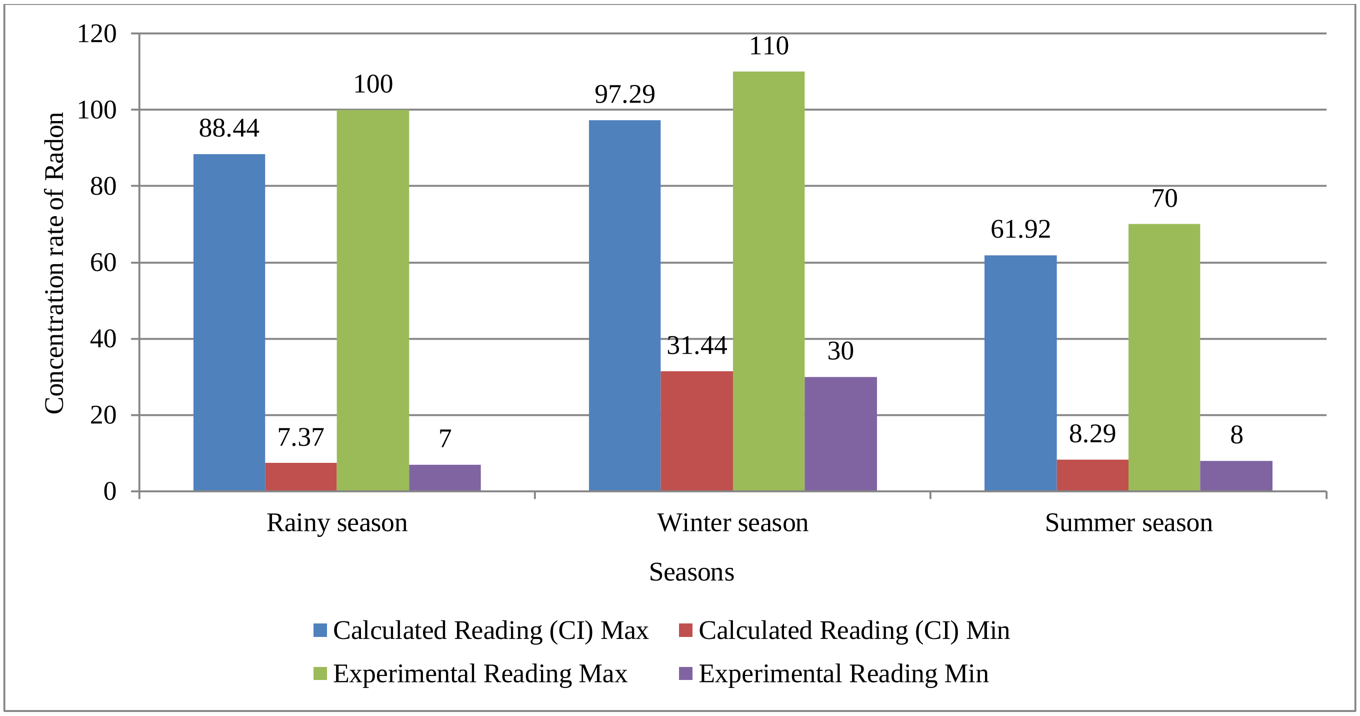

Fig. 14 Concentration rate of radon from different buildings and different seasons for Needkara- Kerala

In Needkara, Kerala, the concentration rates of radon exhibit variations across different seasons and types of buildings, as shown in Figure 14. During the rainy season, the maximum calculated reading stands at 88.44 Bq/m³, while the minimum is recorded at 7.37 Bq/m³. Similarly, in winter, the maximum and minimum readings reach 97.29 Bq/m³ and 31.44 Bq/m³, respectively. Conversely, during the summer season, the concentration rates show a decrease, with a maximum calculated reading of 61.92 Bq/m³ and a minimum of 8.29 Bq/m³. These fluctuations are attributed to factors such as building construction materials and ventilation patterns. Solidified construction materials prevalent in the region, such as concrete, sand, blocks, and cement, influence radon accumulation differently across seasons.

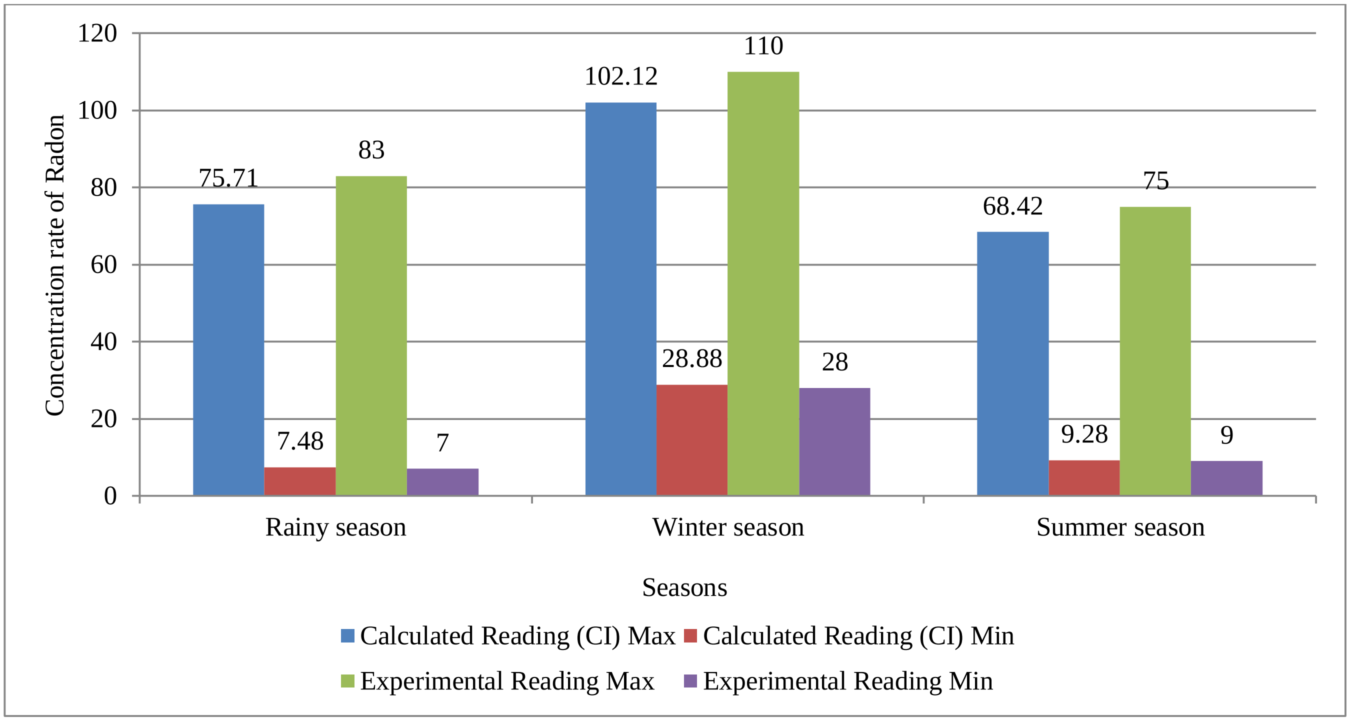

Fig. 15 Concentration rate of radon from different buildings and different seasons for Chavara – Kerala

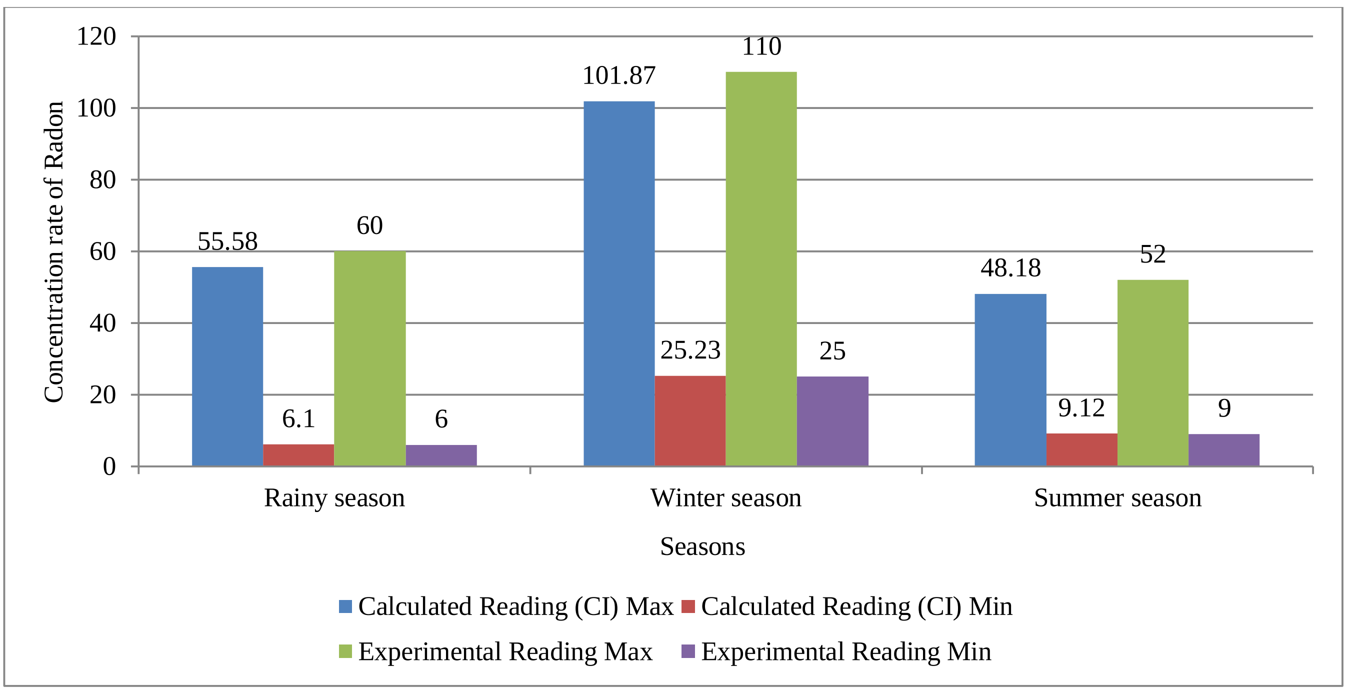

Fig. 16 Concentration rate of radon from different buildings and different seasons for Maruthady - Kerla

In Chavara, Kerala, the concentration rates of radon vary across different seasons and building types, as shown in Figure 15. During the rainy season, radon concentration levels range from 7.48 Bq/m³ to 75.71 Bq/m³, with experimental observations falling between 7 Bq/m³ to 83 Bq/m³. The presence of moisture in the air and on surfaces enhances radon release from building materials, leading to higher indoor radon concentrations. In the winter season, these levels increase, ranging from 28.88 Bq/m³ to 102.12 Bq/m³, with experimental values ranging from 28 Bq/m³ to 110 Bq/m³. This increase is often related to things such as less ventilation from closed doors and windows to keep the indoors warm. Conversely, during the summer season, radon concentration levels decrease, ranging from 9.28 Bq/m³ to 68.42 Bq/m³, with experimental observations ranging from 9 Bq/m³ to 75 Bq/m³. This variation is attributed to factors such as temperature, humidity, and ventilation within different types of buildings, including single-story houses in Kerala.

In Maruthady, Kerala, the concentration rates of radon vary across different seasons and building types, reflecting the influence of construction materials and ventilation practices prevalent in the region, as shown in Figure 16. Radon concentrations during the rainy season range from 6.10 to 55.58 Bq/m³ because solidified building materials such as concrete and mortar are less vented during this time. The relatively tight single-story homes that are typical in Kerala, when paired with this reduced amount of ventilation, lead to an interior buildup of radon gas. In contrast, the concentration rates during the winter season increase from 25.23 to 101.87 Bq/m³, possibly due to reduced ventilation and tighter sealing of buildings to conserve warmth. Similarly, during the summer season, concentrations range from 9.12 to 48.18 Bq/m³.

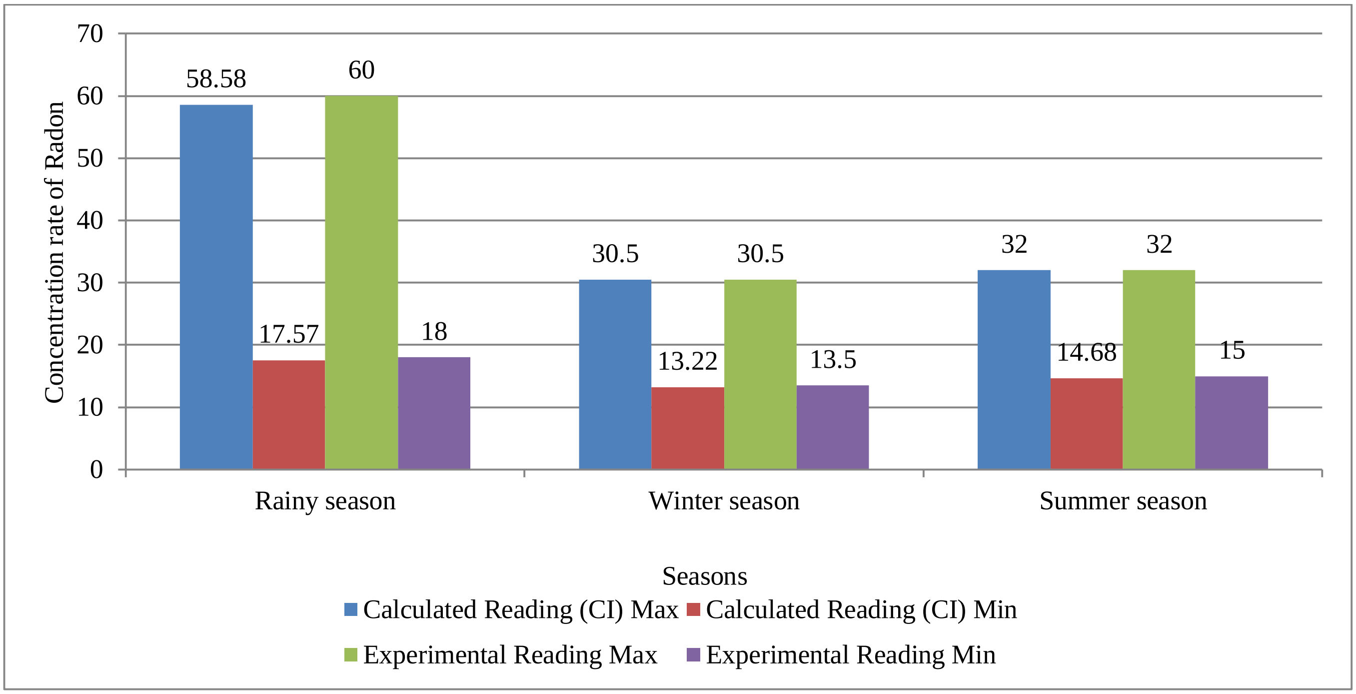

Fig. 17 Concentration rate of radon from different buildings and different seasons for Mumbai – Maharashtra

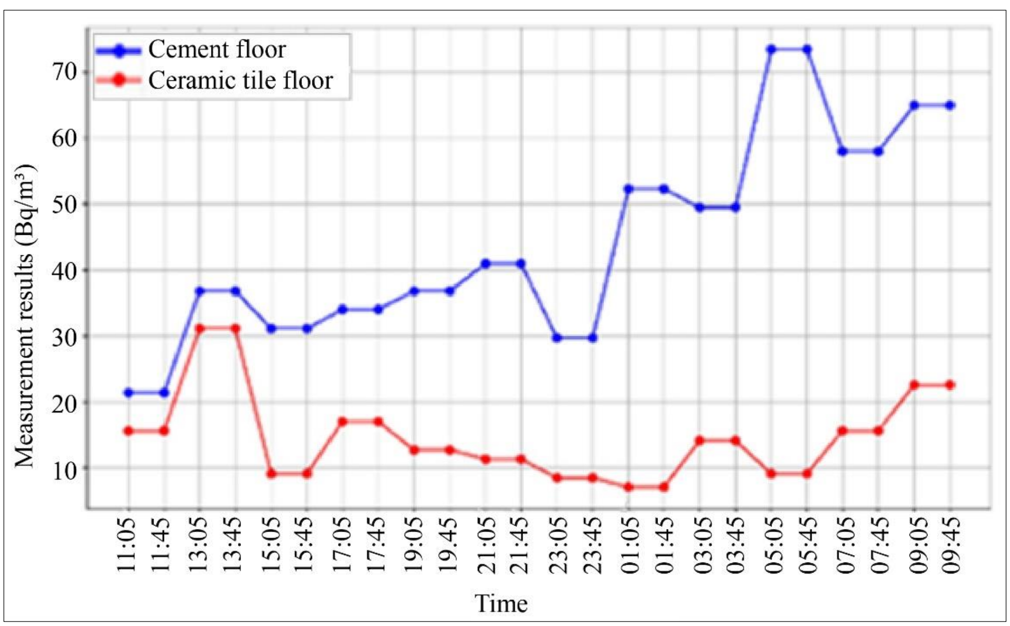

Fig. 18 Indoor air radon concentration based on time

Figure 17 shows the radon concentrations in the city of Mumbai, Maharashtra, which vary based on the season and the type of structure. During the rainy season, the highest determined concentration is 58.58 Bq/m^3, while the lowest is 17.57 Bq/m^3. These numbers are consistent with experimental data, demonstrating the reliability of the computations. During the winter season, the estimated maximum and minimum concentrations are 30.50 Bq/m^3 and 13.22 Bq/m^3, which closely match the experimental results. During the summer, estimated concentrations vary from 32.00 Bq/m^3 to 14.68 Bq/m^3. Radon concentrations vary depending on building materials, ventilation rates, and environmental variables. Solidified construction materials such as concrete, sand, and cement found in Mumbai's multi-story buildings lead to elevated radon levels.

The indoor air radon concentrations in a room with a cement floor and a ceramic tile floor over time are shown in Figure 18. The data show dynamic fluctuations in radon concentrations, with daily variations in the quantity of radon present indoors. Radon concentrations in the cement-floored room vary from 24.1 Bq/m^2 to 73.5 Bq/m^2 all over the monitoring period. In the same way, radon concentrations in the room with the ceramic tile floor vary from 7.07 Bq/m^2 to 31.1 Bq/m^2. Numerous factors, including the permeability of flooring materials, ventilation rates, and the underlying geological conditions, are responsible for these variances. Although cement floors exhale radon more quickly than ceramic tile floors, these raise the risk of elevated radon levels.

4.5. Comparison of the Present Study with Existing Studies

The present study provides an advantageous perspective of the geographical differences and variables influencing indoor radon levels by comparing the radon concentrations obtained with those from other studies completed in different parts of India and throughout the world.

Table 2. Comparison of Radon concentration observed in the present study with various studies

Locations	Radon Concentration (Bq m-3)	Reference
Meghalaya, India	56	[20]
Karnataka State, India	63.73	[20]
Kollam Districts, Kerala, India	88.3	[20]
UK	36	[20]
Russia	49	[20]
Nigeria	144	[20]
Poland	51.8	[20]
Kumaun Himalaya, Uttarakhand	11.0-64	[22]
Visakhapatnam, India	24.32	[22]
Nalgonda district, Telangana State, India	14 - 675	[19]
Belagavi district of Karnataka, India	Monsoon 30.45 Autumn 56.45 Winter 38.75 Summer 21.8	[20]
Nainital District of Uttarakhand, India	9–99	[21]
Jammu & Kashmir	18–59	[28]
Bagewshwar Uttarakhand	23–147	[29]
Shivamogga District, Karnataka, India	8.14–146.24	[23]
Mandya City, Karnataka, India	22.4 ± 1.5	[25]
Jakrem	60 ± 6	[30]
Wahkaji	61 ± 6	[30]
Rangmaw	42 ± 5	[30]
Mawkyrwat	61 ± 6	[30]
Lunglei – Mizoram	23.67-96.36	Present study
Serchhip – Mizoram	22.41-86.91	
Mamit - Mizoram	28.6-105.23	
Needkara - Kerala	15-93.33	
Chavara - Kerala	14.67-89.33	
Maruthady - Kerala	13.3-74	
Mumbai –Maharashtra	15.6-40.83	

Overall data, Mamit in Mizoram had the highest radon concentrations across seasons, with readings ranging from 91.58 to 148.64 CI. Mumbai, Maharashtra, has the lowest radon concentration, ranging between 30.50 and 60.00 CI. Winter radon concentrations are typically greater than summer and wet seasons in most areas, except Maruthady, Kerala, where summer measurements were the lowest. Overall, Mamit in Mizoram has the greatest radon concentrations, whereas Mumbai, Maharashtra, has the lowest amounts throughout all seasons. These findings highlight the need to consider both geographical location and seasonal fluctuations when monitoring indoor radon levels and adopting mitigation techniques to assure indoor air quality and occupant healthiness. The results of this study help design effective mitigation strategies that ensure indoor air quality and occupant health by educating lawmakers, building developers, and residents about the potential risks connected with radon exposure.

Many existing studies on indoor radon levels have focused on specific regions or limited geographical areas. In contrast, this study encompassed multiple regions across India, including Mizoram, Kerala, and Maharashtra, over a full year and across all three seasons (winter, rainy, and summer). This extensive geographical scope allows for a more comprehensive understanding of how regional geology and climate influence radon levels. The combination of comprehensive data collection, advanced detection technologies, integrated modeling approaches, and robust statistical analyses enabled to achievement of better results in the assessment of indoor radon levels compared to state-of-the-art techniques. These findings revealed substantial seasonal fluctuations, with higher concentrations in winter due to reduced ventilation, a detail often overlooked in previous studies. Also underscores the importance of considering a wide range of factors and their interactions when evaluating radon exposure risks, ultimately contributing to more effective mitigation strategies and improved indoor air quality for occupants.

5. Conclusion

The extensive study on "Radon Transport & Analysis of Radon Level in Existing Building Structures in India" concludes by revealing the significant seasonal fluctuations in indoor radon concentrations in different parts of the nation. The study, which extended a full year and included all three seasons, highlights the intricate interactions between a variety of elements. The mathematical model used to estimate radon concentration considered various elements, including building design, construction materials, and environmental conditions. It helped in an understanding of how radon was transmitted inside interior spaces and into the surrounding environment. The study and measurements undertaken in several locations in India demonstrate the need to consider seasonal fluctuations and the stack effect when assessing indoor radon levels. The stack effect, generated by air exiting through the roofs of dwellings, results in greater radon concentrations in the winter when windows are usually closed, while lower levels were reported in the summer and rainy seasons due to enhanced ventilation and decreased air pressure on ground floors. The investigation of radon concentrations across different districts and seasons reveals significant variability**:**

- In the Lunglei District, radon concentrations range from 17.44 Bq/m^3 to 56.67 Bq/m^3 during the wet season. It varies between 24.59 and 125.27 Bq/m^3 during the winter season. Similarly, in the summer, the radon concentration ranges from 25.25 Bq/m^3 to 86.541 Bq/m^3. When comparing radon concentrations by season, winter had the greatest values, and rain had the lowest.
- In Serchhip District, during the rainy season, radon concentrations vary from 14.65 Bq/m^3 to 66.02 Bq/m^{3,} whereas in winter, it was found to vary from 32.94 Bq/m^3 to 133.93 Bq/m^3. It ranges from 23.76 Bq/m^3 to 62.35 Bq/m^3 in summer. Comparing concentrations, radon levels are high in winter and low in rainy months.
- In Mamit District, during the rainy season, radon concentrations vary from 24.18 Bq/m^3 to 91.58 Bq/m^{3,} whereas in the winter season, the level was found to vary from 35.367 Bq/m^3 to 148.639 Bq/m^3. In summer, it ranges from 24.993 Bq/m^3 to 64.478 Bq/m^3. Comparing the concentrations, radon levels are maximum in winter and minimum in the summer season.
- In the NEEDAKARA_Kollam District, the concentrations of radon vary from 7.37 Bq/m^3 to 88.44 Bq/m^3 during the rainy season. During the winter season, it ranges from 31.44 Bq/m^3 to 97.29 Bq/m$^{3.}$ Likewise, in the summer part, the radon concentration deviates from 8.29 Bq/m^3 to 61.92 Bq/m^3. Comparing the concentrations of each season, radon level is highest in the winter part and minimum in the Rainy months.
- In CHAVARA_Kollam District, the concentrations of radon vary from 7.48 Bq/m^3 to 75.71 Bq/m^3 during the rainy season. During the winter season, it ranges from 28.88 Bq/m^3 to 102.12 Bq/m$^{3.}$ Likewise, during the summer season, the radon concentration varies from 9.28 Bq/m^3 to 68.42 Bq/m^3. Comparing the concentrations of each season, radon level is highest in the winter part and minimum in the Rainy months.
- In Maruthady_Kollam District, the concentrations of radon vary from 6.10 Bq/m^3 to 55.58 Bq/m^3 during the rainy season. During the winter season, it ranges from 25.23 Bq/m3 to 101.87 Bq/m$^{3.}$ Likewise, in the summer months, the radon concentration deviates from 9.12 Bq/m^3 to 48.18 Bq/m^3. Comparing the concentrations of each season, radon level is highest in the winter part and minimum in the Rainy months.
- In Mumbai, Maharashtra state, the concentrations of radon vary from 17.57 Bq/m^3 to 58.58 Bq/m^3 during the rainy season. During the winter months, it ranges from 13.22 Bq/m^3 to 30.50 Bq/m$^{3.}$ Likewise, in the summer

part, the radon concentration varies from 14.68 Bq/m^3 to 32 Bq/m^3. Comparing the concentrations of each season, radon level is maximum in the Rainy months and minimum in the winter parts.

The data analysis and measurements done across multiple districts reveal seasonal fluctuations in indoor radon concentrations, highlighting the need for efficient efforts to reduce radon exposure risks, particularly during the winter.

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