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Indoor Air Radon study in different local houses in and around Susunia hill area, Bankura District of West Bengal, India

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Title page

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Title: **Indoor Air Radon study in different local houses in and around Susunia hill area, Bankura District of West Bengal, India**

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Indoor Air Radon study in different local houses in and around Susunia hill area, Bankura District of West Bengal, India

Abstract

A preliminary survey was conducted to assess indoor air radon concentrations in 70 living rooms across various houses located in and around the Susunia hill region of Bankura district, West Bengal, India. Measurements were carried out using an AlphaGUARD portable radon monitor. Among the surveyed dwellings, 89% were mud houses and 11% were brick houses. The indoor radon concentrations ranged from 24 to 239.7 Bq/m³, with an overall mean of 77.5±5.5 Bq/m³. The average radon concentration in mud houses (80.8±6.1 Bq/m³) was notably higher than that in brick houses (51.7±3.6 Bq/m³). Approximately 27% and 10% of the measured rooms exceeded the reference levels of 100 Bq/m³ (by the WHO, IAEA) and 148 Bq/m³ (by the USEPA and EU) respectively. Various physical characteristics of the dwellings were recorded to investigate potential factors contributing to the observed variations in radon levels. Additionally, correlations between indoor radon concentrations and meteorological parameters such as air pressure, humidity, and temperature were analyzed. The annual effective dose and excess lifetime cancer risk for the residents were also estimated for infants, children, adult male and female using established UNSCEAR 2019 model. The findings indicate the need for further comprehensive studies and potential mitigation strategies in radon-prone areas of the region.

Keywords: Air radon level, Bankura district, AlphaGUARD, Seasonal Effective Radon Dose, Health Risk

Introduction

Indoor air pollution, a significant global public health concern, is adversely affected by both natural and anthropogenic factors. According to the World Health Organization (WHO), household air pollution was responsible for an estimated 3.2 million deaths worldwide in 2020, including over 237,000 deaths among children under the age of five [Dlamini L. P. 2025; Ganie et al. 2025; Valavanidis A. 2023]. Different indoor air pollutants namely particulate matter, carbon monoxide and ionizing radiation—particularly from radon gas (^{222}Rn)—pose significant health risks [Tsakas et al. 2011] and is considered one of the most hazardous exposures due to its radioactive nature and widespread presence in homes. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has also highlighted that, for the same radiation dose, children and young adults (under 20 years of age) face a higher health risk from ionizing radiation exposure compared to adults [UNSCEAR 2020].

Radon exposure is recognized as the second leading cause of lung cancer globally, after tobacco smoking. According to WHO and the U.S. Environmental Protection Agency (USEPA), approximately 3–14% of lung cancer cases are attributed to long-term radon exposure [WHO 2009; USEPA 2002, Mirdoraghi et al. 2020]. Although outdoor radon typically disperses harmlessly into the atmosphere, its accumulation in confined indoor spaces—especially in poorly ventilated buildings—can significantly elevate health risks [Yousefian et al. 2024]. These risks are exacerbated in many low and middle-income countries where houses often lack adequate ventilation systems. Long-term low level exposure to indoor radon is estimated to contribute approximately 3–20% of all lung cancer deaths [ICRP 115; Yousefian et al. 2024; Deb et al. 2017].

Radon originates naturally as part of the decay chain of uranium-238 (^{238}U), which is ubiquitously present in rocks, groundwater, soils as well as common building materials like granite, marble, concrete, cement, and bricks [WHO 2010; Giustini et al. 2019; Hatungimana et al. 2019; Rizo Maestre & Echarri Iribarren 2018]. Radon can migrate from the ground into homes, particularly in uranium-rich area or where building structures in direct contact with soil. Radon gas infiltrates indoor environments through cracks in floors, walls, and foundations, as well as gaps around pipes and drains. Being approximately 7.5 times heavier than air, the infiltrated ^{222}Rn gas accumulates indoors in the absence of adequate ventilation, [Gazi et al. 2022; Deb et al. 2017; Boryło et al. 2013]. Its physical characteristics—colorless, odorless, and tasteless—make it imperceptible to human senses allowing it to be inhaled unknowingly [Vaupotič 2024; Naskar et al. 2023; Ahmad et al. 2017; Titipornpun et al. 2017]. After inhalation nearly all of the inhaled gas is subsequently exhaled. However, ^{222}Rn decays into a series of solid short-lived radioisotopes which deposit within the respiratory tract. Due to their relatively short half-lives ($\leq$ 30 minutes) the radon progeny mainly decay in the lungs before clearance can take place. Two of these short-lived progeny, polonium-218 and polonium 214 emit alpha particles which deposit dose to the lung and increases the associated risk of lung cancer [IAEA 2013; Gazi et al. 2022].

Globally, numerous studies have assessed indoor radon levels to better understand and mitigate associated health risks [WHO 2010]. Large-scale epidemiological studies conducted in Europe, North America, India, and China have confirmed that radon exposure is a significant risk factor for lung cancer [Reste et al. 2021; Baltrėnas et al. 2020; Mahdi 2018; Yarmoshenko et al. 2018; Nero 2018; Vimercati et al. 2018; Madureira et al.

2016]. Our previous study in the Susunia hill region of Bankura district, West Bengal, India revealed that nearly 40% of tested tube-well water samples exceeded WHO and USEPA recommended limits for radon concentration [Naskar et al. 2022]. Despite these findings, no comprehensive study has been undertaken to assess indoor air radon levels in this region. The absence of baseline data raises concerns about the potential underestimation of radon-related health risks in this area. The geological features of Susunia including its varied soil types, rocky regions, and subsurface fissures create favourable conditions for radon migration and indoor accumulation.

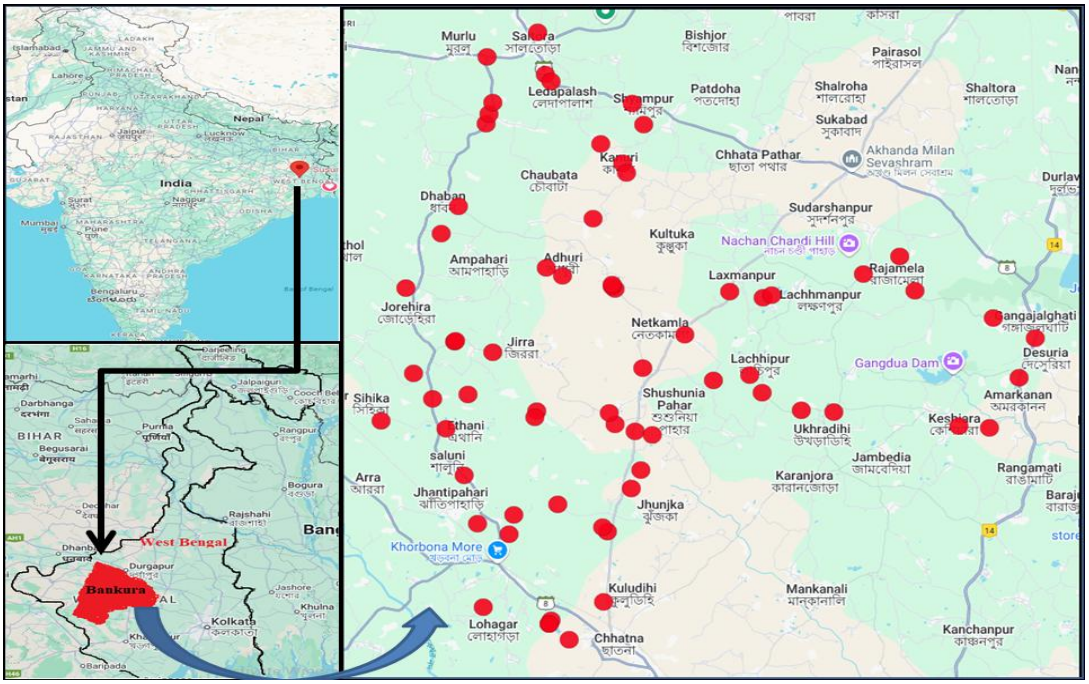
Under this scenario, the present study aims to address this lacuna by systematically measuring indoor air radon concentrations in residential houses across Susunia and its surrounding areas. The specific objectives of this study are to quantify indoor radon levels across different types of dwellings, identify environmental and structural factors influencing radon concentrations and compare the measured values against international safety standards to assess potential health risks.

Extent and geology of the Study Area

The Susunia Hill region (approximately 23°23′39″N, 86°59′11″E), located in the Bankura district of West Bengal, India, holds significant geological and cultural interest. Renowned for its picturesque landscapes, sacred springs, and diverse flora, Susunia is also a popular tourist destination. Geologically, it forms part of the southwestern fringe of the Archean Chhotanagpur Plateau, a terrain marked by complex topography ranging from rugged hills and undulating lands to alluvial plains interspersed with rocky outcrops [Biswas 2014].

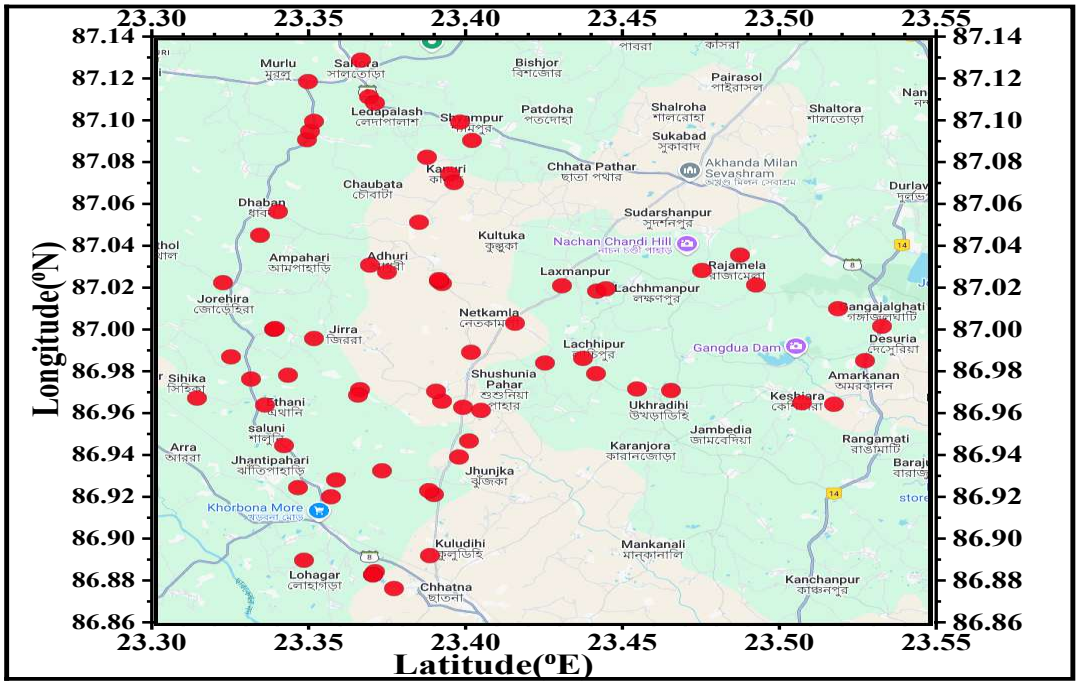
Susunia is characterized by ancient hill formations and exposed rock outcrops composed mainly of granitic and metamorphic rocks. These formations are known to host a variety of mineral deposits, including uranium-bearing minerals. The surrounding geology includes sillimanite- and kyanite-bearing schists and quartzites, indicating the presence of shear zones [Mahapatra & Chakrabarty 2011]. Subsurface rock layers in the region include granite, granitic gneiss, mica schist, anorthosite, shale, quartzite, sandstone, and limestone—reflecting the area's complex geological history [Das 2017].

Figure 1 presents the geographical location of the study area and Figure 2 shows the distribution of the sampled houses which were clearly marked according to their respective GPS coordinates obtained by GNSS Viewer (v-3.2), an android-based GPS application.



131

132 **Fig. 1** Sampling locations in and around Susunia hill area, Bankura, India.



133

134 **Fig. 2** The measurement locations of the houses in the study area. Source: Google plot.

135 **SELECTION OF HOUSES**

136 In this study, houses were selected randomly across the Susunia hill region and its adjacent areas. In each
137 selected house, one living room was chosen for indoor air radon activity measurement.

138 Two distinct categories of houses were included in the study, based on the primary construction materials:

1. Cemented Houses:
   These houses were constructed using bricks and cement and typically having relatively good ventilation. Most of these structures were used as permanent residential dwellings and represent modern housing types in the study area.
2. Mud Houses:
   Given the predominance of mud houses in the region, this category was specifically included to reflect the local housing conditions. These structures were built using locally available soil and stones with walls coated with a thin layer of mud paste. Ventilation in such houses is generally poor compared to cemented houses.

This classification will allow for the comparison of indoor radon levels across different construction types and ventilation conditions.

Radon concentration measurement procedure and Data Collection

Indoor radon concentration measurements were carried out using the AlphaGuard PQ2000 PRO portable radon monitor (Saphymo GmbH, Frankfurt/Main, Germany) a high-sensitivity ionization chamber-based instrument commonly used in environmental radiation studies [Deb et al. 2017; AlphaGuard M 2012]. The AlphaGuard instrument (Saphymo GmbH, Germany) was factory calibrated and is known for its long-term stability, with a calibration uncertainty of only about 3% [AlphaGuard M 2012]. Owing to this reliability, it is commonly used worldwide for calibration checks. The AlphaGuard can reliably measure radon concentrations ranging from 2 Bq/m^3 (<0.05 pCi/L) to 2,000,000 Bq/m^3 (54,000 pCi/L) [AlphaGuard M 2012].

Measurements were conducted between February and March 2025 across various residential houses in the study area. The device was operated in diffusion mode with a 10-minute measurement cycle. For each house, three consecutive readings were initially recorded. However, in cases where significant fluctuations in radon levels were observed, additional readings were taken to ensure accuracy and stability in the measured values. The average radon concentration for each room was then calculated from the valid readings.

The radon monitor was placed at least 30 cm above the ground and 1 m away from the windows, doors, and walls, following standard protocols to minimize external influence on readings. For background correction, the monitor was also placed in an adjacent open outdoor area both before and after each indoor measurement session to record the ambient (background) radon concentration. Average of these two readings was taken the background radon concentration.

Additional parameters such as the number of windows and doors in each room were recorded, as they influence natural ventilation and radon accumulation. The geographic coordinates (latitude and longitude) and altitude of each sampling location were also noted using a handheld GPS device to pursue geostatistical analysis.

Annual effective Dose (AED)

A critical parameter for assessing radiation exposure and its associated health risk is the Annual Effective Dose (AED), expressed in Sievert (Sv) or more commonly in millisieverts (mSv). The AED provides a standardized measure of the cumulative radiation dose an individual receives over the course of a year, accounting for the type of radiation and its biological effect on various tissues and organs. Higher AED values reflect elevated long-term health risks.

In this study, the AED due to inhalation of indoor radon (^{222}Rn) was calculated using the equation recommended by UNSCEAR and the International Commission on Radiological Protection (ICRP) [UNSCEAR 2000; ICRP 1993]:

$$AED(\mu Sv/yr) = C_{Rn}. D. F_{Rn}. T_{Rn} \quad \ldots\ldots(1)$$

where,

C_{Rn} is the ^{222}Rn concentration in Bq/m^3.

D: Dose Conversion Factor for inhalation radon exposure

The inhalation dose conversion factors for infants (1 year old), children (10 years old) are 21 mSv/WLM and 20 mSv/WLM respectively as proposed by UNSCEAR 2019. The same for adult male and female is 18 and 17 mSv/WLM respectively [UNSCEAR 2019].

F_{Rn}, the indoor ^{222}Rn equilibrium factor, is a measure of degree of radioactive equilibrium between radon and its decay products. F_{Rn} is taken to be 0.4 [UNSCEAR 2000; UNSCEAR 1999; ICRP 1993; 2010; 2011].

T_{Rn}, the total in room occupancy time in a year. The study area is warm. The primary source of income for the local population is agriculture. Local adult male persons spend 8 to 10 hours a day in the farm and on an average spend 12 hours indoors, for infants and adult females it is 18 hours and children spend 16 hours. Taking into account the local conditions, we used the annual average indoor occupancy time (I) of 4380 (12×365), 6570 and 5840 hours respectively for adult male, infants and adult female and children respectively in this study's for annual effective dose calculation.

Assessment of excess life time cancer risk

Several large-scale epidemiological studies—namely the European pooling study, North American pooling study, and Chinese pooling study—have established a linear dose-response relationship between indoor radon exposure and lung cancer risk, with no evidence of a safe threshold [NRC 1999; Libin et al. 2004; Bochicchio et al. 1995]. These studies suggest that for every 100 Bq/m^3 increase in indoor radon concentration, the risk of developing lung cancer increases by approximately 10%.

The Excess Lifetime Cancer Risk (ELCR) represents the additional probability of developing cancer over a lifetime due to chronic exposure to ionizing radiation, in comparison to an unexposed population [ICRP 2010]. Calculating ELCR from indoor radon levels is essential for understanding long-term public health implications, particularly in radon-prone regions.

In this study, ELCR was calculated using the following standard formula [UNSCEAR 2000; ICRP 2010; Naskar et al. 2023]:

$$ELCR = AED \times L \times F_{Risk} \quad \text{.....(2)}$$

Where;

AED = total annual effective inhalation dose (mSv/yr),

L = average duration of life. For this calculation, the average life expectancy (L) was taken as 67.3 years, based on the WHO estimate for India in 2021 [WHO 2009].

F_{Risk} = fatal cancer risk factor. It was assumed to be 5.5×10^{-2} Sv^{-1} as recommended by the ICRP [ICRP 2015; 2010].

This approach allows for quantifying the long-term carcinogenic risk associated with indoor radon exposure, thereby developing mitigation strategies and public health policy in the studied region.

Results and Discussions

Indoor air ^{222}Rn activities were measured in 70 living rooms of residential houses located across various sites in the Susunia hill region and surrounding areas in Bankura district, West Bengal, India. Measurements were conducted during February to March 2025 using the AlphaGUARD portable radon monitor. To facilitate analysis, each house was assigned a label corresponding to its measurement sequence. The house measured first was designated House 1 (H1), followed by House 2 (H2), and so forth.

The measured indoor radon concentrations ranged from 24.0±2.0 Bq/m³ to 239.7±13.1 Bq/m³, with an average value of 77.5±5.4 Bq/m³ and a median value of 61.2 Bq/m³. The average background radon level measured in nearby open ground spaces was found to be 22.1±0.5 Bq/m³. A graphical representation of the indoor radon levels across all sampled houses (Panel A: radon profile; Panel B: frequency distribution) is provided in Figure 3. Panel A of Figure 3 indicates the presence of high radon accumulation in a significant number of houses. Whereas, panel B of figure 3 shows the frequency distribution of measured indoor radon concentrations revealing a non-symmetrical right skewed (Skewness -1.5) pattern with most values clustered between 0-80 Bq/m³. Skewness is a measure of the symmetry of a distribution. Whereas, Kurtosis is a measure of the peakedness of a distribution relative to the centre of the distribution. The radon frequency distribution shows a positive Kurtosis (2.0) indicating tall peaks and heavy tail.

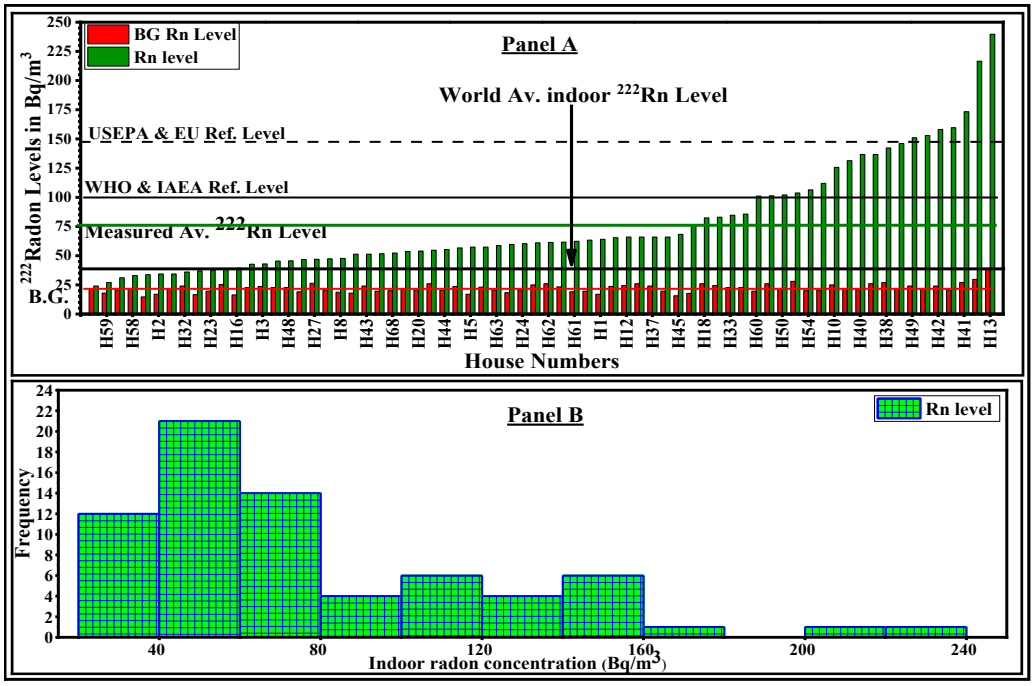


Fig. 3 Indoor radon level profile (panel A) and frequency distribution (panel B) of the houses in the study area

To protect public health, several international agencies established reference levels for indoor air radon activity. The World Health Organization (WHO) and International Atomic Energy Agency (IAEA) recommended a reference level of 100 Bq/m³, while the United States Environmental Protection Agency (USEPA) and the European Union (EU) have a reference level set at 148 Bq/m³[WHO 2009, 2010; IAEA 2013: USEPA 2002]. Whereas, the ICRP has set a much higher limit of 300 Bq/m³ for the indoor air radon level [ICRP 115; Bochicchio 2014].

Although the average radon concentration in the study area remains below all the five international reference levels, it is approximately double the global average indoor radon concentration of 40 Bq/m³ [Celebi et al. 2015] indicating a potentially elevated baseline for the region. The distribution demonstrates that while the majority of homes (51 out of 70 houses) (average ^{222}Rn activity: 53.5±2.1 Bq/m³) had radon levels below the safety thresholds of 100 Bq/m³ set by WHO and IAEA, a significant number of houses (19) exhibited elevated concentrations beyond the limit with several exceeding even the reference level of 148 Bq/m³ set by USEPA and EU. It was seen that the measured radon concentration in 27% of the houses (average ^{222}Rn activity: 120.4±5.1 Bq/m³) exceeded the WHO and IAEA reference level, while 10% of the houses (average ^{222}Rn activity: 178.8±13.3 Bq/m³) surpassed the USEPA and EU reference level. No indoor radon activity exceeded the reference level (300 Bq/m³) set by ICRP.

Figure 4 shows the three–dimensional spatial distribution of indoor air radon concentration across the study region. The surface plot illustrates the variation in radon activity (Bq/m³) as a function of geographic coordinates, where the X- and Y-axes represent longitude (°N) and latitude (°E), respectively. The Z-axis denotes measured indoor radon activity (Bq/m³). The color gradient, shown by the accompanying color bar, ranges from low (light yellow) to high (deep red) radon activity, enabling clear visual identification of spatial trends and hotspot regions. Whereas, the 2D contour plot (figure 5) provides a complementary top-view

visualization, allowing clearer identification of the spatial spread and boundaries of high (deep red zones) and low (light blue zones) radon zones.

The 3D surface and 2D contour plots together clearly demonstrate that indoor radon activity within the study region is highly heterogeneous, with distinct spatial gradients and multiple localized hotspots. Both visualizations indicate that indoor radon activity exceeds the WHO reference level across several localized latitude–longitude clusters particularly in the Saltora, Gangajalghati, Lachhmanpur, Chhatna and Jhantipahari regions, as illustrated in Figure 4. Furthermore, radon concentrations surpass the USEPA reference limit in the Saltora area (highlighted as Circle A in Figure 4) as well as in the Gangajalghati and Lachhmanpur zones (highlighted as diamond shape B and circle C respectively in Figure 4), demonstrating distinct spatial hotspot zones of elevated radon levels. Probably these areas are influenced by underlying lithology, soil gas permeability, and possible underneath fault pathways. The 3D plot emphasizes the magnitude of radon peaks, while the 2D contour map more clearly represents the horizontal extent and boundaries of specific radon regions. The close spacing of contour lines around hotspot zones further highlights steep radon gradients over short distances, indicating the localized nature of radon concentration. Overall, the information from both the plots show the existence of three localized hotspot zones with high radon buildup above reference limits by several international agencies and also show the significance of site-specific mitigation and awareness.

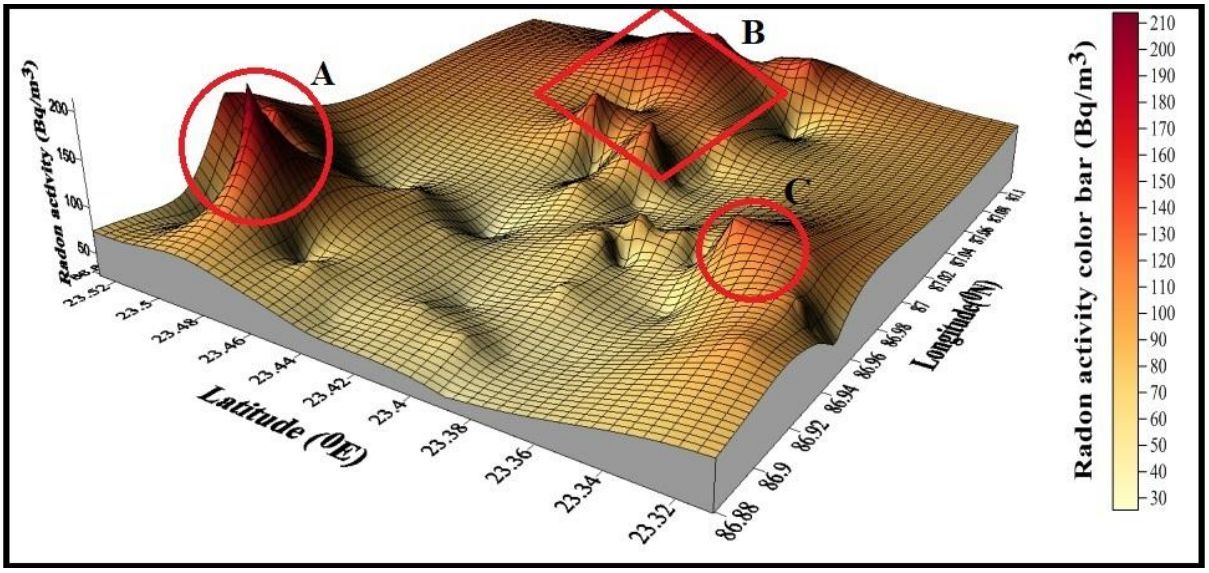


Fig. 4 The simulated 3-D surface plot of the study area.

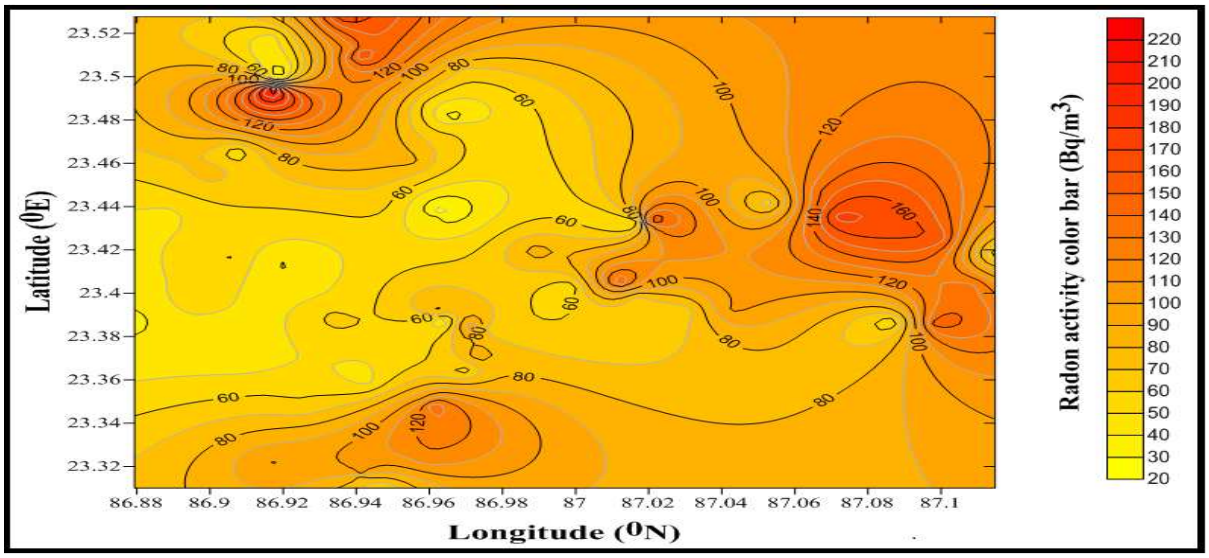


Fig. 5 2D contour view of the study area

The average indoor radon concentration observed in this study (77.5±5.5 Bq/m³) falls within the worldwide range of reported values listed in Table 1. The lowest average radon concentration was reported in Ghana (34.90±20.18 Bq/m³) and Cameroon (41±24 Bq/m³) while the highest average value was observed in Poland (280±15 Bq/m³). The present study shows a value that is moderate in the global context and is close to values reported in Jaduguda, India (79±24 Bq/m³), Turkey (79 Bq/m³), Canada (71 Bq/m³), Volta Region, Ghana (70.4 Bq/m³) and China (65 Bq/m³) indicating comparable indoor radon conditions. Overall, the results suggest that the study area does not exhibit unusually high radon levels and remains well within the global variability range reported for indoor environments though there are few elevated radon regions.

Table 3: Comparative view of worldwide indoor air ^{222}Rn level

Country of Investigation	No. of samples	Range (Bq/m^3)	Average Value (Bq/m^3)	Reference
İzmir province, Turkey	431	21.3-751.2	225.4	Masruoğlu et al. 2025
Jaduguda, India	39	35-130	79±24	Singh et al. 2024
Cameroon	140	15-140	41±24	Ndjana Nkoulou et al. 2024
Poland	9	259-302	280±15	Szczepanik-Scislo et al. 2024
China	2875	7-800	65	Miao et al. 2024
Volta Region, Ghana	120	24.8-190.1	70.4	Amable et al. 2024
Greater Accra region, Ghana	95	36-92	50.8±3.4	Akuo-ko et al. 2023

Dhaka, Bangladesh	15	11-360	63 ± 33	Pervin et al. 2022
Latvia	941	1-460	48	Reste J et al. 2022
Croatia	15	56-509	42.5±30.8	Ptiček et al. 2020
Iran	30	31-460.2	104	Shahbazi Sehrani et al. 2019
Ghana	30	11.6-111.07	34.90±20.18	Ansre et al. 2018
Canada	7600	15-2500	71	Whyte et al. 2019
Romania	12	26-415	138.1	Nita et al. 2013
Susunia, India	**70**	**24-239.7**	**77.5±5.5**	**This Study**

Among the 70 houses included in this study, 89% (62 houses) were constructed using mud, while 11% (8 houses) were brick houses. Analysis based on construction material reveals that mud houses exhibit significantly higher indoor radon concentrations compared to brick houses. The radon concentration in mud houses ranged from 24.0 to 239.7 Bq/m³, with an average of 80.8±6.1 Bq/m³ and a median of 62.0 Bq/m³. In contrast, brick houses showed radon levels ranging from 38.7 to 66.0 Bq/m³, with a lower average of 51.7±3.6 Bq/m³ and a median of 49.5 Bq/m³. This information is visually represented in Figure 6, with Panel A showing radon levels in mud houses and Panel B for brick houses.

Notably, radon level in 19 mud houses (30.6%) exceeded the WHO reference level of 100 Bq/m³, and 7 houses (11.4%) surpassed the USEPA threshold of 148 Bq/m³. In contrast, none of the brick houses exceeded even the WHO reference level, indicating a relatively safer profile (average of 51.7±3.6 Bq/m³) in terms of radon exposure. This may be primarily attributed to the better ventilation system for the brick houses and easy potholes for radon transportation from soil for mud houses.

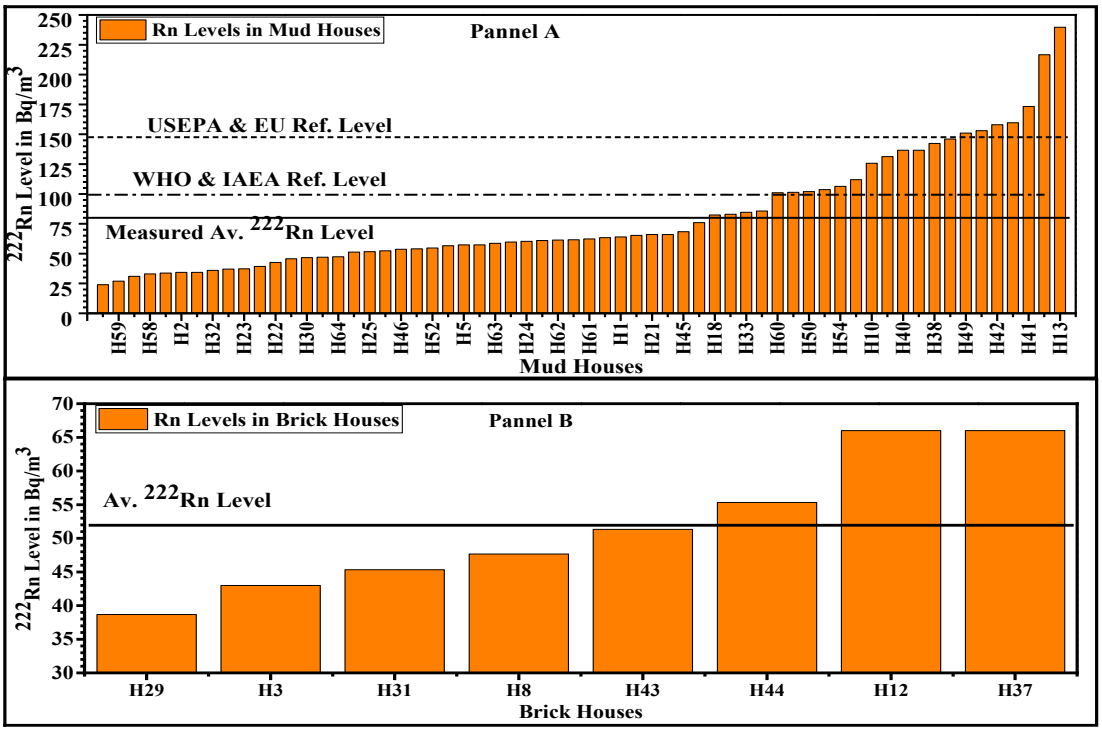
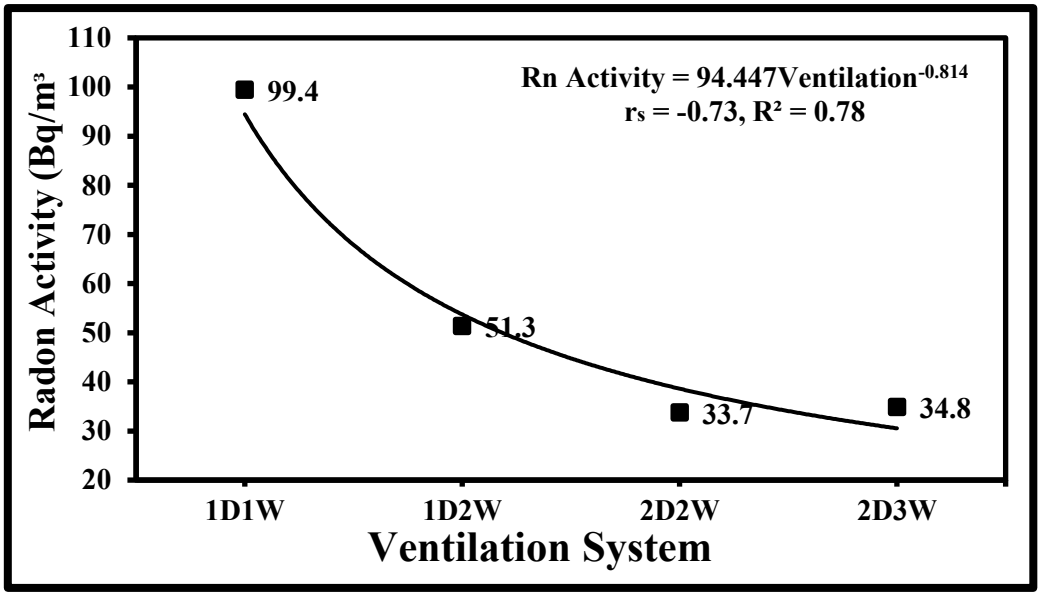


Fig. 6 Indoor air ^{222}Rn level profile for the mud (panel A) and brick (panel B) houses.

Difference in ventilation system appeared to play a critical role in radon accumulation. Most mud houses had limited ventilation, typically with only one door (D) and one window (W), whereas brick houses tended to have better ventilation features. On average, mud houses had 2.0 openings (doors and windows combined), compared to 3.0 openings in brick houses.

To quantify the strength of association between radon level and selected parameters, we used the Spearman's correlation coefficient (r_s) and Pearson correlation coefficient (r) widely recognized tool for measuring non-linear and linear relationships between variables respectively [Steele, J. M., 2004]. Figure 7 presents the variation of indoor radon concentration as a function of ventilation conditions using a power-law model. The relationship follows the equation ^{222}Rn Activity = 94.44Ventilation System$^{-0.814}$ with a strong negative strong Spearman's coefficient of -0.73 ($p < 0.03$) and coefficient of determination R^2=0.78 indicating an excellent fit between measured and modeled values. The data clearly show a sharp decline in radon concentration with increasing ventilation. The radon level decreased from approximately 99.4 Bq m^{-3} under low-ventilation conditions (1D1W) to 34.8 Bq m^{-3} under the highest ventilation condition (2D3W). This inverse relationship suggests that enhanced ventilation effectively reduces indoor radon accumulation by increasing air exchange and diluting radon gas concentration. The strong coefficient of determination (high R^2) demonstrates that ventilation rate is a dominant factor controlling indoor radon levels, and that the decrease follows a nonlinear, power-type decay pattern in indoor environments. Altendorf et al. 2022 also reported the effectiveness of ventilation for reduction of indoor air ^{222}Rn activity. Choi J. et al. 2022 reported that reduction of indoor air radon was more effective in bidirectional ventilation than unidirectional.



317

318 **Fig. 7** Radon activity as a function of ventilation system.

319 The recorded altitudes of the surveyed houses ranged from 205 m to 260 m with an average value of
320 225.9±1.4 m. It was observed that several houses shared nearly equal altitudes when rounded to the nearest
321 integer value. To analyze the effect of altitude, all measured altitudes were classified into twelve distinct
322 altitude groups and the corresponding indoor radon concentrations were averaged within each group. Figure
323 8 illustrates the variation of indoor radon concentration as a function of altitude, fitted using a power-law
324 model. The relationship follows the equation ^{222}Radon Activity=144.83Altitude$^{-0.432}$ with a strong
325 Spearman's coefficient (r_s) of -0.67 ($p < 0.001$) and coefficient of determination R^2=0.50 indicating a strong
326 inverse correlation between indoor air radon concentration and altitude. This suggests that radon activity
327 decreases noticeably as altitude increases. The relatively high R^2 value signifies that altitude accounts for a
328 substantial portion of the variability in indoor radon concentration. The power-law trend implies that the rate
329 of decrease in radon concentration is more pronounced at lower altitudes and gradually stabilizes with
330 increasing elevation. Ansre et al. reported statistically significant relationship between indoor air radon
331 activity and altitude [Ansre et al. 2018].

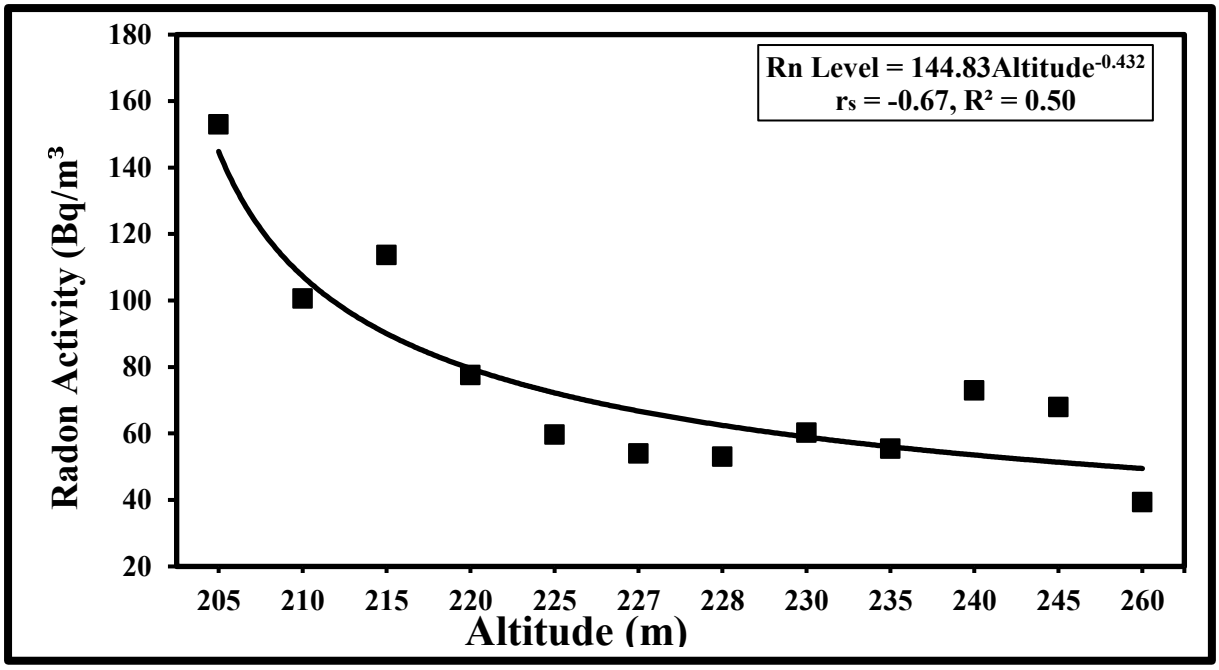


Fig. 8 Indoor air radon concentration variation with altitude.

We also analysed the fluctuations of ^{222}Rn concentration in relation to three key meteorological parameters: temperature, relative humidity, and atmospheric pressure. These parameters were simultaneously recorded by the AlphaGuard radon monitor and were presented graphically with the measured ^{222}Rn levels in Figure 9 to explore any potential influence on radon behaviour. The adjacent data points of each parameter were connected with lines to guide the reader's eye and highlight the overall trend. A common X-axis is used to represent the individual house numbers while each variable is displayed on its own Y-axis: radon concentration (Bq/m³), relative humidity (%), temperature (°C), and atmospheric pressure (mbar).

Pearson correlation coefficient (r) was use to quantify the strength of association between radon levels and selected meteorological parameters. In our analysis, we obtained correlation coefficients of +0.33 for temperature ($p < 0.001$), –0.32 for atmospheric pressure ($p < 0.001$), and –0.30 for relative humidity ($p < 0.009$). These results indicate that atmospheric pressure and humidity exert weak negative influence on indoor air radon concentration, whereas temperature shows a weak positive correlation with radon levels. Similar trends were documented by other studies: for example, an indoor-radon investigation found a positive correlation of r=+0.45 with temperature and negative correlation with barometric pressure (r= –0.26) [Spasić, D. & Gulan L. 2022]. In contrary to the above, another study reported a negative correlation with temperature (r=0.22) and a moderate positive correlation (r=0.44) with humidity with indoor radon activity [Kumar M. et al. 2025].

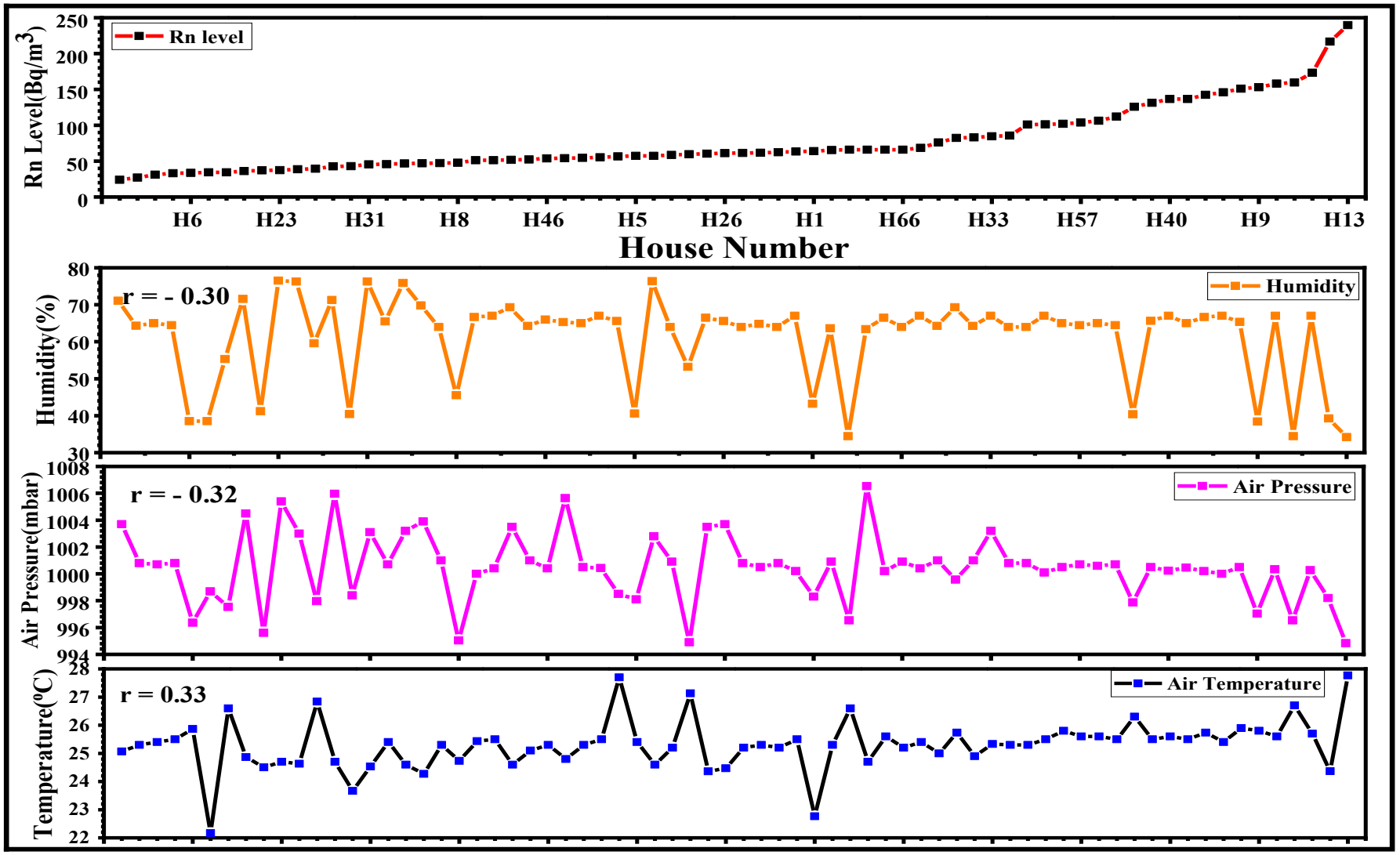


Fig. 9 Variation of ^{222}Rn level with the meteorological parameters.

The calculated annual effective dose (AED) values provide a direct estimate of the radiological burden to which individuals may be exposed through inhalation of indoor radon. In the present study, the AED values derived (using equation 1) from the measured radon activities indicate the magnitude of internal exposure arising from continuous indoor radon inhalation over a year. These dose estimates serve as an essential metric for evaluating compliance with internationally recommended safety limits, such as those suggested by the WHO, UNSCEAR and ICRP.

Figure 10 presents the annual effective dose (AED) from inhalation of indoor radon to four population groups, namely infants, children, adult female and male, in the study area through Box–Whisker plot. The rectangular box's middle blue line represents the median, while the lower and upper lines represent the first and third quartile respectively. The red square inside the box represents the mean AED. The lowest and highest AED are represented by the lower most and upper most small horizontal blue lines. Whiskers are the red colored extension on either side of the box up to maximum and minimum AED value. Above the upper whisker, the black-coloured diamond shapes indicate upper outliers. The results reveal an age-dependent patterns with infants receiving the highest mean annual effective dose (6.7 mSv/yr), followed by children (mean dose is 5.7 mSv/yr), adult females (mean dose is 5.5 mSv/yr), and adult males (mean dose is 3.8 mSv/yr). These values substantially exceed the WHO reference level of 1 mSv/yr and approach or surpass the upper end of the ICRP and IAEA action-level band of 3–10 mSv/yr [WHO 2009; ICRP 115; IAEA 2013]. Rani et al. reported nearly similar order of AED (~4.9 mSv/yr) in northern Indian dwellings [Rani et al. 2013]. High exposures were reported by Shovi Furaeli Sawe (2025) with an average indoor AED of 12.0±1.0 mSv/yr in phosphate-rich regions while Otanšev et al. documented mean indoor inhalation doses around 8 mSv/yr in Turkish dwellings. By contrast, many global studies showed lower averages, such as ~1.4 mSv/yr in Egyptian homes [Hussein A. 2025] a mean of 2.1 mSv/yr in living and bedrooms in Chiang Mai, Thailand [Thumvijit T. et al. 2020]. Another report by Akuo-ko E. O. et al. reported annual mean effective dose of 1.3 mSv/yr in Greater Accra region, Ghana [Akuo-ko, E. O. et al. 2024]. The present study indicates an elevated indoor-radon exposure scenario particularly for infants, children and adult females underscoring the need for targeted mitigation and improved ventilation in the affected area.

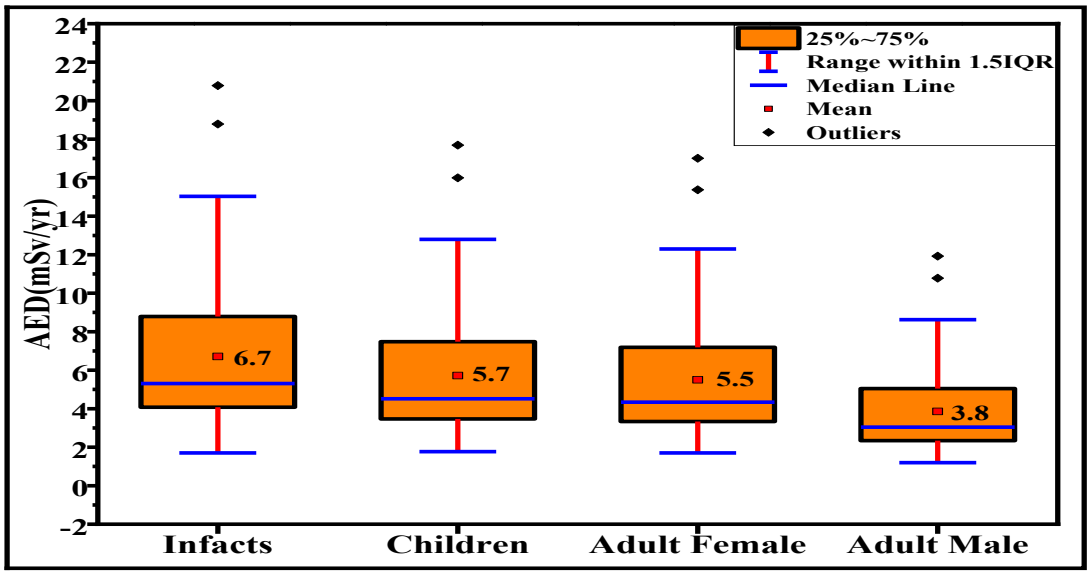


Fig. 10 Annual Effective Dose for four groups of population.

To further interpret the public-health implications, the excess lifetime cancer risk (ELCR) was evaluated. ELCR reflects the probability of developing cancer over a lifetime due to cumulative radon exposure. In this study, the ELCR values for four population groups were calculated using Relation 2. For infants, the ELCR ranged from (6.3–76.9)×10^{-3} with an average of (24.9±1.8)×10^{-3} , for children (6.6–65.5)×10^{-3} with an average of (21.2±1.5)×10^{-3}, for adult females (6.3–63)×10^{-3} (average = (20.4 ± 1.5)×10^{-3}) and for adult males (4.4–44.1)×10^{-3} (average = (14.3±1.0)×10^{-3}). The mean ELCR values for all the four groups are markedly elevated compared to the commonly referenced global baseline of 0.29×10^{-3} [Naskar et al. 2023; Ugbede & Echeweozo 2017; Avwiri et al. 2016].

Comparable high ELCR values were also reported in different studies in other radon-prone regions. Sherafat et al. (2019) reported mean ELCR values of approximately 10.1 ×10^{-3} in Iranian dwellings, with maximum values reaching 42.6 ×10^{-3} in high-exposure locations. Otanšev et al. (2022) documented a mean ELCR of 26 ×10^{-3} in Turkish homes, while Shovi Furaeli Sawe (2025) reported indoor ELCR values reaching 40 ×10^{-3} in phosphate-rich environments. Dadashpoor et al. (2025) reported an average ELCR of 9.7 ×10^{-3} in a mountainous region of northern Iran.

Conclusion

The research aims to report indoor air ^{222}Rn activities in and around the Susunia hill region of Bankura district, West Bengal, India. The measured average ^{222}Rn activity in seventy numbers of local houses is 77.5±5.5 Bq/m^3 which is much lower than the reference level by the WHO, and IAEA but nearly twice than the world average indoor ^{222}Rn level. The average ^{222}Rn level in 27% and 10% houses exceeded the WHO (and IAEA) and USEPA (and EU) reference level of 100 and 148 Bq/m^3 respectively. The maximum ^{222}Rn level is 239.7 Bqm^{-3}. It is seen that mud houses exhibit significantly higher indoor radon concentrations compared to brick houses. Overall, radon distribution is clustered rather than uniform reinforcing the need for site-specific monitoring in identified high-risk areas.

The data clearly show a sharp decline in radon concentration with increasing ventilation and altitude. No significant correlation between indoor radon activity and recorded meteorological parameters is found.

The average AED and ELCR values of all the four groups surpass the recommended dose limit by international agencies.

The findings in this study clearly indicate a substantial public health concern associated with indoor radon in the region. The markedly elevated AED and ELCR values—particularly for more sensitive population subgroups—underscore the urgent need for targeted radon monitoring awareness campaigns and mitigation interventions (such as improved ventilation, sealing entry points, or installation of radon reduction systems) to reduce exposure and minimize long-term cancer risks for residents. Further epidemiological studies in the area could help quantifying actual health outcomes and support evidence-based policy measures.

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Author contributions

Mahasin Gazi: Conceptualization, Methodology and Data collection, Data analyzation, Software, Writing original draft preparation Arindam Kumar Naskar: Data collection, Revising the draft Argha Deb: Conceptualization, Supervision, Reviewing and Editing the draft. All authors read and approved the final manuscript.

Ethical Approval

NA

Consent to Participate

NA

Consent to Publish

NA

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Availability of data

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.