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Evaluation of the Concentration of Radon in a Single-family House in a Province Northwest of Madrid

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ABSTRACT

Indoor radon concentrations have become a significant health concern due to their long-term deleterious effects on the lungs. Radon exposure is a leading cause of lung cancer, especially among non-smokers, making it critical to understand the risk factors associated with radon presence. This article evaluates radon levels in a single-family house located to the northwest of Madrid. The study was conducted during both summer and winter seasons, which are the predominant periods for this region. The research aims to analyze the varying radon concentrations observed during these seasons, considering factors such as ventilation, seasonal temperature differences, and the specific construction materials used in the house. The accumulation of radon can be influenced by the permeability of the building's

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foundation, materials, and the effectiveness of natural ventilation systems. In winter, reduced ventilation can lead to higher radon levels due to the sealing of windows and doors to retain heat, while summer conditions may provide more opportunities for ventilation, potentially reducing concentrations. This study examines how these factors interact, exploring the relationship between indoor air quality and radon levels. Measurements before and after ventilation renewal are included to assess any changes in radon concentrations. The findings aim to provide a better understanding of the behavior of radon in residential settings and offer practical recommendations for mitigating its health risks, especially in homes with poor ventilation and specific construction characteristics. Ultimately, the results could guide strategies for improving indoor air quality and reducing radon exposure in similar homes.

Keywords: Construction Materials; Indoor Air Quality; Health Concern; Radon Exposure and Ventilation

1. Introduction

In some parts of the world, radon gas from geological beds and building materials can accumulate indoors and reach high concentrations of activity, exceeding the reference or performance levels established by national and local legislation [1–3]. The main mitigation strategies are based on sealing cracks, protecting buildings with barrier materials against radon, increasing ventilation of homes (natural or forced ventilation) and pressurizing rooms.

This paper deals with radon barrier materials available on the market, along with forced ventilation [4,5]. Radon barriers are impermeable materials that block radon from entering the building. By sandwiching them between the foundation and the ground, these barriers are now mandatory in new homes located in areas known to have high radon levels. Older homes or workplaces with elevated radon levels should take advantage of other radon mitigation measures, such as increased ventilation and a radon pump, in addition to or as an alternative to radon barriers [6,7].

These materials can be applied to all built surfaces horizontally and vertically, thus isolating the building from radon exhaled from the subfloor and from the walls of the building. Among the products available on the market, the most popular are polymeric barrier materials, bituminous membranes and aluminum sheets, alone or coupled in various ways, often reinforced with a polyester fiber or fiberglass matrix. Liquid membranes, such as bituminous emulsions or epoxy resin coated on solid panels, are also used. The suitability of a material as a radon-proof barrier can be assessed using the radon diffusion coefficient, a property that defines the transport of radon through the material [8,9]. Impermeable materials commonly used to protect buildings have a radon diffusion coefficient ranging from 10–11 to 10–13 m^2s^{-1} [10–12]. The experimental procedures for the determination of the diffusion coefficient of radon are based on ISO/TS11665-13:2017 [13]. Several studies have used this method to illustrate the procedure and classify materials.

Exposure of the population to radon indoors has been shown to increase the risk of lung cancer [13] and is considered one of the leading causes of lung cancer after smoking [14]. Therefore, current national and international regulations [15] set requirements aimed at reducing radon-related risks. Based on the principle of optimizing radiation protection, these regulations have introduced the new concept of reference level (NR): countries will prioritize reducing indoor radon concentration when it exceeds NR, but will continue to take some measures to reduce exposure even when the concentration is below NR [15,16]. Since the reference level is expressed in terms of annual radon concentration, protocols for radon concentration measurements are designed to assess long-term (i.e., annual) radon concentrations by averaging the temporal variations that occur over shorter periods [17].

Although measuring radon concentration over a year is the most reliable approach, many countries have adopted protocols that consider shorter measurements, usually a few months in duration, to assess the average annual concentration [18]. Some of these protocols also include the use of normalization factors that consider the typical seasonal cycle of radon concentration throughout the year with higher levels in the colder months and lower levels in the warmer months [19–22].

However, several studies have reported observations of atypical or inverse seasonal variations in indoor radon concentration [23–30]. More in-depth investigations into the reasons behind these occurrences and the trends experienced by radon concentration are quite rare [31].

In another study, it was observed that two dwellings not only had reverse seasonality but also had high average annual radon concentrations. Radon concentrations were measured over two years in one of these houses using a continuous radon monitor to study the trend throughout the year. The same measurements were resumed after ten years to verify whether these inverse variations were still observed and, if so, to investigate possible variations in magnitude, temporal extent, and period of occurrence.

Assessing and reducing indoor radon concentration is one of the 12 recommendations of the European Code Against Cancer. Specifically, the ninth item on this list, is "Find out if you are exposed to radiation from naturally elevated levels of radon in your home, take steps to reduce elevated radon levels." In this context, the WHO recommends indoor radon concentrations below 100 Bq/m^3 [32–39].

In Europe, there are large differences between countries in terms of radon exposure in homes. Countries with large amounts of granite or uranium-rich soil often have very high levels of radon. There are several areas prone to radon, such as the Bohemian Massif, northwestern Spain, the Massif Central, the Fennoscandian Shield, the Vosges Mountains, the Central Alps, northern Estonia, and certain volcanic structures in central Italy [40]. Although the International Commission on Radiological Protection (ICRP) and the Council of the European Union have recommended reference levels of radon for homes and workplaces, only a few countries have applied cutoff levels, each setting different specific radon limits. For example, Germany has a recommended reference level of 250 Bq/m^3, while Switzerland and Sweden have 400 Bq/m^3 and Spain 300 Bq/m^3 [41].

In 2006, the European Commission's Joint Research Centre launched a project to map radon on a European scale, as part of a planned European Atlas of Natural Radiation. Currently, this map includes data from 29 countries, covering a large part of Europe [42]. Interestingly, more than 30% of the surface area of the countries participating in the European Indoor Radon Map has an average concentration above 100 Bq/m^3, and 4.2% is above 300 Bq/m^3 [42].

The 2013 European Directive on basic safety standards obliged European Union member states to establish a national action plan in relation to radon exposure and the European Atomic Energy Commission (2013/59/EURATOM) established a directive stipulating not to exceed 300 Bq/m^3 in European households [32,42]. In the United States of America (USA), the EPA recommends radon concentrations below 150 Bq/m^3, in Australia the recommended limit is 200 Bq/m^3 and in Canada 800 Bq/m^3. In Asia, South Korea has set the limit at 148 Bq/m^3, while in China it is 300 Bq/m^3 for existing buildings and 100 Bq/m^3 for new buildings. In Japan, the Radon Council has not yet established a baseline level of indoor radon exposure [42–44]. On the other hand, the prevention of radon exposure in new buildings can be achieved through appropriate provisions in the construction phase or by installing a radon-proof barrier at ground level [45].

This study was carried out to obtain the levels of radon inside a single-family house, considering the causes of the presence of ventilation in summer and winter periods and the characteristics of the construction materials responsible for the accumulation of radon based on records and evaluation of the results obtained.

2. Methodology

In this section, it will be carried out in three phases: (i) behavior and use of space in the home, (ii) registration of research parameters, and (iii) assessment of study indicators, as can be seen in **Figure 1**.

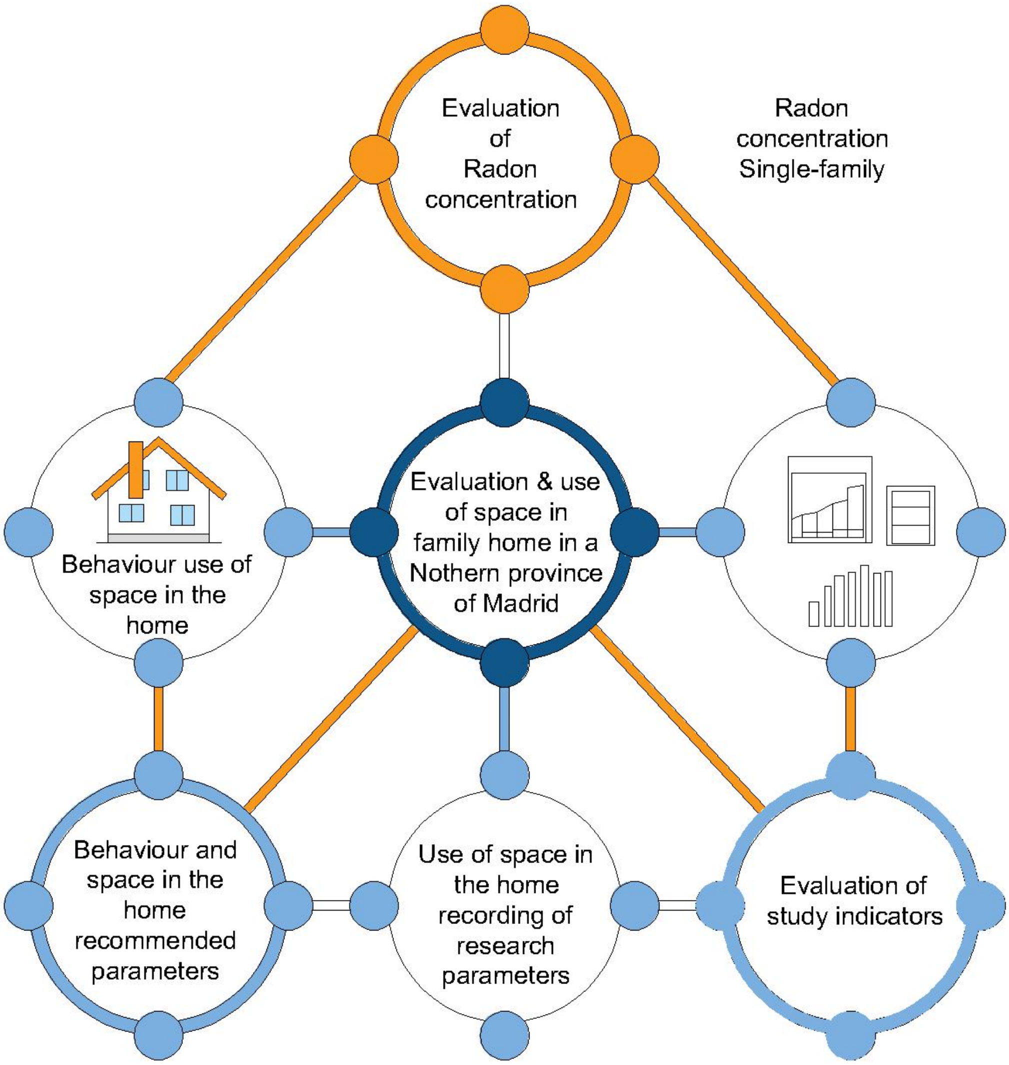

Figure 1. Study Methodology.

2.1. Behavior and Use of Space in the Home

Residents' ventilation and usage habits are recorded, including their schedules, use of appliances, smoking habits, and the presence of mechanical ventilation systems. This is illustrated in **Figure 2**.

2.1.1. Profile of the Users of the Dwelling Occupancy Hours

Where it will include the hours in which residents spend time in the home during working days.

2.1.2. Use of Spaces and Ventilation Rooms

The frequency and duration of natural ventilation (window opening). Use of mechanical ventilation, if applicable (fans, extractors).

2.1.3. Appliances in Use and Heating and Cooling Systems

List of main appliances (kitchens, washing machines, dryers, televisions, computers) and the mechanical ventilation systems present in the home (exhaust fans, controlled ventilation systems, boilers). Frequency of daily or weekly use of each appliance. In turn, if there is a presence of smokers in the house as well as specific places where smoking is allowed (indoors, outdoors) and the number of cigarettes consumed daily.

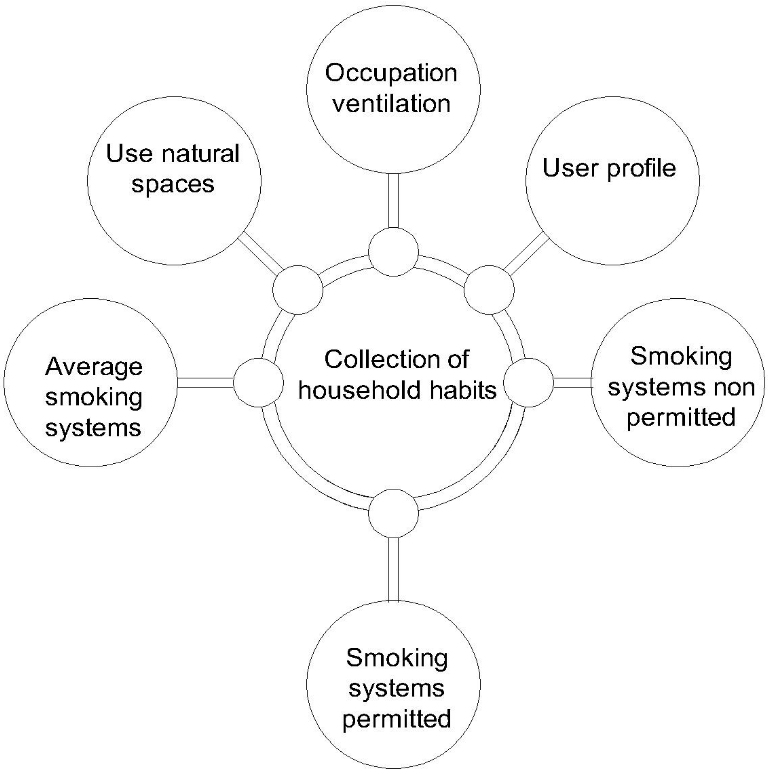

Figure 2. Collection of habits of residents in homes.

2.1.4. Construction Materials

List of materials that make up the house, defining the degree of thermal conductivity of each component

This study focuses on a house located to the northwest of Madrid, as illustrated in **Figure 3**.

Figure 3. Studio Housing.

2.2. Recording of Research Parameters

For this study, measuring equipment will be used to quantify the variables and perform an analysis. The Airthing Wave Plus model device will be used, as seen in **Figure 4**.

Figure 4. Wave Plus Instrument.

Airthings Wave Plus is the first battery-powered smart IAQ monitor, measuring radon; it's also an indoor air quality (IAQ) meter, with sensors for CO2, TVOC, temperature, humidity and air pressure. Users can view their first results in just one hour and manage fast and accurate results directly on their smartphone via a Bluetooth connection or via Smartlink (long-range wireless communication).

It is a measuring equipment suitable for integration into a smart device connection environment at home or work. It connects with Amazon Alexa, Google Assistant and IFTTT via Bluetooth.

Radon is present in the soil, and its concentration differs between soil types according to parameters such as permeability and mineral composition. As radon penetrates buildings primarily through cracks and fractures at the foundation level, this area requires focused investigation.

The features of the Airthings Wave Plus device are:

Radon sensor: Passive diffusion chamber sampling with alpha spectrometry detection

Measurement range:

Bq/m^3 : 0 to 20,000

pCi/L: 0 to 500

Accuracy after 30 days of continuous monitoring at 5.4 pCi/L (200 Bq/m^3):

7-day average: ±10%

Long-term average: ±5%

VOCs: Metal oxide semiconductor (MOS) sensor

Measurement range: 0–10,000 ppb

Resolution: 1 ppb

CO_2: Non-dispersive infrared (NDIR)

Relative humidity:

Accuracy: ±3% RH at 25°C (77 °F) in 20%–80% RH

Temperature:

Accuracy in °F: ±0.9°F at 77°F and ±1.8°F from 32–140°F

Accuracy in °C: ±0.5°C at 25°C and ±1°C from 0–60°C

Air pressure:

Absolute accuracy: ± 0.6 mBar/hPA

Relative accuracy: ± 0.12 mBar/hPA

2.3. Assessment of Study Indicators

Considering the study variables, the possible behaviors of radon measurements across different seasons of the year will be analysed. This will also allow verification of radon values against regulations. The Regulation for the Protection of Health against the risks derived from exposure to ionizing radiation, approved by Royal Decree 1029/2022 of 20 December 2022, establishes a reference level of 300 Bq/m^3, referring to the annual average radon concentration (Article 72).

3. Results

The analysis of the measurements obtained in the home, both in summer and winter, makes it possible to identify patterns of behavior in temperature, humidity, radon and CO_2, as well as to assess the suitability of construction materials in relation to indoor air quality and thermal comfort.

3.1. Behavior and Use of Space in the Home

The following table summarizes the habits of the users, including the number of inhabitants and their time of stay, the scheduled times for window opening, and the devices present in the house that affect air quality. These data are used for both the summer and winter seasons and are presented in **Table 1**.

As important data of the house, the opening of windows is done in an interval of six hours in summer, since in winter they are not opened. The time of ignition of ventilation gave us an interval in summer of eleven hours of ventilation and in winter nineteen hours of heating with the ventilation system by means of mini-split equipment calibrated at 20°C in summer and 25°C in winter, users both their period of time inside the home, appliances and devices that the house has, as well as that there is no presence of smokers

Table 1. Survey carried out in the studio home.

People (Female or Male)	Age (Years)	Winter/Summer Housing Schedule (Hours)	
		Monday to Friday	Weekends
Man A	58	12:00–11:30 AM; 20:00–23:59PM	12 AM–8:30 AM; 20:30–23:59PM
Woman B	50	12:00–7:10 AM; 20:30–23:59PM	12:00 AM–14:00 PM; 20:00–23:59PM
Woman C	26	12:00–11:30 AM; 20:30–23:59PM	12:00 AM–14:00 PM; 20:00–23:59PM

Table 1. *Cont.*

People (Female or Male)	Age (Years)	Winter/Summer Housing Schedule (Hours)	
		Monday to Friday	Weekends
Woman D	73	12AM–16:30PM; 19:30–23:59PM	12:00 AM–14:00 PM; 20:00–23:59PM
Pets Indoors			1 Cat
Pets Outside			2 Dogs
Ventilation hours			
Window Opening	Monday to Friday from 10:00 AM–16:00 PM (summer only) in winter they are **closed**		
Information about household appliances			
Mini Split with heat pump	Every day from 20:00–23:59 PM–1:00 AM–7:00 AM in summer Daily from 12:00–16:00 PM; 20:00–23:59 PM–1:00 AM–11:59 AM in winter Quantity :5		
Water heater	Gas Boiler		
Appliances	Refrigerator (1), Washing Machine (1), Dryer (1) Microwave(1) Cooker(1) Oven(1)Television(4) Laptop (1) & Printer (1)		
Heating and ventilation temperature	For heating 24 °C and ventilation 20 °C		

Bearing in mind that we determined that for this study two months are handled both for winter (January and February) and for summer (July and August) to see the behavior of radon, which is the study factor and in turn carbon dioxide, relative humidity and temperature.

At the same time, the data of the construction materials are included, which give us the thermal envelope, which is the means of study where the respective measurements will be taken, and which can be seen in **Figure 5**.

All this data was extracted from the property registry, and the conductivity coefficients of the construction elements were taken from the Valero Group [46].

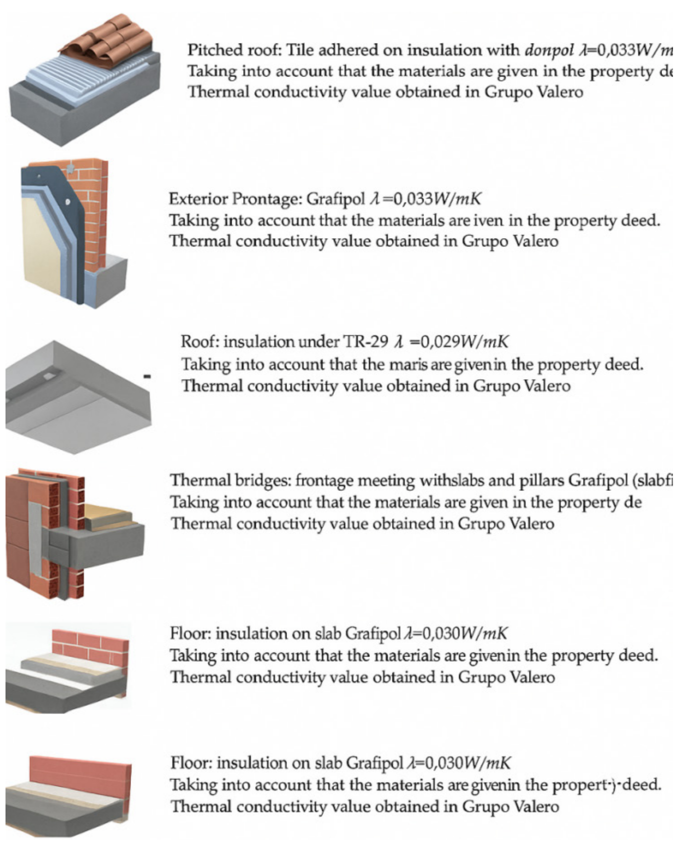

Figure 5. Construction Materials of the Studio Housing.

3.2. Recording of Research Parameters

The study devices were placed at different points of the house, which can be seen in **Figure 6**, where they were arranged according to the occupancy in the house, since one of the artifacts was located in the lobby and the other two in the rooms indicated in the plans that can be seen in the image, keeping them at a prudent distance from the carpentry of the house, since they are required data that are not affected by construction materials.

With this, the following measurements were extracted through the use of the Wave Plus device, which gives us the behavior over this period of two months, in which the temperature and relative humidity can be seen, bearing in mind that the results obtained where the devices were placed presented similar values with little variability, and in that way, only a general graph will be presented for each of the study variables, which can be seen in **Figure 7**.

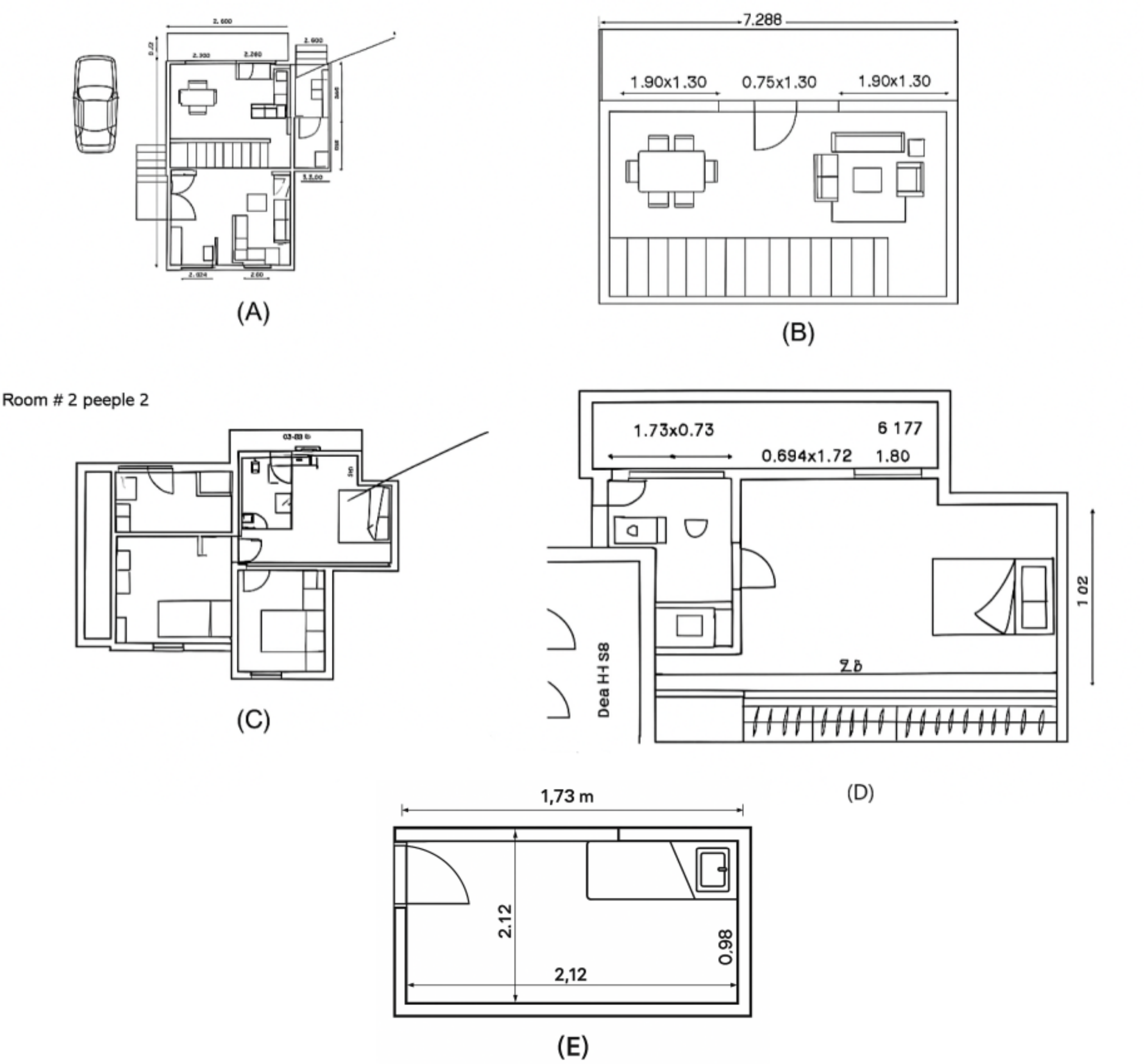

Figure 6. (A) First floor of the house and signage in the lobby; **(B)** Signage for the location of the measuring devices in the lobby; **(C)** Second floor of the house and signage in the study rooms; **(D)** Signage for the location of the measuring devices in room numbers 1, 2, 3, and 4; **(E)** Signage for the location of the measuring devices in room number 2.

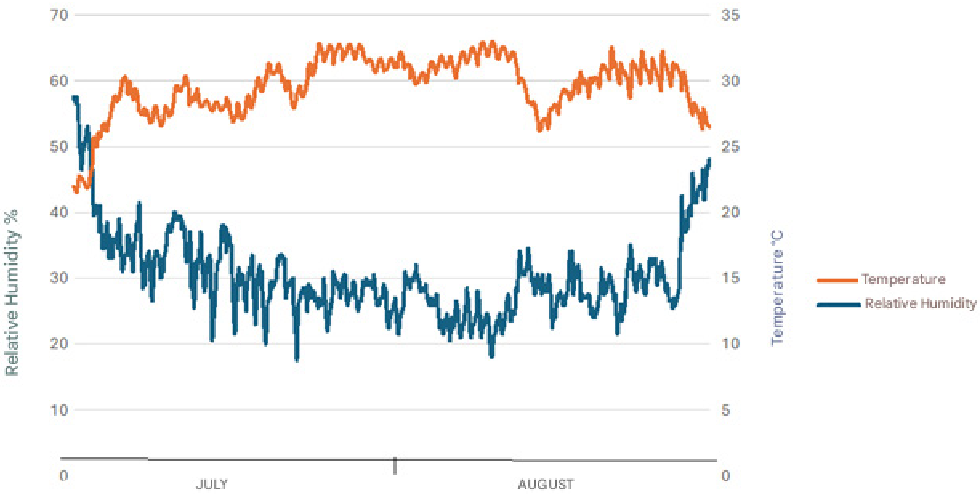

Figure 7. Relative humidity (%) and temperature (°C) in the room as a function of the weather (summer).

What can be seen is that it remains in those margins based on the fact that it is a time of high temperatures ranging between 22–33°C and humidity levels between 17%–57%, taking into account that the daily maximum temperatures range from 23°C to 28°C and rarely drop below 17°C or exceed 35°C, the highest average daily maximum temperature is 31°C on July 31, considering that these temperatures and humidity are inside the house.

Daily minimum temperatures range from 10°C to 14°C and rarely drop below 7°C or exceed 19°C. The highest daily average low temperature is 15°C on August 6.

We base the comfort level of humidity on the dew point, as this determines whether sweat will evaporate from the skin, thus cooling the body. When dew points are lower it feels drier and when they are high it feels wetter. Unlike the temperature, which generally varies considerably between night and day, the dew point tends to change more slowly, so even if the temperature drops at night, on a humid day the night is generally humid [47–50].

In turn, the values of carbon dioxide and radon were obtained as a function of summer weather, which can be seen in **Figure 8**.

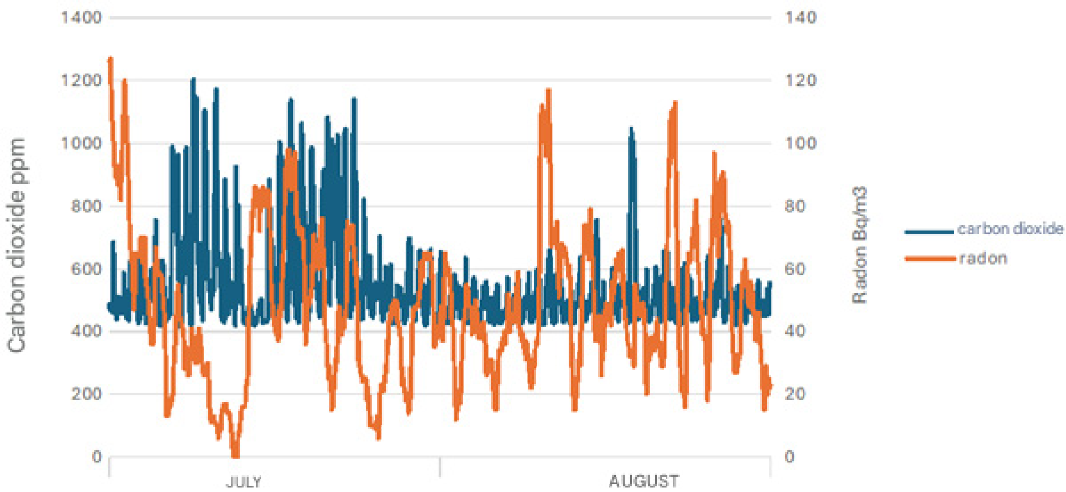

Figure 8. Carbon dioxide (ppm) and radon (Bq/m3) in the living room depending on the weather (summer).

Taking into account the values obtained, what can be observed is in accordance with the provisions of the new Technical Building Code, the level that should not be exceeded is 300 Bq/m^3 and this is fulfilled because the ranges obtained for radon are 4–126 Bq/m^3. In turn, the ranges for carbon dioxide (CO_2) are as follows. According to the Technical Building Code (CTE) in Spain, the recommended levels of carbon dioxide (CO_2) indoors should not exceed 1,000 ppm to maintain acceptable air quality and this is what can be seen to be maintained in those margins although there are times when it exceeds, since the ranges are 459–1250 ppm. In general terms, when the concentration of CO_2 exceeds 1200 ppm. The air is considered to be of poor quality, but this is not constant. However, when this happens, it is because there is a greater number of users inside the house at the time of taking values.

However, a reference level is not impermissible limit, but a value that is recommended not to be exceeded, to facilitate the monitoring and control of the exposure of the population as a whole

For the winter, measurements were made by placing the device in the room, which was in the same position in the same way in winter, which can be seen in **Figure 6**.

And with this, the following measurements were extracted using the Wave Plus device, which shows us the behavior over this two-month period, in which the temperature and relative humidity can be see in **Figure 9**.

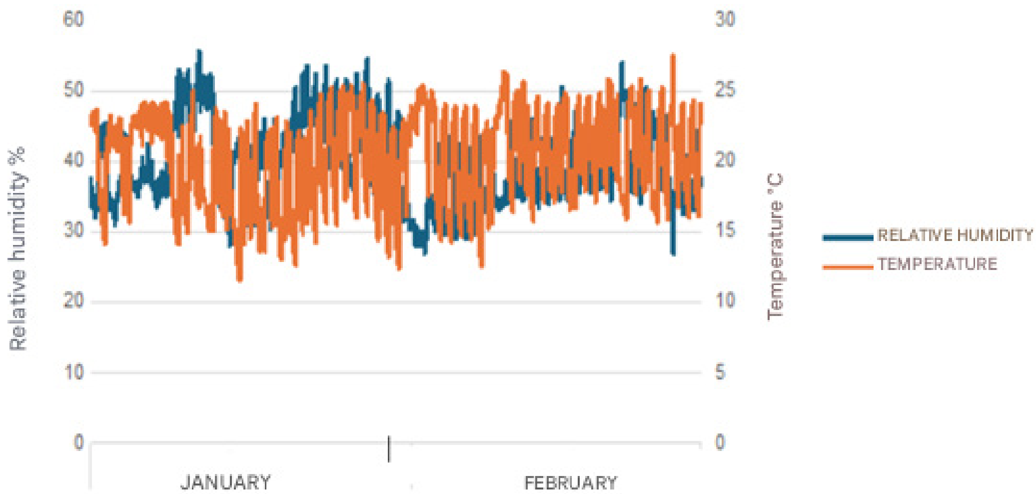

Figure 9. Relative humidity (%) and temperature (°C) in the room as a function of the weather (winter).

During this climatic period, temperatures were recorded inside the house that ranged between 11.6°C and 26.3°C, with humidity levels ranging between 25% and 58%.

At outdoor levels, minimum temperatures are close to 0 °C, with values rarely falling below −5°C or exceeding 6°C. The lowest average minimum temperature occurs on January 16, with about −1°C. Indoor temperatures were found in a range of 23°C to 28°C, with values rarely dropping below 14.6°C or exceeding 26.3°C indoors.

Lowest average maximum temperature: It was recorded on January 9, with approximately 11°C.

The values recorded indicate relatively stable conditions, with humidity between 25% and 58% within a moderate range, although levels close to 25% can generate a dry environment that affects comfort and respiratory health, with temperatures that, although they vary, do not present extreme changes.

In turn, the values of carbon dioxide and radon were obtained as a function of the winter weather, which can be seen in **Figure 10**.

According to the Technical Building Code (CTE) in Spain, the recommended indoor radon concentration limit is 300 Bq/m^3. However, the values obtained in the house range from 2 to 529 Bq/m^3, which indicates that at certain times the recommended limits were exceeded.

Low levels of 2 Bq/m^3 indicate well-ventilated areas or areas with low gas accumulation. Maximum values of 529 Bq/m^3 exceed the recommended threshold, suggesting the need for corrective measures to reduce exposure, such as improved ventilation and sealing cracks in floors and walls.

The CTE states that recommended indoor CO_2 levels should not exceed 1,000 ppm to maintain acceptable air quality. The values obtained in the house ranged between 468 and 1,370 ppm, which indicates moments of variable air quality.

Lower values (468 ppm) are within the optimal range and suggest good ventilation at certain times. However, peaks of up to 1,370 ppm exceed the recommended threshold of 1,000 ppm and the threshold of 1,200 ppm, beyond which air quality is considered poor. It is observed that higher levels coincide with higher occupancy in the home, highlighting the importance of adequate ventilation when there are more people in space.

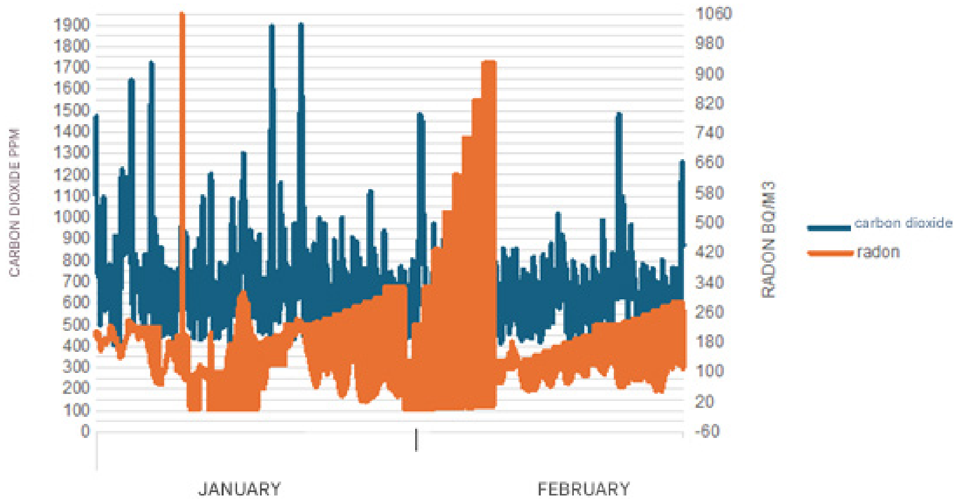

Figure 10. Carbon dioxide (ppm) and radon (Bq/m3) in the living room depending on the weather (winter).

3.3. Assessment of Study Indicators

3.3.1. Temperature and Humidity in Summer

Indoor temperature range: 11.6°C–26.3°C

Average maximum temperature: 31°C (July 31)

Indoor humidity range: 17%–57%

The results of the analysis of temperature and humidity in summer are:

- The interior temperature is stable and follows the behavior of the outside, indicating moderate thermal insulation.
- Humidity varies significantly, with low values (17%) that can cause dryness in the environment and affect respiratory health.
- It is recommended to improve moisture retention in the air with materials such as clay plasters or the use of humidifiers on dry days.

3.3.2. Radon Levels in Summer

Registered radon range: 4–126 Bq/m³

CTE recommended limit: ≤ 300 Bq/m³

The results of the analysis of radon levels in summer are:

- Radon values are kept within the recommended limit, indicating that natural ventilation in summer is sufficient to prevent build-up.
- The maximum value of 126 Bq/m³ suggests that at times the radon concentration increases, possibly when windows are closed on days of intense heat.
- It is recommended to ensure cross ventilation to avoid occasional accumulation.

3.3.3. Carbon Dioxide Levels in Summer

Recorded range: 459–1250 ppm

CTE recommended limit: ≤ 1000 ppm

Poor air quality threshold: ≥ 1200 ppm

The results of the analysis of CO_2 levels in Summer are:

- Most of the time, carbon dioxide levels are within the recommended range.
- However, peaks of 1250 ppm indicate poor air quality at certain times, likely when the home is occupied by multiple people and without sufficient ventilation.
- The use of extractors or mechanical ventilation systems is recommended to improve air renewal on hot days when windows are closed due to high temperatures.

3.3.4. Temperature and Humidity in Winter

Indoor temperature range: 11.6°C–26.3°C

Average minimum temperature: −1°C (January 16, outdoors)

Indoor humidity range: 25%–58%

The results of the analysis of temperature and humidity in winter are:

- The house maintains adequate temperatures inside, which indicates good thermal insulation in winter.
- Humidity is more stable than in summer, but values close to 25% can generate dryness in the environment, affecting comfort.
- It is recommended to use natural humidifiers, such as plants or materials that absorb and release moisture (lime or clay plasters).

3.3.5. Radon Levels in Winter

Registered radon range: 2–529 Bq/m³

CTE Recommended Limit: ≤ 300 Bq/m³

The results of the analysis of radon levels in winter are:

- Radon levels well above the recommended threshold (529 Bq/m³) were recorded at certain times.
- This indicates that radon accumulation is higher in winter, due to less ventilation and the use of heating, which can generate a suction effect from the subsoil.
- It is recommended to implement anti-radon barriers in foundations and soils, along with controlled mechanical ventilation to prevent the concentration of the gas.

3.3.6. Carbon Dioxide Levels in Winter

Recorded range: 468–1370 ppm

CTE recommended limit: ≤ 1000 ppm

Poor air quality threshold: ≥ 1200 ppm

The results of the CO_2 level analysis of in winter are:

- An increase in carbon dioxide is observed in winter, reaching peaks of 1370 ppm, which indicates poor air quality at times of high occupancy and low ventilation.
- This is due to prolonged window closures due to the cold and the use of heating systems, which can reduce the circulation of fresh air.
- It is recommended to ventilate at least 10 minutes a day, preferably at times of lower outdoor temperature, and consider ventilation systems with heat recovery so as not to lose thermal efficiency.

With the analysis presented, the following comparison is established, giving us the most important factors of the study house, which can be seen in **Table 2**.

Table 2 . Comparison between Summer and Winter weather.

Study Parameters	Summer	Winter	General Analysis
Temperature	11.6°C–26.3°C (max. 31°C)	11.6°C–26.3°C (min. −1°C)	Stable in both seasons
Humidity	17%– 57%	25%–58%	More stable winter, drier summer
Radon	4–126 Bq/m³	2–529 Bq/m³	Greater problem in winter due to less ventilation
Carbon dioxide	459–1250 ppm	468–1370 ppm	Increased accumulation in winter

3.4. Evaluation of Construction Materials

3.4.1. Thermal Insulation and Its Impact on Temperature

The house maintains relatively stable temperatures in winter and summer, suggesting that the building materials have a moderate thermal insulation capacity.

However, the accumulation of radon and CO_2 indicates that the materials may be limiting natural ventilation, preventing proper air renewal.

3.4.2. Radon Buildup

Deficiencies in Material Permeability

The radon range found (2–529 Bq/m³) indicates that there is leakage of gas from the subsurface.

This suggests that the materials used in foundations and screeds are not completely watertight, allowing radon to infiltrate.

3.4.3. Possible Problems with Materials

- Lack of waterproof membranes under the foundation.

- Poorly sealed joints on the floor and walls.

3.4.4. Air Quality and CO_2 Accumulation

The accumulation of CO_2 at times indicates that the materials are not facilitating breathability or air exchange.

3.4.5. Problematic Materials

Excessive use of plastic sealants or synthetic paints that prevent walls from breathing.

Glass windows with hermetically sealed frames without integrated ventilation systems.

3.4.6. Positive Aspects of the Façade

- Good thermal insulation, avoiding sudden changes in temperature.
- Heat conservation in winter, avoiding energy losses.
- Relatively airtight structure, which helps with energy efficiency.

3.4.7. Negatives Aspects

Radon buildup, indicating that soil and foundation materials do not have adequate barriers.

Low breathability of the walls, which prevents the correct regulation of humidity and air renewal.

Accumulation of carbon dioxide at certain times, suggesting a lack of ventilation built into the materials.

3.5. Recommendations for Improving Building Materials

3.5.1. Radon Reduction: Improving Foundation and Screed Materials

- Install anti-radon barriers: Incorporate high-density polyethylene (HDPE) membranes under the screed to block radon from entering.
- Use concrete with waterproofing additives: This helps reduce porosity and prevents gas seepage from the subfloor.
- Sealing of joints and fissures: Apply epoxy resins or specific sealants at points of possible infiltration.
- Implement an underground ventilation system: A passive or active suction system under the house reduces radon buildup.

3.5.2. Improve the Breathability of Materials

- Replace plastic paints with lime or silicate paints: They allow the walls to breathe and regulate humidity without compromising air quality.
- Use porous materials such as clay bricks or lime and hemp blocks: These materials allow the diffusion of CO_2 and moisture, reducing the feeling of “enclosed” air.
- Incorporate natural wood panels in interiors: Materials such as solid wood help regulate indoor humidity without retaining pollutants.

3.5.3. Integrated Ventilation in Materials

- Install windows with controlled mechanical ventilation: These windows allow air to enter without compromising thermal insulation.
- Use lime or clay plasters indoors: These materials absorb and release moisture, helping to stabilize air quality.
- Incorporate natural wood or breathable ceramic flooring instead of vinyl or synthetic flooring that can completely seal out the environment.

4. Discussions

Current materials appear to be adequate in terms of thermal insulation, but they have deficiencies in ventilation and breathability, which contributes to the accumulation of radon and CO_2 at certain times.

To improve these conditions, it is recommended:

- Implement anti-radon barriers in foundations.
- Improve breathability with lime paints, clay plasters, and natural materials.
- Incorporate passive and active ventilation in floors and walls to reduce pollutants.

By making these improvements, a healthier indoor environment can be achieved, with better air quality and greater thermal comfort without compromising energy efficiency.

The analysis reveals that the home requires improvements in ventilation and sealing, rather than in its thermal insulation, to ensure a healthier and safer environment for its occupants. Implementing the proposed improvements will reduce health risks, improve air quality and optimize thermal comfort in all seasons.

Continuous monitoring is essential to assess the effectiveness of these measures and adjust strategies as needed. In addition, it is recommended to explore technological alternatives such as air quality sensors and smart ventilation systems to ensure adequate regulation of environmental parameters in the home.

4.1. Seasonal Variation in Temperature and Humidity

The values obtained reflect good thermal stability inside the house in both seasons. However, in summer, humidity levels drop to 17%, which generates a dry environment that can affect respiratory health and the feeling of thermal comfort. In winter, although humidity is more stable (25%–58%), lower values can still generate a feeling of dryness in the environment.

Current building materials seem to offer adequate thermal insulation, as the temperatures inside do not present extreme changes.

However, moisture levels are not optimal, suggesting the need to improve moisture retention by using hygroscopic materials such as clay or lime plasters.

4.2. Evaluation of Radon Levels

Radon levels varied significantly between summer and winter:

In summer: 4–126 Bq/m³ → Within the recommended limit of 300 Bq/m³.

In winter: 2–529 Bq/m³ → Exceeds the recommended limit, with values that may pose a long-term health risk.

In summer, natural ventilation contributes to the dissipation of radon, keeping it at safe levels.

In winter, radon buildup increases considerably, indicating that the home has problems with sealing the ground or foundation, which allows gas to infiltrate.

This can pose a health risk, as prolonged exposure to high levels of radon is linked to an increased risk of lung cancer.

4.3. Air Quality and CO_2 Levels

CO_2 levels also showed differences between seasons, with higher values in winter. In summer: 459–1250 ppm Occasional moments of poor air quality are observed, but generally it remains within acceptable levels. In winter: 468–1370 ppm It frequently exceeds 1000 ppm, which indicates poor ventilation when there is greater occupancy in the house.

In summer, natural ventilation allows for better air renewal, reducing the accumulation of carbon dioxide. In winter, because the windows are kept closed, the CO_2 concentration exceeds the recommended levels.

When values exceed 1200 ppm, air quality is considered poor and can lead to drowsiness, lack of concentration, and fatigue.

4.4. Evaluation of Construction Materials

Since temperature levels and thermal insulation seem adequate, there are problems with humidity, radon and air quality, some observations can be made about the suitability of building materials:

Possible Problems Identified:

Lack of moisture retention → Current materials do not regulate humidity well, which generates dry environments in summer.

Radon infiltration → Cracks in the foundation or porous materials may allow the gas to pass through.

Deficiency in air renewal because the current design does not favor ventilation in winter.

5. Conclusions

The radon levels measured in the single-family house in the study do not pose a health risk, as they do not approach the limit of 300 Bq/m³ at any time.

Even when there are fluctuations in concentration, they remain within safe values, which indicates that the ventilation and structural conditions of the house allow adequate control of exposure. However, it is recommended to continue periodic monitoring, especially at times of the year where natural ventilation is lower, to ensure that these levels remain adequate over time.

The house maintains stable temperatures inside, despite the colder external conditions. Humidity levels are within an acceptable range, although values close to 25% can cause discomfort.

Radon levels have been recorded above the recommended limit, which makes it necessary to improve ventilation and seal possible leaks.

The CO_2 concentration has occasionally exceeded the recommended threshold, indicating the need for more efficient ventilation at times of high occupancy.

Author Contributions

Conceptualization, M.I.P.-H., S.M.-T., R.A.G.-L.; methodology M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P.; software. M.I.P.-H.; validation R.A.G.-L. and T.A.P.; formal analysis M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P., investigation M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P.; resources M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P.; data curation M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P.; writing—original draft preparation, M.I.P.-H., S.M.-T., R.A.G.-L.; writing—review and editing, T.A.P.; visualization M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P.; supervision M.I.P.-H., S.M.-T., R.A.G.-L. and T.A.P.; project administration R.A.G.-L.; funding acquisition R.A.G.-L.. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data used in this study can be provided upon request.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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