BILINGUAL PUBLISHING GROUP

Research in Ecology
https://journals.bilpubgroup.com/index.php/re

ARTICLE

Influence of Natural Ventilation on Indoor Air Quality in a Single-Family Dwelling in the Northwest Area of Madrid

Melany Isabel Pinilla-Hernandez [1] **, *Sofia Melero-Tur*** [1] **, *Tamar Awad Parada*** [2] **, *Roberto Alonso Gonzalez-Lezcano*** [1*]

[1] *Architecture and Design Department, Escuela Politécnica Superior, Universidad CEU San Pablo, Montepríncipe Campus, 28668 Boadilla del Monte, Spain*

[2] *Departamento de Ideación Gráfica Arquitectónica, Escuela Técnica Superior de Arquitectura de Madrid, Universidad Politécnica de Madrid, 28040 Madrid, Spain*

ABSTRACT

Indoor air quality (IAQ) is a fundamental characteristic of eco-friendly buildings and sustainable environments, significantly impacting the well-being and behavior of occupants. Even in low-occupancy residences, maintaining good IAQ is essential for health and comfort. Buildings must meet both regulatory standards and occupant satisfaction to ensure a healthy indoor environment. Regardless of external conditions, people are constantly exposed to their surroundings, making air quality management a critical challenge. This study evaluates the impact of natural ventilation on IAQ in a single-family home in northwest Madrid through continuous monitoring of particle concentrations and CO_2 levels. The results reveal that daily indoor activities—particularly cooking, cleaning, and evening occupancy—significantly influence pollutant levels. Cleaning processes release particles ranging from 1 μm to 10 μm, while midday cooking generates notable emissions from stoves and ovens. CO_2 concentrations regularly exceed 1000 ppm at night in bedrooms with poor ventilation, whereas the living room maintains levels close to outdoor air due to consistent daily ventilation practices of approximately 3 h typically below 600 ppm. The monitoring also showed that volatile organic compounds (VOCs) are heavily influenced by furnishings, pets, tobacco, airflow patterns, temperature and humidity, among other factors with greater variability than CO_2. Based on these findings, the study provides targeted recommendations to optimize natural ventilation, emphasizing schedule-based airing routines and material

*CORRESPONDING AUTHOR:
Roberto Alonso Gonzalez-Lezcano, Architecture and Design Department, Escuela Politécnica Superior, Universidad CEU San Pablo, Montepríncipe Campus, 28668 Boadilla del Monte, Spain; Email: rgonzalezcano@ceu.es

ARTICLE INFO
Received: 20 October 2025 | Revised: 21 January 2026 | Accepted: 29 January 2026 | Published Online: 27 April 2026
DOI: https://doi.org/10.30564/re.v8i3.12506

CITATION
Pinilla-Hernandez, M.I., Melero-Tur, S., Parada, T.A., et al., 2026. Influence of Natural Ventilation on Indoor Air Quality in a Single-Family Dwelling in the Northwest Area of Madrid. Research in Ecology. 8(3): 1–19. DOI: https://doi.org/10.30564/re.v8i3.12506

considerations for furnishings. These insights will be valuable to homeowners, architects, engineers, and public health professionals seeking sustainable, health-focused indoor environments. By enhancing IAQ through passive strategies, this study advances occupant well-being and environmental sustainability.

Keywords: Environment; Energy Conservation; Indoor Environmental Quality (IEQ); Natural Ventilation; Carbon Dioxide and Volatile Organic Compounds

1. Introduction

Indoor environmental quality (IEQ) is a core attribute of sustainable buildings, with a well-established influence on occupants' behavior and well-being, particularly in residential contexts.

Even in buildings with low occupancy densities, ensuring acceptable indoor air quality (IAQ) remains crucial. One of the most effective approaches to achieving this goal is by optimizing the efficiency of the ventilation system, which plays a pivotal role in maintaining IAQ by ensuring adequate air exchange between indoor and outdoor environments [1].

The environmental performance of a building is determined not only by physical factors but also by the interaction between the physical environment and its occupants. While a building must meet certain standards for indoor environmental conditions, it must also address the specific needs and satisfaction of its inhabitants. This dual requirement highlights the necessity of understanding the relationship between the design of the indoor environment and the health and comfort of those living in it. In this sense, the quality of indoor air directly affects the occupants' health, and poor indoor air quality can result in various health issues, including respiratory conditions, allergies, and other chronic diseases. Therefore, maintaining a healthy and comfortable environment is a key challenge in modern building design [2]. As noted by Bernell and Howard (2016), the term 'chronic disease' generally refers to conditions that require ongoing management over extended periods and cannot be resolved through short-term medical intervention.

When designing indoor environments for people, it is essential to consider not only the physical characteristics of the space but also how people interact with it. Factors such as temperature, humidity, noise, and the presence of airborne chemicals or biological pollutants can all influence indoor air quality and, by extension, the health and comfort of the building's users. Among the radioactive pollutant (radioactive gas), mold, bacteria, and dust mites are common, while radon gas is a significant natural pollutant that increases the risk of lung cancer for occupants [3,4]. Given the potential hazards posed by these pollutants, it is essential to control their concentration in indoor environments.

Different regulations have been established internationally to set acceptable parameters for indoor air quality. The National Ambient Air Quality Standards (NAAQS) provide guidelines for outdoor air quality in the United States, while the Occupational Safety and Health Administration (OSHA) sets values for industrial environments. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established guidelines for indoor environments, particularly for buildings with heating, ventilation, and air conditioning (HVAC) systems. In addition, the World Health Organization (WHO) provides air quality guidelines aimed at protecting public health in general environments [5,6]. According to ASHRAE Standard 55-2017, indoor temperatures should be maintained between 20.3 °C and 23.9 °C in winter and between 23.9 °C and 26.9 °C in summer to ensure comfort and minimize health risks related to thermal discomfort [1,7]. Similarly, the U.S. Environmental Protection Agency (EPA) recommends maintaining indoor relative humidity between 30% and 60% to prevent mold growth and other associated health issues [8,9].

In Spain, however, there is no specific legislation or consensus regarding sanitary reference values for indoor environments. While the Reglamento de Instalaciones Térmicas en los Edificios (RITE) provides hygrothermal recommendations, and the Código Técnico de la Edifi-

ción (CTE) includes basic sanitary requirements, there are no established reference values for indoor air quality [9]. Similarly, emissions of certain chemical pollutants within indoor air are not explicitly regulated, although the UNE 171330 provides comfort criteria based on WHO and national recommendations [10]. New European directives, especially following the COVID-19 health crisis, have emphasized the importance of prioritizing health alongside environmental and energy efficiency considerations, thus highlighting the need to improve indoor air quality [11].

Buildings constructed today are expected to remain in use for the next 50 to 80 years, but increasing energy costs and stricter environmental regulations may challenge the sustainability of energy-intensive buildings [12]. While energy-efficient buildings reduce external energy consumption, poor ventilation can lead to various indoor air quality problems, such as excessive humidity, fungal and bacterial growth on interior surfaces and building materials rather than within air distribution system, and the buildup of pollutants like CO_2, which indicates inadequate air exchange. Such issues are characteristic of "sick buildings," where poor ventilation can cause symptoms like eye irritation, dry skin, and nasal congestion among occupants [13]. In extreme cases, insufficient air exchange can also increase the presence of harmful chemical and biological pollutants that pose longer-term health risks.

Among the most significant pollutants in indoor environments are volatile organic compounds (VOCs), which are emitted from materials and products such as cleaning agents, paints, and air fresheners. Prolonged exposure to certain VOCs has been associated with respiratory issues, cardiovascular diseases, and even cancer [14–18]. Some studies suggest that indoor VOC concentrations are often higher than outdoor levels, making indoor air quality a critical concern, especially since people spend most of their time indoors [15,19–23]. The World Health Organization has established guidelines for certain VOCs, such as benzene and formaldehyde, which are commonly found in indoor environments and have been linked to various health risks [16,24–26]. According to the WHO indoor air quality guidelines, the recommended short-term exposure limit for formaldehyde is 0.1 mg/m^3 (30 min average) to protect health over a lifetime [27]. For benzene, WHO does not specify a single threshold but provides unit-risk based reference concentrations indicating that even low levels (e.g., ~0.17 μg/m^3 for a 1×10^{-6} lifetime cancer risk) are associated with carcinogenic risk [27].

To mitigate these risks, it is essential to measure and control the concentration of indoor air pollutants. Ventilation systems play a key role in this process, and it is critical to design buildings with effective air exchange rates that meet both comfort and health standards. The study of IAQ in residential settings, such as in single-family homes, can provide valuable insights into the impact of ventilation systems and pollutant sources on overall air quality.

By evaluating air flow patterns and conducting surveys to understand the behaviors and activities of occupants, we can gain a better understanding of the factors that influence indoor air quality and suggest improvements that could reduce pollutant levels and enhance occupant health and comfort.

This paper aims to assess indoor air quality in a single-family dwelling in Collado Villalba, Spain. The study will focus on factors such as airflow rates, ventilation efficiency, and the influence of occupant behaviour on indoor air quality. By analysing the sources of indoor pollutants and evaluating ventilation strategies, the study will offer recommendations to improve IAQ and create healthier living environments for occupants.

2. Materials and Methods

To investigate indoor air quality (IAQ) in residential settings, this study focuses on case studies conducted in single-family dwellings located in Madrid, Spain, building upon previous research such as Indoor Air Quality Monitoring in Dwellings: Case Studies in Madrid, Spain [17].

To ensure methodological transparency and reproducibility, the main measurement techniques, sampling conditions, and analytical parameters used in this study are summarized in **Table 1**. The table compiles the procedures applied for the assessment of gaseous, particulate, and biological contaminants, as well as the method used to evaluate ventilation performance and data quality.

Table 1. Summary of measurement methods and analytical parameters.

Parameter	Method Description
Volatile Organic Compounds (VOCs)	VOCs were quantified using active sampling on Tenax TA sorbent tubes, followed by thermal desorption and gas chromatography–mass spectrometry (GC-MS). Sampling was conducted for 60 min at a constant flow rate of 200 $mL \cdot min^{-1}$. Method detection limits ranged between 0.1 and 0.5 $\mu g \cdot m^{-3}$ depending on the compound. The methodology followed ISO 16000-6:2011 and EPA Method TO-17.
Particulate Matter (PM)	PM_{10}, $PM_{2.5}$, and PM_1 concentrations were measured gravimetrically by collecting airborne particles on pre-weighed filters during 24 h sampling periods, using low-volume samplers. Filters were conditioned and weighed before and after sampling to determine particle mass concentrations. Optical particle counters (OPCs) were used for real-time particle number concentrations.
Biological Contaminants	Bioaerosol sampling was conducted using filtration methods, capturing airborne moulds and bacteria on sterile filters for subsequent culture analysis. Samples were incubated at 30 °C for 72 h prior to colony identification and enumeration, following ISO 16000-16:2007.
Air Change Rate (ACH)	Ventilation performance was evaluated using the tracer gas decay method. A known concentration of tracer gas (CO_2) was released into the indoor space, with an initial target concentration of approximately 1500 ppm, and its decay rate was monitored to calculate ACH, following ISO 12569:2017.
Quality Assurance and Data Analysis	All sampling equipment was calibrated before each campaign, and field blanks were collected to assess background contamination. Data analysis consisted of descriptive statistical analysis and correlation assessment between IAQ parameters and occupant behavior, using spreadsheet-based tools for data processing and visualization to identify pollutant sources and evaluate ventilation performance.

2.1. Data Collection

2.1.1. Description of Study Area

Single-family homes were chosen to represent a diverse example of Madrid's residential environment, considering factors such as building age, ventilation type (natural or mechanical), number of occupants, and geographical location.

2.1.2. Occupant Surveys

Structured surveys provided insights into occupant behavior, such as ventilation habits (e.g., window-opening frequency), use of cleaning products, smoking behaviors, and overall dwelling use patterns. These surveys were essential for linking occupant activity to observe IAQ trends.

Table 2 outlines key variables related to occupancy patterns and ventilation behaviour within the dwelling. It considers weekday occupancy by analysing the average hours spent at home across different times of the day. For weekends, variations in occupancy schedules and the main activities performed are identified to capture changes in residential use. In addition, the frequency and duration of window opening are examined to assess natural ventilation practices and their potential impact on indoor environmental conditions. It examines the presence and use of mechanical ventilation devices, ventilation practices in common areas, and specific periods when cross ventilation is applied. Additionally, it includes information on major household appliances and their frequency of use, as well as the types and operating hours of heating and cooling systems. Finally, smoking-related variables are considered, including the number of smokers, designated smoking areas, consumption frequency, and mitigation measures through additional ventilation.

Table 2. Case study habit survey.

Category	Variables Considered
Occupancy patterns	Weekday and weekend occupancy schedules; time spent indoors (morning, afternoon, evening).
Household activities	Main daily and weekend activities influencing indoor air quality.
Natural ventilation	Frequency and duration of window opening; cross-ventilation periods.
Mechanical ventilation and cooling	Use of exhaust fans and wall-mounted air conditioning units.
Room-specific ventilation	Ventilation practices in living rooms, kitchens, and bathrooms.
Appliances and equipment	Type of household appliances and frequency of use.
Heating and cooling systems	Type of installed systems and typical hours of operation.
Smoking-related variables	Presence of smokers, smoking locations, frequency, and mitigation through additional ventilation.

2.2. Data Collection and Monitoring

2.2.1. Equipment and Instruments Used in Monitoring

IEQ parameters were monitored over an extended period using advanced portable sensors.

These devices captured data on temperature, relative humidity, carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter (PM_{10} and $PM_{2.5}$). Monitoring devices were strategically placed in bedrooms, living areas, and kitchens to detect spatial and temporal variations.

All monitoring instruments, their measurement variables, deployment location (indoor/outdoor), and main purpose are now summarized concisely in **Table 3**. In addition, **Figure 1** presents the corresponding images of each device, allowing visual identification without overloading the methodological description.

Table 3. Sensors used in the case study.

Instrument	Location	Variables Measured	Main Purpose
Dioxcare DX700	Indoor	Temperature (°C), relative humidity (%), CO_2 (ppm)	Continuous monitoring of indoor thermal conditions and CO_2 levels to assess ventilation efficiency.
Aranet4	Outdoor	Temperature (°C), relative humidity (%), CO_2 (ppm)	Outdoor reference measurements for comparison with indoor conditions.
Blower Door 5102	Indoor (building envelope test)	Air changes per hour (ACH_{50}), effective leakage area (ELA)	Evaluation of building airtightness and ventilation performance under standardized pressure conditions.
PCE-PCO 1	Indoor/Outdoor	Particulate matter (PM_1, $PM_{2.5}$, PM_{10}) ($\mu g/m^3$)	Measurement of airborne particulate concentrations in indoor and outdoor environments.

(**a**) Dioxcare DX700.

(**b**) Aranet4.

(**c**) Blower Door 5102.

(**d**) PCE-PCO 1.

Figure 1. Monitoring equipment used in the case study.

2.2.2. Data Analysis and Modelling Framework

Regulatory Comparison

According to ASHRAE Standard 62.1, indoor CO_2 concentrations above outdoor levels by more than 700 ppm indicate inadequate ventilation, WHO, and UNE, use this to assess compliance and identify areas for improvement. In particular, the study examines adherence to recommended levels for CO_2, VOCs, and relative humidity [18].

Indoor Particulate Matter (PM) Pollution

Particulate matter (also known as PM or particle pollution) is a complex mixture of solid and/or liquid particles suspended in the air. These particles can vary in size,

shape, and composition. Once inhaled, the particles can affect the heart and lungs and, in some cases, cause serious health effects.

The UNE-EN ISO 14644-1 standard focuses primarily on the classification of air cleanliness in terms of the concentration of airborne particles in cleanrooms and controlled environments. It does not specifically deal with volatile organic compounds (VOCs).

However, for the control of volatile particulate matter, other standards and complementary methods are often used.

Only particle groups that have distributions based on limiting particle size ranges (lower limit) between 0.1 μm and 5 μm are considered for classification purposes.

Regulations Applicable to the Permeability of Buildings

The regulations on building permeability, DB HE1 of the 2019 Technical Building Code (CTE), set limits for the air exchange ratio (n50) at a differential pressure of 50 Pa for residential buildings with a usable area greater than 120 m^2. The goal is to control unwanted air infiltration, optimizing energy performance by reducing heat or cold loss, which decreases the energy demand for heating and cooling. Additionally, it enhances indoor air quality and thermal comfort for occupants, contributing to their well-being. This regulation also aims to reduce greenhouse gas emissions, aligning with sustainability commitments and climate goals, thus improving both energy efficiency in buildings and the quality of life for residents.

2.3. Analysis of the Quality of the Air Outside and Inside the House

In this section, based on the measurement sensors, the analysis of the house is carried out, both the parameters obtained outside and inside (**Table 4**).

The collected data is analyzed statistically to identify trends and correlations between IEQ parameters and influencing factors such as ventilation rates, outdoor air quality, and occupant behaviors. In this case, Microsoft Excel was employed for analyzing data related to indoor environment quality (IEQ), ventilation rates, and occupant behavior. The analysis focused on leveraging Excel's capabilities for statistical evaluations and visualizations, complemented by simplified airflow modeling using data-driven techniques.

Table 4. Indoor and outdoor environment quality.

Parameter	Indicator/Pollutants	Guideline/Reference Values
Outdoor air quality	$PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2 (NAQI)	Madrid Air Quality Network; NAQI categories
Indoor air quality (IAQ)	CO_2, VOCs, PM, RH, CO	WHO / ASHRAE guidelines
Carbon dioxide (CO_2)	Ventilation indicator	<1000 ppm (ASHRAE 62.1)
Particulate matter	$PM_{2.5}$, PM_{10}	$PM_{2.5}$ < 10 μg/m^3; PM_{10} < 20 μg/m^3 (WHO, annual)
Volatile organic compounds (VOCs)	Benzene, toluene, xylene (TVOC)	<300 μg/m^3 (UBA guidance)
Relative humidity (RH)	Comfort and biological growth indicator	30–60%
Carbon monoxide (CO)	Combustion by-product	<9 ppm (8 h average, WHO)

3. Results

3.1. Data Processing and Analysis

3.1.1. Analysis of Study Area

The sector where the study house is located is Collado Villalba which is a municipality located in the Community of Madrid, Spain. It has a population of approximately 65,657 inhabitants [19], although this number may vary depending on the time of year and other factors. Located at 40°38' and at an altitude of 917 m above sea level, its climate is characterized by a transition between a cold semi-arid climate (Köppen BSk) and a Mediterranean climate (Csa), with an average annual temperature of about 13 °C (**Figure 2**).

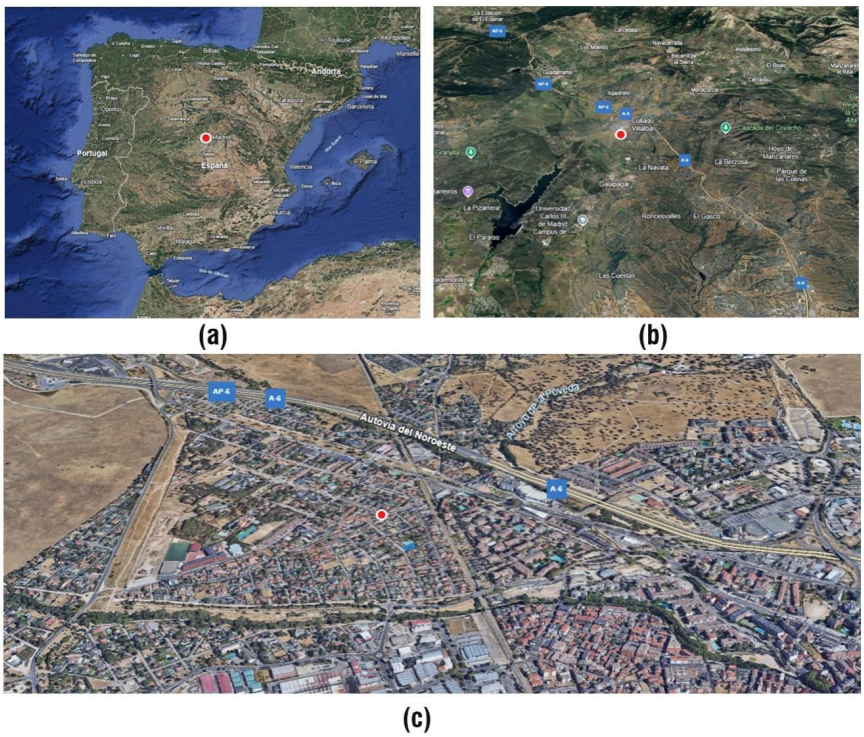

Figure 2. Location of Collado Villalba: (**a**) Geographical location in Spain; (**b**) Delimitation of the area; (**c**) Location of the study house.

Winters are moderately cold, with average temperatures in the coldest month (January) of around 6 °C. Summers are hot, with an average temperature above 25 °C in July, with average maximum temperatures between 32 and 33.5 °C.

The daily temperature oscillation is significant in the periphery of the city (around Δt 13 K) but is smaller the same occurs in the urban area of the city (the daily Δt is usually below 10 K). The annual thermal amplitude is also high: between 19 and 20 °C.

This climatic context traditionally favored the use of natural ventilation. Houses were designed to be semi-open, with most windows open for a significant part of the year, a trend that is decreasing in southern European cities due to outdoor pollution and other factors, such as noise and changes in behavioral patterns, as pointed out by Domínguez-Amarillo et al. [25].

This situation makes the area particularly relevant as a typical situation for analyzing the behavior of the household stock, which shared many buildings and behavioral characteristics with other urban agglomerations in southern Europe during the pandemic.

The most widespread residential buildings are multi-family dwellings, either linear or H. blocks [20] (**Figure 3**).

Figure 3. Study Dwelling.

3.1.2. Occupants Living Spaces

Table 5 summarizes user habits, including their activities inside the home, as well as the use of devices that affect air quality.

3.2. Indoor Environmental Data Evaluation

3.2.1. Variable Measurement

The study devices were placed in different points of the dwelling, see **Figure 4**, one was placed in the living room, another two in rooms inside the dwelling in which there are inhabitants.

Figure 4 shows the floor plans of the dwelling with the scaled location of the measuring devices. In all monitored spaces, the sensors were positioned in a central area of each room, ensuring a minimum distance greater than 0.5 m from partition walls, doors, and fixed furniture. This placement was selected to avoid boundary effects, thermal gradients, and localized airflow disturbances, allowing the measurements to be representative of the average indoor conditions of each space.

In the hall (**Figure 4a,b**), the measuring device was located approximately at the geometric center of the space, at distances ranging between 1.9 and 2.8 m from the surrounding walls, depending on the orientation, ensuring uniform exposure to indoor air conditions.

On the second floor (**Figure 4c**), the sensor was placed in the central circulation area, maintaining clear separation from adjacent bedrooms and sanitary spaces to minimize interference from localized pollutant sources.

In study room 1 (**Figure 4d**), with approximate internal dimensions of 6.18 m × 2.80 m, the sensor was positioned near the midpoint of the room, at distances of about 1.4 m from the longitudinal walls and more than 2.5 m from the façade and interior partitions.

In study room 2 (**Figure 4e**), with internal dimensions of approximately 2.12 m × 1.73 m, the sensor was located at the center of the room, maintaining distances of roughly 1.06 m from the longer walls and 0.86 m from the shorter walls. This ensured that the device was not closer than 0.5 m to any enclosure element.

Overall, the sensor placement strategy complies with ISO 7726:1998 recommendations, ensuring that the collected data reflect representative indoor environmental conditions rather than localized effects near walls or ventilation openings.

Each study room is occupied by two residents. Room #1 is inhabited by two women aged 25 and 72, while Room #2 is occupied by a 57-year-old man and a 49-year-old woman. The measuring equipment was installed within the study rooms, following standardized placement criteria to ensure uniform measurements throughout the dwelling, including adequate separation from partition walls and enclosures to avoid interference. One study room is equipped with a mini-split system with a heat pump, whereas the other study room has no mechanical ventilation system. In addition, the mini-split systems operate exclusively in recirculation mode and do not supply outdoor air to the indoor spaces.

Table 5. Survey conducted in the study house.

Category	Description
Number of occupants	4 people
Occupant profile	Male (57 years), Female (49 years), Female (25 years), Female (72 years)
Weekday occupancy (Mon–Fri)	Male (57): 00:00–08:30 Female (49): 00:00–08:00 Female (25): 00:00–06:30 Female (72): 00:00–16:30 and 19:30–23:59
Weekend occupancy (Sat–Sun)	Male (57): 00:00–08:30 and 20:30–23:59 Female (49): 00:00–14:00 and 20:00–00:00 Female (25): 00:00–07:30 and 16:00–23:59 Female (72): 00:00–23:59
Pets	1 indoor cat; 2 outdoor dogs
Natural ventilation	Window opening from Monday to Friday, 10:00–13:00
Mechanical systems	Mini-split heat pump systems (2 units), operating daily from 20:00 to 07:00
Water heating system	Water heater
Heating system	Gas boiler
Household appliances	Refrigerator (1), Washer (1), Dryer (1), Microwave (1), Stove (1), Oven (1), TVs (3), Laptop (1), Printer (1)

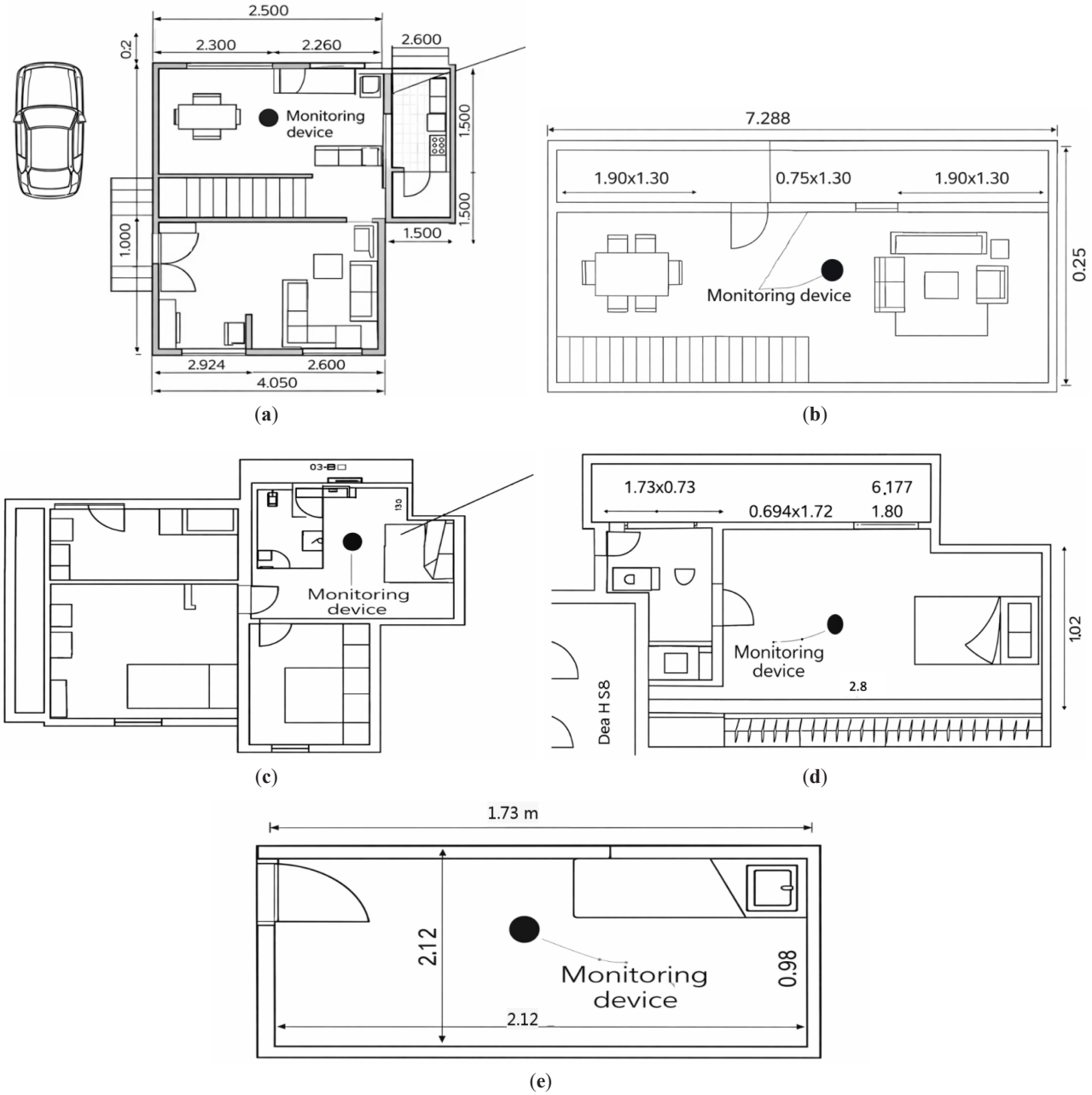

Figure 4. (**a**) First Floor of the Dwelling and Signage of the hall; (**b**) Signage for location of measuring devices in the hall; (**c**) Second Floor of the Dwelling and Signage of Study Rooms; (**d**) Location signage of measurement devices in room number 1; (**e**) Location signage of measuring devices in room number 2.

Note: units (m).

3.2.2. Statistical Analysis and Indoor Air Quality Modelling

The indoor air quality data collection was carried out during five weeks, monitoring several variables inside and outside the dwelling. A summary of the data obtained is to be used for the analysis of outdoor and indoor air quality in the dwelling.

3.3. Analysis of Outdoor and Indoor Air Quality in the Dwelling

To assess the actual exposure of the occupants to indoor air pollutants, a five-week measurement campaign was conducted starting on May 20, 2024. Indoor air quality parameters were monitored continuously using the equipment described in Section 2.2.1, in accordance with the

instrumentation and methodological requirements of ISO 7726:1998.

For data presentation and analysis purposes, results were summarized at three representative time intervals per day, selected to reflect typical occupancy and activity patterns; however, continuous monitoring ensured that short-term variations and daily IAQ dynamics were fully captured.

3.3.1. Outdoor Air Quality Analysis

The outdoor air was analyzed during the test period. Sources of pollutants included heating systems of other buildings around the study cases and traffic [21,22]. According to Spanish regulations, the National Air Quality Index (NAQI) allows users to check the air quality of measuring stations and understand potential health problems caused by different pollutants [23].

The pollutants considered in the index are particulate matter with a diameter less than or equal to 2.5 μm ($PM_{2.5}$), those with a diameter of 2.5 to 10 μm (PM_{10}), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2).

Figure 5 shows the variation of outdoor air quality in the town of Villalba during the different weeks of measurement; however, only a representative example of the observed behavior is presented.

Sources of indoor and outdoor pollutants can have different origins. For example, the main cause of high NO_2 concentrations is often road traffic. Indoor sources include tobacco smoke, cookers, furnaces and fireplaces burning gas, wood, oil and coal. Photochemical processes in the atmosphere produce ozone. For CO and SO_2, the main indoor sources maybe fossil fuel combustion and smoking, although both have outdoor origins, such as traffic and thermal power plants, and the behavior had the same trend over the weeks.

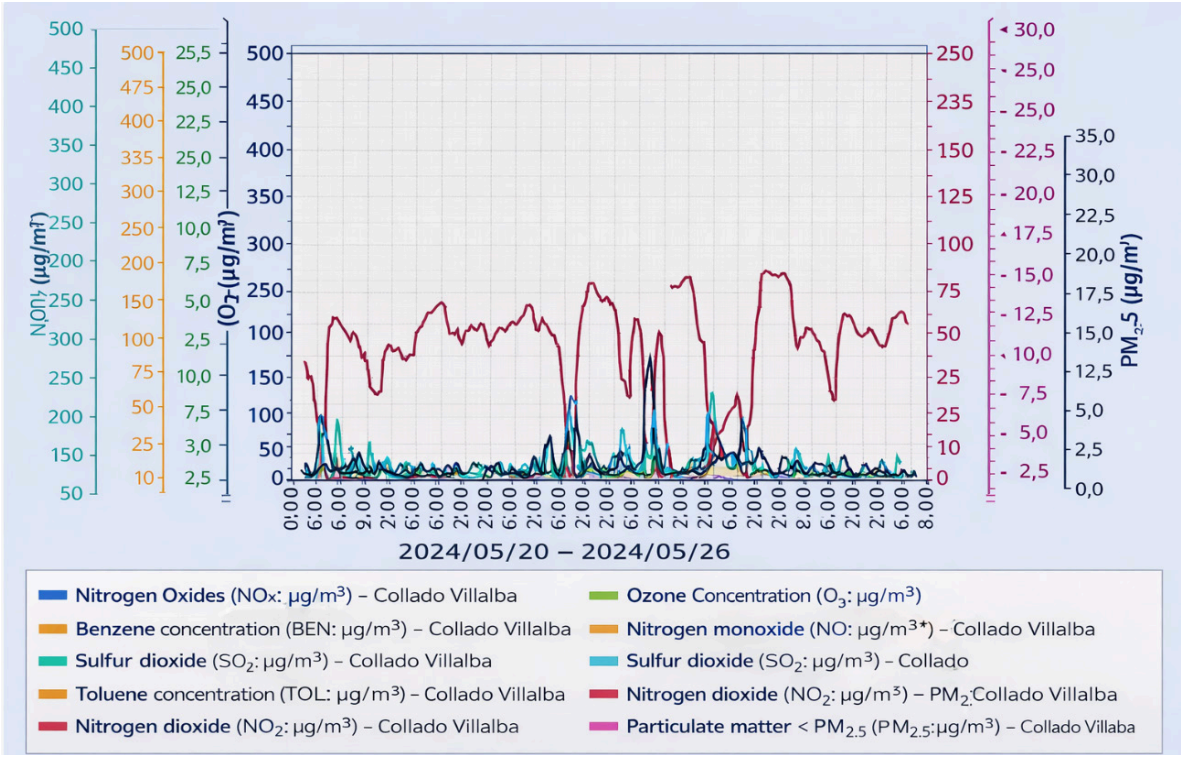

Figure 5. Particulate matter concentration graph for ozone, benzene, nitrogen monoxide, sulphur dioxide, toluene, nitrogen dioxide and particulate matter < $PM_{2.5}$, Week 1.

3.3.2. Indoor Air Quality Analysis

Everyday activities contribute to indoor air pollution. Cleaning activities can cause the emission of particles originally embedded in surfaces such as carpets and furniture, generating particles between 1 μm and 10 μm. In the

midday hours, the values of pollutants emitted in ovens and stoves are considered the most important source of indoor pollutants.

In the evening hours and at weekends, the presence of CO_2 is remarkable. Throughout the day, variations between the number of pollutants of 0.3 µm, 0.5 µm, 1 µm, 2.5 µm, 5 µm and 10 µm can be observed.

Considering that there are many measurements, we decided to highlight the most relevant ones to give the respective recommendations for the dwelling under study.

Therefore, in the said monitoring it can be seen that both bedroom 1 and the bedroom have an instant during the night when the threshold of 1000 ppm is reached: the living room is maintained at recommendable values due to the good ventilation habits in the dwelling of ventilating 3 h during the day; where it can be seen that the CO_2 content of the living room is similar to that of the outside air. Not so the amount of volatile organic compounds that depend on the material of the carpets, cleaning periods, cooking times, pets, tobacco fumes and air movement inside the room (**Figure 6**).

Volatile organic particulate matter values of 0.3–0.5 µm are high because they come from pet dander or furniture mites: although these values are not harmful to health below 250.000 particles/L. The same trend can be observed over the weeks. CO_2 values remain healthy in the living room reflecting good natural ventilation. House dust particles in the order of 1 µm remain at healthy values and 2.5 and 10 µm particles that can affect the eyes, nose and throat remain at healthy values (**Figure 7**).

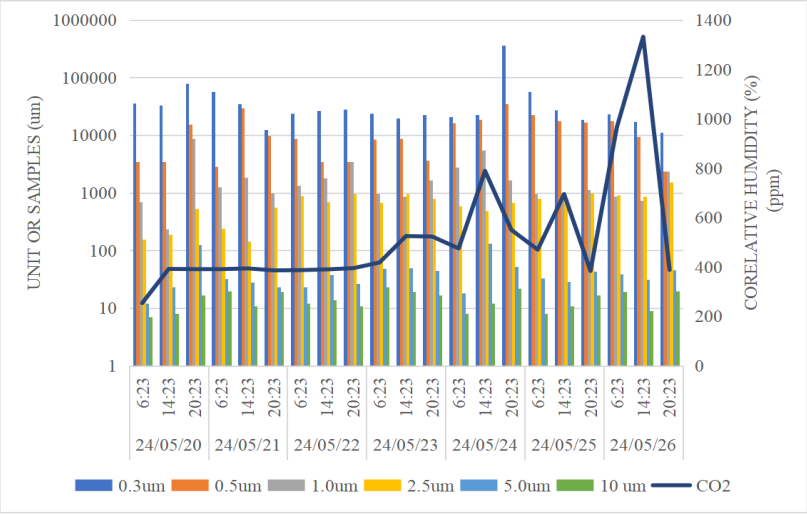

Figure 6. TVOC and CO_2 particles in room 1 as a function of time in week 1.

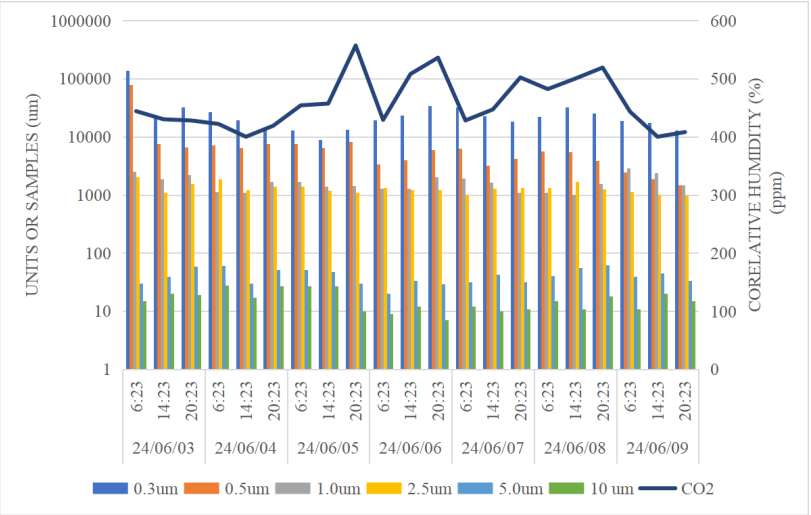

Figure 7. TVOC and CO_2 particles in the hall as a function of time in week 3.

Dwellings have different characteristics from non-residential buildings in terms of recommended ventilation rates. Occupancy is totally different from non-residential buildings, as it varies at different times of the day. Occupants sleep, clean, cook, shower or watch TV in the dwellings. In addition, the concept of adaptation is of great importance in a private space where people stay for a long time. Therefore, ventilation systems must consider the flexibility of the use of different rooms and the habits of their occupants; it is therefore important to monitor the habits of the occupants to understand the ventilation needs.

Sufficient outdoor airflow should be provided in the living spaces of dwellings to ensure that, in each location, the annual average CO_2 concentration is less than 1000 ppm. In addition, the outdoor air flow supplied must be sufficient to remove pollutants not directly related to human occupancy.

Figure 8 shows a similar CO_2 content value between the living room and outside, and room 1 and room 2 are higher than the outside air quality. A quasi-stability in CO_2 values is shown when there is no ventilation and no people in the rooms, indicating a low permeability in the dwelling.

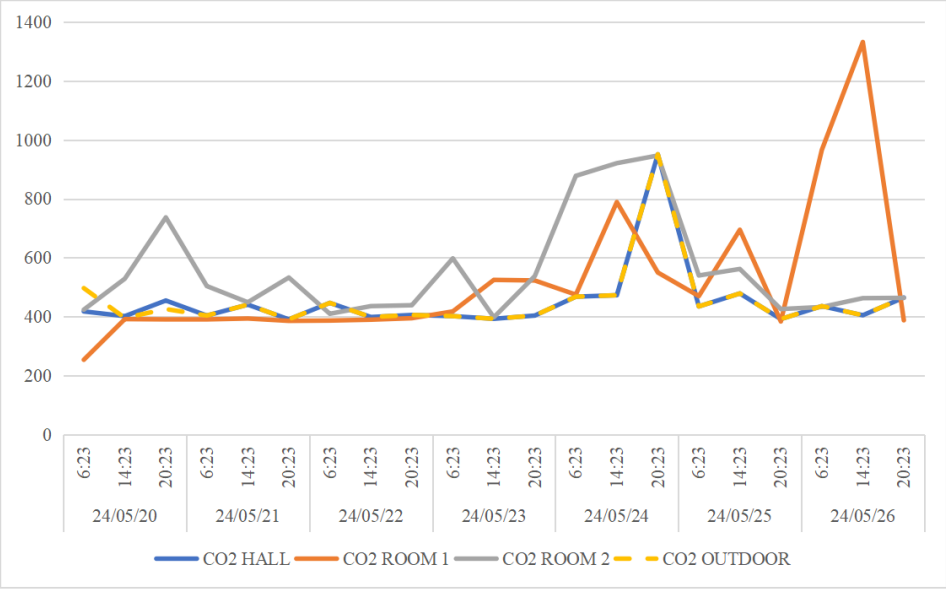

Figure 8. Particulate matter per million CO_2 in the hall, rooms 1 and 2 and outdoors as a function of TVOC particle measurement time in week 1.

Figure 8 shows the similarity between the amount of CO_2 from outside and the living room, and the difference between rooms 1 and 2 differs with the occupancy and the permeability of the window frames, when there is no occupancy. Room 2 shows higher humidity contents than room 1, and at the same time lower temperatures. Room 2, having a lower temperature, is expected to have a higher percentage of humidity; and it happens as expected. Room 1 is in warmer conditions. **Figure 9** presents the variation of particulate matter per million CO_2 measured in the hall, bedroom, and bedroom 2, as well as in the outdoor environment, as a function of TVOC particle measurement time during week 1. The results illustrate the temporal evolution of indoor and outdoor conditions, allowing comparison between rooms and assessment of differences in particulate behaviour relative to CO_2 concentration throughout the monitoring period.

As occupants sleep, clean, cook, shower or watch TV in dwellings, the concept of adaptability is of great importance in a private space where people stay for a long time.

Therefore, ventilation systems must consider the flexibility of use of the different rooms and the habits of their occupants. During night-time occupancy, CO_2 concentrations in both bedrooms frequently exceeded recommended limits, reaching values between 1200 and 1500 ppm, while the living room remained below 900 ppm due to regular daily ventilation practices of approximately 3 h. Outdoor CO_2 levels during the same period remained close to background concentrations (≈420–450 ppm).

During occupancy and cleaning activities, particle number concentrations in the size range 0.3–0.5 µm increased noticeably, reaching peak values of approximately 180,000–230,000 particles/L in the bedrooms. Larger particle fractions ($PM_{2.5}$ and PM_{10}) remained below health-relevant thresholds, with concentrations generally below 20 µg/m^3, consistent with WHO guideline values.

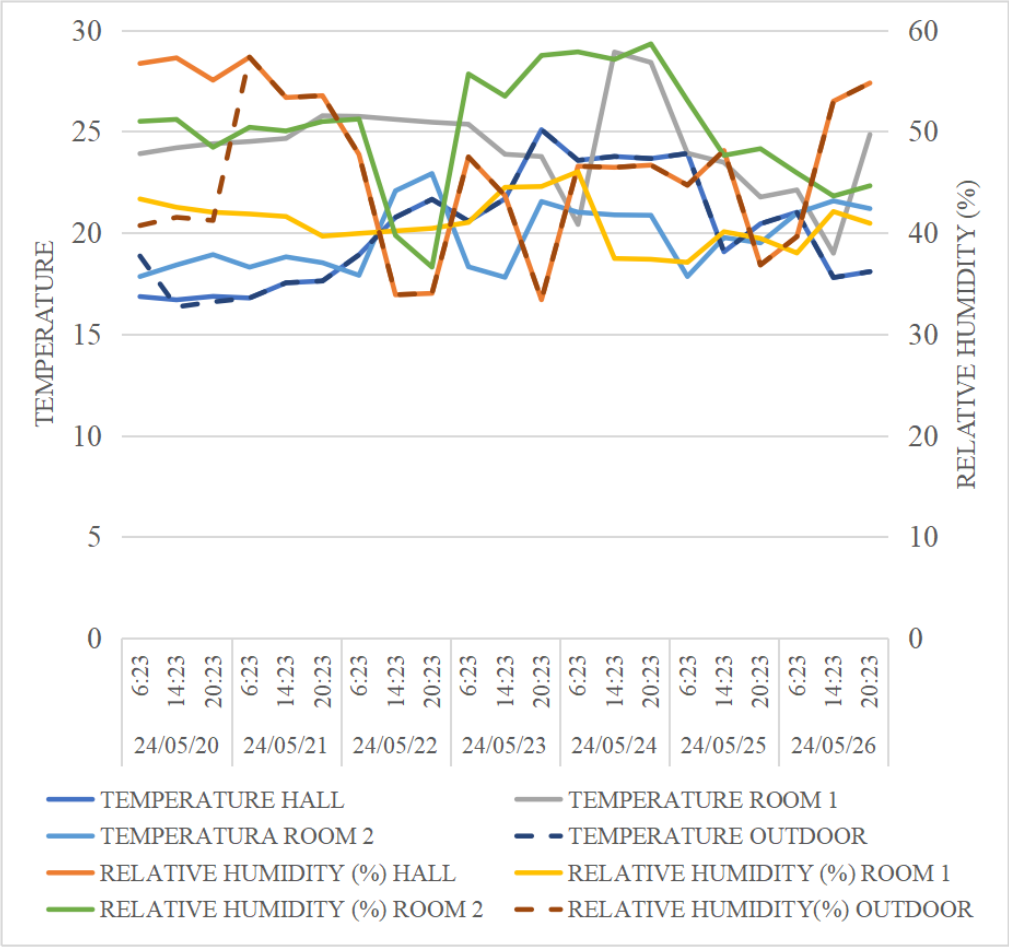

Figure 9. Temperature and relative humidity of the hall, rooms 1, 2 and outside with respect to the TVOC particle measurement time in week 1.

3.3.3. Blower Door Test

In all the tests, the atmospheric conditions were suitable for carrying out the pressurization and depressurization measurements, as the pressure difference between the inside and outside of the dwelling was below 3 Pa and the outdoor wind speed was lower than 3.6 m·s^{-1}, in accordance with ISO/DIS 9972.

The assessment of the building envelope permeability was conducted following Method B (building envelope test) described in UNE-EN 13829 [21], using the fan-assisted pressurization method (Blower Door Test). Measurements were performed under both pressurization and depressurization conditions within the intentionally conditioned internal volume of the dwelling. During the test, all intentional openings in the building envelope were sealed, while internal doors between rooms remained open to ensure uniform pressure distribution.

An automated measurement procedure was applied, collecting a total of twelve pressure–flow data points. The infiltration curve was obtained using the power-law relationship. Equation (1) is about infiltration curve.

$$V_{env} = C_{env} (\Delta p)^n \quad (1)$$

where V_{env} is the airflow rate through the building envelope [$m^3 \cdot h^{-1}$], C_{env} is the airflow coefficient [$m^3 \cdot (h \cdot Pa^n)^{-1}$], Δp is the induced pressure difference [Pa], and n is the airflow exponent (ranging between 0.5 and 1 depending on flow regime).

From this relationship, standard airtightness indicators were derived using a reference pressure difference of 50 Pa. These include the airflow rate at 50 Pa (V_{50}), the air change rate at 50 Pa ($n_{50} = V_{50} / V$, where V is the internal volume of the dwelling), and the air permeability at 50 Pa ($q_{50} = V_{50} / A_F$, where A_F is the envelope surface area).

The pressurization and depressurization tests yielded comparable results, confirming that external conditions did not significantly influence the measurements.

The Blower Door test results allowed the calculation of the equivalent infiltration area (ELA), which represents the combined area of all unintended air leakage paths in the building envelope. In this case, an ELA value of 124.6 cm2 was obtained. This corresponds approximately to a single opening of about 10 cm × 12 cm**,** providing a clear physical interpretation of the overall air leakage level of the dwelling.

This level of airtightness has direct implications for energy performance and indoor environmental quality. A larger equivalent infiltration area increases uncontrolled air exchange with the outdoors, leading to higher heating and cooling energy demand and potentially affecting thermal comfort through drafts and temperature instability. Consequently, the obtained ELA value provides a quantitative basis for evaluating both the energy efficiency and indoor comfort conditions of the studied dwelling.

4. Discussion

4.1. Energy Losses through the Envelope

The European Union aims to reduce greenhouse gas emissions through a decarbonized energy system by 2050. The building sector accounts for 36% of CO_2 emissions and 50% of final energy consumption, mainly for heating and cooling. Transforming buildings into nearly zero-energy structures is key to achieving this goal.

Uncontrolled infiltration through the building envelope generate higher energy consumption and affect the health of the occupants. Spanish regulations (Technical Building Code) do not establish minimum airtightness requirements for dwellings, which can lead to over-dimensioning of ventilation systems.

The estimated annual energy loss of 635.15 kWh/year was calculated based on the equivalent leakage area obtained from the Blower Door test (ELA = 124.6 cm^2) and assuming typical heating season conditions for the study area. The calculation considers uncontrolled air infiltration driven by pressure differences between indoor and outdoor environments, together with an average temperature difference representative of the local climate. This simplified approach provides an order-of-magnitude estimate of the thermal energy required to compensate for infiltration-related heat losses over one year.

The annual energy loss associated with air infiltration was calculated using the following expression. Equation (2) is about the annual energy loss associated with air infiltration.

$$Q_{inf} = \rho \, c_p \, \dot{V}_{inf} \, \Delta T \, t \tag{2}$$

where

ρ is the air density (1.2 $kg \cdot m^{-3}$),

c_p is the specific heat capacity of air (1005 $J \cdot kg^{-1} \cdot K^{-1}$),

$\dot{V}_{inf}$ is the infiltration airflow rate derived from the measured equivalent leakage area,

ΔT is the average indoor–outdoor temperature difference during the heating season (assumed as 10 K), and t is the annual number of heating hours (approximately 1800 h).

Based on an equivalent leakage area of 124.6 cm^2, the resulting annual energy loss due to infiltration was estimated at 635.15 kWh/year.

4.2. Indoor Air Quality

Concentrations of CO_2 and particulate matter of different sizes were monitored. The results indicate that CO_2 concentrations frequently exceeded 900 ppm during weekends and evening periods, coinciding with higher occupancy levels. Fine particle concentrations (0.3 μm and 0.5 μm) increased due to indoor sources such as pet dander, dust mites, and smoke, occasionally exceeding recommended comfort thresholds during periods of limited ventilation. In contrast, effective natural ventilation contributed to main-

taining coarse particle concentrations ($PM_{2.5}$ and PM_{10}) within acceptable guideline ranges. Overall, increasing natural ventilation proved to be an effective strategy for reducing indoor pollutant levels. However, these results also confirm that relying solely on CO_2 as an indicator of indoor air quality is insufficient, as it may mask the presence of other relevant pollutants. **Table 6** summarizes the main indoor air pollutants measured in the dwelling and compares the observed concentration levels with applicable reference standards and guideline values.

Table 6. Comparison of measured indoor air quality parameters with international standards.

Pollutant	Size/Indicator	Unit	Observed Levels	Reference Standard	Guideline/Limit Value
Carbon dioxide (CO_2)	Ventilation indicator	ppm	Peaks > 900	ASHRAE 62.1	≤1000 ppm
Particulate matter	0.3 µm	particles/L	Elevated during occupancy	—	No health-based limit
Particulate matter	0.5 µm	particles/L	Elevated during indoor activities	—	No health-based limit
Particulate matter	$PM_{2.5}$	µg/m^3	Generally within acceptable range	WHO (2021)	15 µg/m^3 (24 h mean)
Particulate matter	PM_{10}	µg/m^3	Low concentrations	WHO (2021)	45 µg/m^3 (24 h mean)
Total volatile organic compounds (TVOC)	—	µg/m^3	Variable depending on ventilation	German Environment Agency (UBA)	<300 µg/m^3 (guidance value)

4.3. Impact of Ventilation on Comfort and Consumption

The use of natural ventilation maintained good overall air quality, although chemical stress increased during weekends due to intensive disinfection activities. This resulted in high levels of COCTV during mealtimes and family activities.

Ventilation habits, together with the average airtightness of the dwelling, significantly influence indoor air quality and thermal comfort, affecting energy consumption.

5. Conclusions

5.1. Reducing Energy Consumption and Emissions

Improving the airtightness of the building envelopes in residential buildings is essential to minimize energy losses due to infiltration and to optimize the performance of ventilation systems. This measure directly contributes to the achievement of nearly zero-energy buildings (nZEBs) by significantly reducing energy consumption and greenhouse gas emissions. Additionally, enhancing airtightness aligns with broader sustainability goals, fostering energy-efficient building design and operation.

The presence of indoor pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and elevated levels of CO_2 highlights the critical role of effective ventilation systems. These systems are not only necessary for maintaining acceptable indoor air quality but also for ensuring occupants' health and well-being. Furthermore, promoting healthy natural ventilation habits can complement mechanical systems, reduce pollutant buildup and foster a healthier indoor environment.

5.2. Airtightness and Regulations

Currently, the absence of minimum airtightness requirements in Spanish regulations may be limiting the efficient design and operation of ventilation systems. This regulatory gap can lead to increased energy consumption, reduced thermal comfort, and higher operational costs. Establishing airtightness standards would encourage the design of buildings that maximize energy efficiency while supporting optimal ventilation system performance. Such measures would bring Spanish regulations in line with those of other countries with more advanced energy and environmental policies.

The monitoring results demonstrated a strong dependence on natural ventilation to maintain acceptable indoor air quality, with indoor pollutant concentrations—particularly CO_2 and fine particulate matter—varying significantly according to occupancy patterns and window-opening behaviour. Similar findings have been widely reported in residential buildings across southern Europe, where insufficient envelope airtightness limits the effective control of ventilation rates and indoor pollutant removal [23,24].

In this context, the absence of minimum airtightness requirements in current Spanish building regulations may

constrain the efficient design and operation of ventilation systems. Scientific evidence indicates that inadequate airtightness leads to uncontrolled air infiltration, reducing ventilation efficiency while increasing energy demand for heating and [25]. This phenomenon contributes to higher operational costs, reduced thermal comfort, and inconsistent indoor air quality performance, particularly in dwellings that rely primarily on natural ventilation strategies [26].

Establishing mandatory airtightness standards would facilitate better airflow management, allowing ventilation systems—both natural and mechanical—to operate as designed. Studies conducted in European residential buildings demonstrate that improved airtightness, when combined with appropriate ventilation strategies, enhances energy efficiency while maintaining healthy indoor environmental conditions [27,28]. Implementing such requirements would therefore support the reduction of pollutant exposure observed in this study and align Spanish regulations with those of countries that have adopted more advanced energy efficiency and indoor air quality policies.

5.3. Ventilation Efficiency

The findings demonstrate that combining an airtight building envelope with a well-designed and controlled ventilation system can significantly enhance both thermal comfort and indoor air quality. This integrated approach minimizes heat loss, ensures consistent airflow, and prevents issues such as excessive humidity or pollutant accumulation. Properly calibrated ventilation systems can thus provide a balanced indoor environment that supports energy efficiency and occupant comfort simultaneously [29].

A comprehensive assessment of indoor air quality requires consideration of multiple indicators beyond CO_2 concentrations. As Pinilla-Hernandez et al. point out, the joint analysis of parameters such as concentrations of suspended particles, volatile organic compounds, relative humidity, and temperature allows for a more accurate characterization of indoor environmental conditions and potential health risks. This multidimensional approach facilitates the detection of pollutants that might go unnoticed in limited assessments and contributes to the identification of specific strategies for improving the indoor environment [30].

5.4. Future Considerations

To provide a more comprehensive assessment of indoor air quality, it is necessary to incorporate multiple indicators beyond CO_2 levels. Monitoring additional parameters, such as PM concentrations, VOC levels, humidity, and temperature, can offer a clearer picture of indoor environmental conditions. This holistic approach minimizes the risk of exposure to undetected pollutants and enables the identification of specific areas for improvement.

Future research should therefore include the simultaneous monitoring of additional parameters such as particulate matter concentrations ($PM_{2.5}$ and PM_{10}), volatile organic compound (VOC) levels, relative humidity, and indoor temperature. This multi-parameter approach would enable a more accurate characterization of pollutant dynamics, reduce the risk of exposure to undetected contaminants, and support the identification of targeted mitigation strategies.

Another relevant research gap in Spain concerns the limited availability of long-term field studies evaluating the interaction between building envelope airtightness, ventilation strategies, occupant behaviour, and indoor air quality performance under Mediterranean climatic conditions. The absence of minimum airtightness requirements in current Spanish regulations may hinder the efficient design and operation of ventilation systems, leading to uncontrolled air infiltration, increased energy consumption, reduced thermal comfort, and higher operational costs. Future studies should therefore focus on quantifying the combined impact of airtightness and ventilation control on both energy efficiency and indoor environmental quality.

Furthermore, the integration of advanced monitoring technologies and real-time data analysis could enhance the management of indoor air quality in residential buildings.

The results of the research can be summarized in the following set of recommendations.

1. To reduce energy consumption and emissions: the airtightness of building envelopes must be improved to limit uncontrolled infiltration and enhance energy performance.
2. To improve indoor air quality: effective ventilation systems must be in place, healthy natural ventilation habits must be promoted, the accumulation of pollutants must be reduced, a healthier indoor environment

must be encouraged, and adequate air renewal rates should be ensured.

3. The establishment of airtightness standards in Spanish regulations would encourage the design of buildings that maximize energy efficiency and promote the optimal performance of both natural and mechanical ventilation systems.
4. The results show that combining an airtight building envelope with a well-designed and controlled ventilation system can significantly improve both thermal comfort and indoor air quality.
5. Monitoring additional parameters, such as $PM_{2.5}$ concentrations, VOC levels, humidity and temperature, can provide a clearer picture of environmental conditions.

Author Contributions

Conceptualization, M.I.P.-H., S.M.-T. and 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. and 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.

Funding

This work was supported by CEU San Pablo University Foundation through funds dedicated to the ARIE Research Group under the Project “IEQ to guarantee the health and well-being of vulnerable people in multi-family homes” of the Call for “Knowledge Generation Projects” within the framework of the State Plan 2021–2023. The project reference was PID2023-151422OB-I00 and was funded by the Ministry of Science, Innovation and Universities of Spain and the European Regional Development Fund (ERDF) of the European Union.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

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

Acknowledgments

The authors wish to thank CEU San Pablo University Foundation for the funds dedicated to the ARIE Research Group, through the Project Ref. G20/6-06- MGI24RGL provided by the CEU San Pablo University.

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.

References

[1] The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2017. ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy. ASHRAE: Peachtree Corners, GA, USA.

[2] World Health Organization (WHO), 2000. Air Quality Guidelines for Europe, 2nd ed. WHO: Geneva, Switzerland.

[3] Mendell, M.J., Chen, W., Ranasinghe, D.R., et al., 2024. Carbon dioxide guidelines for indoor air quality: A review. Journal of Exposure Science & Environmental Epidemiology. 34(4), 555–569. DOI: https://doi.org/10.1038/s41370-024-00694-7

[4] Sherman, M.H., Walker, I.S., Logue, J.M., 2012. Equivalence in ventilation and indoor air quality.

HVAC&R Research. 18(4), 760–773. DOI: https://doi.org/10.1080/10789669.2012.667038

[5] Rodríguez-Soria, B., Domínguez-Hernández, J., Pérez-Bella, J.M., et al., 2014. Review of international regulations governing the thermal insulation requirements of residential buildings and the harmonization of envelope energy loss. Renewable and Sustainable Energy Reviews. 34, 78–90. DOI: https://doi.org/10.1016/j.rser.2014.03.009

[6] Borrallo-Jiménez, M., LopezDeAsiain, M., Esquivias, P.M., et al., 2022. Comparative study between the Passive House Standard in warm climates and Nearly Zero Energy Buildings under Spanish Technical Building Code in a dwelling design in Seville, Spain. Energy and Buildings. 254, 111570. DOI: https://doi.org/10.1016/j.enbuild.2021.111570

[7] Rey-Álvarez, B., Sánchez-Montañés, B., Silvestre, E., 2026. Harmonizing indoor air quality standards across Europe: A comparative analysis framework for building material regulations and public health protection. Building and Environment. 288, 113967. DOI: https://doi.org/10.1016/j.buildenv.2025.113967

[8] Kan, H., 2022. World Health Organization air quality guidelines 2021: Implication for air pollution control and climate goal in China. Chinese Medical Journal. 135(5), 513–515. DOI: https://doi.org/10.1097/CM9.0000000000002014

[9] U.S. Environmental Protection Agency, 1991. Building Air Quality Guide: A Guide for Building Owners and Facility Managers (No. 91-114). U.S. Environmental Protection Agency: Washington, DC, USA. Available from: https://www.epa.gov/indoor-air-quality-iaq/building-air-quality-guide-guide-building-owners-and-facility-managers

[10] López, A., Fuentes-Ferragud, E., Mora, M.J., et al., 2024. Air quality of health facilities in Spain. Chemosphere. 362, 142615. DOI: https://doi.org/10.1016/j.chemosphere.2024.142615

[11] Linares, P., García-Ortega, S., Larrumbide, E., 2018. The influence on surface condensation risk of lower ventilation rates: The case of the proposal of indoor air quality requirement for the Spanish regulations. International Journal of Ventilation. 17(4), 272–286. DOI: https://doi.org/10.1080/14733315.2018.1431358

[12] López Plazas, F., Sáenz de Tejada, C., 2024. Natural ventilation to improve indoor air quality (IAQ) in existing homes: The development of health-based and context-specific user guidelines. Energy and Buildings. 314, 114248. DOI: https://doi.org/10.1016/j.enbuild.2024.114248

[13] World Health Organization (WHO), 2021. Roadmap to Improve and Ensure Good Indoor Ventilation in the Context of COVID-19. WHO: Geneva, Switzerland. Available from: https://www.who.int/publications/i/item/9789240021280

[14] González-Sancha, R., Marín-García, D., Duarte-Pinheiro, M., et al., 2022. Legal regulation of ventilation rates in homes in Europe 2010–2022: Evolution and comparison study regarding Covid-19 recommendations. Building and Environment. 226, 109696. DOI: https://doi.org/10.1016/j.buildenv.2022.109696

[15] European Union (EU), 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Renovation Wave for Europe—Greening Our Buildings, Creating Jobs, Improving Lives. EU: Brussels, Belgium. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0662

[16] Levy, J.I., Kibilko, K., 2025. Indoor Air Quality in Multi-Family Housing: Drivers and Interventions. Current Environmental Health Reports. 12(1), 4. DOI: https://doi.org/10.1007/s40572-024-00470-7

[17] Obeidat, L.M., Jones, J.R., Mahaftha, D.M., et al., 2024. Optimizing indoor air quality and energy efficiency in multifamily residences: Advanced passive pipe system parametrics study. International Journal of Environmental Science and Technology. 21(16), 10003–10026. DOI: https://doi.org/10.1007/s13762-024-05624-6

[18] Hormigos-Jimenez, S., Padilla-Marcos, M.Á., Meiss, A., et al., 2019. Assessment of the ventilation efficiency in the breathing zone during sleep through computational fluid dynamics techniques. Journal of Building Physics. 42(4), 458–483. DOI: https://doi.org/10.1177/1744259118771314

[19] Wang, M., Li, L., Hou, C., et al., 2022. Building and Health: Mapping the Knowledge Development of Sick Building Syndrome. Buildings. 12(3), 287. DOI: https://doi.org/10.3390/buildings12030287

[20] Chamseddine, A., Elzein, I.M., Hassan, N., 2025. Indoor Air Quality in Critical Indoor Environments: A Review Paper. Water, Air, & Soil Pollution. 236(13), 885. DOI: https://doi.org/10.1007/s11270-025-08512-y

[21] Islam, B., Masum, M.H., Hoque, A., 2024. Classroom indoor air quality and noise level assessment of different educational institutions in a university area in Bangladesh. Journal of Air Pollution and Health. 9(3). DOI: https://doi.org/10.18502/japh.v9i3.16677

[22] del Ama Gonzalo, F., Sanglier Contreras, G., López Fernández, E.J., et al., 2024. Indoor Air Quality Mon-

itoring in Dwellings: Case Studies in Madrid, Spain. Journal of Green Building. 19(3), 117–138. DOI: https://doi.org/10.3992/jgb.19.3.117

[23] Ai, Z.T., Mak, C.M., 2015. From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement. Building and Environment. 94, 489–503. DOI: https://doi.org/10.1016/j.buildenv.2015.10.008

[24] Mercader-Moyano, P. (Ed.), 2015. The Sustainable Renovation of Buildings and Neighbourhoods. Bentham Science Publishers: Singapore. DOI: https://doi.org/10.2174/97816810806421150101

[25] Domínguez-Amarillo, S., Fernández-Agüera, J., Sendra, J.J., et al., 2018. Rethinking User Behaviour Comfort Patterns in the South of Spain—What Users Really Do. Sustainability. 10(12), 4448. DOI: https://doi.org/10.3390/su10124448

[26] Mayer, E., 1987. Physical Causes for Draft: Some New Findings. ASHRAE Transactions. 93(1), 540–548.

[27] World Health Organization (WHO), 2010. WHO Guidelines for Indoor Air Quality: Selected Pollutants. WHO: Geneva, Switzerland. Available from: https://www.who.int/publications/i/item/9789289002134

[28] International Organization for Standardization (ISO), 2011. Part 6: Determination of Volatile Organic Compounds in Indoor and Test Chamber Air by Active Sampling on Tenax TA Sorbent, Thermal Desorption and Gas Chromatography Using MS or MS-FID. ISO: Geneva, Switzerland.

[29] U.S. Environmental Protection Agency, 2017. Compendium of Methods for the Determination of Airborne Particles. EPA Office of Air Quality Planning and Standards: Washington, DC, USA.

[30] Pinilla-Hernandez, M.I., Melero-Tur, S., Parada, T.A., et al., 2025. Evaluation of the Concentration of Radon in a Single-family House in a Province Northwest of Madrid. Research in Ecology. 7(4). DOI: https://doi.org/10.30564/re.v7i4.10549