

AIR TIGHTNESS OF PRECARIOUS HOUSING IN INFORMAL SETTLEMENTS IN LIMA, PERU

HERMETICIDAD AL AIRE DE VIVIENDAS PRECARIAS EN BARRIOS INFORMALES DE LIMA, PERÚ

HERMETICIDADE AO AR DE HABITAÇÕES PRECÁRIAS EM ASSENTAMENTOS INFORMAIS DE LIMA, PERU

Martín Wieser

Doctor en Arquitectura
 Docente investigador, Departamento de Arquitectura
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0000-0002-4556-3507>
mwieser@pucp.edu.pe

Ronald Mas

Doctor en Ingeniería
 Docente investigador, Departamento de Ingeniería
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0000-0003-1507-462X>
rmass@pucp.edu.pe

Enrique Barrantes

Magíster en Ingeniería
 Docente investigador, Departamento de Ingeniería
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0000-0002-9037-3358>
ebarran@pucp.edu.pe

Enrique Mejía-Solis

Magíster en Ingeniería
 Docente investigador, Departamento de Ingeniería
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0000-0002-5512-1286>
enrique.mejia@pucp.edu.pe

Alessandra Gonzales

Bachiller en Arquitectura
 Asistente de investigación, Facultad de Arquitectura y Urbanismo
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0009-0004-5184-1907>
a20201689@pucp.edu.pe

Jimena Valdivia

Bachiller en Arquitectura
 Asistente de investigación, Facultad de Arquitectura y Urbanismo
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0009-0007-5170-5245>
a20200320@pucp.edu.pe

Luis-Ricardo Chirinos-García

Doctor en Ciencias Ambientales
 Docente investigador, Departamento de Ingeniería
 Pontificia Universidad Católica del Perú
 Lima, Perú
<https://orcid.org/0000-0002-5620-3312>
lchirin@pucp.edu.pe

ABSTRACT

The level of air tightness in a dwelling directly affects its thermal, acoustic, and health-related conditions. Due to the lack of studies providing such data at a local level, this research aimed to determine both the values and the contributing factors that condition the level of air tightness in precarious housing built in informal settlements in Lima. Using the blower door method, measurements were conducted in five dwellings, revealing air change rates between 40 and 280 ACH (Air Changes per Hour) at a differential pressure of 50 pascals, which are remarkably high and indicate poor airtightness. These findings constitute the first empirical approach to airtightness in precarious housing, providing preliminary data useful for analyzing thermal comfort in contexts of high urban vulnerability.

Keywords

sloping construction, sustainable development, thermodynamics

RESUMEN

El nivel de hermeticidad al aire de una vivienda influye directamente en las condiciones térmicas, acústicas y de salubridad que se presentan en su interior. Ante la ausencia de estudios que abordan el tema en el ámbito local, la presente investigación tuvo como objetivo identificar el valor y los factores que condicionan el nivel de hermeticidad de viviendas precarias construidas en barrios informales de la ciudad de Lima. Mediante el método de 'puerta sopladora', se realizaron mediciones en cinco viviendas que evidenciaron tasas de renovación de aire de entre 280 y 40 ACH (renovaciones de aire por hora) a una presión diferencial de 50 pascales, valores considerablemente altos que reflejan la baja hermeticidad de estas viviendas. Estos hallazgos constituyen una primera aproximación empírica a la hermeticidad al aire en viviendas precarias, al aportar datos preliminares útiles para el análisis del confort térmico en contextos de alta vulnerabilidad urbana.

Palabras clave

construcción en pendiente, desarrollo sustentable, termodinámica

RESUMO

O nível de hermeticidade ao ar de uma habitação influencia diretamente as condições térmicas, acústicas e de salubridade que se apresentam em seu interior. Diante da ausência de estudos que abordem o tema no âmbito local, a presente pesquisa teve como objetivo identificar o valor e os fatores que condicionam o nível de hermeticidade de habitações precárias construídas em assentamentos informais da cidade de Lima. Por meio do método da "porta ventiladora" (blower door), realizaram-se medições em cinco habitações, que evidenciaram taxas de renovação de ar entre 280 e 40 ACH (renovações de ar por hora) a uma pressão diferencial de 50 pascals — valores consideravelmente elevados, que refletem a baixa hermeticidade dessas edificações. Estes resultados constituem uma primeira abordagem empírica sobre a hermeticidade ao ar em habitações precárias, ao fornecerem dados preliminares úteis para a análise do conforto térmico em contextos de alta vulnerabilidade urbana.

Palavras-chave

construção em encosta, desenvolvimento sustentável, termodinâmica

INTRODUCTION

Airtightness is a key property of the energy and environmental performance of buildings, directly related to uncontrolled air leakage between the outdoor and indoor environments. This characteristic significantly affects energy consumption, thermal comfort, and indoor air quality. High airtightness helps minimize unwanted air flows, reducing energy losses associated with heating or cooling (Ambrosio Alfano et al., 2012). Similarly, the airflow and temperature differences caused by these leaks can lead to local thermal discomfort for occupants (Kalamees, 2007). On the other hand, the entry of outdoor air from these leakages can negatively affect indoor air quality, as it is not subject to the filtering and control processes typical of mechanical ventilation systems (Buonanno, Morawska & Stabile, 2009).

STUDIES ON THE AIR TIGHTNESS OF BUILDINGS

The first studies on airtightness in buildings highlighted the importance of controlling leakage as part of efficient building design. Hutcheon (1953) was one of the pioneers in highlighting the need to limit the flow of unwanted air through the envelope. Since the energy crisis of the 1970s, airtightness has acquired a more prominent role, particularly due to its potential to reduce winter heat losses and, therefore, the energy consumption associated with heating (Etheridge, 2015).

In 1998, the first airtightness limit values were established in Germany through the DIN V 4108-7 standard, which set a maximum of 3.5 air changes per hour (ACH) for buildings with natural ventilation and 1.5 ACH for those with mechanical ventilation (Guyot, Schild & Carrié, 2010). At the same time, in the United States, ASHRAE regulations included procedures for evaluating airtightness using the 'blower door' pressurization test. This regulation also classified the levels of airtightness in homes: 2 ACH was considered an excellent value, 5 ACH represented an average level, 10 ACH a common value, and above 20 ACH was classified as a house with low airtightness; all evaluated under a standard differential pressure of 50 Pa (Persily, 1998).

In recent decades, in industrialized countries, airtightness control has become increasingly important, driven mainly by the need to reduce energy consumption for both economic and environmental reasons (Zheng et al., 2019). In the particular case of residential buildings, typical airtightness values, measured under a differential pressure of 50 Pa, currently range between 1 and 3 ACH, depending on the type of ventilation, natural or mechanical (Poza-Casado et al., 2020). In this context, some high-energy-performance certifications, such as Passivhaus

in Germany and Minergie in Switzerland, establish even stricter criteria requiring airtightness values below 0.6 ACH.

In contrast, in the Global South, the approach to airtightness has been more closely tied to the need to build habitable shelters and reduce health risks (Kulshreshtha, Khare & Seetharaman, 2008; Lambert et al., 2023). Inadequate ventilation can lead to high concentrations of particulate matter, polluting gases such as CO, SO₂, and NO₂, and toxic compounds emitted by stoves and cooking systems, increasing the incidence of respiratory diseases (Kulshreshtha et al., 2008). In addition, poor ventilation control can foster mold growth, a problem especially prevalent in low-income housing (Choi et al., 2020). In general, ventilation conditions are not a priority in the design of informal housing, exposing occupants to health risks from both insufficient and excessive uncontrolled ventilation.

Despite differences in regional priorities, experimental studies on airtightness using the 'blower door' pressurization method have also been conducted in the Global South. 189 homes were evaluated in different climatic zones of Chile, obtaining an average airtightness of 12.9 ACH at 50 Pa (Bobadilla et al., 2014). In this study, light wooden buildings were the least airtight (24.6 ACH), whereas massive concrete buildings were the most airtight (9 ACH). Based on these results, Chile updated its "Thermal Regulation" in November 2025, establishing airtightness limits ranging from 4 to 8 ACH at 50 Pa, depending on the bioclimatic zone. On the other hand, in Uruguay, heavy traditional masonry buildings (fired ceramics) were analyzed, reporting ACH values of 3.5 and 5.2 at 50 Pa for two houses (Rodríguez Muñoz et al., 2020). These results are comparable with European studies carried out in various typologies and materials: in Estonia, an average of 4.9 ACH was reported in detached single-family houses of light construction with wooden frames (Kalamees, 2007); in Lithuania, an average of 4.73 ACH in single-family houses built with bricks or masonry blocks (Sfakianaki et al., 2008); and in Greece, a value of 7.0 ACH in stone, concrete and brick single-family dwellings (Šadauskienė et al., 2016). Finally, in multifamily masonry typologies, averages of 7.26 ACH have been recorded in apartments in Spain (Feijó-Muñoz et al., 2018), and 6.25 ACH in a concrete-and-brick apartment in Montenegro (Tombarević, Vušanović & Šekularac, 2023).

In this study, airtightness measurements were conducted using the pressurization method with a blower door in informal housing built with limited resources in a peri-urban area of Lima, Peru. According to our review of the literature, no previous studies have applied this technique in homes with similar characteristics. This work seeks to address this space by

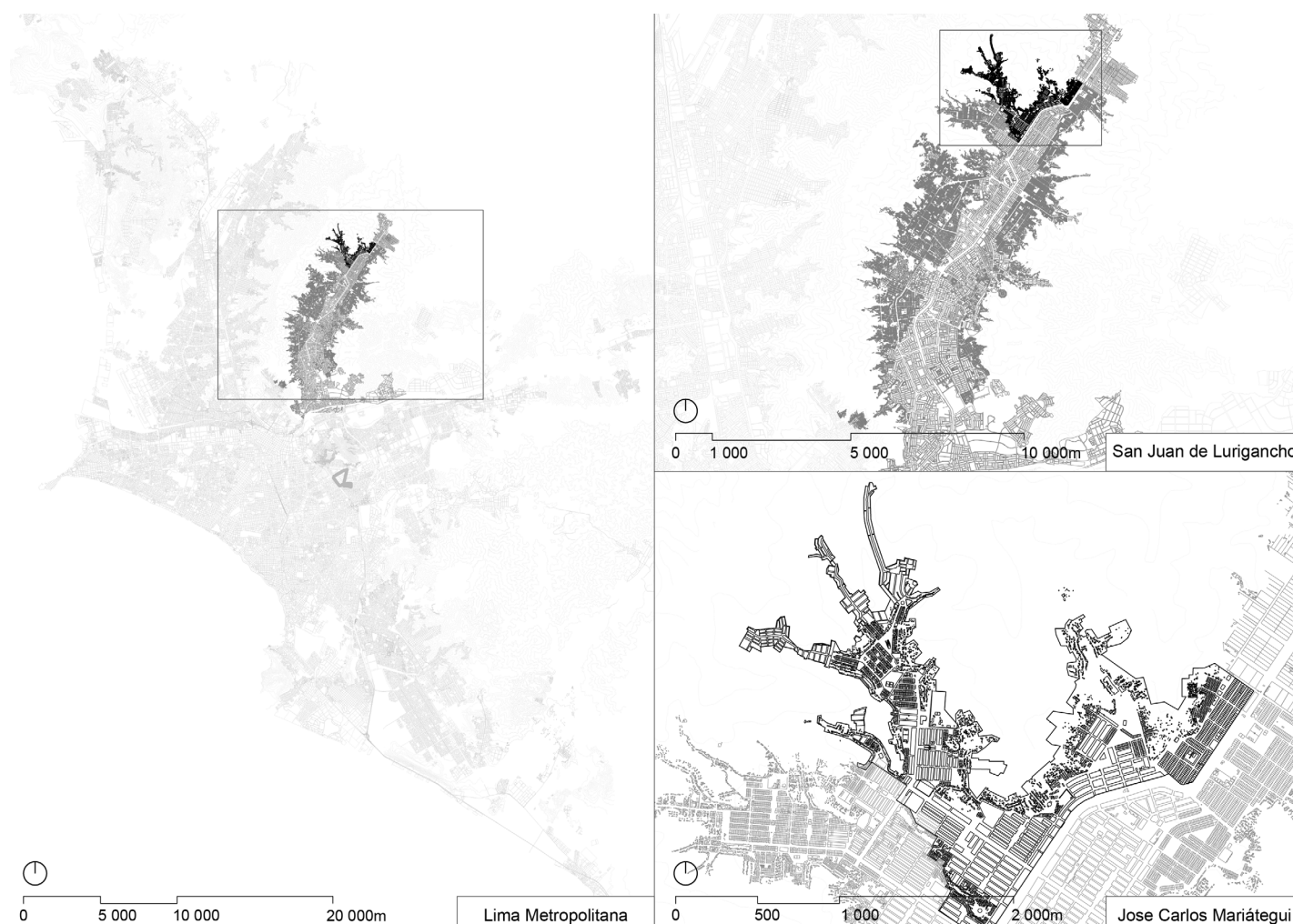


Figure 1. Location of the José Carlos Mariátegui neighborhood in the San Juan de Lurigancho district of Lima. Source: Prepared by the Authors.

exploring airtightness in unconventional buildings. The importance of generating this evidence lies in the fact that, by providing initial empirical data on infiltrations in precarious contexts, starting points for the study of thermal comfort and habitability (Oraiopoulos et al., 2023) can be established. Consequently, these findings could offer a first empirical approach to feed the debate on informal housing retrofitting strategies and the relevance of applying international standards in highly vulnerable contexts.

CASE STUDY

THE NEIGHBORHOOD OF JOSÉ CARLOS MARIÁTEGUI

The neighborhood of José Carlos Mariátegui, located in the district of San Juan de Lurigancho, Lima, originated as an informal settlement in the mid-1980s on flat, arid land lacking basic infrastructure. Located between the Andean foothills, approximately

15 kilometers from the center of Lima and at an altitude of 400 masl (Figure 1), this neighborhood has experienced progressive, unplanned growth, based mainly on self-construction. Over time, new settlements have occupied increasingly elevated areas on the slopes surrounding the original esplanade.

This growth pattern reflects a common dynamic in the urban peripheries of many Latin American cities, where informal urban expansion has been the primary driver of housing stock growth. In the specific case of Lima, it is estimated that about 2 million people live in homes with roofs built from light, precarious materials such as wood, calamine, or similar materials, representing approximately 20% of the population (National Institute of Statistics and Informatics [INEI], 2018). These precarious conditions tend to persist for an average of 10 to 15 years before housing reaches some level of consolidation in both construction and the provision of basic services (Lambert et al., 2023).



Figure 2. Overview of the José Carlos Mariátegui neighborhood. Source: Prepared by the Authors.



Figure 3. Location of the houses tested on a satellite image. Source: Prepared by the Authors using an image from Google Earth.

Equipment	Brand	Model
Blower door equipment, pressure gauge (integrated), and airflow meter (orifice plate).	The Energy Conservatory	Minneapolis Blower Door with differential-pressure sensor, DG-700. Software TECLOG 4 version 4.2.0.37
Signal recorder	Yokogawa	MW100
Differential pressure sensors	Yokogawa	EJX110A
Temperature and relative humidity recorders	Onset	Hobo data logger U12-006
Micro weather station	Onset	Hobo data logger Microstation H21-002

Table 1. Instruments used to measure leakage levels. Source: Prepared by the Authors.

The lower degree of consolidation of both housing and infrastructure in the higher areas of informal neighborhoods is readily identifiable. It is usually associated with an increased risk of landslides and difficulties in accessing and providing basic services. The initial precariousness of the buildings is manifested in the use of light materials, such as board or *triplay* walls and corrugated metal plate roofs (Figure 2). These constructive conditions, combined with the desert, coastal, and temperate climates of Lima, generate extremely uncomfortable indoor environments, characterized by overheating in summer and very low temperatures in winter (Wieser, Verdiere & Fennell, 2022). Mild and moderate breezes are constant throughout the year (usually between 1 and 2 m/s). However, they do not mitigate the effects of intense summer solar radiation (5.7 kWh/m² per day on average), high relative humidity (60% in summer and 80% in winter on average), or frequent winter fog (Oraiopoulos et al., 2025).

METHODOLOGY

Airtightness tests were carried out in five dwellings (Figure 3) using the blower door method in accordance with the ASTM E779-19 standard, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (Advanced Standards Transforming Markets [ASTM], 2019). This procedure, widely applied in conventional buildings (Hsu et al., 2021), quantifies air leakage through the building envelope by creating a controlled pressure difference with a fan to pressurize and depressurize the indoor space. The instrumentation used in the tests is detailed in Table 1. Although the number of homes evaluated is small, this limitation is inherent to the exploratory nature of the study and the difficult conditions of the context: accessibility,

safety, and availability of families. The study is conceived as an exploratory approach that provides initial empirical background on airtightness in this type of building, a gap in the literature to date. The values obtained are not intended to be statistically representative of the universe of informal housing in Lima, but to provide initial empirical data that guide future research and serve as input for energy modeling and the formulation of public policies, in line with similar studies in hard-to-access contexts (Rodríguez Muñoz et al., 2020; Oraiopoulos et al., 2023).

The envelope of the studied dwellings consisted of corrugated metal plate roofs (zinc calamine) and walls built of wood, drywall, Oriented Strand Board (OSB), or brick (Figure 4). For house selection, convenience sampling was used, subject to families' willingness and geographical proximity. The aim was to document the actual condition of the houses in the neighborhood, where imperfections and deterioration in the structures are a common result of self-construction and economic constraints. However, four of the five homes were located on hillsides, approximately 300 meters from the vehicle access point, and at a height difference of nearly 90 meters, which posed an additional challenge for transporting the equipment needed for the tests. For the equipment to work properly, an additional electric generator capable of providing a starting current of 8-10 amps was needed, since the local network in the upper parts of José Carlos Mariátegui is unstable and supplies only 4-5 amps.

Prior to the tests, a thorough inspection was carried out in each dwelling, making sure that doors and windows remained completely closed and that there were no additional openings that could affect the accuracy of the measurements. The blower door equipment was then installed, preliminary tests were carried out, and a pressure of 10 Pa was applied, increasing it in 5 Pa increments until reaching 50 Pa.

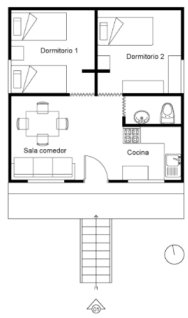
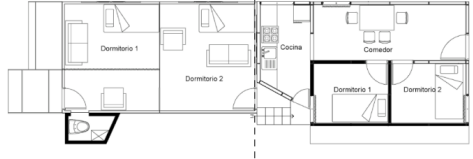
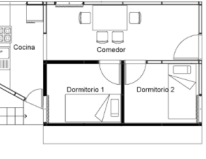
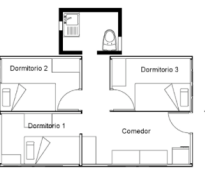
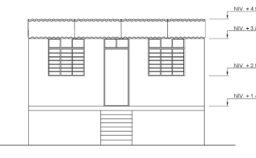
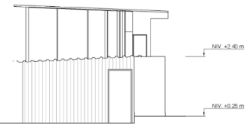
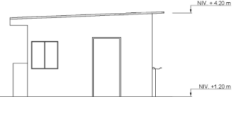
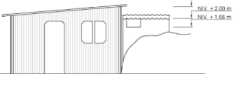
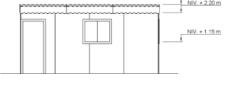
	V01	V02	V03	V04	V05
PLANTA					
ELEVACIÓN					
CARACTERÍSTICAS	Área techada: 40.19 m ² Volumen de aire: 111.54 m ³ Materialidad: Techo: Calamina Piso: Cemento Muros: Albañilería	Área techada: 29.52 m ² Volumen de aire: 67.75 m ³ Materialidad: Techo: Calamina Piso: Cemento Muros: Listones de madera	Área techada: 31.85 m ² Volumen de aire: 90.78 m ³ Materialidad: Techo: Calamina Piso: Cemento Muros: Drywall	Área techada: 30.80 m ² Volumen de aire: 68.88 m ³ Materialidad: Techo: Calamina Piso: Cemento Muros: Listones de madera	Área techada: 30.00 m ² Volumen de aire: 69.00 m ³ Materialidad: Techo: Calamina Piso: Cemento Muros: OSB
FOTOGRAFÍA					

Figure 4. Tested housing. Floor plans and features. Source: Prepared by the authors.

It should be noted that in dwellings with high leakage due to poor construction, achieving the required pressure differences was challenging. To ensure the reliability of the data obtained, the readings from the pressure gauge integrated into the blower door equipment were compared with measurements from four additional calibrated pressure gauges.

During the tests conducted in each house, the blower door system fan generated a pressure difference ΔP throughout the building envelope. To characterize this condition, differential pressure measurements were recorded at three strategic points inside the house. Simultaneously, the equipment measured the airflow rate (Q) required to maintain the pressure difference. From these data, the air leakage coefficient (C) and the pressure exponent (n) were determined by fitting the obtained values to the airflow model equation as a function of pressure (Equation 1).

$$Q = C(\Delta P)^n \quad (\text{Equation 1}).$$

The number of air changes per hour (ACH) was calculated by multiplying the airflow rate (Q) by 3600 (the number of seconds in an hour) and dividing the result by the dwelling's interior volume (V), according to the conventional formula used in airtightness studies (Equation 2).

$$ACH = \frac{Q \times 3600}{V} \quad (\text{Equation 2}).$$

Additionally, both indoor and outdoor environmental parameters were recorded during the tests. The detailed list of instruments used is presented in Table 1. Figure 5 and Figure 6 illustrate the installation and operation of the equipment in the field.

Dwelling V01 was used as a reference case to compare the pressure-difference measurements recorded by the blower-door pressure gauge with those obtained by the other four pressure gauges used in the experiments



Figure 5. Left. Blower door installed in Dwelling V03. Source: Prepared by the Authors.
 Figure 6. Right. Sensors installed in Dwelling V02. Source: Prepared by the Authors.

(Figure 7). Throughout the entire pressure range tested, no significant differences were observed between the instruments. This allowed validating the reliability of the measurements.

RESULTS AND DISCUSSION

The leakage airflow and air change values recorded in the evaluated dwellings far exceeded the ranges commonly reported in the specialized literature (Figure 8 and Figure 9). At a differential pressure of 50 Pa, leakage rates ranged from 40 to 285 ACH. In the particular case of dwellings V02, V03 and V04, it was not possible to reach the target pressure of 50 Pa due to the high leakage rates, typical of highly permeable constructions; in those cases, these values were estimated from the extrapolation of the airflow curve, by applying the equation of the power law model ($Q=C(\Delta P)^n$) with the coefficients C and n

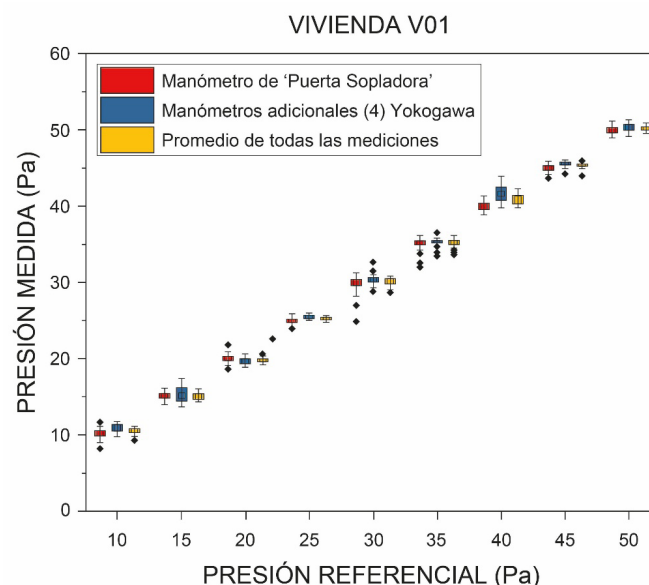


Figure 7. Average pressure measurements in dwelling V01. Source: Prepared by the Authors.

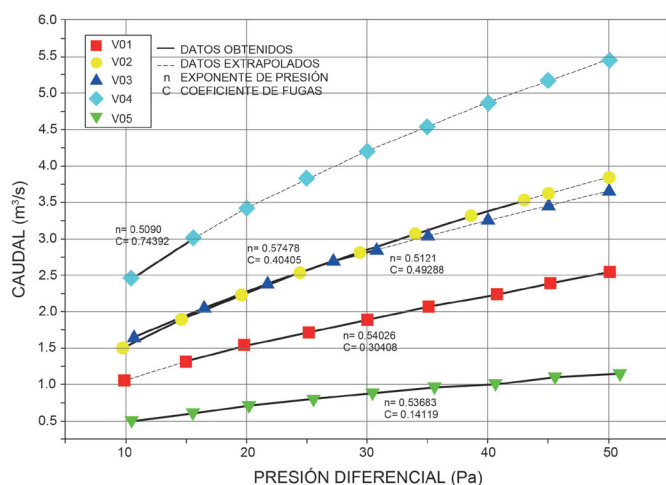


Figure 8. Air leakage in each dwelling. The dashed lines indicate the values extrapolated when the desired pressure difference could not be reached during the experiment. Source: Prepared by the Authors.

derived from the least squares adjustment of the measured points. However, it should be noted that in the V04 dwelling, due to its extreme permeability, only two measurement points could be obtained; therefore, the result is presented as an indicative estimate, as it did not meet the minimum of five points required by the ASTM E779-19 standard.

These unusually high leakage levels reflect the structural deficiencies typical of the informal housing analyzed. For reference, the highest values reported in the literature were 24.6 ACH in Chilean wooden houses (Bobadilla et al., 2014) and 23.3 ACH in an Italian building built in 1950 (Ambrosio Alfano et al., 2012). The main causes identified were the presence of visible interstices in both the openings and the joints between the walls and the corrugated iron roof. In the sample, the houses with wooden slatted walls (V02 and V04) and drywall (V03) had significantly higher leakage levels than those built with masonry walls (V01) and OSB panels (V05). This difference is explained by construction systems based on assembled elements, such as boards or drywall sheets, which create multiple potential leakage points that tend to expand over time due to wear, weather exposure, and material expansion, thereby accentuating the loss of airtightness.

The logarithms of the measured leakage airflow (Q) and pressure difference (ΔP) values were closely related across all dwellings, with coefficients of determination (R^2) near 1 (Figure 10 and Table 2). This makes it possible to identify the predictability of air-leak behavior, which, in turn, allowed the

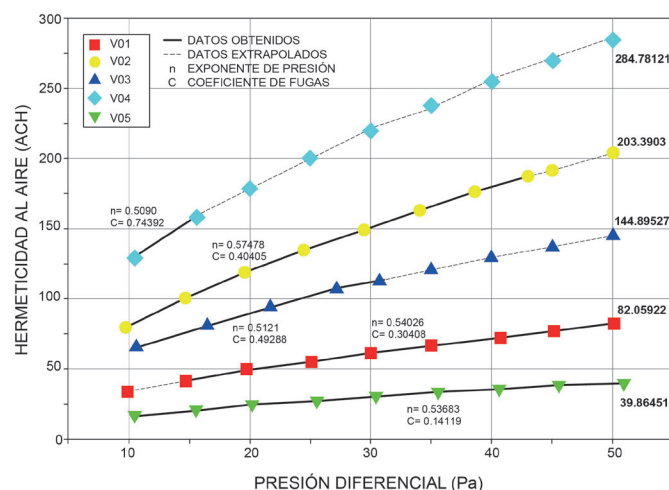


Figure 9. Air renewal per hour in each dwelling. The dashed lines indicate values that were extrapolated to facilitate comparison. Source: Prepared by the Authors.

extrapolation of data in cases where the desired pressure difference could not be generated during the experiments. The air leakage graph (Figure 10) shows, for each dwelling, the fan-generated air inflow relative to the applied air pressure. For example, in Dwelling V01, the airflow varies between 1.3 and 2.5 m^3/s depending on the pressure exerted. However, it should be noted that for dwelling V04, the values obtained are indicative estimates, as the property's extreme permeability prevented the collection of the minimum of five points required by the ASTM E779-19 standard. In this specific case, the R^2 coefficient lacks interpretative value, and the results should be read with the caution typical of findings under conditions of extreme constructive precariousness.

During fieldwork, in test preparations, and during instrument placement, it was possible to identify in all the dwellings conditions that foreshadowed very high levels of leakage. Interstices, grooves, perforations, inaccuracies in the joints of the constructive components, and even gaps without enclosing capacity were identified (Figure 11). In the case of dwelling V02, the identified opening in the ceiling is an intentional design feature for ventilation and lighting. During the survey of information in the area, it was observed that this type of solution is part of the spontaneous constructive logic of several inhabitants, which allows considering this case as an example of how certain habitability practices severely impact airtightness. That which, in formal contexts, would be classified as a defect or constructive damage in precarious housing, represents a habitual condition derived

GRÁFICAS DE FUGA DE AIRE

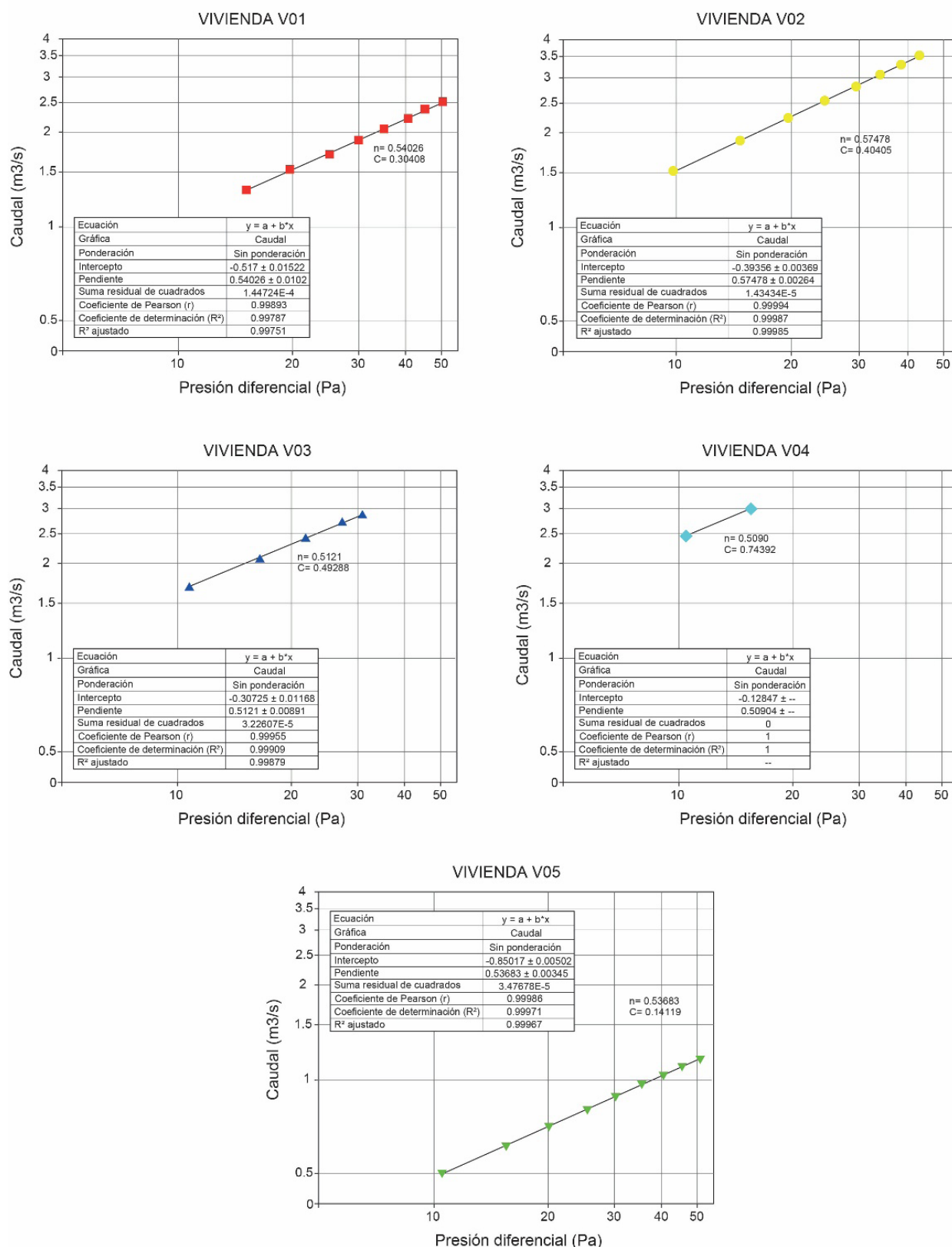


Figure 10. Air leakage results in the five tested dwellings. For dwelling V04, the values represent indicative estimates, as the property's extreme permeability prevented obtaining the minimum of five points required by the ASTM E779 standard. Source: Prepared by the Authors.

Housing	Material	Air leakage exponent, n	Leakage coefficient, C	Flow rate (m ³ /s) at 50 Pa	ACH to 50 Pa	R2
V01	Brick	0.540	0.304	2.5	82	0.99787
V02	Wooden panel	0.575	0.404	3.8	203	0.99987
V03	Drywall	0.512	0.493	3.7	145	0.99909
V04	Wooden panel	0.509	0.744	5.4	285	1.00000 a
V05	OSB	0.537	0.141	1.1	40	0.99971

*Value obtained with only two measuring points because the building's extreme permeability prevented the required pressure differentials from being reached by the equipment. In this case, the R2 coefficient has no interpretative value for the quality of the adjustment, and the results should be considered indicative estimates rather than validated against the minimum criteria (5 points) of the ASTM E779 standard.

Table 2. Values obtained from the tests. Source: Prepared by the Authors.

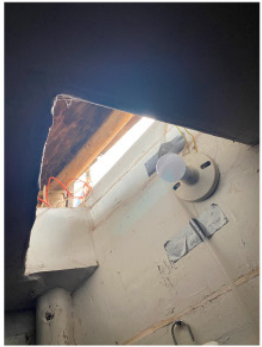
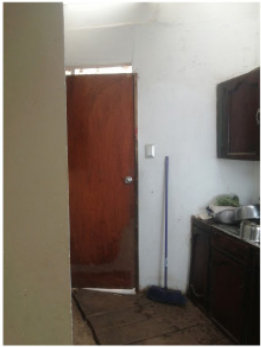
	V01	V02	V03	V04	V05
FOTOGRAFIA					
AMB.	Dormitorio	Baño	Cocina	Dormitorio	Dormitorio
INTERSTICIOS	-Vanos con partes sin cerramiento vidriado -Ladrillos con orificios debido a rajadura	-Abertura en el techo del baño -Intersticio entre el cerramiento y la calamina	-Aberturas en la puerta de entrada	-Rotura de listones de madera -Intersticio entre el muro del baño y de los dormitorios	-Intersticio entre el cerramiento y la calamina

Figure 11. Images of situations that reduce the level of airtightness of homes. Source: Prepared by the Authors.

from self-construction and lack of maintenance due to economic limitations. The observed constructive precariousness aligns with previous socio-economic diagnoses in these informal settlements (Wieser et al., 2022), which show that income constraints in self-construction limit families' ability to invest in appropriate technical solutions and to improve their homes' envelopes.

These extreme leakage levels have significant implications for the thermal comfort, health, and indoor air quality of the occupants. On the one hand, the presence of air currents, leaks, and loss of thermal control of the living space can generate severe thermal discomfort, especially during winter. In addition, the high, uncontrolled air change makes

it difficult to maintain stable indoor temperatures, which negatively impacts the dwelling's overall habitability. Consequently, the continuous, unfiltered entry of outdoor air can introduce pollutants, moisture, and suspended particles, which increase the risk of respiratory diseases, aggravate pre-existing conditions such as asthma, and promote mold growth. This problem is exacerbated by the large presence of sand outside.

The relevance of this study lies not only in being the first to perform systematic measurements of airtightness in informal housing in the Peruvian context, but also in its potential to nurture future energy and thermal comfort simulations. The availability of empirical airtightness data for self-

built and precarious homes is essential for calibrating models that estimate energy losses, habitability, and intervention scenarios. In contexts where data collection is difficult and expensive, these results allow the definition of realistic infiltration ranges for comparative studies, impact evaluations, or improvement proposals in retrofitting programs and public policies.

To assess the magnitude of the recorded results, note that a dwelling with 100 ACH at 50 Pa — an intermediate value within the recorded range — experiences an involuntary air renewal rate several times higher than the recommended rate to ensure minimum conditions of habitability and comfort. In practical terms, this implies that any passive thermal conditioning strategy—such as the use of mass or insulation—would have a marginal effect without a prior intervention on the envelope that reduces such leakage. Similarly, the identified leakage levels make the eventual efficient use of active heating systems practically infeasible, since the generated heat would dissipate almost immediately to the outside.

All these considerations are especially relevant in the context of Lima's winter, characterized by temperatures that, although not extreme in absolute terms, are difficult to cope with indoors without thermal control, due to the combination of high relative humidity, little direct solar radiation, and the inability to finance heating systems (Wieser et al., 2022). Consequently, improving the airtightness of homes in this context should be considered a priority and a relatively low-cost intervention before other comfort and energy-efficiency improvements.

CONCLUSIONS

Based on the values obtained, it is seen that air leakage levels in precarious housing in informal neighborhoods in Lima are extremely high compared to international regulations and even to housing in other countries in the region. This lack of airtightness, combined with the enclosure's lightness and low insulation, leaves the inhabitants exposed to extreme conditions, reducing thermal comfort, especially during the winter months. Taking into account the identified material characteristics and the sector's economic vulnerability, which limits the viability of autonomous, rigorous interventions by the inhabitants, improving the airtightness of these homes suggests the need to implement public support programs.

Additionally, the results suggest that possible simple and low-cost interventions aimed at increasing

airtightness in these homes, such as sealing interstices and improving the fit of doors and windows, would have a significant thermal impact, making it necessary to consider them in the design of eventual improvement programs and public housing policies aimed at these populations. The results obtained constitute a fundamental input for the development of regulations and intervention strategies to improve habitability in contexts of urban vulnerability.

Given the recognized direct relationship between airtightness and thermal comfort in naturally ventilated, non-active-thermal-conditioning buildings, greater attention is needed to include these aspects in the local academic and public debate. Finally, there is a need to significantly expand the number of measurements to establish a baseline that covers the different types of construction in the country's housing stock, across both the formal and informal sectors. This baseline will support the development of technical regulations adapted to local realities and calibrate energy simulation models applicable to housing contexts in other cities in the country and the region.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, M.W.; Data curation, M.W., R.M., E.B., E.M., A.G., J.V., L.C.; Formal analysis, M.W., R.M., E.B., E.M., L.C.; Acquisition of M.W. funding; Research, M.W., R.M., E.B., E.M., A.G., J.V., L.C.; Methodology, M.W., R.M., E.B., E.M., A.G., J.V., L.C.; Project Management, M.W.; Supervision, M.W., R.M., E.B., E.M., A.G., J.V.; Validation, M.W., R.M., E.B., E.M., L.C.; Writing – original draft, M.W.; Writing – revision and editing, M.W., R.M., E. B., E.M., A.G., J.V., L.C.

ACKNOWLEDGMENTS

This study has been carried out thanks to the financing of the following units of the Pontifical Catholic University of Peru: Department of Architecture, CIAC Architecture and City Research Center, Energy Laboratory of the Department of Engineering, and the Academic Direction of Social Responsibility DARS. We are grateful to the families who allowed us to conduct measurements in their homes and to the NGO CENCA for support with fieldwork and engagement with the community.

BIBLIOGRAPHIC REFERENCES

Ambrosio Alfano, F., Dell'Isola, M., Ficco, G., & Tassini, F. (2012). Experimental analysis of air tightness in Mediterranean buildings using the fan pressurization method. *Building and Environment*, 53, 16-25. <https://doi.org/10.1016/j.buildenv.2011.12.017>

Advancing Standards Transforming Markets [ASTM]. (23 de enero de 2019). *ASTM 779-19. Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*. ASTM International. <https://doi.org/10.1520/E0779-19>

Bobadilla, A., Díaz, M., Figueroa, R., & Arriagada, R. (2014). Proposal of Acceptable Air Tightness Classes for Buildings in Chile. *Revista de la construcción*, 13(1), 15-23. <https://doi.org/10.4067/S0718-915X2014000100002>

Buonanno, G., Morawska, L., & Stabile, L. (2009). Particle emission factors during cooking activities. *Atmospheric Environment*, 43(20), 3235-3242. <https://doi.org/10.1016/j.atmosenv.2009.03.044>

Choi, Y., Lim, Y., Kim, J., & Song, D. (2020). Why Does a High Humidity Level Form in Low-Income Households Despite Low Water Vapor Generation? *Sustainability*, 12(18), 7563. <https://doi.org/10.3390/su12187563>

Etheridge, D. (2015). A perspective on fifty years of natural ventilation research. *Building and Environment*, 91, 51-60. <https://doi.org/10.1016/j.buildenv.2015.02.033>

Feijó-Muñoz, J., Poza-Casado, I., González-Lezcano, R. A., Pardal, C., Echarri, V., Assiego De Larriva, R., Fernández-Agüera, J., Dios-Viéitez, M. J., Del Campo-Díaz, V. J., Montesdeoca Calderín, M., Padilla-Marcos, M. Á., & Meiss, A. (2018). Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study. *Energies*, 11(4), 704. <https://doi.org/10.3390/en11040704>

Guyot, G., Schild, P. G., & Carrié, R. (abril de 2010). *Stimulation of good building and ductwork airtightness through EPBD*. ASessment and Improvement of the EPBD Impact [ASIEPI]. <https://www.aivc.org/resource/stimulation-good-building-and-ductwork-airtightness-through-epbd>

Hsu, Y.-S., Zheng, X., Cooper, E., Gillott, M., & Wood, C. J. (2021). Evaluation of the indoor pressure distribution during building airtightness tests using the pulse and blower door methods. *Building and Environment*, 195, 107742. <https://doi.org/10.1016/j.buildenv.2021.107742>

Hutcheon, N. B. (1953). Fundamental considerations in the design of exterior walls for buildings. Technical Report No.13 of the Division of Building Research Ottawa. *NRC*, 2057(37), 1-25. <https://publications-cnrc.canada.ca/eng/view/object/?id=e03a98e6-9755-42d8-a9ea-f8b34680bde>

Instituto Nacional de Estadística e Informática [INEI]. (2018). *Resultados definitivo de los Censo Nacional 2017. Región Lima*. XII de Población, VII de Vivienda y III de Comunidades Indígenas. https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1550/

Kalamees, T. (2007). Air tightness and air leakages of new lightweight single-family detached houses in Estonia. *Building and Environment*, 42(6), 2369-2377. <https://doi.org/10.1016/j.buildenv.2006.06.001>

Kulshreshtha, P., Khare, M., & Seetharaman, P. (2008). Indoor air quality assessment in and around urban slums of Delhi city, India. *Indoor Air*, 18(6), 488-498. <https://doi.org/10.1111/j.1600-0668.2008.00550.x>

Lambert, R., Escalante, C., De los Rios, S., Verdiere, M., & Wieser, M. (2023). *Dignified housing and energy justice: Learning from low-income neighbourhoods in Lima*. University College London (UCL). <https://discovery.ucl.ac.uk/id/eprint/10181093/>

Oraopoulos, A., Wieser Rey, M., Verdiere, M., Fennell, P., & Ruyssevelt, P. (September 4–6, 2023). *Thermal comfort in low-income housing in informal settlements in Lima, Peru. Towards a localised adaptive comfort standard* [Conference paper]. Building Simulation 2023: 18th Conference of International Building Performance Simulation Association [IBPSA], Shanghai, China. <https://doi.org/10.26868/25222708.2023.1474>

Oraopoulos, A., Wieser, M., Verdiere, M., Lambert, R., Fennell, P., & Ruyssevelt, P. (2025). Improving habitability in informal settlements in the Global South: Exploring the impact of community urban green infrastructure on outdoor heat stress. *Building and Environment*, 287(Part A), 113787. <https://doi.org/10.1016/j.buildenv.2025.113787>

Persily, A. K. (December 6–10, 1998). *Airtightness of commercial and institutional buildings: Blowing holes in the myth of tight buildings*. Thermal Performance of the Exterior Envelopes of Buildings VII: proceedings of the Conference. Clearwater, Florida, EE.UU. https://www.aivc.org/sites/default/files/airbase_13149.pdf

Poza-Casado, I., Cardoso, V. E. M., Almeida, R. M. S. F., Meiss, A., Ramos, N. M. M., & Padilla-Marcos, M. Á. (2020). Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America. *Building and Environment*, 183, 107221. <https://doi.org/10.1016/j.buildenv.2020.107221>

Rodríguez Muñoz, J. M., Sevrini, A., Gil, G., & Bove, I. (2020). Estudio experimental de la permeabilidad al aire de edificios en Uruguay. *ENERLAC. Revista de energía de Latinoamérica y el Caribe*, 4(2), 76-91. <https://enerlac.olade.org/index.php/ENERLAC/article/view/119>

Šadauskienė, J., Šeduikytė, L., Paukštys, V., Banionis, K., & Gailius, A. (2016). The role of air tightness in assessment of building energy performance: Case study of Lithuania. *Energy for Sustainable Development*, 32, 31-39. <https://doi.org/10.1016/j.esd.2016.02.006>

Sfakianaki, A., Pavlou, K., Santamouris, M., Livada, I., Assimakopoulos, M.-N., Mantas, P., & Christakopoulos, A. (2008). Air tightness measurements of residential houses in Athens, Greece. *Building and Environment*, 43(4), 398-405. <https://doi.org/10.1016/j.buildenv.2007.01.006>

Tombarević, E., Vušanović, I., & Šekularac, M. (2023). The Impact of Windows Replacement on Airtightness and Energy Consumption of a Single Apartment in a Multi-Family Residential Building in Montenegro: A Case Study. *Energies*, 16(5). <https://doi.org/10.3390/en16052208>

Wieser, M., Verdiere, M., & Fennell, P. (December 13-14, 2022). *The impact of built environment on thermal comfort in informal settlements. The case of José Carlos Mariátegui, Lima, Perú* [Conference paper]. Sixth Building Simulation and Optimisation Virtual Conference. Hosted by University of Bath, UK. https://publications.ibpsa.org/proceedings/bsa/2022/papers/bsa2022_52.pdf

Zheng, X., Cooper, E. W., Mazzon, J., Wallis, I., & Wood, C. J. (2019). Experimental insights into the airtightness measurement of a house-sized chamber in a sheltered environment using blower door and pulse methods. *Building and Environment*, 162, 106269. <https://doi.org/10.1016/j.buildenv.2019.106269>