

Article

Indoor Air Quality Assessment of Latin America's First Passivhaus Home

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Abstract: Sustainable building design, such as the Passivhaus standard, seeks to minimise energy consumption, while improving indoor environmental comfort. Very few studies have studied the indoor air quality (IAQ) in Passivhaus homes outside of Europe. This paper presents the indoor particulate matter (PM_{2.5}), carbon dioxide (CO₂), and total volatile organic compounds (tVOC) measurements of the first residential Passivhaus in Latin America. It compares them to a standard home in Mexico City. Low-cost monitors were installed in the bedroom, living room, and kitchen spaces of both homes, to collect data at five-minute intervals for one year. The physical measurements from each home were also compared to the occupants' IAQ perceptions. The measurements demonstrated that the Passivhaus CO₂ and tVOC annual average levels were 143.8 ppm and 81.47 µg/m³ lower than the standard home. The PM_{2.5} in the Passivhaus was 11.13 µg/m³ lower than the standard home and 5.75 µg/m³ lower than outdoors. While the results presented here cannot be generalised, the results suggest that Passivhaus dwellings can provide better and healthier indoor air quality in Latin America. Further, large-scale studies should look at the indoor environmental conditions, energy performance, and dwelling design of Passivhaus dwellings in Latin America.

Keywords: Passivhaus; indoor air quality (IAQ); Latin America; particulate matter (PM_{2.5}); carbon dioxide (CO₂); total volatile organic compounds (tVOC)

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1. Introduction

Sustainable building design is in constant evolution; such a process has been emphasised due to climate change issues. Sustainable architecture aims to deliver buildings that balance their ecological impact, and even go further. The construction industry has faced significant challenges, to reduce energy demand while providing better indoor environmental quality [1]. Buildings have reduced heat losses through the building envelope and introduced active and passive techniques to reduce energy use further. However, these changes have been mainly motivated by environmental concerns, energy prices, and an increased demand for housing [2]. Other factors, such as indoor environmental comfort and health, have not been addressed adequately in the past, but have seen increased attention, particularly indoor air quality (IAQ); after the COVID-19 lockdowns [3,4]. Different organisations have developed benchmarking systems and certifications to promote and recognise energy-efficient buildings through different design and construction criteria. Some examples include BREEAM (Building Research Establishment Environmental Assessment), LEED (Leadership in Energy and Environmental Design), and the Passivhaus standard, on which this work is based.

A Passive House, or 'Passivhaus', which is the original German term, is '[...] a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality

conditions—without the need for additional recirculation of air [5]'. Nevertheless, the Passivhaus does not have specific criteria for IAQ and relies on the DIN1946 suggested air-flow rates to manage ventilation and, hence, the removal of indoor air pollutants. The German standard DIN1946 establishes air flow rates between 0.5 and 1.0 ach⁻¹, suggesting that these ventilation rates should be sufficient to avoid CO₂ peaks above 1500 ppm.

The Passivhaus standard is based on five fundamental concepts: thermal insulation, thermal bridge-reduced design, airtightness, adequate ventilation strategy (usually through mechanical ventilation with heat recovery (MVHR) systems), and the use of Passivhaus windows and doors (for a detailed explanation of the Passivhaus principles see [6]). Additionally, the building must adhere to strict design criteria detailed in the Passive House Planning Package (PHPP, currently version 9) [7]. Although the Passivhaus standard was first developed for cold central European countries, its methodology has been introduced to warmer climates such as those found in Latin America.

Between 1990 and 2005, a few Passivhaus homes were built, mainly in cold climates from European countries. The interest in Passivhaus buildings has expanded outside of Europe. According to the Passivhaus Institute in Latin America (ILAPH), the uptake of the Passivhaus standard in Latin America started in 2010 with a non-residential Passivhaus pilot building in Chile. However, it was not until 2014 that the first dwelling received certification, in Mexico. Since then, other dwellings have achieved certification, but have only been subject to scientific scrutiny through virtual modelling, mainly through the PHPP; until now. These studies show evidence of the thermal comfort [8], energy [9,10], economic [11,12], and environmental [13] performance, as well as the feasibility [14,15] of Passivhaus buildings in Latin America. Their measured performance evaluation is limited to thermal comfort [16], energy [17], or limited to short (≤ 3 months) term studies [18]. Passivhaus dwellings have attracted scientific scrutiny of their energy performance [19–21], thermal comfort [22–25], and IAQ [21,26–29] in other parts of the world.

Indoor air quality (IAQ) refers to the indoor concentration of air pollutants that can harm human wellbeing [30]. Nevertheless, what constitutes safe or adequate levels is a current debate. Some authors claim that this should be a complete absence of air contaminants [31]. In contrast, others suggest that low concentrations, which are not detrimental to public health, are acceptable [32]. In 2000, the World Health Organisation (WHO) recognised healthy air as a human right [33] and published guidelines for safe thresholds of different indoor air pollutants [34]. The Passivhaus standard does not explicitly address off-gassing from building materials or other air pollution issues in buildings. Instead, it relies on ventilation rates (30 m³/h per person or 0.3 ach/h) to achieve acceptable levels. Hence, IAQ in Passivhaus dwellings is a topic that has captivated the interest of researchers.

Several studies [35–39] suggest that Passivhaus dwellings have the means to achieve acceptable IAQ, even when compared to other non-Passivhaus homes [40–44]. However, very few have compared the measured IAQ to the occupant's IAQ perception [29,45,46]. Other studies show conflicting results, suggesting that the IAQ in a Passivhaus may not be adequate [47–49]. Some of the Passivhaus principles, airtightness and ventilation, directly impact the IAQ in homes. For instance, the required levels of airtightness (≤ 0.6 h⁻¹ @50 Pa) in Passivhaus dwellings help avoid condensation and conserve energy by reducing air infiltration. However, it is unclear whether an airtight building envelope has clear IAQ benefits [39,50] or not [51]. Nevertheless, occupants' satisfaction with IAQ and indoor humidity is better than those living in non-Passivhaus dwellings [44].

A previous study [26] suggested further work on long-term studies, to understand the IAQ performance of Passivhaus worldwide, in climates different from those found in central European countries. To the authors' knowledge, this work is the first to measure and evaluate the long-term IAQ performance of a Passivhaus dwelling in Latin America. Indoor air quality parameters were measured using low-cost monitors with remote access capabilities. Additionally, the occupants' perception of IAQ was assessed and compared to the physical measurements. Finally, this paper discusses further work to support the

development of the Passivhaus standard in Latin American countries. This work focuses on IAQ, as the thermal performance of this Passivhaus dwelling is discussed elsewhere [16].

2. Method

This study presents results from a monitoring campaign of a certified Passivhaus dwelling, and another built with the standard building practices in Mexico City. This campaign took place between 1 June 2016 and 31 May 2017. Locations with an Oceanic Subtropical Highland Climate (Cwb), such as Mexico City, are characterised by warm and wet summers, with dry and warmer winters [52]. Foobot was used to monitor air temperature (-40 – 125 °C; ± 0.4 °C), relative humidity (0–100% RH; ± 4 % RH), particulate matter 2.5 μm ($\text{PM}_{2.5}$) (0–1300 $\mu\text{g}/\text{m}^3$; ± 4 $\mu\text{g}/\text{m}^3$ or ± 20 %), and total volatile organic compounds (tVOC) (125–1000 $\mu\text{g}/\text{m}^3$; ± 1 $\mu\text{g}/\text{m}^3$ or ± 10 %). As the Foobot does not have a dedicated carbon dioxide (CO_2) sensor, a Netatmo (0–5000 ppm; ± 50 ppm or 5%) was used for these measurements. The accuracy of both the Foobot [53] and Netatmo [54] monitors has been tested and validated for carrying out long-term IAQ monitoring. The calibration equations used in this study are described in greater detail in a previous study from our research group [53].

We adopted a novel monitoring methodology for this research, avoiding researcher visits to the homes. Instead, the participants were asked to install the monitors and asked for the surveys online, as described in [55]. They received a pack with information on how to operate the monitors and where to place them. These monitors were used as they could be deployed remotely, with remote data collection, and were acceptable to the building owners who installed them. The Foobot monitors were installed in the living room, kitchen, and bedroom, while the Netatmos were only placed in the living room and bedroom. The sensors collected data continuously at five-minute intervals, for one year. As this was a long-term study, using these low-cost monitors for outdoor monitoring would have been difficult and added challenges for the building occupants to install a different set of sensors (i.e., outdoor air quality, doors, windows, and movement sensors). Hence, outdoor parameters were collected from the 'Hospital General de México (HGM)' station (<1 km from the homes) of Mexico City's official local atmospheric monitoring program (<http://aire.cdmx.gob.mx/> (accessed on 16 August 2021), see location in Figure 1).

Occupant perceptions of IAQ were collected through a certified indoor environmental survey [56], which was adapted to an online format. Building occupants were asked to complete the surveys after the end of the monitoring phase, considering their experiences throughout the previous year. This survey examined their perception of air freshness, moisture, movement, the outdoors, and their overall satisfaction with the air quality. The survey was based on seven-option rating scales, was unipolar and bipolar, and assessed following the survey guidelines (see [56] for detailed instructions). As this was a long-term study, it was also not viable to ask the participants to keep a detailed diary of their activities, therefore, participants were asked to provide the general weekly occupancy pattern of the dwelling and window opening patterns on which the analysis is based.



Figure 1. Location of the homes in Mexico City. The red highlighted area shows the Roma Norte. The navy dot represents the location of the monitoring station. The yellow circle highlights the area of the city centre. The blue arrows the main wind direction. Source: Authors, based on Google map image.

2.1. Indoor Air Quality Criteria

Standard protocols for measuring the IAQ in homes are limited. Usually, such protocols are designed for general IAQ monitoring (i.e., CIBSEKS17, ASTM D6245-12, and the BS EN ISO 16000-1:2006) and are adapted for residential studies. In this study, we followed the recommendations from BS EN ISO 16000-1:2006 and used the following thresholds:

- PM_{2.5}: 25 µg/m³ at 24 h mean and annual mean of 10 µg/m³, as defined by WHO [33].
- tVOC: 300 µg/m³ over 8 h mean, as defined by the WHO [33].
- CO₂: 1000 ppm, as defined by IDA3 (moderate IAQ based on the EN 13779:2007 [57])
- Relative humidity: 40–60%RH (ideal) and 30–70%RH (extended) as defined by CIBSE [58].

2.2. Household Characteristics

The dwellings are located within the Roma Norte neighbourhood in the west of Mexico City's historic centre, within less than 500 m of each other (Figure 1). The Roma Norte encompasses diverse building uses residential, restaurants, bars, clubs, shops, churches, and galleries. The borders of the neighbourhood are three principal avenues, which have dense and constant traffic, this is in combination with the winds in the city, which bring the surrounding pollution of the industrial zones to the central neighbourhoods.

Both dwellings have the same orientation, north to south, facing the predominant winds (north-west). While the homes are different in size and floor plan layout (Figure 2a, b), it was deemed adequate to compare them, as the standard home represents the most common typology [59]. Both dwellings have similar occupancy and multipurpose rooms (kitchen, living room, and dining area). Two adults and one child occupied each of the dwellings. Table 1 describes the frequency of window opening and the occupancy

patterns, as depicted in the occupancy diaries. Table 2 shows a summary of the building characteristics and construction details.

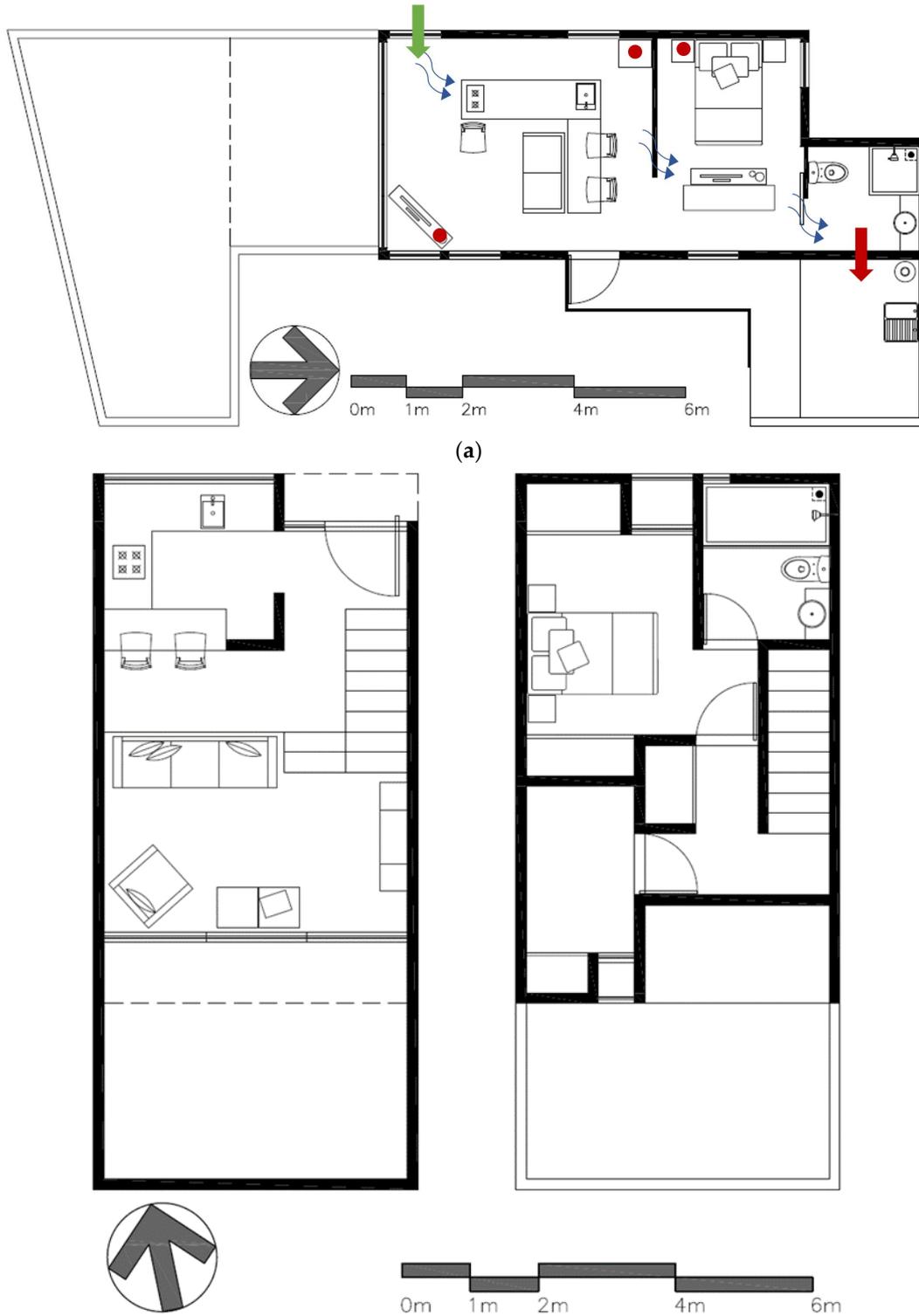


Figure 2. (a) Passivhaus dwelling floor plan. The red dots indicate the placement of the sensors. The blue arrows indicate the ventilation flow. The green and red arrows represent the inlet openings and extraction fan, respectively. Source: authors. (b) Standard dwelling floor plan. Source: Authors.

Table 1. Household characteristics. Source: Authors.

Household Characteristic	Passivhaus Dwelling	Standard Dwelling
Household occupancy	2 Adults, 1 child (>16).	2 Adults, 1 child (>16).
Age range (years)	40–50, <16	40–50, 50–60, <16
Smoking	No, only outdoors	No, only outdoors
<i>Occupancy Pattern (Daily)</i>		
Bedroom	00:00–06:30; 22:30–24:00	00:00–06:30; 22:30–24:00
Kitchen	07:30–09:00; 14:00–16:00; 20:30–21:30	07:30–09:00; 11:00–16:00; 20:30–21:30
Living room	09:00–09:30; 14:00–16:00; 21:30–22:30	09:00–09:30; 11:00–16:00; 21:30–22:30
<i>Frequency of Window Opening</i>		
Morning	Rarely	Constantly
Afternoon	Occasionally	Regularly
Evening	Regularly	Occasionally
Night	Constantly	Rarely

Table 2. Main building characteristics of the Passivhaus and Standard Dwellings. Source: Authors.

Building Characteristic	Passivhaus Dwelling	Standard Dwelling
Airtightness (n_{50})	0.59 h ⁻¹	Not tested
Floor area	42 m ²	57 m ²
Main door	PVC (Passivhaus certified)	Wood (standard)
U _g -value (window)	1.64 W/(m ² K)	5.78 W/(m ² K)
U-value (floor slab)	0.33 W/(m ² K)	13.66 W/(m ² K)
U-value (roof)	0.36 W/(m ² K)	13.66 W/(m ² K)
U-value (wall)	0.37 W/(m ² K)	1.18 W/(m ² K)
Ventilation	Mechanical extraction and cross natural ventilation. Due to the mild climate, no MVHR was needed. An extraction fan ran intermittently to provide 42 m ³ /h as calculated by the PHPP calculations; no kitchen hood.	Natural (cross and stack). Calculated ventilation (89.6 m ³ /h) depending on the outdoor conditions Kitchen hood fans with no extract.
Window type	Double-glazing 6 mm/ 12 mm air, 4 mm low-e-clear-claro (Passivhaus certified)	Single glazing 3 mm (Standard)
Building Standard	Passivhaus (certified)	Mexico City's Standard Building Regulation

In warmer climates, the Passivhaus ventilation strategy may differ from the one recommended in European countries. Rather than using mechanical ventilation with a heat recovery (MVHR) system, the ventilation can rely on mechanical and natural ventilation (hybrid). This Passivhaus dwelling used mechanical extraction ventilation, in the toilet, and three openings with a total of 0.05 m², in the living room, at the other end of the house (see green and red arrows in Figure 2a). These inlet openings were initially fitted with an F7 filter—for fine dust and PM_{1–10}. As the filters were difficult to find on the Mexican market at the time, they were removed as they could not be periodically changed. Therefore, during this study, no filters were present. Before the monitoring phase, the ventilation system was recommissioned to ensure that the air flows were as stated in the PHPP (42 m³/h).

3. Results

3.1. Passivhaus Ventilation

A Passivhaus design for hybrid ventilation must ensure that the required ventilation is still met in the most unfavourable conditions, when windows are closed, and natural ventilation is restricted. Therefore, the Passivhaus still needs to provide the ventilation required by the Passivhaus calculation through mechanical means. The air flows in the house were tested and adapted accordingly to the PHPP calculation (42 m³/h). The extraction fan claimed to have a capacity of 95 m³/h. However, this was reduced to 74.30 m³/h after being installed. Nonetheless, this was still higher than the 42 m³/h required by the PHPP. The difference was compensated using a timer that regulated the fan operation at 34 min per hour and allowed manual activation/deactivation.

The CO₂ levels were used as a ventilation metric [60] (CO₂ levels are examined in detail in the next section). The CO₂ concentrations in the room were modelled using Equation (1).

$$c = (q \div nV)[1 - (e^{-nt})] + (c_0 - c_i)(1 \div e^{-nt}) + c_i \quad (1)$$

Equation (1). Model for CO₂ Concentrations in Rooms with People. Source: [61].

where

c = carbon dioxide concentration in the room (m³/m³)

q = carbon dioxide supplied to the room (m³/h)

V = volume of the room (m³)

e = the constant 2.718

n = air changes per hour (1/h)

t = time (hour, h)

c_i = carbon dioxide concentration in the inlet ventilation air (m³/m³)

c_0 = carbon dioxide concentration in the room at start, $t = 0$ (m³/m³)

Figure 3 shows the measured CO₂ levels (continuous blue line) on 26 March 2017. The calibration model (orange short dashed line) was produced using the real occupancy and ventilation patterns (Density: two persons; activity: sleeping; time interval: 5 min; CO₂ emissions per person: 0.015 m³/h; ventilation rates (calibration model): each hour from 0:00–0:15 at 0.001 ach, 0:15–0:30 at 0.9789 ach (74.3 m³/h), 0:30–0:40 at 0.001 ach, and 0:45–1:00 at 0.9789 ach (74.3 m³/h); room volume: 75.9 m³; and outdoor CO₂: 500 ppm) assuming an outdoor level of 500 ppm, as recommended on the EN 13779:2007 [62]. Another model (blue dash-dot-dash line) evaluated the same condition but changed the extraction to a continuous rate of 42 m³/h, as suggested by the PHPP calculations (Density: two persons; activity: sleeping; time interval: 5 min; CO₂ emissions per person: 0.015 m³/h; ventilation rates (continuous flow): 42 m³/h; room volume: 75.9 m³; and ambient CO₂: 500 ppm). Finally, the last model (Density: two persons; activity: sleeping; time interval: 5 min; CO₂ emissions per person: 0.015 m³/h; ventilation rates (continuous flow): 74.3 m³/h; room volume: 75.9 m³; and ambient CO₂: 500 ppm) (red long dashed line) evaluated with the total capacity of the installed fan (74.3 m³/h). The effect can be observed in Figure 4.

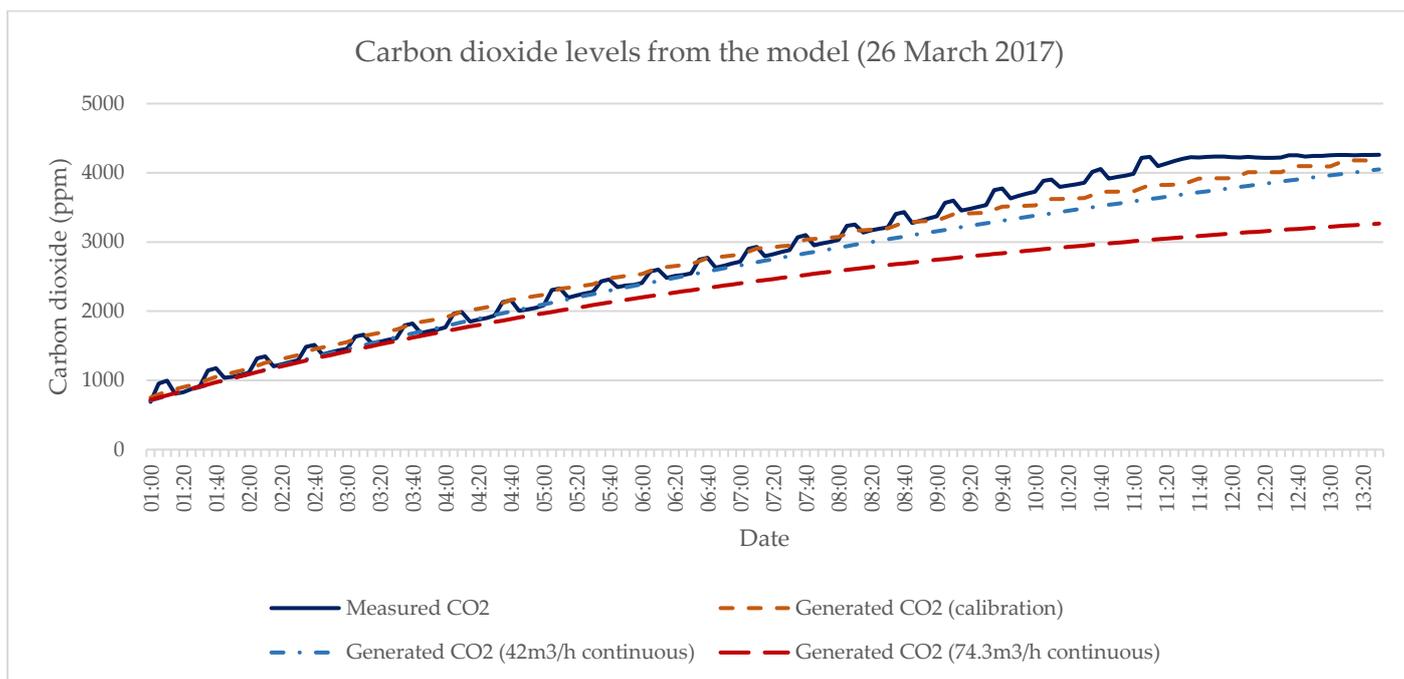


Figure 3. Measured and modelled overnight CO₂ levels. Source: Authors.

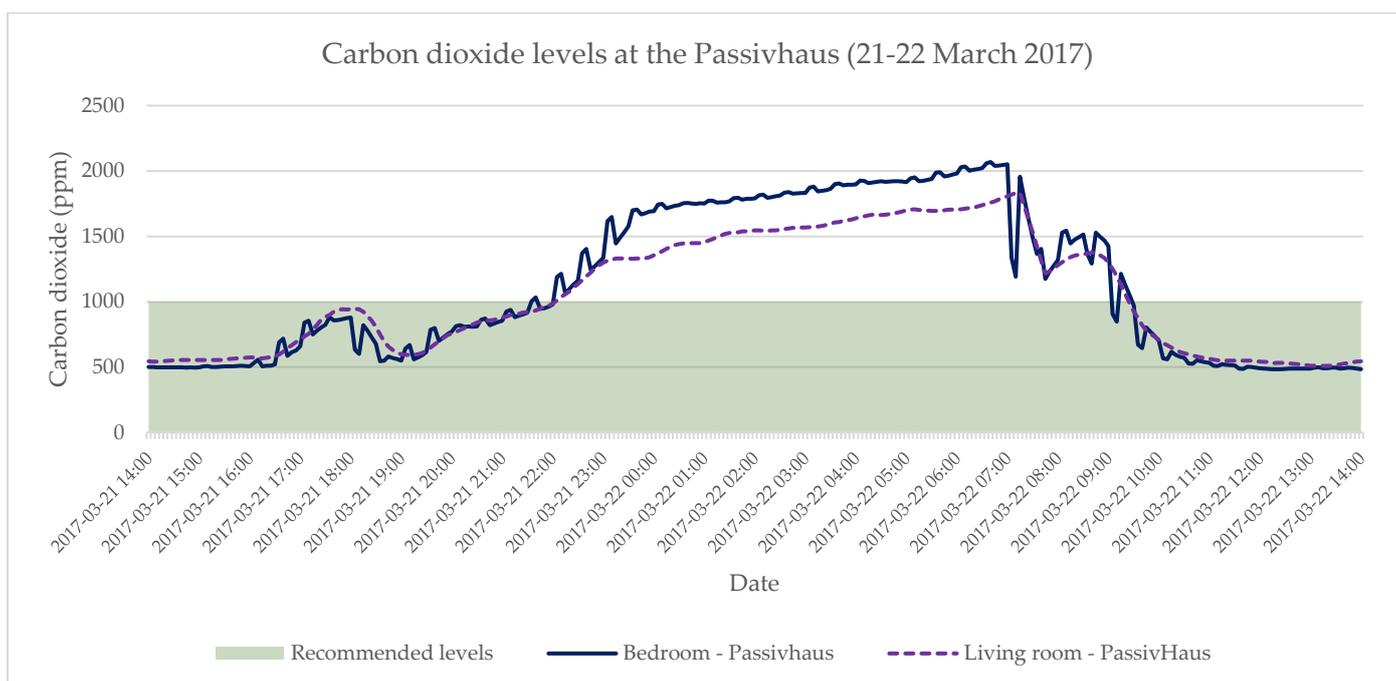


Figure 4. Monitored CO₂ levels in Mexico’s Passivhaus (21–22 March 2017). Source: Authors.

3.2. Carbon Dioxide Levels

The CO₂ levels in both monitored spaces, the living room and bedroom, exceeded the recommended 1000 ppm throughout the year. The results showed that the highest levels peaks were during the colder months, when one would expect the windows to remain closed. Nonetheless, the monthly mean levels in both spaces remained below the recommended levels (Figure 5). The overall CO₂ levels in the Passivhaus were better compared to those in the standard dwelling. They remained below the recommended 1000 ppm for 85.9% of the year in the bedroom and 90.1% in the living room in the Passivhaus. In contrast, the standard dwelling bedroom CO₂ levels were above 1000 ppm for 42.9% of the

time and 97.5% in the living room. The CO₂ levels of the bedroom of the standard home were of particular concern, particularly at night. A potential explanation could be the differences in the ventilation regulation in the Mexican building regulations, and the fact that windows remained closed during the night due to security concerns. Monthly CO₂ levels and a statistical analysis can be found in the Supplementary Table S1.

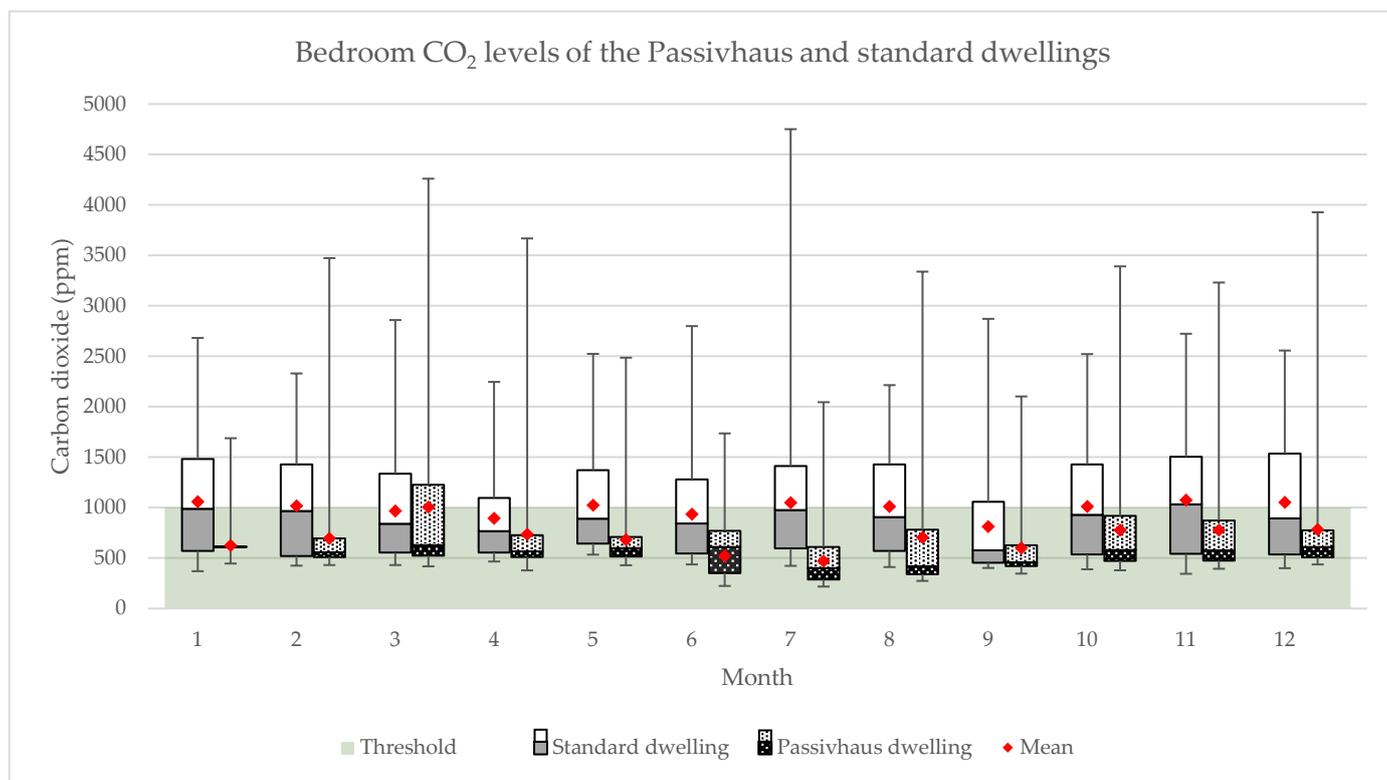


Figure 5. Bedroom annual CO₂ levels in the Passivhaus and Standard dwellings. Source: Authors.

3.3. Particulate Matter 2.5 μm

The recommended PM_{2.5} thresholds of 10 $\mu\text{g}/\text{m}^3$ and 25 $\mu\text{g}/\text{m}^3$ were exceeded outdoors and in both dwellings (Figure 6). The measured PM_{2.5} levels outdoors and in both dwellings are shown in Table 3. In comparison, previous studies found that the mean indoor PM_{2.5} concentrations ranged between 28.9 $\mu\text{g}/\text{m}^3$ [63] and 35.1 $\mu\text{g}/\text{m}^3$ [64]. These levels were significantly higher than those in the Passivhaus dwelling.

The PM_{2.5} levels in the Passivhaus ($r_s = 0.539\text{--}0.587$, ($p < 0.001$)) and the standard ($r_s = 0.539\text{--}0.611$, ($p < 0.001$)) dwellings were statistically similar to that outdoors, which is similar to another study where this relationship was significant at $r_s = 0.56$, ($p < 0.001$) [65] (see Section 3.3.1.). Nonetheless, further examination revealed that indoor PM_{2.5} levels were also affected by indoor behaviours and ventilation strategies. For instance, cooking originated significant pollution peaks, rapidly dissipated in the standard home (Figure S1) due to higher ventilation rates, compared to the Passivhaus dwelling (Figure S2), where the pollution peaks took longer to dissipate. However, once the pollution peaks dissipated, indoor PM_{2.5} levels remained lower in the Passivhaus dwelling than in the standard home. Monthly PM_{2.5} levels and a statistical analysis can be found in Supplementary Table S2.

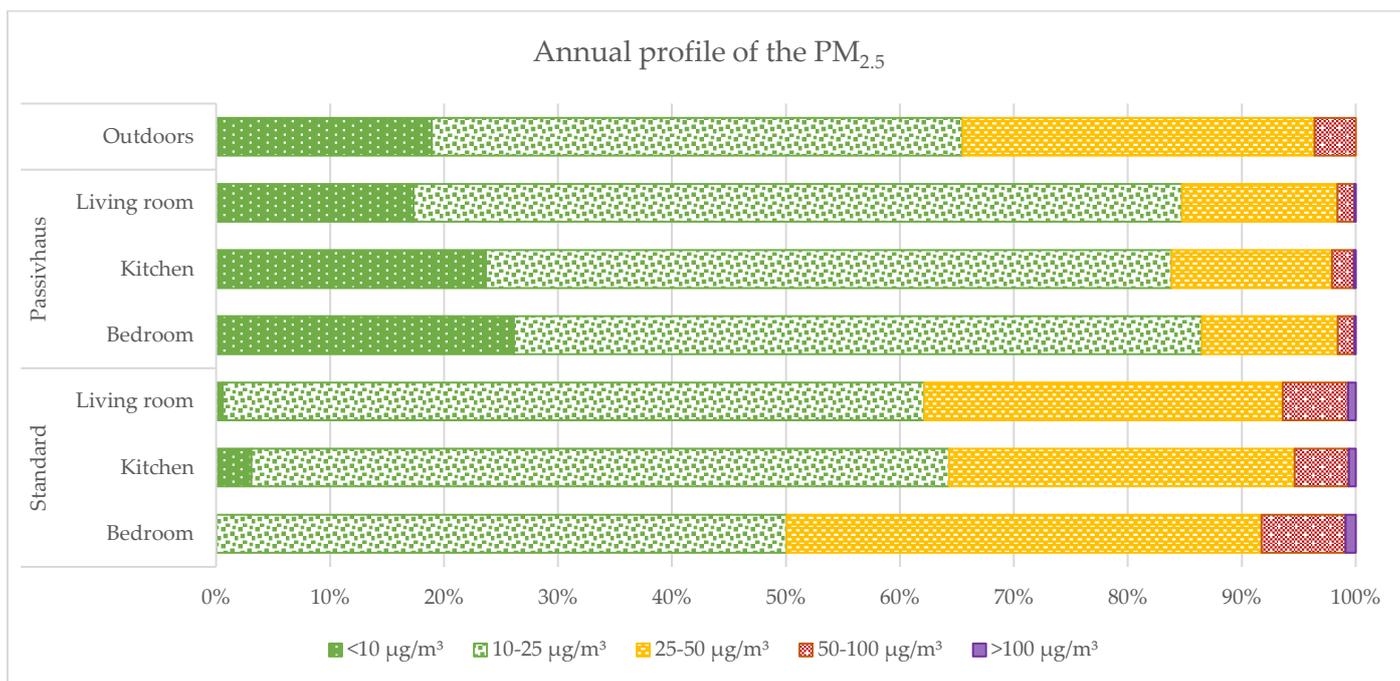


Figure 6. Annual PM_{2.5} profile in the Passivhaus and standard dwellings. Source: Authors.

Table 3. Annual PM_{2.5} means compared to the recommended thresholds. Source: Authors.

		Annual Mean Standard De- (µg/m ³)	viation	% of Time above 10 µg/m ³	% of Time above 25 µg/m ³	Number of Days above 25 µg/m ³
Passivhaus	Bedroom	15.8	10.9	73.8%	10.7%	40
	Living room	16.9	10.5	82.7%	12.1%	44
	Kitchen	17.2	12.0	76.3%	13.7%	50
Standard home	Bedroom	29.4	18.8	100.0%	66.0%	241
	Living room	27.8	17.1	99.4%	52.6%	173
	Kitchen	26.1	16.9	96.9%	47.4%	192
	Outdoors	22.4	13.3	81.1%	35.3%	129

Indoor-Outdoor PM_{2.5} levels

A previous study that looked at indoor and outdoor PM_{2.5} concentrations in Mexico City found that they were statically similar at $r_s = 0.56$ ($p < 0.001$), regardless of the season [64]. In this study, we found similar relationships in both dwellings. The Passivhaus indoor–outdoor correlation was significant at $r_s = 0.539–0.587$ ($p < 0.001$) and in the standard home at $r_s = 0.539–0.611$ ($p < 0.001$). Although indoor–outdoor PM_{2.5} levels were significantly correlated, there were some differences between the indoor–outdoor levels measured.

PM_{2.5} levels in the Passivhaus dwelling were between 5.22 µg/m³ to 6.54 µg/m³ below outdoor levels and those in the standard home were between 3.65 µg/m³ and 7.04 µg/m³ above those outdoors as shown in Table 4. Hence, the results in this study suggest that these differences could be related to building related issues or differences in the building occupants’ behaviour. Outdoor PM_{2.5} levels are described in Table S2.

Occupant behaviour, particularly cooking, window opening, and the use of sprays, have an important role in the PM_{2.5} profiles in homes. Therefore, the impact of cooking and window opening on PM_{2.5} was analysed in both homes. For instance, cooking fumes produced higher peak levels of PM_{2.5} as pollution continued to accumulated (being slowly dissipated/driven outdoors). PM_{2.5} levels were observed to rise in the kitchen during cooking. However, the particles travelled to the adjacent rooms, where PM_{2.5} levels started rising minutes after (Figures S1 and S2).

Table 4. Monthly indoor–outdoor differences of the PM_{2.5} levels. Source: Authors.

	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Standard home	Bedroom	2.42	5.4	3.2	0.4	9.7	4.6	5.8	12.9	9.7	11.9	11.2	7.1	7.0
	Kitchen	−0.92	1.2	−0.7	0.7	2.3	2.0	0.3	4.0	10.9	11.3	9.6	3.2	3.7
	Living room	1.81	1.6	5.6	−2.6	0.3	2.7	4.2	9.7	12.6	13.7	13.0	2.4	5.4
Passivhaus	Bedroom	−13.67	−9.6	−6.1	−8.8	−9.5	−7.5	−7.1	−4.0	−4.4	1.5	−1.9	−7.7	−6.5
	Kitchen	−13.49	−6.8	−4.9	−7.3	−6.2	−6.5	−5.9	−3.0	−4.4	−0.0	0.8	−4.9	−5.2
	Living room	−14.00	−7.0	−2.8	−8.8	−10.0	−5.5	−5.9	−4.0	−5.4	2.1	−0.1	−4.5	−5.5

3.4. Total Volatile Organic Compounds

As part of the study, indoor tVOC levels were measured. However, it was not possible to collect outdoor measurements, as they were not measured by the local air pollution network and the specifications of the low-cost monitors. A 7-month study found that outdoor tVOC levels in Mexico City were 1462 µg/m³ (±763 µg/m³) in residential neighbourhoods but could peak at up to 5364 µg/m³ [66]. Mean indoor tVOC levels ranged between 569 µg/m³ to 578 µg/m³ in the Passivhaus, while in the standard home they were 587 µg/m³ to 786 µg/m³, as illustrated in Figure 7. Peak pollution levels were commonly observed when the occupants reported using personal cleaning products, cooking, and cleaning activities. These activities impacted the most in the early mornings, when windows usually remained closed and the ventilation rates were lower, as evidenced by the CO₂ levels. The effect of the lack of ventilation had a significant impact on the dissipating of indoor tVOC concentrations. Finally, tVOC concentrations were not directly associated with building or furnishing materials. During non-occupied periods, the levels remained relatively low (<300 µg/m³). This could be because both dwellings are more than five years, and tVOC off-gassing is usually higher in new (<2 years) materials [67]. Monthly tVOC levels and statistical analyses can be found in Supplementary Table S3.

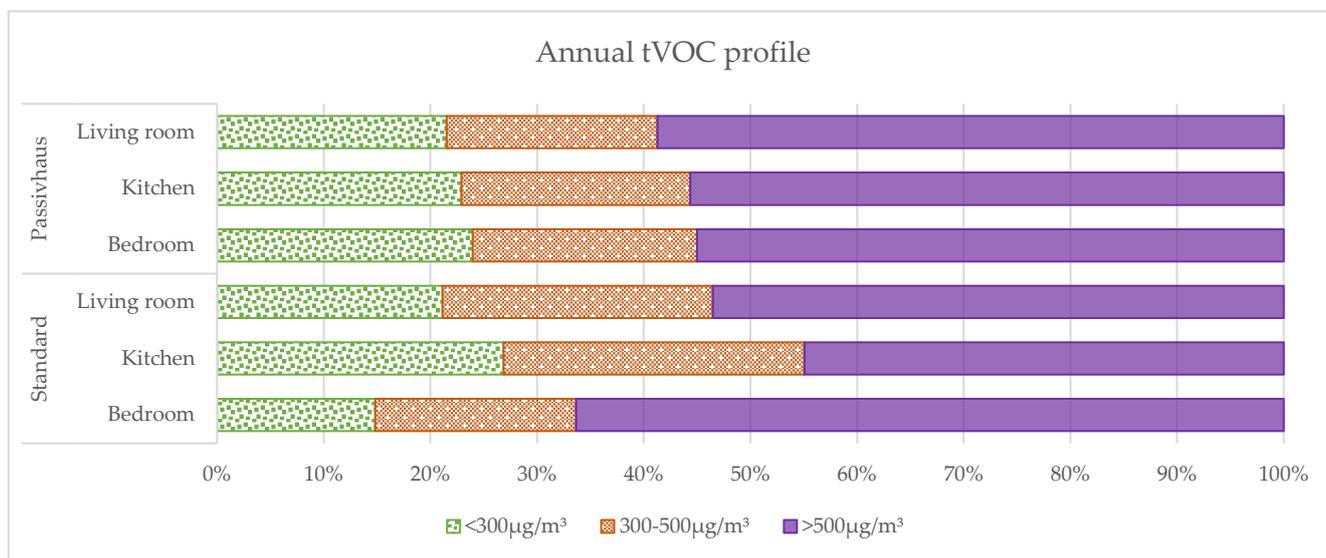


Figure 7. Annual tVOC profile in the Passivhaus and Standard dwellings. Source: Authors.

3.5. Indoor Air Quality Perception

Table 5 shows a summary of the occupants’ summer IAQ perceptions. The surveys suggest that the Passivhaus fresh–stuffy scale (M = 4.67) for the summer months was rated poorly. It showed that while occupants were satisfied overall with the IAQ conditions, they did not perceive the freshness of the air as an important factor. The survey analysis suggests that occupants from the standard home had a constant dissatisfaction (M = 4.00) with the IAQ in their home, as participants perceived the air to be stale (M = 4.67), draughty (M = 5.67), and smelly (M = 5.33).

Table 5. Statistical analysis of the IAQ perceptions during summer for both homes. Source: Authors.

IAQ Perception	Home Type	Resident	Score	Mean	SD	Mean + SD	Mean - SD	Min	Max
Fresh (1)–stuffy (7) scale	Passivhaus	R1	4	4.7	0.6	5.2	4.1	4	5
		R2	5						
		R3	5						
	Standard	R1	3	3.0	0.0	3.0	3.0	3	3
		R2	3						
		R3	3						
Dry (1)–humid (7) scale	Passivhaus	R1	4	4.0	1.0	5.0	3.0	3	5
		R2	5						
		R3	3						
	Standard	R1	4	4.7	0.6	5.2	4.1	4	5
		R2	5						
		R3	5						
Still (1)–draughty (7) scale	Passivhaus	R1	3	3.3	0.6	3.9	2.8	3	4
		R2	4						
		R3	3						
	Standard	R1	5	4.7	0.6	6.2	5.1	5	6
		R2	6						
		R3	6						
Odourless (1)–smelly (7) scale	Passivhaus	R1	1	2.3	1.5	3.9	0.8	1	4
		R2	4						
		R3	2						
	Standard	R1	5	5.3	0.6	5.9	4.8	5	6
		R2	5						
		R3	6						
Satisfactory overall (1)–unsatisfactory overall (7) scale	Passivhaus	R1	1	1.3	0.6	1.9	0.8	1	2
		R2	1						
		R3	2						
	Standard	R1	3	7.0	1.0	5.0	3.0	3	5
		R2	5						
		R3	4						

The analysis of the winter IAQ perception surveys suggests that Passivhaus occupants rated the air as stale ($M = 3.33$). However, they stated being ($M = 1.3$) satisfied overall with the IAQ. Occupants of the standard home stated the air was stale ($M = 4.67$), draughty ($M = 2.33$), and smelly ($M = 5.00$), rating all these scales poorly. This may have led the occupants to rate very poorly the overall IAQ perception ($M = 5.33$), as shown in Table 6.

Passivhaus occupants reported that they did not experience condensation on windows or doors. However, they had experienced odours coming from outdoors; this may be related to the lack of filters in the inlet. Nonetheless, participants rated the odour scale on the odourless side, suggesting that the odours were not uncomfortable. Occupants of the standard home reported condensation on windows and the presence of mould in the bathroom. They also perceived smells coming from the kitchen, toilets, laundry closet, and outdoors. A possible explanation for the indoor odours could be that the windows remain closed for prolonged periods, causing the air to be stale and stuffy, as stated in the survey scale ratings.

Table 6. Statistical analysis of the IAQ perceptions during winter for both homes. Source: Authors.

IAQ Perception	Home Type	Resident	Score	Mean	SD	Mean + SD	Mean – SD	Min	Max
Fresh (1)–stuffy (7) scale	Passivhaus	R1	4	3.3	1.2	4.5	2.2	2	4
		R2	4						
		R3	2						
	Standard	R1	5	4.7	0.6	5.2	4.1	4	5
		R2	5						
		R3	4						
Dry (1)–humid (7) scale	Passivhaus	R1	3	4.0	1.0	5.0	3.0	3	5
		R2	4						
		R3	5						
	Standard	R1	3	3.3	0.6	3.9	2.8	3	4
		R2	4						
		R3	3						
Still (1)–draughty (7) scale	Passivhaus	R1	4	3.7	0.6	4.2	3.1	3	4
		R2	4						
		R3	3						
	Standard	R1	2	2.3	0.6	2.9	1.8	2	3
		R2	3						
		R3	2						
Odourless (1)–smelly (7) scale	Passivhaus	R1	1	2.7	1.5	4.2	1.1	1	4
		R2	4						
		R3	3						
	Standard	R1	5	5.0	0.0	5.0	5.0	5	5
		R2	5						
		R3	5						
Satisfactory overall (1)–unsatisfactory overall (7) scale	Passivhaus	R1	1	1.3	0.6	1.9	0.8	1	2
		R2	1						
		R3	2						
	Standard	R1	5	5.3	0.6	5.9	4.8	5	6
		R2	6						
		R3	5						

4. Discussion

This work presents long-term indoor air quality measurements conducted alongside airflow testing of the first residential Passivhaus building in Latin America. The results suggest that, in big cities in Latin America, dwellings built to the Passivhaus standard have the potential to achieve better IAQ compared to standard dwellings. This is of particular interest, as outdoor pollution in these cities usually exceeds the recommended levels of exposure [68]. Through this study, several lessons were learned that could help to develop further the Passivhaus standard in warm/temperate climates, such as the one in Mexico City.

The approach to the ventilation system may be the most important of these lessons. While the Passive House Institute would still recommend a MVHR in these climates, this study shows that hybrid ventilation may still be a viable option. However, the mechanical component of the ventilation method still needs to provide minimum airflow rates. It is recommended to use adequate filters, to ensure the best IAQ performance. It is also recommended to provide continuous, rather than intermittent, ventilation.

The levels of indoor air pollutants at the Passivhaus dwelling were lower than those in the standard home. However, pollution peaks took longer to dissipate in the Passivhaus home. This could have been related to the fact that the standard home relied on natural

ventilation. Higher airflows helped to dissipate the air pollutants. Another potential explanation is related to the fact that the mechanical ventilation was not continuous (34 min on–26 min off). If a pollution event occurred during or close to when the fan was off, indoor air pollutants were not removed through ventilation. Similarly, indoor air pollutants, particularly tVOCs (Figure S3), in the standard home were higher during the night, when the windows were closed.

The PM_{2.5} and tVOC decay rates were lower in the Passivhaus dwelling compared to the standard dwelling, particularly those related to fine particles after cooking. The PM_{2.5} pollution decay in the Passivhaus (1.1 h⁻¹) was longer compared to the conventional home (0.24 h⁻¹) [69]. Similar to this study, a spike of PM_{2.5} was measured immediately after cooking events, but levels dropped quickly and then the peak concentrations began to decay gradually. In this study, a higher stability of PM_{2.5} levels across the different rooms was noted in the Passivhaus homes. This indicates the likely transport of particles from the source room to others, assisted by longer decay rates and doors opening/closing between spaces, facilitating further distribution of PM_{2.5}.

Filters with F7 or higher levels of filtration are designed to filter PM_{2.5} and are recommended for Passivhaus. However, their use could lead to higher fan demands, noise, filter costs, maintenance, and even energy penalties. Ventilation rates and particle sedimentation primarily influence PM_{2.5} decay rate, whereas tVOC may also depend on operative room temperature and relative humidity. However, proper ventilation remains the best way to control indoor pollution. In this study, it was observed that window opening behaviour was the most effective technique to control indoor pollution.

Further works should test at larger scale the indoor air quality alongside thermal comfort and energy performance in other Passivhaus dwellings in Latin America. Such a study could support the positive impact on the Sustainable Development Goals 03 (health and wellbeing), 07 (affordable and clean energy), and 09 (industry, innovation, and infrastructure) for Latin American countries.

This study suffered from some apparent limitations. First of all, this work presents the monitoring results of two homes that are different in typology. As the standard dwelling was a typical representation of the housing typologies in Mexico City, it was deemed appropriate for comparison. In addition, it was not possible to find another dwelling of a similar layout within an appropriate radius from the Passivhaus, so that the outdoor air pollution was similar between both dwellings. In addition, at the time of this research, there was no other Passivhaus dwellings in Latin America to conduct the study. Second, the use of low-cost monitors could represent a compromise in accuracy. In order to overcome this barrier, we installed three different monitors in each room, developed calibration equations, and tested the accuracy of the monitors in real-life settings, as suggested by [53, 55]. Third, the long-term (one year) coverage of this study made it difficult and too onerous for the participants to keep detailed activity and occupancy diaries. Therefore, the analysis was based on a general pattern. We also considered using other low-cost sensors to monitor the door/window use, but this was not economically feasible at the time of this study. Having data on the window opening could have allowed a better data analysis, but this was not feasible in this study. Finally, difference in the monitoring technologies between the indoor and outdoor air pollution sensors could represent minimal discrepancies between the readings.

5. Conclusions

This work presented the IAQ monitoring of the first Passivhaus residential dwelling in Latin America. The measurements demonstrate that the Passivhaus CO₂ and tVOC annual average levels were 143.8 ppm and 81.47 µg/m³ lower than the standard home. PM_{2.5} levels in the Passivhaus were 11.13 µg/m³ lower than the standard home and 5.75 µg/m³ lower than those outdoors. While these results give insights into the trends and relative levels air pollution, some lessons were also learned for the development of the Passivhaus in Latin America. It is possible to use a hybrid ventilation strategy to provide adequate

ventilation in Passivhaus dwellings. While the use of MVHR units could be dependent on outdoor weather conditions, it is still preferable to use them, particularly in cities with high outdoor pollution. The ventilation strategy, independent of the use of the MVHR unit, needs to run continuously to provide adequate airflow levels and, hence, adequate indoor air pollution removal.

While the results presented here cannot be generalised, the results suggest that Passivhaus dwellings have the potential to provide better and healthier indoor air quality in Latin America. Further large-scale studies should consider the indoor environmental conditions, energy performance, and dwelling design of Passivhaus dwellings in Latin America.

Supplementary Materials: The following are available online at www.mdpi.com/article/10.3390/atmos12111477/s1, Table S1. Summary of CO₂ levels in both homes; Figure S1. Standard home PM_{2.5} profile 29–30 June 2016; Figure S2. Passivhaus home PM_{2.5} profile 20–21 December 2016, Table S2. Summary of PM_{2.5} levels in both homes; Table S3. Summary of tVOC levels in both homes; Figure S3. Hourly tVOC levels in the Passivhaus and Standard dwelling's bedrooms.

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Data Availability Statement: The data for this study were part of a PhD published in 2019 [55] with an embargo until March 2024. Data could be made available upon request from the corresponding author.

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