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Case study

Indoor Fine Particle ($PM_{2.5}$) Pollution and Occupant Perception of the Indoor Environment During Summer of the First Passivhaus Certified Dwelling in Latin America

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Abstract

This study compares the only residential Passivhaus in Mexico (located in Mexico City) to a conventional building-practice home in terms of indoor environmental quality during summer, specifically indoor air quality (IAQ) and the occupants' perceptions towards it. Temperature, relative humidity, carbon dioxide, and $PM_{2.5}$ were monitored during May, June and July 2016 in the living room, bedroom and kitchen of each home. Simultaneous outdoor air measurements were collected from the local pollution monitoring network. Online surveys were used to obtain data on building-related illnesses; while occupant perception of IAQ and thermal comfort and occupant diaries helped to provide insights into occupant behavior. Results from this case study suggest that Passivhaus design strategies could help to protect building occupants from outdoor air pollution, based on the lower concentrations of $PM_{2.5}$ that were found in the Passivhaus apartment compared to the external environment. This contrasted with the results of the control home where $PM_{2.5}$ levels were higher than ambient levels. Whilst the results cannot be generalized, they do provide much needed evidence on the indoor environmental performance of a Passivhaus-certified dwelling in Latin America, highlighting areas for improvement and providing recommendations to help inform future developments adopting these principles in a subtropical highland climate.

Nomenclature

%RH	Relative humidity percentage
BREAAM	Building Research Establishment Environmental Assessment Method
BSI_5	Building Symptom Index, based in 8 SBS
BSI_8	Building Symptom Index, based in 5 SBS
CO	Control apartment
CO_2	Carbon dioxide
h_e	Time in hours
IAQ	Indoor air quality
NAMA	Nationally Appropriate Mitigation Actions
PH	Passivhaus apartment
$PM_{2.5}$	Particulate matter 2.5 μm
PSI_5	Personal Symptom Index, based on 8 SBS
PSI_8	Personal Symptom Index, based on 5 SBS
SBS	Sick Building Syndrome
T_{max}	Maximum temperature
T_{min}	Minimum temperature
T_{od}	Temperature of the previous day
T_{rm}	Outdoor running mean temperature
W_e	Weighted exceedance
WF	Weighting factor
ΔT	Difference between operative temperature and maximum temperature

1. Introduction

Interest in the influence of the indoor environment on human health in energy efficient dwellings is growing, especially with regard to indoor air pollution **[1]**. However, many of the studies conducted on low-energy buildings tend to focus on energy consumption **[2]** and thermal comfort **[3]**. Research investigating the impact of energy efficient design strategies on indoor environmental quality remains lacking **[4]** and, moreover, an absence of knowledge and skills **[5]** for design decision-making makes it harder to understand their impact. Despite this, research suggests that increased airtightness of building envelopes, low ventilation rates, use of new ventilation technologies and new building materials may diminish the quality of the indoor environment **[6]** if they are not adequately considered.

Few studies have examined the trade-off between energy efficient buildings and human health **[7]**. For instance, limited data are available to contrast the indoor air quality (IAQ) of low-energy dwellings with similar dwellings built using standard building practices. Indoor pollutants such as particulate matter 2.5 μm ($PM_{2.5}$) may impact human health causing respiratory problems, irritation and reddened eyes, runny noses, cancer, cardiovascular problems **[8]**–**[11]** and hypertension **[12]**. $PM_{2.5}$ can penetrate deep into the human respiratory system causing increases in hospital admissions and premature deaths **[13]**. In buildings, indoor sources of $PM_{2.5}$ pollution are varied and could be related to either building materials and human activities and behavior **[14]**. As concern for the effects of $PM_{2.5}$ on human health increases **[15]**, especially in the case of residential buildings **[4]**, different thresholds have been set for $PM_{2.5}$ exposure. One of the most accepted was proposed by the World Health Organization (WHO), indicating that levels above 25 $\mu g/m^3$ are considered harmful to human health **[13]**.

There is a scope for studies to focus on comparing IAQ of low-energy buildings as alike as possible to "conventional" buildings, excluding building elements related to energy efficiency **[16]**. There is a significant need for indoor air quality research in contemporary energy efficient dwellings, especially in polluted urban environments, where indoor air pollution of outdoor origin may have a bigger impact on human health.

Few studies have investigated indoor air pollution in contemporary housing. One study that investigated indoor air quality in eight new-build homes in the UK, both mechanically and naturally ventilated, found that both housing types had inadequate IAQ and thermal comfort, and that the ventilation system was not capable of ensuring adequate ventilation. Problems with maintenance of the ventilation systems were also identified **[6]**. Another study focused on assessing the approach to IAQ of different building certifications and standards, such as BREAAM multi-residential, BREAAM EcoHomes, BREAAM Domestic Refurbishment, the Code of Sustainable Homes, and Passivhaus. It concluded that all ignore fundamental strategies for protecting human health and well-being **[17]**. The Passivhaus concept is an evolution of passive solar architecture and super-insulated homes developed in Sweden. Sweden's national interest to reduce space heating and improve the U-values of the building fabric, windows and doors is evident in the Swedish SBN1975 Building code. Bo Adamson investigated the trade-offs from super-insulated buildings compared to conventional central heating systems in Swedish homes from the 1960s. Such experimentations would become associated with the Passivhaus standard **[18]**.

The actual term of Passivhaus was forged from a research idea between Professor Bo Adamson from Lund University (Sweden) and Professor Wolfgang Feist from the Institute for Housing and Environment (Germany) in 1988 **[19]**. In 1990, derived from those experiments, the first Passivhaus dwellings were built in Darmstadt, Germany and later in 1996 the Passive House Institute was established. A Passive House or Passivhaus, the original German term, is **[20]** "*a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass[1], which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air*." In the present study, the term "Passivhaus" adheres to the above definition. This distinction is made as the words "passive house" could also refer to buildings that use passive or solar design techniques to achieve low-energy consumption or higher indoor environmental quality, while not necessarily adopting the solutions or certification for the Passivhaus standard.

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[1] As defined by the DIN1946, the Passivhaus definition by the PHI does not include the DIN1946. However, ventilation calculations are based on this German standard of ventilation.

Studies have looked at how increased levels of airtightness required for low-energy homes, including Passivhaus, can be a problem if indoor pollution sources are not adequately addressed and if there is insufficient ventilation. For instance, airtight homes with less than 5 $m^3/m^2/h$ @50Pa that rely on trickle vents for background ventilation may result in IAQ issues **[21]** related to problems in the design, construction and operation of the ventilation strategies **[22]**.

Low-energy homes are relatively new in Mexico. The NAMA project for Sustainable Housing in Mexico in 2013 **[23]**, **[24]** and policies such as sustainable building/environmental criteria and minimum requirements (NMX-AA-164-SCFI-2013) **[25]** are part of the Mexican government's efforts to combat climate change. Studies in Mexican low-energy homes tend to be more focused on energy consumption **[26]**, **[27]**, carbon dioxide (CO_2) emissions **[28]** and urban planning **[29]**. Moreover, air pollution studies have been focused on outdoors rather than indoors **[12]**, **[30]**–**[35]**; and studies conducted on IAQ often examine schools, offices or non-energy efficient buildings for their impact on health **[36]**–**[38]**. While studies on thermal comfort in Mexican dwellings are commonplace **[39]**, **[40]**, there remains insufficient evidence of thermal comfort in energy-efficient homes.

This study aims to (a) investigate the indoor air quality of the first Passivhaus in Mexico City during summer and (b) to compare the results with a home built with standard practices but otherwise alike as possible to the Passivhaus. This study was conducted through physical IAQ measurements with low-cost monitors, alongside occupants' diaries, in a Passivhaus and a conventional building practice home. Online surveys were supplied to gain information on building characteristics and occupant perceptions of indoor air quality, presence of Sick Building Syndrome (SBS) symptoms, thermal comfort perception and occupant behavior. This paper discusses the methodological approach, presents the results of the study and discusses their implications. Finally, further research opportunities and conclusions are described.

2. Methodology

A quantitative approach to a case study **[41]** was adopted to examine IAQ in a certified Passivhaus apartment in Mexico. This approach includes investigations into the effect of occupant behavior on IAQ, the performance of the ventilation strategies, building related illnesses and perception of the indoor environment.

The case study is limited to one Passivhaus and one conventional building practice home (control home). Both meet the following criteria: occupancy of 2 adults, vertical residences on second floor (apartments), similar location, and close to local air pollution monitoring (< 1 km). Each of the occupants were approached by the designer of the Passivhaus dwelling (INHAB), followed by a visit to explain the study. Air quality data were simultaneously recorded every five minutes in the living room, main bedroom and kitchen during the summer of 2016 (May-July). Occupant diaries were supplied to obtain information on activities which might influence the results, such as fluctuations in occupancy.

Physical IAQ measurements were conducted in accordance with the ASTM Volume 11.07 Air Quality - D7297-14 - Standard Practice for Evaluating Residential Indoor Air Quality **[42]**. The monitored parameters included temperature, relative humidity, CO_2, and $PM_{2.5}$. A series of three Foobot (temperature ±0.4 °C, humidity ±4.0 %RH, $PM_{2.5}$ ±4 $\mu g/m^3$ or ±20 %) and three Netatmo (temperature ±0.3 °C, humidity ±3.0 %RH, CO_2 ±50 ppm or 5%) devices were installed in each room and to eliminate any bias caused by the equipment, the accuracy of the monitors was tested in a previous publication **[43]**. The mean from the three devices in each room was used as suggested, together with the calibration equations in order to reduce possible bias and improve the accuracy and robustness by repetition and corroboration of the measurements. The use of three devices in each room not only allowed increased spatial resolution, but also reduced uncertainty as the measurements of each monitor were compared to each other avoiding variation of pollutant concentrations by the sensors of each device. The individual measurements of each individual monitor (Netatmo and Foobot) were compared to GrayWolf monitors (IQ-410, PC-3016A, and TG-502 TVOC) previous to the setup from which calibration equations were derived, thus reducing the bias for the accuracy of the sensors. These calibration equations were applied to the measurements of each individual monitor. Outdoor measurements were downloaded from the closest monitoring point (HGM station) on Mexico City's local pollution monitoring network (REDMET and RAMA).

Information on the building characteristics, occupant perception of IAQ and the indoor environment, and building-related health problems was collected using a respondent-friendly self-administrated **[44]**–**[46]** online survey. These questionnaires were designed using validated procedures **[14]**, **[42]**, **[47]**–**[50]**; one questionnaire was applied for building characteristics and three for occupant perception in each household. The data was exported to Excel for initial inspection and then to SPSS for statistical analysis.

2.1 Building and household characteristics

The Passivhaus (PH) (**Figure 1**A) and the control home (CO) (**Figure 1**B) are located in Mexico City, within 280 m of each other. They are one and two-bedroom apartments respectively, with no central heating systems installed. The Passivhaus uses an extraction fan as a ventilation system, achieving a total airflow of 42 m^3/h (11.66 l/s), whereas the standard apartment relies completely on passive ventilation in the form of window opening. According to the surveys, none of the participants smoke indoors. **Table 1** shows the main characteristics of both apartments.

2.2 Building construction

Both dwellings are located in a residential area in *Delegación Cuauhtémoc*, Mexico City. Dwelling construction and energy efficiency are presented in **Table 2**.

Figure 1: Facade of the PH (A) and CO (B) apartments in Mexico City.

Table 1: Household characteristics.

Household profile	PH	CO
No. occupants	2 adults, 1 baby	2 adults, 1 child
Cooking fuel	Electric	Gas
Heating fuel	--	Electric (when needed)
No. of smokers	1	1
Cigarettes ever smoked at home	No	No
Mean hours occupied during weekdays	18	15
Mean hours occupied during weekends	16	13

Table 2: Building characteristics.

Building characteristic	PH	CO
Airtightness (q50)	0.59 $m^3/h*m^3$	Never tested
Floor area	42 m^2	70 m^2
Main door	PVC (Passivhaus certified)	Wood (standard)
U_g-value (window)	1.64 $W/(m^2K)$	5.78 $W/(m^2K)$
U-value (floor slab)	0.33 $W/(m^2K)$	1.37 $W/(m^2K)$
U-value (roof)	0.36 $W/(m^2K)$	1.37 $W/(m^2K)$
U-value (wall)	0.37 $W/(m^2K)$	1.18 $W/(m^2K)$

3. Results

3.1 Particulate Matter 2.5 results

The $PM_{2.5}$ levels were usually lower in the PH than the CO (as illustrated in **Table 3**). High levels of $PM_{2.5}$ (> 25 μg/m^3) **[13]**, **[51]**) were recorded in both homes. However, when averaged, levels in the PH (M=17.87 μg/m^3) remain lower than the recommended guidelines of 25 μg/m^3, whereas those in the CO (M=26.24 μg/m^3) exceeded this level. Figure 2 compares $PM_{2.5}$ levels over a week (in July) in the living rooms of both dwellings and the outdoors. Mean $PM_{2.5}$ in the living room in the PH (M=18.40 μg/m^3) remained below that of the CO (M=25.30 μg/m^3); similar results were found throughout the three months of the study in the bedrooms, kitchens and living rooms. The difference between indoor and outdoor levels suggests that the PH ventilation strategy may provide some level of protection, as it appears to dissipate the pollution adequately over an extended period of time due to controlled airflow levels and high levels of airtightness. Ambient $PM_{2.5}$ concentrations may have an impact on indoor levels, as it was observed that indoor $PM_{2.5}$ levels raised above the background levels on some occasions, especially when combined with indoor pollution events. This suggests that the ventilation strategy of the PH offers some protection against exposure to ambient $PM_{2.5}$, though could be improved further with better air filtration. Peaks in levels of $PM_{2.5}$ in the CO were found to be associated with cooking episodes, however a close relation to background levels was also noticed. Noise problems from the ventilation system were identified in the PH, where occupants reported turning the system off at night due to the constant background noise.

3.2 Carbon dioxide results

Night time recorded CO_2 levels in the Passivhaus dwelling exceeded the recommended level of 1,000 ppm during the month of July. However, in the control house (CO), levels exceeded this threshold in all three monitored months. Specifically, peak levels above 3,000 ppm were recorded in the control house (CO) bedroom during the nights in June and July, and above 2,000 ppm during May. Significantly higher peak levels (> 2,000 ppm) were observed in the CO, peaking up to 3,202 ppm in the bedroom at night. As illustrated in **Figure 3**, CO_2 concentrations in the bedrooms were significantly higher during the night periods when the apartments were reported occupied. Significantly high carbon dioxide levels (> 2,000 ppm) were recorded in the control house (CO) bedroom on three nights, with PH bedroom levels below the recommended guideline (1,000 ppm) **[52]**, **[53]** (see **Table 4**). Mean CO_2 levels were considerably higher in the bedroom of the control house (CO) than the other rooms. This suggests major problems with ventilation in the main bedroom, as there is no ventilation strategy for the night (in situations where the windows are typically closed) and therefore no possibility to dissipate the CO_2.

Table 3: Statistical analysis of the $PM_{2.5}$ ($\mu g/m^3$) levels of the PH and CO in Mexico City.

Statistical Analysis	PH									CO								
	May			June			July			May			June			July		
	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed
Max	68.0	110.5	144.2	54.8	48.2	43.4	146.6	121.6	133.1	150.8	192.6	285.4	249.7	106.9	106.3	226.2	248.8	119.2
Min	7.2	8.8	9.4	4.2	2.8	3.9	4.0	3.7	2.5	19.7	18.5	15.6	8.6	9.9	11.8	8.6	9.1	7.5
Mean	21.4	24.5	23.0	13.4	14.4	15.8	17.1	16.3	15.0	34.3	33.0	31.5	23.9	21.1	25.2	22.0	21.8	23.3
Standard Dev.	9.2	9.2	9.7	6.6	6.7	6.3	13.4	13.1	13.1	11.1	14.2	16.1	14.4	9.0	12.5	15.8	13.5	15.6
Outdoor –Indoor difference	11.9	8.7	10.2	7.9	6.9	9.2	0.6	1.4	2.7	-1.1	0.2	1.7	-2.5	0.1	-1.7	-4.3	-4.1	-5.6
Kit= kitchen, Liv= Living room, Bed= Bedroom																		

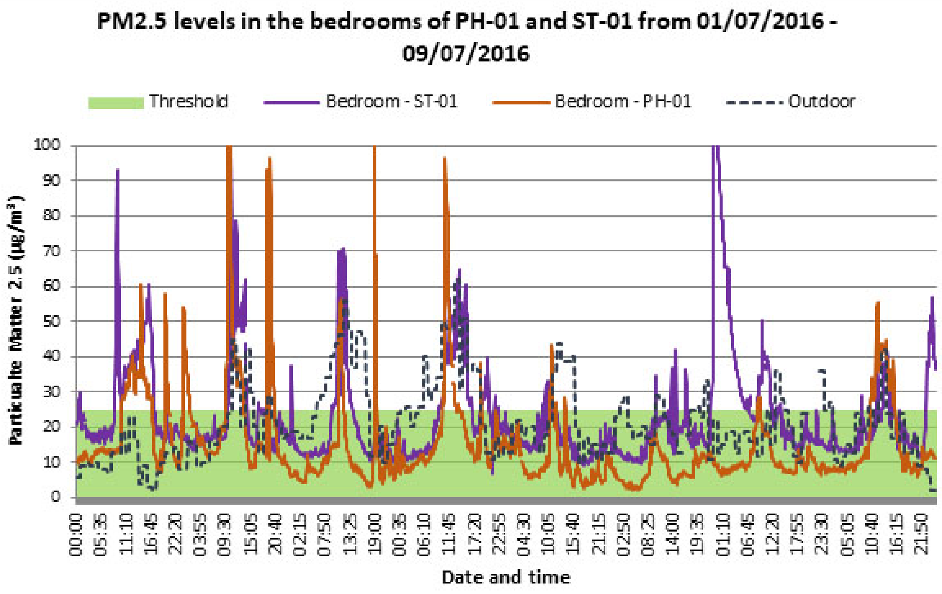

Figure 2: Indoor and outdoor $PM_{2.5}$ concentrations in the living rooms at PH and CO (01-09/07/2016).

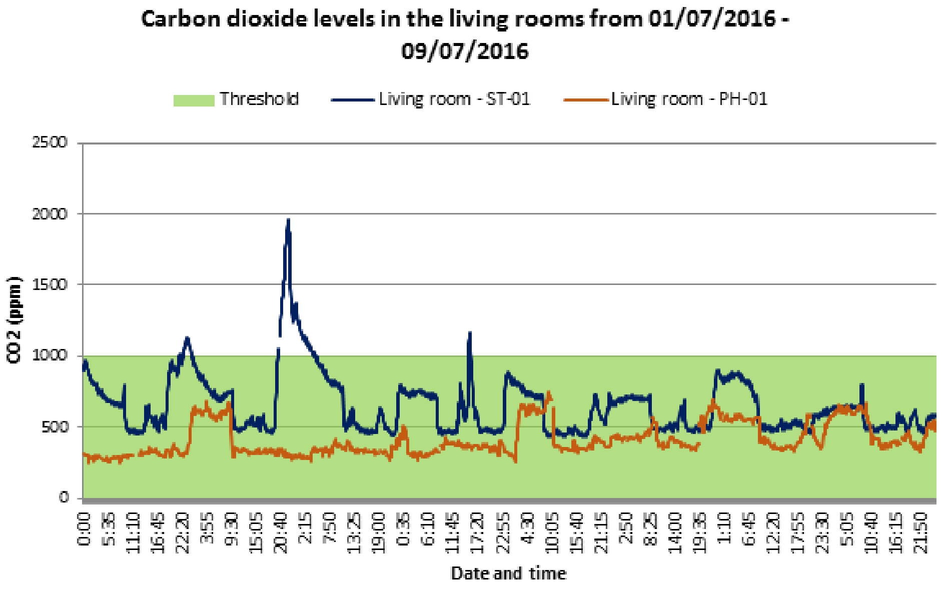

Figure 3: Carbon dioxide concentrations in the bedroom of the PH and CO in Mexico City (01-09/07/2016).

Table 4: Statistical analysis of the $PM_{2.5}$ ($\mu g/m^3$) levels of the PH and CO in Mexico City.

Statistical Analysis	PH									CO								
	May			June			July			May			June			July		
	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed
Max	685	685	779	1431	1431	1604	752	752	633	1115	1115	2167	1135	1135	3064	1964	1964	3202
Min	225	225	247	252	252	218	251	251	210	446	446	472	428	428	436	439	439	424
Mean	363	363	370	479	479	441	411	411	340	587	587	964	593	593	971	653	653	1037
Standard Dev.	83	83	100	190	190	208	113	113	112	587	587	437	136	136	412	209	209	504

3.3 Temperature results

The criteria for calculating overheating are based on the Passivhaus, CIBSE and the Adaptive approach. Passivhaus defines overheating with a static criterion of greater than 25 °C of temperature for ≥ 10 % of the time) **[54]** equal to the one set by the Mexican government **[25]**. On the other hand, CIBSE defines overheating as greater than 25 °C in temperature for > 5 % of the time, and/or greater than 28 °C for more than 1 % of the time **[55]**. The adaptive approach is based on the CIBSE TM52 category II **[55]**:

Upper limit:

$$T_{max} = 0.33T_{rm} + 18.8 + 3 \quad (1)$$

Lower limit:

$$T_{min} = 0.33T_{rm} + 18.8 - 3 \quad (2)$$

Where T_{rm} represents the outdoor running mean temperatures from 7 days before the monitored period and is calculated as follows:

$$T_{rm} = T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7} \quad (3)$$

$$T_{rm} = (1 - \alpha)\, T_{od-1} + \alpha T_{rm-1} \quad (4)$$

and is based on the following three criteria **[56]**:

- Hours of expedience: limits the number of hours (> 3 % of the time) that the operative temperature can exceed the maximum acceptable temperatures.

$$\Delta T \leq 1\ °C \quad (5)$$

- Daily weighted exceedance (W_e): limits the severity of overheating in any one day (W_e ≤ daily limit).

$$W_e = \sum (h_e \times WF) \quad (6)$$

$$\square\ W_e=(h_{e0} \times 0)+(h_{e1} \times 1)+(h_{e2} \times 2) \quad (7)$$

Where $WF = \Delta T$ and h_{ey} is the time in hours.

- Upper temperature limit: limits the maximum daily temperature for a building ($\Delta T \leq 4$ °C) at any time.

Therefore, this study considers that a room may suffer from overheating when the temperature exceeds the limits of two of these criteria.

As shown in **Table 5**, living room temperatures peaked at 29.45 °C in the PH during May. High temperatures were also observed in the bedroom and the kitchen during the same month exceeding both Passivhaus and CIBSE thresholds for overheating, suggesting the need for further study during the spring season. On the other hand, peak temperatures in the CO ranged between 24.36 °C and 27.07 °C during May, exceeding the Passivhaus overheating threshold in the living room and the kitchen. Mean temperatures in the PH ranged from 25.01 °C to 25.73 °C and in the CO from 21.91 °C to 24.52 °C. On the online surveys, participants indicated general satisfaction with their thermal comfort on both apartments, despite stating that on some occasions it gets too warm. **Table 6** and **Table 7** show the assessment of overheating according to the static and adaptive criteria.

Table 5: Statistical analysis of the temperature (°C) concentrations of the PH and CO in Mexico City.

Statistical Analysis	PH									CO								
	May			June			July			May			June			July		
	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed	Kit	Liv	Bed
Max	29.3	29.4	27.6	24.7	25.2	23.5	25.7	25.0	24.0	27.1	25.5	24.4	23.3	22.6	24.1	23.2	23.2	24.0
Min	20.6	19.1	20.8	20.2	18.9	20.1	20.1	19.3	21.9	21.7	20.2	20.3	20.3	19.5	22.0	20.3	19.0	21.9
Mean	25.7	25.0	25.1	22.4	21.3	22.0	22.4	22.0	22.0	24.5	23.8	21.9	21.7	21.4	23.2	21.9	21.5	23.0
Standard Dev.	2.1	2.4	1.7	0.9	1.6	0.6	1.2	1.2	0.4	1.3	1.0	0.9	0.7	0.7	0.4	0.7	0.7	0.4

Kit= kitchen, Liv= Living room, Bed= Bedroom

Table 6: Overheating status during summer based on static criteria.

House	Passivhaus and Mexican									CIBSE									CIBSE								
	>10 % >25 ºC									>5 % >25 ºC									>1 % >28 ºC								
	May			June			July			May			June			July			May			June			July		
	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K
PH	•	•	•							•	•	•								•	•						
CO	•	•	•								•	•															

Table 7: Overheating status during summer based on adaptive criteria.

House	Adaptive method																										
	Criterion 1									Criterion 2									Criterion 3								
	May			June			July			May			June			July			May			June			July		
	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K	B	L	K
PH		•																									
CO																											

3.4 Relative Humidity results

Levels of relative humidity were observed above the recommended 60 %RH across the rooms during June and July, with mean levels ranging from 44.4 %RH to 58.1 %RH in both homes (**Table 8**). Levels above 70 %RH were observed in the PH during June only, and during June and July at the CO, which indicates conditions that could result in mold growth **[57]**, **[58]**. This corresponds to the online surveys in which the CO occupants reported the presence of mold in the last 12 months.

3.5 Indoor air quality perception

Occupants were asked to rate the IAQ in their homes, using a rating scale of seven points. The scales were either unipolar (one extreme good, the other bad) or bipolar (the center as ideal) depending on the variable as suggested by Raw **[50]**:

- Unipolar scale: ideal score: 1. A score higher than 3 requires further investigation and a score above 5 is cause for concern. Any score greater than the mean should be investigated further and any figure above one standard deviation above the mean should be cause for concern. The unipolar scales are fresh-stuffy, odorless-smelly, overall satisfactory-overall unsatisfactory, comfortable-uncomfortable, and stable-varies during the day.
- Bipolar scale: ideal score: 4. A score outside the range 3-5 requires further investigation, a score outside the range 2-6 is cause for concern. Any figure above or below one standard deviation from the mean should also be cause for concern. The bipolar scales are dry-humid, still-draughty, and temperature (too hot-too cold).

The scales rate the air in terms of freshness (fresh-stuffy), dryness (dry-humid), odors (odorless-smelly), air movement (still-draughty), and overall satisfaction (overall satisfactory-overall unsatisfactory). The mean score of the PH for the fresh-stuffy scale (M=4.67) suggests that further investigation is required. The occupants were generally satisfied with the conditions of the PH on the whole, even though they did not perceive the air to be particularly fresh. The mean at the CO for the movement scale (M=5.67) requires further investigation, whereas the odor scale (M=5.33) and the overall satisfaction scale (M=4.00) indicate cause for concern. This suggests a constant dissatisfaction with the IAQ in the CO as participants perceived the air to be either draughty or stuffy, in particular, perception of odors and overall satisfaction was poor (see **Table 9**).

Table 8: Statistical analysis of the relative humidity (%RH) concentrations of the PH and CO in Mexico City.

Statistical Analysis	PH									CO								
	May			June			July			May			June			July		
	K	L	B	K	L	B	K	L	B	K	L	B	K	L	B	K	L	B
Max	54.2	60.1	53.4	71.3	73.8	69.4	65.6	68.9	65.2	54.8	60.3	56.9	75.0	72.3	62.3	70.4	74.4	63.9
Min	30.5	28.3	35.0	43.6	43.6	46.1	39.8	41.4	42.7	31.7	33.5	32.4	42.4	40.7	38.4	44.1	44.1	43.6
Mean	44.4	45.7	45.8	55.9	57.6	56.8	55.3	56.1	56.3	46.0	47.7	47.5	57.1	57.6	54.2	56.9	58.1	56.3
Standard Dev.	4.3	5.6	3.2	4.8	6.4	4.1	5.2	5.0	4.1	4.8	5.1	5.1	5.7	6.5	4.3	4.8	5.3	4.3

Table 9: Statistical analysis of the IAQ perception of the PH and CO in Mexico City.

IAQ perception scale	House	Mean	SD	Mean + SD	Mean - SD	Max	Min
Fresh-stuffy scale	PH	4.67	0.58	5.24	4.09	5.00	4.00
	CO	3.00	0.00	3.00	3.00	3.00	3.00
Dry-humid scale	PH	4.00	1.00	5.00	3.00	5.00	3.00
	CO	4.67	0.58	5.24	4.09	5.00	4.00
Still-draughty scale	PH	3.33	0.58	3.91	2.76	4.00	3.00
	CO	5.67	0.58	6.24	5.09	6.00	5.00
Odorless-smelly scale	PH	2.33	1.53	3.86	0.81	4.00	1.00
	CO	5.33	0.58	5.91	4.76	6.00	5.00
Overall satisfactory - overall unsatisfactory scale	PH	1.33	0.58	1.91	0.76	2.00	1.00
	CO	4.00	1.00	5.00	3.00	5.00	3.00

3.6 Thermal comfort perception

As with IAQ perception, participants were asked to complete online thermal comfort surveys using seven point rating scales, with unipolar and bipolar scales using the scoring system suggested by Raw **[50]**. The scales rate the thermal perception in terms of comfort (comfortable-uncomfortable), temperature (too hot-too cold), condition (stable-varies during the day), and overall satisfaction (satisfactory overall-unsatisfactory overall).

Results from both the PH and CO were generally satisfactory. In fact, both apartments have equal results in the temperature scale (M=3.67). However, small differences were observed between the comfort scales (PH, M=2.00; CO, M=1.67), condition scales (PH, M=2.67; CO, M=2.33), and overall satisfaction (PH, M=2.00; CO, M=1.67). These scores suggest that thermal comfort is similar in both homes, possibly due to the adaptive comfort and the option to control the indoor environment (**Table 10**).

3.7 Personal and Building Symptom Index perception

Table 11 shows the Building Symptom Index (BSI5 and BSI8) for both the PH and CO. It is clear that the occupants of the PH reported significantly less Sick Building Symptoms (SBS) than those residing in the CO. The high prevalence of SBS for occupants in the CO is a cause for concern and further investigation may be required to identify the cause(s). BSI5 represents five symptoms: blocked or stuffy nose, dry throat, dryness of eyes, headache and lethargy and/or tiredness; the BSI8 also includes dry, itching or irritated skin, itchy or watery eyes, and runny nose and they were assessed based on a validated methodology **[59]**. **Figure 4** illustrates the prevalence of SBS symptoms in the PH and CO apartments.

Table 10: Statistical analysis of the thermal comfort perception of the PH and CO in Mexico City.

Summer							
Thermal perception	**House**	**Mean**	**SD**	**Mean + SD**	**Mean - SD**	**Max**	**Min**
Comfortable-uncomfortable scale	PH-01	2	1	3	1	3	1
	ST-01	1.667	0.58	2.24	1.09	2	1
Too hot-too cold scale	PH-01	3.667	0.58	4.24	3.09	4	3
	ST-01	3.667	0.58	4.24	3.09	4	3
Stable-varies during the day scale	PH-01	2.667	1.15	3.82	1.51	4	2
	ST-01	2.333	0.58	2.91	1.76	3	2
Satisfactory overall-unsatisfactory overall scale	PH-01	2	1	3	1	3	1
	ST-01	1.667	0.58	2.24	1.09	2	1

Table 11: Scores for Personal Symptom Index (PSI) and Building Symptom Index (BSI).

Participant	PH			CO		
	Occupant A	Occupant B	Occupant C	Occupant A	Occupant B	Occupant C
Average PSI_5	3	0	0	6	5	7
Average PSI_8	3	0	2	4	3	5
Average BSI_5	1.00			4		
Average BSI_8	1.66			6		

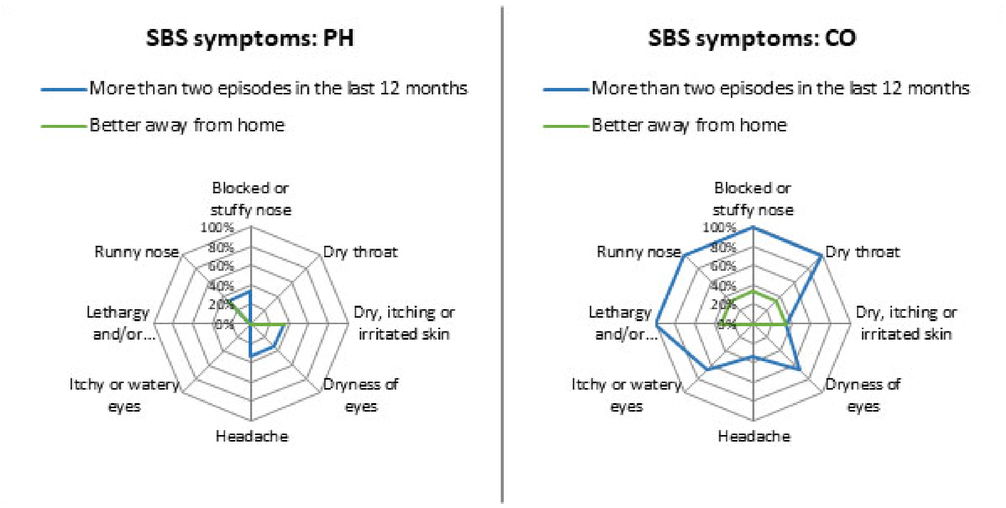

Figure 4: Presence of SBS in the PH and CO in Mexico City.

4. Discussion

PM 2.5 peaked above the recommended 25 µg/m^3 in all months at the PH (Max 146.61 µg/m^3) and CO (Max 285.36 µg/m^3). However, PM$_{2.5}$ concentrations were generally lower in the PH, with mean concentrations higher in the CO dwelling compared to the PH. It was also observed that PM$_{2.5}$ levels in the CO were similar to those found outdoors.

Statistical analysis shows that there is a significant correlation (<0.01) between indoor measurements in both homes and outdoor levels. Nevertheless, significant differences between indoor and outdoor PM$_{2.5}$ concentrations were found. For instance, PH bedroom PM$_{2.5}$ levels (M=17.84 µg/m^3, SD=11.58) were lower than the outdoor levels (M=26.43 µg/m^3, SD=13.72) by 8.59 µg/m^3 (r= 0.489); whereas in the CO PM$_{2.5}$ levels in the bedroom (M=26.80 µg/m^3, SD=14.99) were found to be higher than outdoors (M=25.49 µg/m^3, SD=13.32) by 1.30 µg/m^3. Similar results were observed in the kitchen and the living room.

These results suggest that whilst the ventilation strategy of the CO may be adequate to dissipate air pollution of indoor origin, a trade-off may exist whereby concentrations of pollutants of outdoor origin increase due to increased ventilation levels. On the other hand, the PH in this study was found to be more effective at filtering outdoor pollution, yet indoor pollution appeared to take longer to dissipate due to lower airflows. During the measurement period, high levels of window opening were recorded in the CO, whereas in the PH windows were only open during cleaning and a few other occasions, as stated by the occupants.

Carbon dioxide levels peaked above 1,000 ppm in the living room, kitchen and bedroom during June in the PH and constantly in all rooms at the CO in all months. Levels above 2,000 ppm were observed in the bedroom in May; during June and July levels reached above 3,000 ppm at the CO. These results suggest significant problems with ventilation, therefore improvement of the ventilation strategy is highly recommended, especially in bedrooms at night. Standard building practices in Mexico do not contemplate the use of trickle vents. However, small windows are a common ventilation practice and perhaps a better practice, as on many occasions trickle vents may provide inadequate ventilation **[21]**.

Overheating was found in the PH during May, as it failed the Passivhaus and CIBSE static criteria for overheating. However, when assessing overheating with the Adaptive approach, it only fails in the PH living room during May. These results suggest that the PH is warmer than the CO, which might be beneficial during winter as heating was due to internal gains and building elements rather than radiators. Temperature measurements peaked at 29.26 °C in the PH and 27.07 °C in the CO dwelling, when outdoor temperatures reached 27.20 °C. Neither the PH or the CO used any active cooling strategy for temperature control during the measurement period. In theory, the PH should provide adequate protection from overheating as it is well insulated, but also has solar shading in the windows exposed to the sun. However, if overheating control is not well addressed from the design process, i.e. control of indoor heat sources, higher temperatures may be observed **[56]**, **[60]**–**[63]**. Overheating in UK social housing apartments built to Passivhaus standards has already been identified **[56]**. If overheating is not well addressed, it might cause health problems and peak pollution concentrations **[60]**.

Relative humidity levels rose to 70 % RH in the CO during June and July, which supports the result of the online surveys as occupants reported the presence of mold in the last 12 months. Relative humidity levels above 60 %RH were recorded in the PH during June and July. However, mean levels remained between the recommended levels of 30-60 %RH, whereas outdoor levels reached 80 %RH. Thus, outdoor conditions did not have a significant impact on the results. On the other hand, it was noticed that occupancy had an impact on RH similar to CO$_2$. The presence of the ventilation system in the PH may, therefore, have contributed to lower the humidity as RH levels were consistently lower in the PH dwelling in general.

Results from the occupant surveys suggest problems with the perception of IAQ in both apartments. Surprisingly, overall satisfaction of IAQ was rated as satisfactory in the PH, even where occupants expressed poor perception of air freshness; suggesting that the PH occupants did not consider the freshness of air influential or important to the overall air quality. On the other hand, the occupants of the CO stated overall dissatisfaction with the IAQ; this is supported by the other parameters, since the odor and draught scales were causes for concern and the dryness and freshness of the air were identified as significant issues.

Sick Building Syndrome Symptoms (SBS) were reported for the three occupants in each apartment. The Building Symptom Index (BSI) was taken from the mean values of the Personal Symptom Index (PSI). The BSI8 for the CO was 6 and for the PH 1.66, whereas BSI5 was assessed to 4 for the CO and 1 for the PH, suggesting a high prevalence of SBS in the CO. Consequently CO households recorded an average of 4 SBS (BSI5) per person.

Results indicate that the higher prevalence of SBS, higher levels of $PM_{2.5}$, CO_2 and lower IAQ satisfaction scores converge in the CO. This suggests that improvements to the Passivhaus standard, when achieved correctly, may ensure the provision of higher indoor environment quality and an additional layer of protection against outdoor pollution, resulting in a healthier indoor environment.

Finally, some problems were identified in the PH: maintenance of the ventilation system, air filtration and noise. Solving them could help to provide even higher environmental quality. Maintenance and air filtration are closely related to each other. The owner understands the importance of air filtration, however the F7 Filters, suggested by the Passivhaus Institute, were removed and air filtration was not possible. This was due to the difficulties in replacing such filters periodically as they are difficult to find in Mexico, but moreover, replacement of the filters may require specialised training to access the inlet (**Figure 5**a) to change the filter and recalibrate the airflows to the $42m^3/h$ required. Furthermore, the extractor fan (**Figure 5**b) is inaccessible for cleaning. Background noise was another issue as participants admitted to turning off the ventilation system at night for this reason. Moreover, the extractor fan may remain deactivated during the day at times where the occupants forget to turn it back on again in the mornings. If airtightness is to be achieved in Mexican dwellings in the future, special attention should be paid to the ventilation, not only to provide better indoor spaces but for the protection of the building itself.

Further lines of inquiry could be focused on comparing the PH and the CO when unoccupied to assess the building elements without the bias of occupant behavior and if possible consider the impact of filter quality and maintenance on indoor $PM_{2.5}$ levels in the PH.

5. Conclusion

This study investigated the impact of the Passivhaus standard in the context of a Mexican dwelling. However, due to the limited number of study cases in Mexico (just one Passivhaus at the time of writing), it is not possible to generalise the results. Nevertheless, findings suggest that improvement to the indoor environment and specifically the indoor air quality can be achieved with the implementation of the Passivhaus standard in Mexico City. For instance, low levels of $PM_{2.5}$ and low concentrations of CO_2 were observed in the Passivhaus.

Recorded levels of $PM_{2.5}$ in the CO dwelling were found to be higher than outdoors ($\Delta M_{outdoor\text{-}indoor}$ bedroom 1.30 $\mu g/m^3$, living room 0.01 $\mu g/m^3$, and kitchen 0.79 $\mu g/m^3$); whereas the PH concentrations were lower than outdoors ($\Delta M_{outdoor\text{-}indoor}$ bedroom 8.59 $\mu g/m^3$, living room 6.94 $\mu g/m^3$, and kitchen 8.06 $\mu g/m^3$) despite the high levels of airtightness. Despite this, particular problems with the ventilation system were identified, such as the background noise, maintenance issues and lack of air filtration, which if solved could help to further reduce the pollution coming from outside.

Levels of CO_2 in the Passivhaus dwelling suggest that the ventilation rates are adequate, as the background levels were below those recommended by guidelines, peaking in rare occasions above 1,000 ppm. CO_2 levels in the CO were significantly above the recommended levels, rising above 2,000 ppm on several occasions.

Overheating was identified during May using the static criteria in both homes, wheras the dynamic criteria did not identify overheating as a problem in either dwelling, though the Passivhaus recorded warmer temperatures. Further investigation is required as the occupants of the CO stated feeling uncomfortable during winter.

Figure 5: Inlet (A) and extractor fan (B) of the ventilation system at the PH in Mexico City.

The low levels of relative humidity observed in the Passivhaus suggest that the ventilation strategy may result in a potential reduction of mold proliferation. The higher levels (>70 % RH) in the standard building-practice apartment were associated with the mold growth reported by the participants. No levels below 30 % RH were recorded. Further investigation is recommended during winter, the dry season in Mexico City.

Finally, the occupants' perception of IAQ was satisfactory in the Passivhaus. However, the perception of air freshness suggests further investigation may be required. This in contrast to the CO apartment, for which all the criteria were rated unsatisfactory other than the freshness of the air. This suggests that Passivhaus occupants trade the perception of air freshness for additional protection against outdoor pollution. On the other hand, the high presence of SBS at the CO requires further investigation. Further studies of IAQ in different low energy homes in Mexico are required and should take place on a larger scale, including a comprehensive evaluation of the design, construction and maintenance of ventilation systems and their operation and performance in practice.

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