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Toward Sustainable Indoor Environments: Assessing the Impact of Thermal Insulation Measures on Air Quality in Buildings—A Case Study in Temuco, Chile

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Abstract: In Chile, an Atmospheric Decontamination Plan (PDA) has been developed to reduce concentrations of fine particulate matter (PM 2.5) in cities deemed "saturated" with these particles. The plan includes various measures, such as the thermal insulation of homes and the replacement of heaters. This study presents an analysis of the indices of four indoor air quality variables (temperature, humidity, carbon dioxide, and PM 2.5) in different types of homes with varying levels of PDA implementation in the city of Temuco, Chile. Regarding the temperature variable, only one type of home was found to be within comfort limits, with an average of 20.6 °C and a variation of ±3.52 °C (SD). Concerning humidity, independently owned homes with complete and moderate ADP implementation had average humidity levels between 64.82% ± 7.19% and 55.6% ± 6.11%, respectively. For CO_2, only homes with moderate implementation showed averages slightly below (average 991 ppm) the maximum allowed (1000 ppm). As for PM 2.5, all homes exceeded the standard, ranging from 44.4 µg/m^3 to 130 µg/m^3, with very high variations. This demonstrates that PM 2.5 concentrations consistently exceeded the limits established by the World Health Organization (15 µg/m^3).

Keywords: indoor air quality; environmental quality; refurbishments housing politics; life quality; sustainable building

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1. Introduction

In recent years, there has been a growing development of energy efficiency measures to reduce energy demand in buildings and mitigate greenhouse gas emissions [1–3]. These measures also aim to address the challenges of climate change and promote environmental sustainability through initiatives that encourage energy efficiency and the adoption of cleaner and renewable technologies [4–7]. Additionally, these measures are expected to directly contribute to improving the thermal comfort of inhabitants and the indoor air quality [8–10]. This last aspect is particularly relevant considering that people spend on average more than 60% of their time in their homes [11].

Indoor air quality is determined by the presence of pollutants and the conditions of temperature and humidity that can negatively affect people's health and comfort [12]. Indoor air pollutants primarily originate from (i) outdoor air quality, (ii) user behavior, (iii) construction materials, and (iv) ventilation levels [13–16]. Among the pollutants, carbon dioxide (CO_2) is included, which in high concentrations (>1000 ppm) can lead to reduced concentration, affect sleep, and increase the risk of respiratory diseases [17–19].

Also included are the byproducts of the combustion of fossil energy sources, such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), which in high concentrations (350 μg/m^3 and 100 μg/m^3, respectively) [20,21] cause and exacerbate respiratory diseases [22,23]. Also, as a byproduct of combustion, there is carbon monoxide (CO), which can be particularly hazardous as it is a colorless and odorless gas that, at concentrations exceeding 10 mg/m^3 [21], can cause poisoning and even death [24]. Other pollutants such as fine particulate matter (PM 2.5), as well as volatile organic compounds (VOCs) originating from natural organic matter decomposition, wood combustion, paints, and cleaning products, can also cause severe respiratory diseases [25]. Fine particulate matter, when inhaled, can penetrate the lungs and bloodstream, thereby increasing the risk of respiratory and cardiovascular diseases [26]. Furthermore, volatile organic compounds, when reacting with other pollutants, can form tropospheric ozone and secondary particles, both of which are linked to respiratory issues and allergies [27]. Poor indoor air quality, primarily due to inadequate ventilation, was identified as the most influential risk factor in homes [28]. For this reason, it is crucial not only to understand the effects that public policies related to energy efficiency in buildings have on thermal comfort but also how they impact exposure to indoor air pollutants [28–32].

This study evaluates the impact of the "Atmospheric Decontamination Plan" (PDA) implemented in Chile, which aims to reduce high concentrations of particulate matter in cities declared as saturated by this pollutant [33]. This program involves implementing measures in dwellings such as thermal insulation, reduction of condensation, reduction of air infiltration, improvement of ventilation and control of solar gains. Additionally, it considers the replacing of the heaters with less polluting and more efficient sources, like electrical and gas heaters [33]. This study involved air quality monitoring in a sample of dwellings in Temuco, where variables associated with hygrothermal comfort (humidity and temperature) and air pollutant concentrations (CO_2, PM 2.5, and PM10) were measured. Additionally, the construction conditions and energy consumption of each dwelling are described.

2. Data and Methods

2.1. Data

The data on hygrothermal comfort and indoor air pollutant concentrations in dwellings were obtained from the Chilean National Monitoring Network (ReNaM), which falls under the Ministry of Housing and Urbanism of Chile. This network has been monitoring dwellings in various Chilean cities (Santiago, Temuco, Valdivia, Coyhaique) since 2017. For this study, data from 11 monitored dwellings (ReNaM) in the city of Temuco were analyzed. These have monitoring equipment that allows for recording the measurement of hygrothermal comfort variables and indoor air pollutant concentrations. The monitoring sensors are located in the living room of each dwelling and take data every 15 min. In all cases the monitors were installed at a height of 80 cm above the floor level and in a central sector of the living room, avoiding placing it less than two meters away from the heating equipment. In this way, we tried to avoid a high sensitivity of the temperature measured by the sensor due to the proximity of the heater. Also, it was installed in the center of the room, away from the perimeter to avoid the influence of other heat gains such as windows. The location of the houses allows for covering different urban sectors of the city of Temuco. Another feature to consider is the type of dwellings, thermal envelope surfaces exposed to the exterior, and the subsidy received from the state to implement thermal insulation. These types of dwellings are part of a sample of dwelling of the ReNaM and do not necessarily represent all the dwellings in the city. However, it can be considered that they represent old dwellings that require energy efficiency measures and are therefore suitable for the study proposed in this research. They also consider recurrent architectures and construction systems representative of the southern part of Chile.

Outdoor weather data are sourced from the meteorological station of the National Ministry of the Environment (Figure 1).

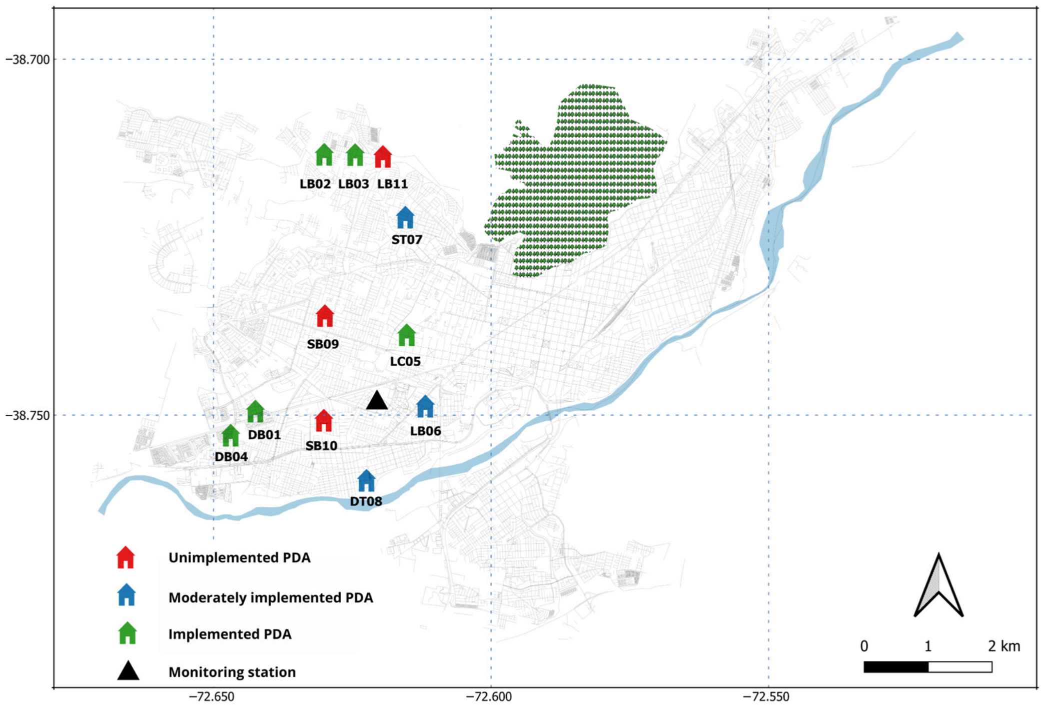

Figure 1. Location of the study dwellings in Temuco (LB: Large Multi-Family Brick; LC: Large Multi-Family Concrete; ST: Semi-Detached Timber; SB: Semi-Detached Brick; DB: Detached Brick; DT: Detached Timber) and the weather monitoring station.

The city of Temuco is in the central-southern region of Chile (−35.74° latitude south, −72.59° longitude west), spanning an area of 464.9 km^2, including both rural and suburban spaces within the city, with an estimated 77,700 dwellings. Most dwellings are situated in the western sector of the city, between Ñielol Hill and the Cautín River (Figure 1). Figure 1 illustrates the spatial distribution of the three types of buildings: Large multi-family (L), which encompasses brick masonry (LB) and concrete (LC) materials; Detached (D), constructed with brick masonry (DB) and timber (DT) materials; and Semi-Detached (S), built using brick masonry (SB) and timber (ST) materials.

In certain cities in Chile, including Temuco, the "Atmospheric Decontamination Plan" (PDA) has been implemented [34]. The plan encompasses a series of actions and measures, one of which involves the use of thermal insulation in building envelopes in order to achieve specified thermal transmittance values for walls (0.45 W/m^{2}K), roofs (0.27 W/m^{2}K), floors (0.50 W/m^{2}K), windows (3.60 W/m^{2}K), and doors (1.70 W/m^{2}K) [33]. Additionally, this plan encompasses the replacement of heating systems (with less polluting sources and higher efficiency). For this reason, the dwellings have been categorized into three groups based on the level of implementation of the PDA. In the case of dwellings where thermal insulation has been applied throughout the envelope and meets the specified thermal transmittance values, the AQIP is fully *implemented* (green houses in Figure 1). Conversely, dwellings lacking thermal insulation are considered *unimplemented* (red houses in Figure 1). Lastly, dwellings with thermal insulation covering 2 to 4 elements (walls, roofs, floors, windows, or doors) of the thermal envelope are classified as *moderately implemented* (blue houses in Figure 1).

Information was also collected (through a survey conducted at each household) regarding the heating sources and systems employed, whether the dwellings used a self-contained heating system located in the living room, and the annual energy consumption for heating per habitable area of the dwelling (kWh/m^{2}a). This was performed to establish a comparative indicator that enables the assessment of the relationship between the dwelling's implementation level and heating energy consumption (Table 1).

Table 1. General characteristic of the selected dwellings.

ID	Living Area [m^2]	Building Type	Heating Systems	Energy Consumption for Heating [kWh/m^2a]	PDA Implementation Level
DB01	128	Detached	Pellet stove	40	Implemented
LB02	42	Large Multi-Family	Electric heater	82	Implemented
LB03	42	Large Multi-Family	Electric heater	51	Implemented
DB04	50	Detached	Wood stove	71	Implemented
LC05	128	Large Multi-Family	Portable gas heater	48	Implemented
LB06	60	Large Multi-Family	Portable kerosene heater	55	Moderately implemented
ST07	55	Semi-Detached	Wood stove	331	Moderately implemented
DT08	90	Detached	Pellet stove	77	Moderately implemented
SB09	50	Semi-Detached	Wood stove	342	Unimplemented
SB10	50	Semi-Detached	Wood stove	513	Unimplemented
LB11	52	Large Multi-Family	Electric heater	59	Unimplemented

In each of the selected dwellings, an Air-Q monitoring device was installed, enabling the monitoring of 11 variables (Temperature, Humidity, CO_2, NO_2, CO, VOC, PM1.0, PM10, PM 2.5, noise, and pressure). In this initial stage of research, four variables will be analyzed (Table 2), classified into two groups: (i) hygrothermal comfort, which encompasses two variables—temperature, within a comfort range of 19 °C to 25 °C, and humidity, considered comfortable when it falls between 30% and 70% [35]. The other group of variables is (ii) indoor air quality, which considers the concentrations of CO_2, with a recommended limit of 1000 parts per million (ppm) for domestic use settings and for exposures not exceeding 24 h on average [36]. Additionally, fine particulate matter 2.5 is also considered, with the World Health Organization recommending not to exceed 15 $\mu g/m^3$ [21].

Table 2. Monitored variable in the selected dwellings with permissible maximum limits.

Classification	Nomenclature	Variable	Limits
Hygrothermal comfort	T HR	Temperature Humidity	19–25 °C 30−70%
Air pollutant concentrations	CO_2 PM 2.5	Carbon dioxide Fine particulate matter	<1000 ppm <15 $\mu g/m^3$

2.2. Data Cleaning and Processing

The records correspond to measurements taken in the year 2022, which were filtered for the two months with the lowest average temperatures in the year (June–July, respectively), as demonstrated in other studies [37,38], as these months have a higher concentration of air pollutants. Additionally, to gain even more detailed insight into indoor air variables, the three days with the lowest temperatures of the season were selected (15–17 July 2022).

Prior to analyzing and graphing the data, a search for data with atypical behavior regarding the variables of interest was conducted, as such data could potentially affect the results. In this regard, one dwelling with a moderate level of implementation (DT08) was found to have significantly higher temperature levels during winter than the other insulated dwellings. However, despite this finding, it was decided to include this dwelling in the study and provide an explanation of the findings in the results discussion.

2.3. Analysis Method

Initially, a descriptive analysis was conducted based on the dwelling type according to the level of implementation of the PDA, contrasting with the established limits of environmental, construction, or human health standards (Table 2). To achieve this, the 11 dwellings were grouped based on the construction type and the level of PDA implementation. First, the dwellings with complete PDA implementation were grouped, including LB02, LB03, and LC05 for the Large Multi-Family (LMF) construction type and DB01 and DB04 for the Detached type. Next, the dwellings with moderately implemented PDA were analyzed, comprising LB06 for LMF, ST07 for Semi-Detached, and DT08 for Detached construction types. Finally, the non-implemented level was considered, encompassing SB09 and SB10 for Semi-Detached and LB11 for LMF construction types. This approach allows for the evaluation and comparison of the impact generated by the levels of implementation of the PDA within each construction type.

The results are presented through graphs and tables that include statistical information such as mean, standard deviation, skewness, and coefficient of variation for each variable of interest. This comprehensive approach allows for an understanding of both the central tendency and the dispersion of the data, as well as its relative positioning within the dataset.

For data analysis and visualization, the R software (version 4.3.1) was employed, utilizing custom developments to depict behavioral patterns and create graphical representations.

3. Results

3.1. Results of Thermal Comfort Monitoring

3.1.1. Temperature

The outcomes of indoor temperature measurements (Figure 2) reveal that the average indoor temperatures range between 14 °C and 20 °C. Additionally, it is evident that most of the time (75%), all monitored dwellings record temperatures that do not exceed the lower comfort limit (19 °C). This implies that occupants of these dwellings experience thermal discomfort for a significant portion of the winter season. This situation becomes more pronounced for the dwellings where the PDA has not been implemented, with average temperatures reaching 14.6 °C, as compared to moderately implemented (18.4 °C) or fully implemented PDA dwellings (17.1 °C).

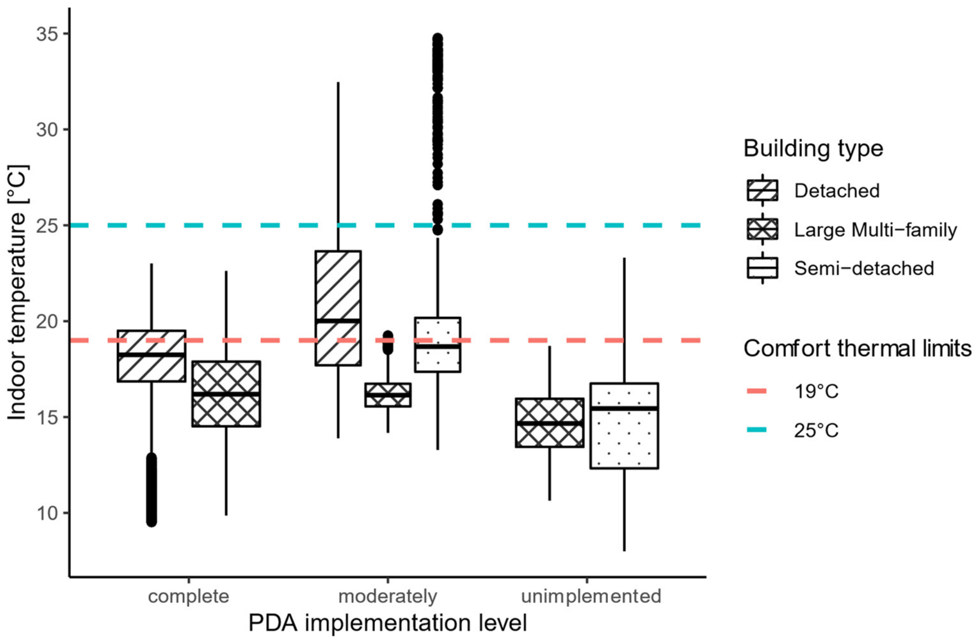

Figure 2. Distribution of indoor temperature within the dwelling according to the type of construction and the level of PDA implementation.

Additionally, it was identified that the LMF construction type recorded lower average temperatures than the other construction types across different levels of PDA implementation, ranging between 15 °C and 16 °C (Table 3). It is also observed that variations in indoor temperature within this construction type, which exhibit a certain level of PDA implementation, tend to cluster around the mean (skew approximately 0), while dwellings without PDA implementation tend to have measurements below the mean (skew below −0.3).

Table 3. Statistical summary of indoor temperature in dwellings.

PDA Implementation Level	Detached				LMF				Semi-Detached			
	Mean	sd	Skew	cv (%)	Mean	sd	Skew	cv (%)	Mean	sd	Skew	cv (%)
Complete	18.03	2.17	−0.90	12.04	16.21	2.22	0.01	13.71	n/a	n/a	n/a	n/a
Moderately	20.60	3.52	0.26	17.08	16.12	0.87	−0.06	5.41	18.92	2.44	2.29	12.90
Unimplemented	n/a	n/a	n/a	n/a	14.57	1.71	−0.32	11.75	14.57	2.86	−0.50	19.62

Note. LMF: Large Multi-Family, n/a: not available.

Similarly, in those dwellings with fully implemented PDA, the variation percentages are very similar for different construction types (Detached CV: 12%; LMF CV: 13.7%). This indicates that the heterogeneity of measurements is expected to be around 13%. However, the same does not apply to dwellings with moderate or no PDA implementation, which exhibit considerable disparity. Among these, LMF-type dwellings displayed lower variation compared to Semi-Detached ones (5.4–12.9% vs. 11.75–19.6%, respectively). Consequently, temperatures tended to be more homogeneous in LMF-type dwellings with moderate PDA implementation.

In Figure 3, the indoor temperature across the three coldest winter days with extreme temperatures is shown. The graph highlights an inverse correlation between indoor and outdoor temperatures: indoor temperature tends to rise as outdoor temperature drops. This phenomenon is attributed to the fact that in the afternoon, as outdoor temperatures decrease, inhabitants typically activate their heating systems. Consequently, this action leads to elevated levels of indoor temperature. Simultaneously, this pattern contributes to an increase in particulate matter concentrations.

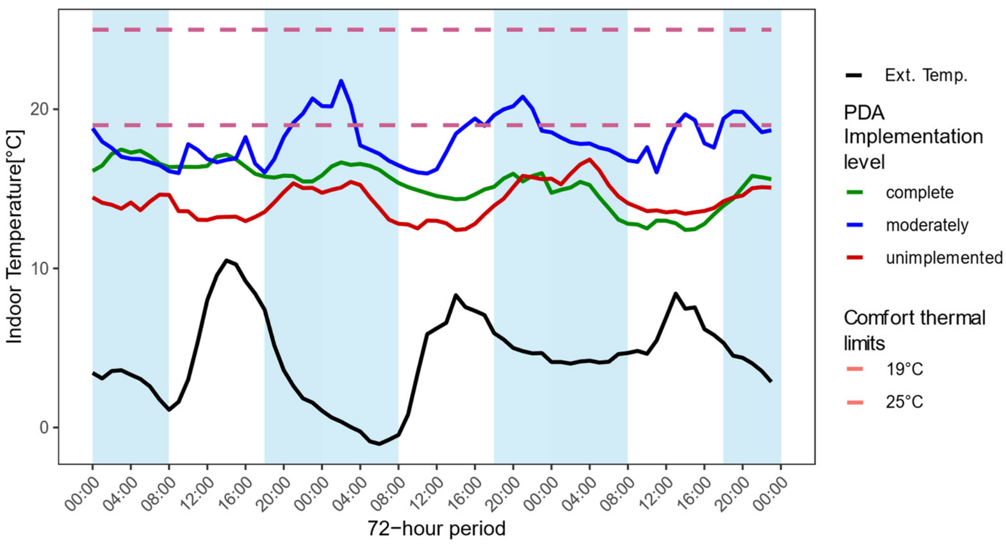

Figure 3. Fluctuation of indoor temperature within the dwelling according to the type of construction based on the level of PDA implementation for days with extreme minimum temperatures during the observed period (15–17 July 2022).

3.1.2. Humidity

In Figure 4, it can be observed that dwellings with fully implemented PDA exhibit uneven behavior, a pattern which also repeats in moderately implemented cases for Detached and LMF construction types. It was noted that the Detached construction type tends to have humidity measurements within the comfort range, while the LMF construction type, at each level of PDA implementation, tends to show measurements exceeding the maximum comfort threshold (70% humidity). Attached dwellings with moderate or complete PDA implementation display a significant number of measurements within the comfort range. However, when observing the non-implemented level of PDA, over 75% of its measurements surpass the upper limit of comfortable humidity.

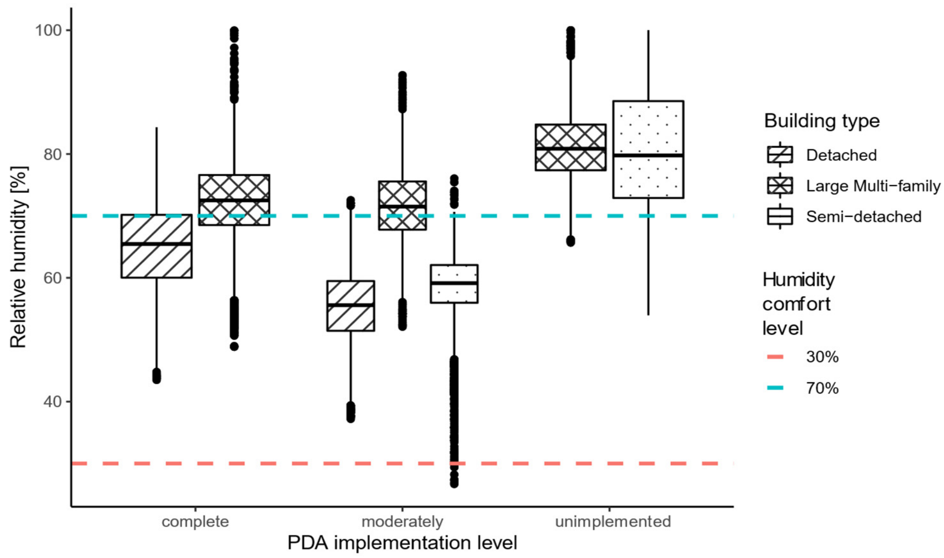

Figure 4. Indoor humidity during the winter season, categorized by construction type and level of PDA implementation.

The average humidity levels in fully PDA-implemented dwellings show an average difference of 7% (Detached 64.8%; LMF 72.4%). Additionally, these homes tend to exhibit readings slightly above the average (skew = −0.34; −0.19).

Regarding homes with moderately implemented PDA, there is a 16% disparity in humidity measurements between Detached and LMF (55.6% and 71.7%, respectively), with both measurements closely aligning with their respective averages (skew = 0.07; 0.05). Furthermore, at this level, the Semi-Detached dwellings demonstrated an average humidity that placed them within the comfort range, exhibiting good homogeneity but with a tendency for readings to be above the average (58.47%; skew = −1.3) (see Table 4).

Table 4. Statistical summary of indoor humidity in dwellings.

PDA Implementation Level	Detached				LMF				Semi-Detached			
	Mean	sd	Skew	cv (%)	Mean	sd	Skew	cv (%)	Mean	sd	Skew	cv (%)
Complete	64.82	7.19	−0.34	11.09	72.40	6.01	−0.19	8.30	n/a	n/a	n/a	n/a
Moderately	55.60	6.11	0.07	10.99	71.73	5.89	0.05	8.21	58.47	5.74	−1.30	9.82
Unimplemented	n/a	n/a	n/a	n/a	80.95	5.35	−0.03	6.61	81.80	11.06	0.41	13.53

Note. LMF: Large Multi-Family, n/a: not available.

In the case of dwellings where the PDA has not yet been fully implemented, it is observed that the average humidity levels exceed 80%. These humidity levels, combined with the low temperatures observed in this same group (Figure 2 and Table 3), indicate that the inhabitants of these dwellings are experiencing significant thermal discomfort. Furthermore, the interior conditions of high humidity and temperature in this group suggest conditions conducive to the appearance and proliferation of mold and fungi.

Figure 5 depicts the indoor humidity behavior within the housing groups during the period of extreme minimum temperatures on 15–17 July 2022. It was observed that dwellings with levels of complete and moderate PDA implementation displayed a better response to low temperatures, generally maintaining humidity levels below the upper limit of comfort (70%). In contrast, dwellings without PDA implementation often exhibited poor humidity control, surpassing the recommended maximum level.

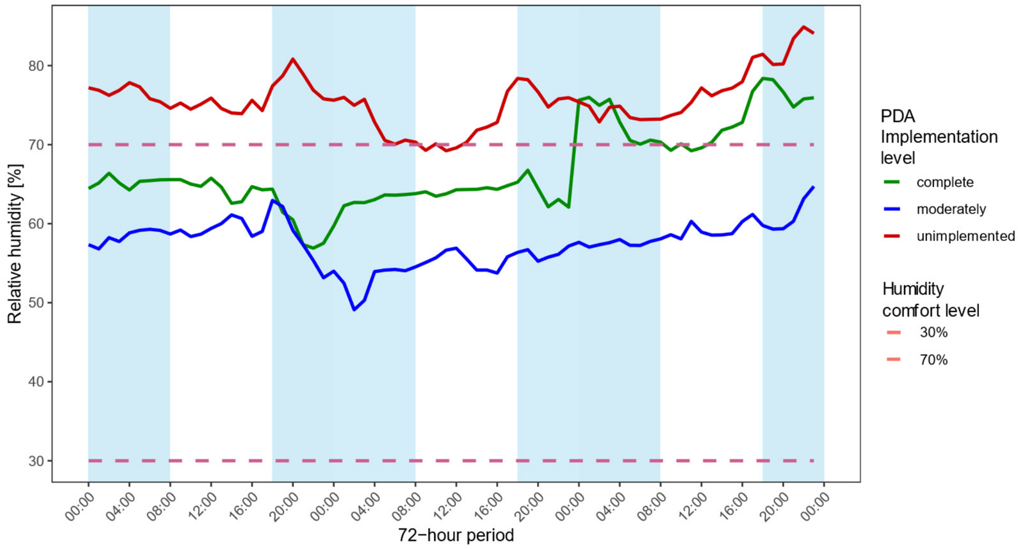

Figure 5. Average fluctuations of indoor humidity within the dwellings, according to the level of PDA implementation, for days with extreme minimum temperatures during the observed period (15–17 July 2022).

3.2. Indoor Air Quality Monitoring Results

3.2.1. Carbon Dioxide

The results of CO_2 concentrations indicate that 75% of measurements within fully implemented and non-implemented PDA households exceed the recommended limit. On the other hand, 75% of measurements for households with moderate PDA implementation do not exceed the recommended maximum limit (Figure 6).

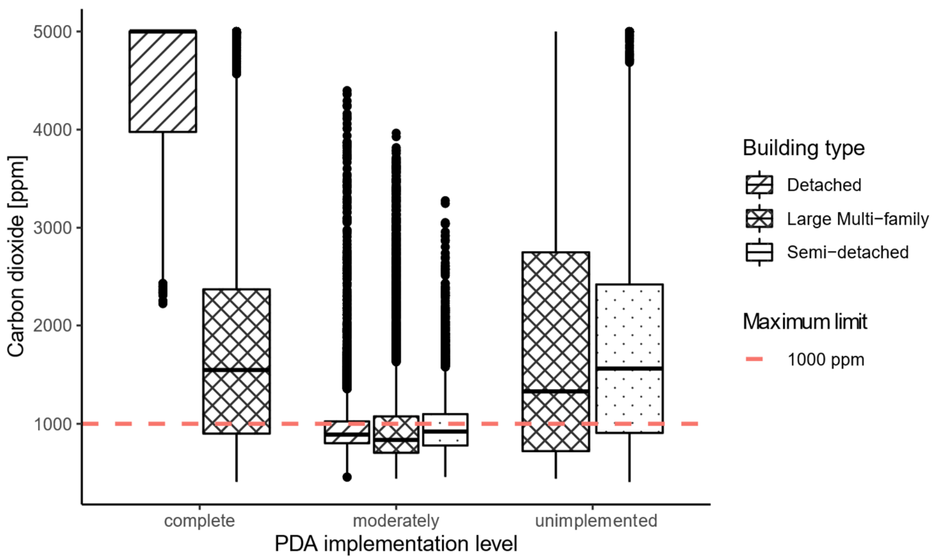

Figure 6. Indoor CO_2 concentrations during the winter season, according to the type of construction and the level of PDA implementation.

The statistical indicators (Table 5) reveal that, in the case of dwellings with PDA fully implemented, there is a significant difference in CO_2 measurement levels. Detached-type houses have an average of approximately 4500 ppm, with measurements tending to concentrate above this average (skew = −1.02). Conversely, LMF-type houses have a much lower average (1387.8 ppm), with measurements tending to be below the average (skew = 1.1). However, Detached houses exhibit a more homogenous behavior compared to LMF houses (cv = 15% and 71.7%, respectively). Dwellings with a moderate level of PDA implementation show averages just slightly below the recommended limit, ranging from approximately 981 ppm to 999 ppm. These measurements tend to cluster well below the average (skew = 4.09, 2.6, 1.9), and the measurements demonstrate a moderate level of heterogeneity (cv = 41.3%, 53.4%, 31.99%).

Table 5. Statistical summary of indoor carbon dioxide concentrations in dwellings.

PDA Implementation Level	Detached				LMF				Semi-Detached			
	Mean	**sd**	**Skew**	**cv (%)**	**Mean**	**sd**	**Skew**	**cv (%)**	**Mean**	**sd**	**Skew**	**cv (%)**
Complete	4494.9	674.9	−1.02	15.0	1936.4	1387.8	1.1	71.7	n/a	n/a	n/a	n/a
Moderately	995.2	410.5	4.09	41.3	999.6	533.8	2.60	53.4	981.8	314.1	1.9	31.99
Unimplemented	n/a	n/a	n/a	n/a	1851.2	1348.8	0.89	72.8	1762	1004.8	0.77	57.01

Note. LMF: Large Multi-Family, n/a: not available.

For unimplemented PDA dwellings, they exhibit averages slightly above the recommended limit (approximately 1851 ppm and 1762 ppm), with a tendency towards measurements below the average (skew = 0.89; 0.77), and with a relatively high level of heterogeneity (cv = 72.8%; 57.1%).

Figure 7 displays the fluctuations of CO_2 within the dwellings during the period from 15 to 17 July 2022 (period of extreme minimum temperatures). In the PDA implementation levels, whether complete or non-implemented, the CO_2 concentrations generally tend to remain significantly above the recommended limit for extended periods (in some cases exceeding 8 h). For the dwellings with moderate PDA implementation, there is a reduced variation and a propensity to remain closer to the recommended limit. In all cases, it can be concluded that the CO_2 concentration levels in the dwellings are not healthy, potentially leading to symptoms such as fatigue, drowsiness, lack of mental focus, and eventually resulting in headaches and nausea, among other effects.

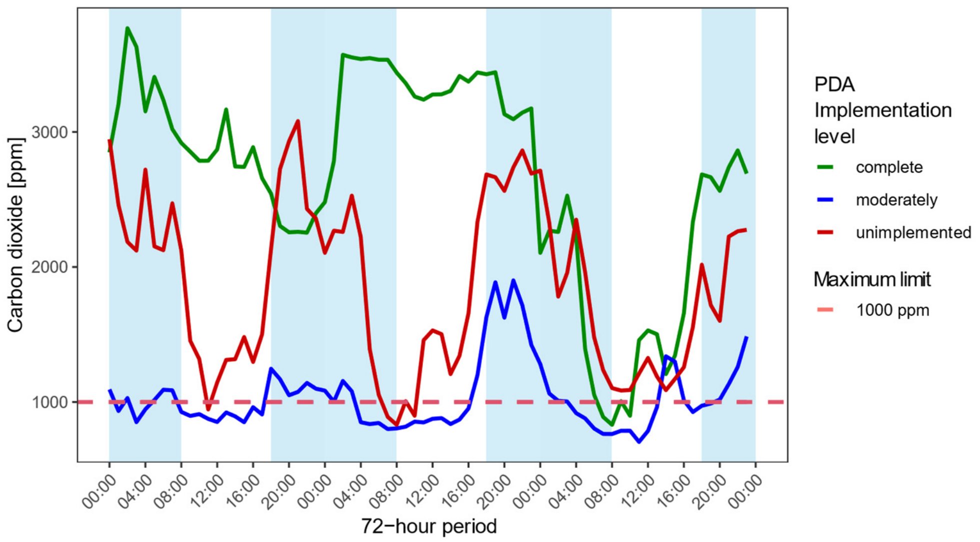

Figure 7. Fluctuations in the average concentration of CO_2 within the dwellings according to the level of PDA implementation for days with extreme minimum temperatures in the observed period (15–17 July 2022).

3.2.2. Particulate Matter 2.5 (PM 2.5)

The results of PM 2.5 measurements indicate that all dwellings, regardless of the level of PDA implementation, exceed the limit recommended by the WHO (15 μg/m^3) for most of the time (86%), reaching as high as 1000 μg/m^3 in some cases (see Figure 8).

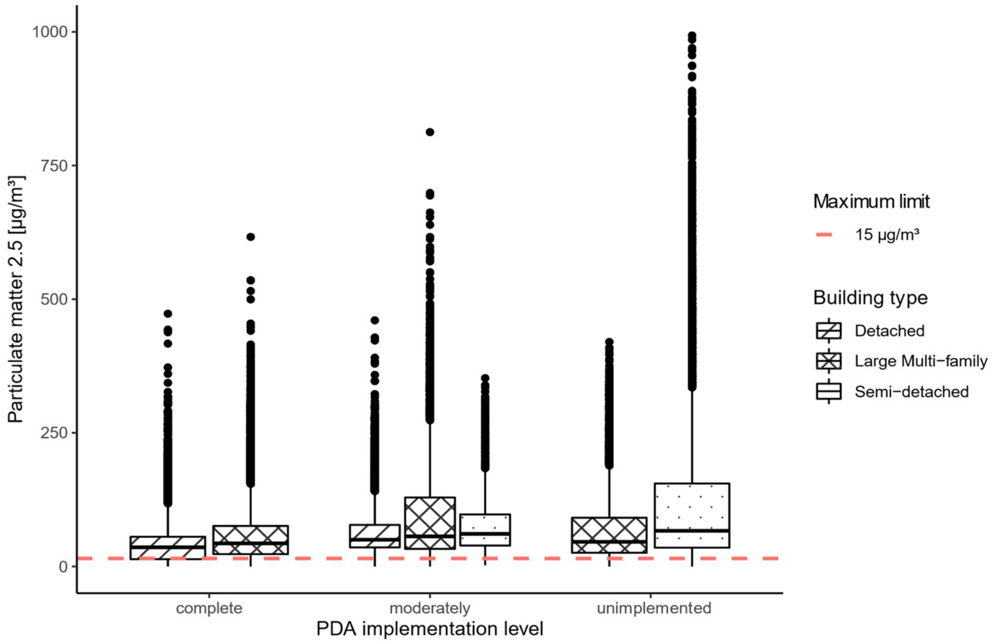

Figure 8. Indoor PM 2.5 concentrations during the winter season, according to the type of construction and the level of PDA implementation.

When examining the averages of dwellings that are completely implemented with PDA, they were found to be close to the recommended limit of 15 μg/m^3 (averages = 44.4 μg/m^3; 63.19 μg/m^3). In the case of dwellings at a moderate level of PDA implementation, the LMF-type construction dwelling exhibited an average of 102.84 μg/m^3, which is clearly above the recommendation. Conversely, the Detached and Semi-Detached construction types tended to have lower averages (64.66 μg/m^3; 73.95 μg/m^3). On the other hand, dwellings without PDA implementation, specifically the Semi-Detached type, showed the highest PM 2.5 levels, reaching up to 130 μg/m^3 and displaying the highest heterogeneity (122.59%). In general, the concentration of measurements (Table 6) tends to be below the average for all levels of PDA implementation and construction types (positive skew). Furthermore, a high level of heterogeneity was observed in these measurements (cv > 70%).

Table 6. Statistical summary regarding indoor PM 2.5 concentrations in the dwelling.

PDA Implementation Level	Detached				LMF				Semi-Detached			
	Mean	sd	Skew	cv (%)	Mean	sd	Skew	cv (%)	Mean	sd	Skew	cv (%)
Complete	44.40	42.95	2.26	96.74	63.19	64.63	2.18	102.28	n/a	n/a	n/a	n/a
Moderately	64.66	48.19	2.16	74.52	98.81	102.84	1.90	104.08	73.95	52.22	1.52	70.61
Unimplemented	n/a	n/a	n/a	n/a	70.48	70.60	1.90	100.17	130.00	159.37	2.40	122.59

Note. LMF: Large Multi-Family, n/a: not available.

In Figure 9, the fluctuation of PM 2.5 measurements during the period of exterior minimum temperatures in the season (15–17 July 2022) is shown. The results indicate that the dwellings where the PDA has not been implemented have higher peaks of particulate matter. However, these concentrations are also high for homes with both complete and moderate PDA implementation. From Figure 9, it can be concluded that regardless of the level of PDA implementation, all homes exceed the healthy limits established by the WHO

(15 μg/m^3) and, on one day (16 July), the indoor particulate concentrations even exceeded those found outdoors (black line in Figure 9).

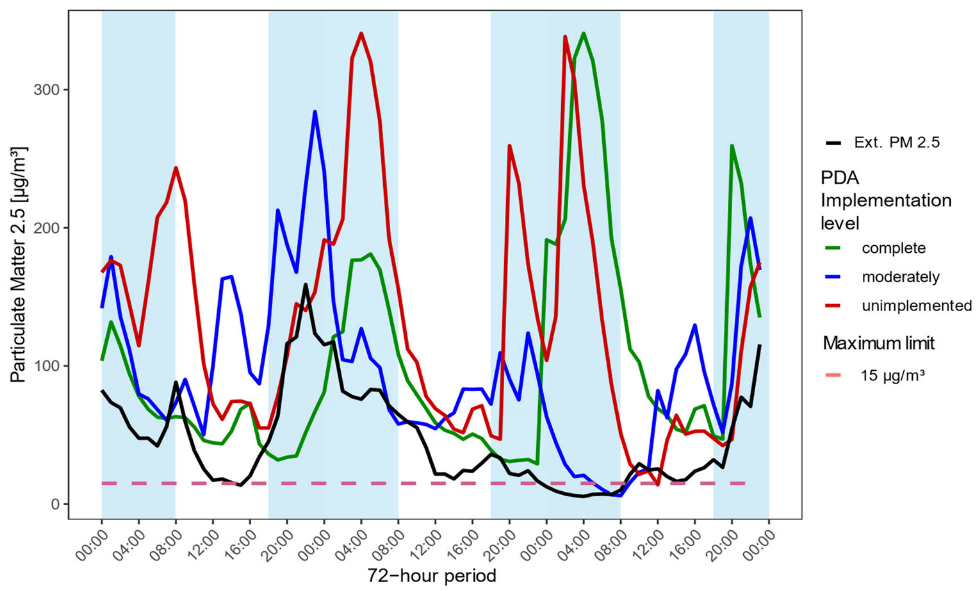

Figure 9. Fluctuations of average PM 2.5 concentrations indoors during the winter season, according to the level of PDA implementation, for days with extreme minimum temperatures in the observed period (15–17 July 2022).

4. Discussion

The PDA aims to reduce the particulate matter pollution produced by the urban residential sector, which clearly has an impact on human health. Through the implementation of the PDA, it is expected that by thermally insulating the houses, energy consumption will decrease, thermal comfort for occupants will improve, and emissions of fine particulate matter (PM 2.5) will be reduced [39,40].

From the analyzed cases in this study, it can be found that houses with complete implementation consume up to three times less energy (59 kWh/m^{2}a) compared to houses with moderate PDA implementation (155 kWh/m^{2}a), and up to five times less energy than houses without implementation (305 kWh/m^{2}a). This indicates initially that the PDA implementation achieves its objective in terms of reducing energy demand in houses. However, the monitoring results show that the hygrothermal habitability conditions do not meet expectations, and indoor air quality continues to be an unachieved challenge. Thus, this study confirms results obtained in Valdivia [41]. At the same time, this study confirms that measures linked to PDAs need to be differentiated and related to specific social contexts [41], as thermal insulation measures reduce energy demand but, if not accompanied by controlled air ventilation, maintain high PM 2.5 indoor levels [41]. Table 1 shows that, regardless of the degree of PDA implementation, dwellings exhibit a similar energy consumption value. This inconsistency can be attributed to the phenomenon of energy poverty, which involves lower energy consumption but at the expense of a decrease in thermal comfort [41]. For example, in Table 1, it is evident that three dwellings with different levels of PDA implementation (LB03 implemented, LB06 moderately implemented, and LB11 not implemented) have an energy demand per square meter close to 50 kWh/m^2. However, when comparing the indoor temperatures for the three days with the lowest outdoor temperatures (Figure 10), it is observed that none of the dwellings reach the minimum level of thermal comfort. Additionally, it is observed that the dwelling with the greatest thermal oscillations was the one without any PDA implementation. From this, it can be deduced that dwellings may have low and/or similar energy demands, but this does not necessarily indicate that they have the same performance in terms of the relationship between thermal comfort and energy demand.

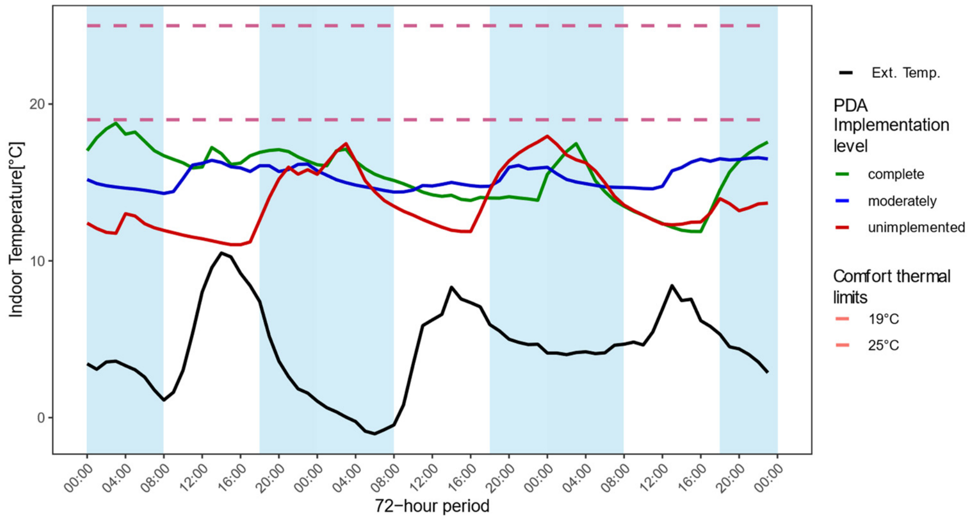

Figure 10. Fluctuation of indoor temperature within the dwellings LB03, LB06, and LB11 during the observed period (15–17 July 2022).

4.1. Hygrothermal Conditions

In general, most houses have an average temperature outside the range of comfortable temperature, which could be explained in a multifactorial manner. In houses with complete PDA implementation, it is important to further investigate why they do not reach the minimum comfort temperature level (19 °C). This point could be addressed by analyzing and considering the occupants' behavior or the temperature they perceive as comfortable indoors [41]. If the minimum thermal comfort temperature in winter is 18 °C, as proposed by various authors [42–44], houses with complete (and moderate) implementation would meet the thermal comfort temperature.

In Table 3, it is observed that moderately implemented LMF-type houses showed less variation than the rest of the houses. This can be explained by the location of the house in the building, which corresponds to a position surrounded by other units (intermediate floor), and it also has only one side exposed to the exterior, resulting in lower energy loss through transmission. This also leads to more stable temperature measurements for this type of housing and its specific location.

4.2. Indoor Air Quality Conditions

Regarding carbon dioxide concentrations, houses with a moderate level of PDA implementation have an average below 1000 ppm. However, in the completely implemented and non-implemented levels, houses show high variation in their measurements, with levels exceeding 3000 ppm and lasting for prolonged periods of time (up to 8 h). This could be related to the airtightness level of completely implemented houses, as well as the ventilation habits of the occupants. Additionally, at this level of implementation, the concentrations reach an average of approximately 4500 ppm. It is necessary to review the positioning of the instrument inside the house, which could affect the accuracy of the measurement. Another element to assess is the presence of new heating equipment not reported as additional or a replacement of existing ones.

Regarding particulate matter, measurements for all houses are above the recommended limit by the WHO. This can be explained in the context of the city where the study is conducted, as outdoor concentrations are high during winter periods and can infiltrate indoors through various pathways such as leaks, occupants' movements, or ventilation habits, especially during periods of environmental pre-emergencies.

In the case of PM 2.5 concentrations, there are periods (Figure 9) when concentrations inside the home are higher than those outside. This could be because many used heating systems have their combustion chambers inside homes [40]. Outdoor PM 2.5 measurements are derived from a specific monitoring station as an outdoor baseline for comparison. However, this does not reflect the immediate exterior measurement of PM 2.5 around dwellings, as the concentration of PM 2.5 within the city can vary. While wood stoves, the primary source of pollution, are scattered throughout the city, PM 2.5 concentrations do not exhibit a uniform distribution. There are spatial dispersion patterns of PM 2.5, with some sectors more polluted than others [38].

In addition, there are external environmental factors that cause the concentrations of particles outside to be lower, for example, wind. When analyzing the relationship between the presence of wind and particulate matter 2.5 (Figure 11), it was observed for the period analyzed (15–17 July 2022) that, in the hours with higher wind speed, the amount of PM 2.5 was lower and vice versa. Accordingly, it is necessary to expand the number and type of variables considered for a better understanding of the phenomenon of pollution in Temuco. For example, this study does not consider types of ventilation systems that can influence indoor air quality and hygrothermal conditions, which may be included in future research. While an energy-efficient house is expected to have better indoor air quality, it is not guaranteed. The outcome depends on various factors, including different ventilation systems, types of inlets and exhausts, flow rates, filters, and the operating system, all of which can influence indoor air quality and hygrothermal conditions [45].

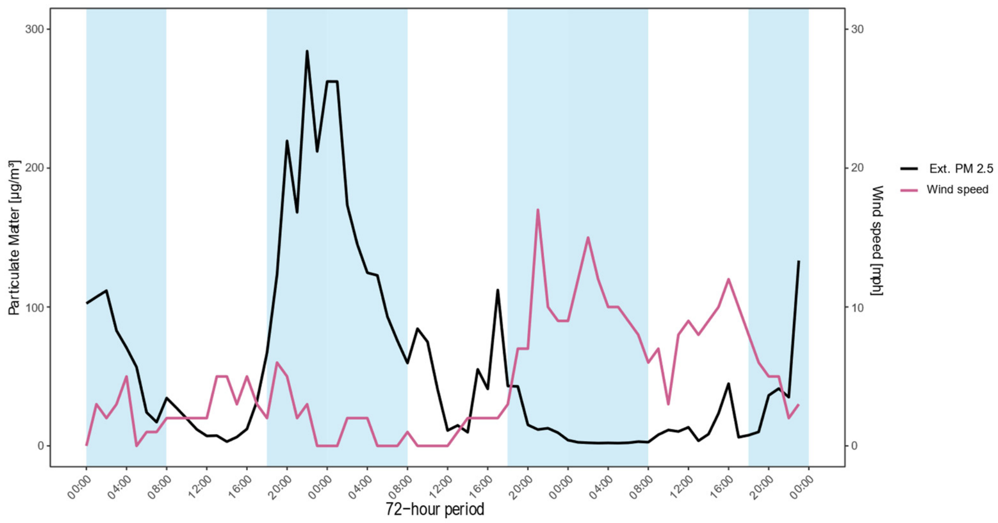

Figure 11. Relationship between wind speed and outdoor particulate matter concentrations, for days with extreme minimum temperatures in the observed period (15–17 July 2022).

This study constitutes a crucial contribution at the intersection of environmental sustainability and health by examining the implications of thermal insulation measures implemented within the framework of the Atmospheric Decontamination Plan (PDA) in Temuco, Chile. Despite notable achievements in reducing energy consumption in fully PDA-compliant homes, the results highlight persistent challenges regarding thermal comfort and indoor air quality, crucial aspects for occupants' health. The significant presence of carbon dioxide (CO_2) and fine particulate matter (PM 2.5), coupled with unfavorable humidity conditions, underscores the need for more holistic approaches addressing not only energy efficiency but also residents' health. The findings emphasize the complexity of balancing energy efficiency with indoor air quality, underscoring the importance of designing sustainable strategies that simultaneously address these crucial aspects to ensure habitable and healthy environments [46]. In this context, the study highlights the urgency of implementing sustainable policies and practices that promote significant improvements in both air quality and the overall well-being of the population, solidifying a holistic perspective on sustainability that prioritizes health and housing comfort [47–49].

5. Conclusions

This study aimed to assess the impact of an environmental decontamination program (PDA) in Chile, focused on improving the thermal insulation of homes and replacing heaters to reduce high concentrations of particulate matter. The results of monitoring variables such as thermal comfort (temperature and humidity), carbon dioxide, and particulate matter concentrations in homes in the city of Temuco are reported.

The results indicate that during the winter season, average indoor temperatures ranged from 14 °C to 20 °C, depending on the type of construction and the level of program implementation (Table 3). On the other hand, a significant number of measurements (75%) were observed in most homes to be below the lower comfort limit (19 °C), suggesting that many occupants in these homes experience thermal discomfort for a significant portion of the winter season. Considering the points discussed regarding energy poverty, there are instances where, despite the implementation of PDA, temperatures within the range of thermal comfort are not achieved.

Regarding humidity, it is observed that in homes with complete or moderate implementation of the PDA, humidity measurements are within the comfort range for much of the time (>75%). On the other hand, in homes where the PDA has not been implemented, most measurements were above the upper limit of comfortable humidity (70%). If these conditions are combined with the previously described temperature conditions, it suggests that occupants are not only exposed to thermal discomfort but also to conditions conducive to the growth of mold and fungi.

Regarding carbon dioxide (CO_2) levels inside the homes, it can be observed that in homes with complete implementation of the program and those without implementation, CO_2 measurements tended to be above the recommended limit in at least 75% of cases. On the other hand, homes with moderate implementation of the program had measurements that were practically 75% below the limit (Figure 7). Completely implemented homes showed a significant difference in CO_2 measurement levels, with "Detached" homes having an average of around 4500 ppm, and measurements tending to concentrate above that value. Conversely, "LMF" homes had a much lower average (1387.8 ppm), with measurements tending to be below the average. In the case of homes with moderate program implementation, the difference between "Detached" and "LMF" was greater, with averages of 55.6% and 71.7%, respectively. Additionally, "Semi-detached" homes had a CO_2 average that fell within comfort ranges, with a good level of homogeneity, but with a tendency for measurements to be above the average (58.47%). This raises the question of the effects of thermal insulation and increased air tightness in homes on CO_2 concentrations. As these results show, improvements in thermal insulation lead to higher CO_2 concentrations inside the homes.

Regarding fine particulate matter (PM 2.5), it was observed that all homes (regardless of the level of PDA implementation) exceed the recommended limits for PM 2.5 concentration set by the WHO (15 $\mu g/m^3$). These results would indicate that while substantial reduction in energy demand is achieved through the implementation of the PDA (up to five times less), decreases in PM 2.5 concentrations inside homes are still not perceptible.

In accordance with the observations from the particulate matter and CO_2 results, several possible solutions can be considered. Regarding CO_2, adopting ventilation habits to allow air renewal inside homes is recommended, along with the implementation of mechanical ventilation, ideally performing air renewals at specified intervals. For particulate matter, different scenarios arise in both winter and summer. In summer, it is advisable to ventilate the home and avoid sources of contamination (cigarettes, incense, chemicals). In winter, the city of Temuco experiences periods of particulate matter concentration due to the use of wood-burning heaters; therefore, it is not recommended to ventilate the home by opening doors and windows, as the interior may become contaminated with suspended particles from the outside. As a solution, it is recommended to install air purifiers with specialized filters to capture fine particles.

In relation to the findings, hypotheses were formulated about variables that could explain the situations observed in indoor environments. In this regard, explanations can be sought through variables associated with the occupants, such as behavior, energy management within the home, age group, and the presence of illnesses, among others, which can influence energy needs. Additionally, other variables related to the characteristics of dwellings, such as location, size, and orientation, among other factors, could be considered. Given the above, it is proposed that future research delve into the relationship and effects that the aforementioned variables may have on the different monitored variables.

In conclusion, the study highlights the discrepancy between energy consumption and indoor environmental conditions of homes under the environmental decontamination program in Temuco. While the implementation of energy efficiency measures significantly reduces energy consumption, thermal comfort and indoor air quality remain problematic. The findings of this study shed light on a broader discourse surrounding the energy transition paradigm. It underscores the need for a more holistic approach, as isolated efforts may inadvertently lead to contradictory outcomes. While commendable reductions in energy consumption are achieved, the unintended consequence of heightened indoor pollution emerges. This dichotomy emphasizes the imperative of further systemic consideration in the energy transition process for residential spaces, particularly in the context of implementing thermal insulation programs within initiatives like the PDA. This duality beckons further research to explore integrated strategies that align energy efficiency with indoor air quality, ensuring a balanced and sustainable approach to urban environmental enhancements.

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