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Research Article

Effects of Positive Pressure Ventilation System on Indoor Particulate Matter Concentrations in a Subtropical Climate

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Air pollution negatively impacts human health, with pollutants such as $PM_{2.5}$ linked to increased mortality, respiratory infections, lung disease, heart disease, and stroke. Recent trends, such as increased building airtightness and changes in occupant behavior during the COVID-19 pandemic, highlight the need for greater attention to indoor air quality (IAQ). Mechanical ventilation (MV) systems are commonly used to improve IAQ and occupant comfort, especially in airtight homes, yet their effectiveness in humid winter conditions remains underexplored. This study examined the impact of MV, specifically positive pressure ventilation (PPV) systems, on IAQ in eight single-family homes in northern New Zealand. Data were collected over 12 weeks in winter, with 6 weeks of monitoring before and after PPV installation. Additionally, the study period overlapped with varying COVID-19 lockdown levels, enabling an assessment of how increased occupancy influenced IAQ. The findings show that PPV system installation resulted in reductions over the winter period of 68% for particulate matter (PM) concentrations (both $PM_{2.5}$ and PM_{10}) and 9% in relative humidity (RH), with no significant changes in temperature. $PM_{2.5}$ concentrations increased by an average of 56% during the COVID lockdown, potentially resulting from increased occupancy levels.

Keywords: COVID-19 lockdown; increased occupancy; indoor air quality; mechanical ventilation; particulate matter

1. Introduction

Indoor air pollution can be detrimental to human health [1–3] and lead to increased mortality rates [4–6]. Numerous studies have shown that human exposure to indoor pollution is often more common than exposure to outdoor pollution [7–10]. The fact that people spend up to 90% of their time indoors [11–14] highlights the importance of understanding how IAQ is influenced by various factors. The COVID-19 pandemic has further emphasized the critical importance of maintaining good IAQ. Several studies have shown that increased concentrations of indoor pollutants, in particular $PM_{2.5}$, are associated with COVID-19 lockdown periods, within both rural and urban residential buildings [15–17].

Inadequate ventilation can trap harmful pollutants from internal sources inside the building [18–22]. Standard residential ventilation rates typically range from 0.35 to 1 ACH [23] and are influenced by factors such as building type and design, construction quality, occupancy, local climate conditions, and relevant standards [24–27]. In the United States, ASHRAE sets a minimum residential ventilation rate of 0.35 ACH and no less than 7.5 L/s per person [28]. New Zealand standards NZS 4303:1990 also adopt this level [29].

To tackle the growing problem of climate change, governments worldwide are taking action to reduce household energy consumption and improve energy efficiency. Building insulation has become a key component of energy efficient design by helping regulate indoor temperatures to reduce energy consumption. However, increasing envelope airtightness has been associated with a decline in IAQ when adequate ventilation in the building is lacking [30, 31]. This has led to a tension between the imperative to reduce carbon emissions and the need for increased ventilation for improved IAQ.

MV therefore plays a vital role in energy-efficient buildings where airtightness is likely to cause an accumulation of indoor air pollutants [31–33]. MV systems are primarily intended to introduce outdoor air into the building, displacing stale indoor air and preventing outdoor pollutants from getting indoors by using filters (e.g., particulate air filters). Despite a rise in the adoption of MV in buildings globally, there remains a lack of evidence demonstrating the effects that MV has on IAQ, in particular in subtropical climates [21, 34].

This study was aimed at investigating the effects of MV (specifically, PPV) systems on residential IAQ in an area with high wintertime humidity (northern New Zealand), focusing on PM concentrations in addition to thermal comfort parameters (temperature and RH). While numerous studies have investigated the effects of MV systems on IAQ, the majority compare air quality between different buildings (those with MV against those with natural ventilation). This study compares natural ventilation against MV within the same building (occupied throughout the study period) by conducting a monitoring campaign before and after installation of a PPV system, thereby minimizing variability due to differences in building and occupant characteristics. Winter was selected for the study period as it typically coincides with higher levels of outdoor pollution due to increased wood burning and vehicle usage [35–38], as well as higher levels of occupancy, with people often spending more of their time indoors [39, 40].

The study period spanned a number of different lockdown levels associated with the spread of COVID-19 during 2021. This circumstance allows analysis of the likely impacts of this disruption on occupancy as well as the resulting IAQ. The expected increase in occupancy rates due to the lockdown has been predicted to have a significant impact on the levels of indoor concentrations of air quality parameters, as demonstrated in recent studies [15, 16].

2. Materials and Methods

2.1. Study Location and Overview of Data Collection. Auckland is the largest city in New Zealand and one of the most remote cities in the world. The city is located on an isthmus in the northern part of the country and has a population of over 1.6 million, expected to reach 2 million by 2030. Hamilton (population 165,000) is New Zealand's fourth most populous city and is located in the North Island, approximately 130 km south of Auckland.

The Auckland region has a humid, subtropical climate with warm, humid summers and mild winters [41]. Hamilton has mild summers and colder, wet winters [42]. This study was carried out during the winter period of 2021, for which the average daily maximum temperature was approximately 19.2°C (Auckland) and 18.3°C (Hamilton) [43, 44]. The winter average ambient PM_{10} concentrations for the period 2017–2020 in Auckland and Hamilton were 16 and 14 $\mu g/m^3$, respectively [45].

This research, which assesses IAQ in eight residential homes, six in Auckland and two in Hamilton, was designed as a longitudinal study, by repeatedly measuring the same parameters over time to track changes and identify emerging trends. The study was carried out over a minimum 6-week period leading up to PPV installation (installations occurred between July 8th and August 6th), followed by a further 6-week period post-PPV installation. Installation of the PPV systems was performed by the supply contractor and was generally complete within a day for each home. An overview of the PPV system is provided in Appendix S1.

Participants were advised to keep all windows and doors closed during PPV operation to maintain positive pressure within the home and optimize system performance. Although window and door usage was not actively monitored during the study period, it is assumed that occupants generally followed this guidance. For the pre-PPV period, participants were asked to ventilate their homes as they normally would, by opening windows and doors as needed to allow fresh air in. Although winter conditions can discourage the opening of windows and doors for ventilation due to colder outdoor temperatures, participants nevertheless reported doing so approximately one to two times per week. This self-reported behavior, while subject to individual variability, provides a general indication of natural ventilation practices during the baseline phase.

Two of the study houses (one in Auckland, one in Hamilton) were located in rural areas, defined as more than 5 km from the metropolitan boundary. The homes selected were those in which a PPV system was scheduled to be installed and where the household comprised three to four occupants, including at least two adults. The number of occupants was chosen to reflect a representative number of occupants in New Zealand homes [46]. The houses ranged in size from 90 to 170 m^2 in floorplan area, each containing three to four bedrooms.

Prior to commencing the experimental campaign, comprehensive data was collected on household characteristics and the physical attributes of the study houses. Concerning occupancy, it was noted that each residence was home to between three and five people, including at least two adults. Specific details included that one household had two adults who smoked indoors and several pets, another housed an essential worker employed as a nurse, and the two rural properties were lifestyle blocks where occupants typically spent considerable time outdoors working on the land. Additionally, standard data on the houses' age, floor plan layout, orientation, and construction materials were gathered.

Table 1 provides detailed characterizations for each house. Seven houses were single-storey, while one (House 1) included a second storey. Each residence featured open-plan kitchen/living areas, apart from House 2. Furthermore, all houses were equipped with single-glazed windows, except House 1, which incorporated double glazing.

2.2. Air Quality Measurements and Analysis. $PM_{2.5}$ and PM_{10} concentrations were measured using low-cost Edi-Green Home AI-2002W monitors as well as in-house

TABLE 1: House characteristics.

House	Altitude, m *Source: Google Earth*	Year	Cladding[a]	Roof	Area (m^2)	No. of occupants	Insulation[b]	Volume (m^3)	PPV system		
									Max. air exchanges/h	No. of fans/ filters	No. of outlets
1	41	2010	GP	Iron	90	4	F, W	243	3.2	1	3
2	60	1920	WB	Iron	120	3	F, R	360	4.3	2	5
3	22	1940	WB	Tin	150	4	F, R	405	3.85	2	5
4	15	1970	WB	Iron	95	3	F, C, W	228	3.4	1	4
5	36	2015	Brick	Iron	170	4	W, R	408	3.8	2	7
6	45	1980	WB	Tile	100	4	—	240	3.25	1	4
7	50	1970	B/T	Tile	100	3	R	240	3.25	1	4
8	20	1970	WB	Tin	96	3	F, C	230.4	3.39	1	4

[a] GP = gypsum plasterboard; WB = weather board; B/T = block/timber.
[b] F = floor; W = walls; R = roof; C = ceiling.

designed Wisp Version 6 monitors. Both types also measured temperature and RH. EasyLog EL-USB-2 probes were used to collect outdoor temperature and RH readings. EdiGreen monitors were located in the master bedroom of each home, while Wisp monitors were placed in living areas. Indoor and outdoor monitors were positioned at least 1.0 m away from walls and between 1.0 and 1.5 m above the floor. Further details of each monitor type are provided in Appendix S2.

In addition to data collected at the study houses, outdoor air quality data, including $PM_{2.5}$ and PM_{10}, was obtained from council-owned urban air quality monitoring (AQM) stations (Figure 1). The network of AQM stations in both Auckland and Hamilton was reviewed and the nearest station to the relevant study house was used, taking into account geographic and topographic characteristics of the area, together with identification of potential significant pollution sources, such as motorways and industrial areas. The selected AQM stations were located within 2–6 km of the relevant study house location. This method of collecting outdoor data from the nearest AQM station with this range has been adopted by other researchers [47–49]. Previous research suggests that PM concentrations in urban areas may show minimal spatial variability and tend to be relatively consistent between monitoring stations [49–52]. Variability appears more influenced by altitude than distance [52].

Auckland Council AQM stations were used to cross-calibrate and validate three monitors: a research-grade PM monitor (Aeroqual Dust Sentry Pro), a low-cost PM monitor (EdiGreen Home AI-2002W), and a temperature and humidity logger (EasyLog EL-USB-2 probe). These monitors were colocated with a Council AQM station over a 1-week period, resulting in cross-calibration R^2 correlation values between 0.91 and 0.94.

All study sensors were pre- and postcalibrated against the cross-calibrated sensors. Linear correlation was performed to assess sensor accuracy, with the corresponding linear equation used to offset measured values. R^2 values ranged between 0.89 and 0.96, indicating the low-cost sensors were well correlated. Similar ranges were observed in some previous studies [53–55], while slightly lower R^2 values (0.55–0.72) have been observed in others [56, 57]. No significant differences were observed between precalibration and postcalibration R^2 values. Similarly, R^2 values for temperature and RH were 0.85 and 0.95, respectively.

Sensor functionality and data reliability were checked online at least fortnightly throughout the monitoring campaign. Upon completion of monitoring, detailed statistical analysis of the field measurements was performed using R (Version 4.4.1).

I/O ratios were calculated to summarize the overall effects of indoor and ambient pollution sources, filtration, and PPV system on the presence of PM in indoor air relative to ambient air. To provide a qualitative assessment of PM levels and the impact of PPV installation, PM mass concentrations were categorized according to the USEPA Air Quality Index (AQI) for fine particle pollution, to determine the percentage of time over the study period that fell within each AQI category.

Building characteristics, such as construction materials, building age, location, floor area, ceiling height, and window coverage, can influence the thermophysical properties and air permeability of a building, which can in turn have a direct or indirect impact on IAQ [58–62]. In this study, the influence of various building characteristics for each house was assessed using linear regression to determine the effect on PM reductions observed post-PPV installation. Additionally, trends in statistical significance as a function of particle size fractions were explored, offering insights into how different particle sizes might be affected by various factors within the buildings. The building characteristics and ventilation system details for each house are summarized in Table 1.

While measurements of both $PM_{2.5}$ and PM_{10} particle sizes were collected, the analysis focuses primarily on $PM_{2.5}$. Although historically, air quality assessments have concentrated on PM_{10} as the primary metric for evaluating particulate pollution, recent research has shifted focus toward fine PM, particularly $PM_{2.5}$, due to its more pronounced and detrimental association with human health outcomes [63–65]. This growing emphasis reflects an

Figure 1: Study house locations—clockwise from right: New Zealand; Hamilton; South Auckland; Central Auckland. Study houses (yellow, 1–8); Council AQM stations (magenta).

evolving understanding of the health impacts of PM, highlighting the need for a more nuanced approach to air quality evaluation that accounts for the finer, more hazardous particulates.

3. Results and Discussion

3.1. Pre-PPV Installation and Post-PPV Installation Average PM Levels. The comparison of indoor PM concentrations averaged over the pre- and post-PPV installation periods is summarized in Table 2. For both $PM_{2.5}$ and PM_{10}, significant reductions in mean PM concentration were observed for seven of the eight houses, with reductions ranging between 53% and 92%. Two of the Auckland houses exhibited a very high reduction in PM concentration after PPV installation (90%–92%), while the majority of the remaining Auckland houses showed a similar reduction, in line with that of the Hamilton houses (53%–67%). This is consistent with previous studies that reported PM removal rates with MV from 50% to 90% [21, 48, 66, 67]. Zhao et al. [66] found that 75% of buildings fitted with MV could achieve PM reductions in excess of 90%, in comparison with 25% from this study. Only one house in Auckland (House 7) presented a low reduction (5%) after the installation of the PPV system. House 7 was initially recorded as being constructed in 1970 from block and timber. A follow-up inspection of the building showed that the external walls were 200-mm concrete block and did not have insulation. A lack of airtightness due to inadequate insulation is likely to inhibit PPV system performance, which may explain the lack of PM reduction observed in this house.

Based on the mean concentrations for the 6-week periods pre- and post-PPV installation, the WHO guideline limit for annual average exposure to $PM_{2.5}$ ($5\,\mu g/m^3$) was exceeded in all study houses prior to PPV installation and in four houses post-PPV installation (three of which were only marginally exceeded). House 4 was the only house to exceed the WHO limit significantly post-PPV installation. The WHO guideline limit for annual average exposure to PM_{10} ($15\,\mu g/m^3$) was exceeded in three houses pre-PPV and in one house post-PPV (House 4).

Figure 2 shows the indoor $PM_{2.5}$ time series for a selection of houses across the entire monitoring period, with installation of the PPV system represented by a vertical line. There was a clear step change reduction in $PM_{2.5}$ concentrations inside Houses 2, 3, and 4 immediately following the PPV installation. House 4 is notable due to the unusually high concentrations pre-PPV installation. A survey of the household of House 4 revealed that the occupants smoke and wear shoes inside and also have several pets (two dogs and four cats). All of these factors are likely to contribute to very high average indoor $PM_{2.5}$ concentrations.

The houses with the larger (two fans/filters) system (Houses 2, 3, and 5) showed the highest levels of reduction in indoor PM concentrations. Of these, two of them (Houses 2 and 3) had the highest average ceiling heights (3.0 and 2.7 m, respectively). House 1 also had 2.7-m ceilings but the smallest floor plan area and the least number of outlets installed. Only House 1 contained double-glazing. With the exception of House 7, House 1 showed the equal lowest relative reduction in PM concentrations (53%).

In four selected houses, the variation of $PM_{2.5}$ and PM_{10} was analyzed across different rooms, comparing the main

TABLE 2: Indoor PM data, pre-PPV installation and post-PPV installation.

Location	House no.	$PM_{2.5}$ ($\mu g/m^3$)							PM_{10} ($\mu g/m^3$)						
		Pre			Post			Δ mean	Pre			Post			Δ mean
		Mean	St dev	Range	Mean	St dev	Range		Mean	St dev	Range	Mean	St dev	Range	
Auckland	2	6.8	8.8	0–65	0.6	2.9	0–61	**−91%**	7.5	10	0–75	0.7	3.3	0–70	**−91%**
	3	7.2	6.8	0–40	0.6	1.4	0–13	**−92%**	8.8	8	0–57	0.9	1.8	0–15	**−90%**
	4	49.8	45.5	0–264	19.4	30.4	0–237	**−61%**	57.5	50.9	0–296	22.8	34.9	0–256	**−60%**
	6	10.2	22.8	0–336	4.7	13.5	0–177	**−54%**	11.5	26.4	0–392	5.3	15.3	0–96	**−54%**
	7	6.6	13.8	0–195	6.3	21.9	0–476	−5%	7.6	15.4	0–207	7.1	23.1	0–486	−7%
	8	15.1	27.8	0–276	5.9	16.6	0–273	**−61%**	18.5	32.4	0–326	7.4	19.9	0–312	**−60%**
Hamilton	1	11.1	16.5	0–239	5.2	12.4	0–203	**−53%**	12.5	18.7	0–239	5.9	14.2	0–231	**−53%**
	5	14.8	21.7	0–245	4.9	14.7	0–244	**−67%**	16.6	24	0–257	5.4	16.1	0–258	**−67%**

Note: Values in bold (negative values) indicate houses where there was a substantial reduction in mean PM concentrations.

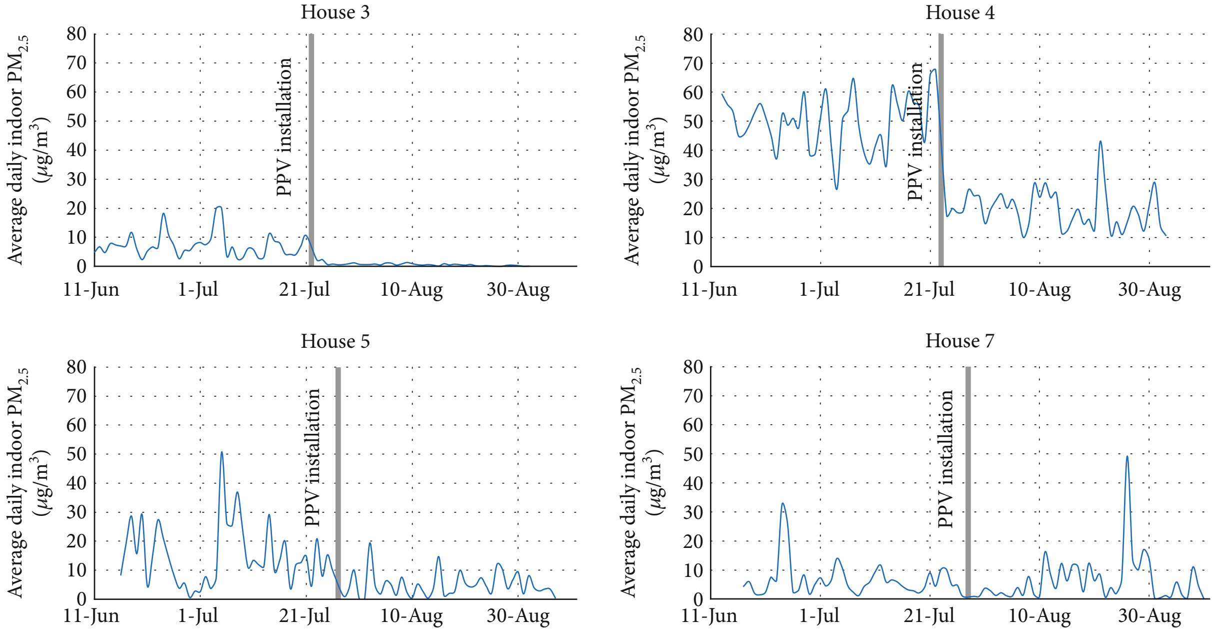

Figure 2: Selected indoor $PM_{2.5}$ profiles pre-PPV installation and post-PPV installation.

bedroom with the living area. These two rooms each had a separate PPV outlet. In one house, the percentage reduction was similar for the bedroom and living room for $PM_{2.5}$ (70% and 71%, respectively) and for PM_{10} (81% and 79%, respectively). In the other three houses, the percentage reduction in $PM_{2.5}$ was 9%–14% lower in the living room, while the percentage reduction in PM_{10} was 6%–20% lower. This may be due to higher occupation in the living (and adjoining kitchen) area and more human activities which can generate PM, such as cooking, vacuuming, and smoking [68–70].

3.2. Ambient PM Concentrations. Outdoor PM concentrations were analyzed over the same monitoring period, showing an average reduction (between the preinstallation and postinstallation periods) of 20% and 15% for Auckland and Hamilton, respectively. This reduction is likely to be influenced by the public lockdown event (due to COVID-19) that was in place over the period post-PPV installation, reducing outdoor human activity, specifically vehicle use. Even though outdoor concentrations have been reduced, it is evident that the reductions observed indoors were significantly greater and therefore more likely to have been influenced by the installation of PPV.

Figures 3 and 4 present indoor and outdoor concentrations for $PM_{2.5}$ and PM_{10} for two of the study houses. Both houses showed substantial decreases in indoor concentrations post-PPV, consistent with the majority of the study houses. For House 3, outdoor PM concentration did not change substantially following PPV installation (4% and 6% increase in $PM_{2.5}$ an PM_{10}, respectively); however, a slight reduction was observed following the lockdown. Reductions in outdoor PM concentrations for House 8 were more in line with the study house average (13% and 12% for $PM_{2.5}$ and PM_{10}, respectively).

Indoor $PM_{2.5}$ concentrations pre-PPV installation tend to be similar or higher than outdoor concentrations over

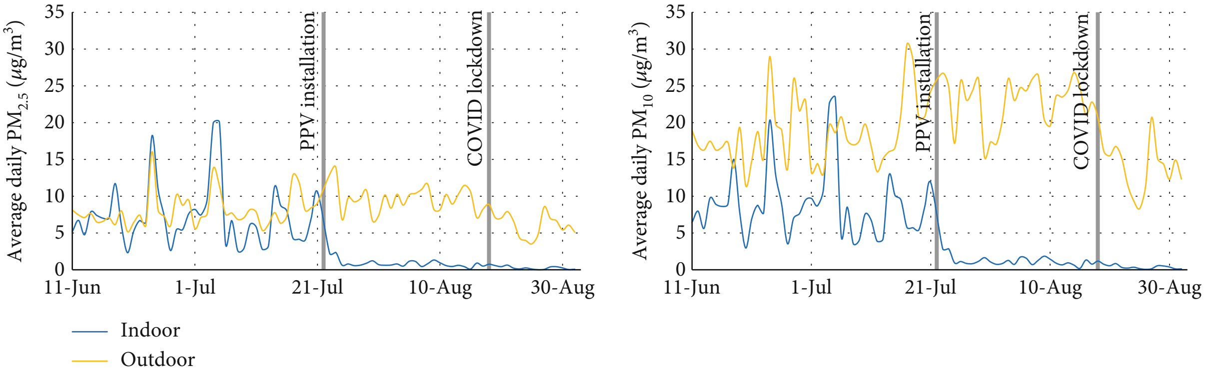

Figure 3: Indoor and outdoor concentrations of $PM_{2.5}$ and PM_{10} for House 3 (Auckland).

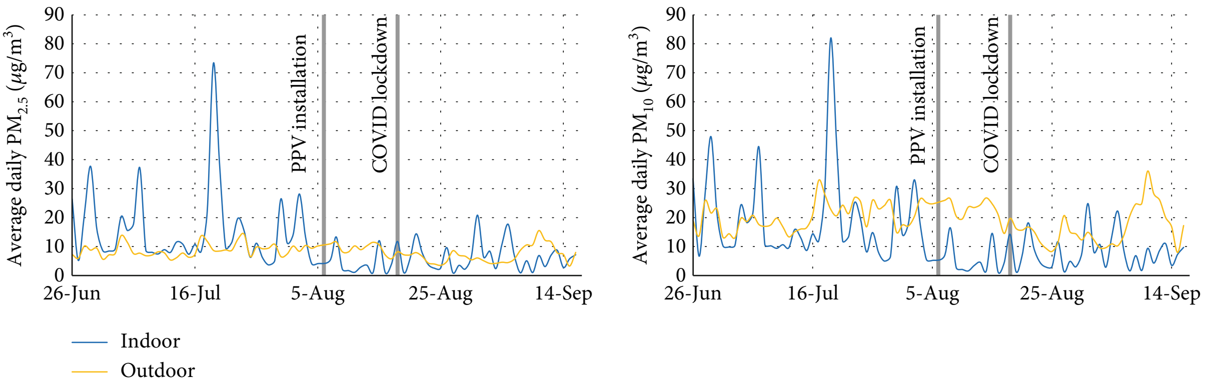

Figure 4: Indoor and outdoor concentrations of $PM_{2.5}$ and PM_{10} for House 8 (Auckland).

the same period, whereas indoor PM_{10} concentrations are lower than outdoor PM_{10} concentrations pre-PPV installation. $PM_{2.5}$ can originate from both indoor and outdoor sources. However, while $PM_{2.5}$ can enter the home via infiltration through the building envelope, indoor $PM_{2.5}$ is more commonly generated by activities within the home. In contrast, PM_{10} is more commonly associated with outdoor sources [71].

3.3. Occupant Comfort. Mean indoor temperature and RH values both pre-PPV installation and post-PPV installation are shown in Table 3. While there is an apparent trend showing the reduction of RH following PPV installation (ranging from 6% to 14%, in relative terms, for six of the eight houses), there appears to be no clear correlation between indoor temperatures and the installation of the PPV system.

Across the eight houses, no significant change in indoor temperatures was identified, with temperatures ranging between 16°C and 20°C in all cases. This was consistent with findings from previous studies showing that MV had limited impact on temperature [21, 48, 67]. Furthermore, changes in temperature were not expected due to the tendency of occupants to manually adjust their room temperature settings to maintain a desired level of comfort.

However, with RH, a clear reduction was observed for the majority of the houses. This reduction was expected, as one of the key features of (and primary drivers for installing) the PPV system is to reduce moisture levels in the home. House 7 was the only house for which an increase in RH was observed. The occupants of House 7 reported that condensation continued to form after the PPV was installed. It has been reported that buildings constructed from uninsulated concrete block in the 1960s and 1970s in New Zealand are commonly prone to serious condensation problems [72], which aligns with our study findings for House 7 and the comments from the occupants.

3.4. Influence of Building Characteristics on PM Concentration. An assessment of the impacts of various building characteristics on PM concentrations and associated reductions was undertaken across each of the study houses. Linear regression analysis was used to establish relationships between individual building characteristics and reductions in PM concentration following PPV installation. House 7 was excluded from the analysis, as it was the only dwelling that did not exhibit a notable PM reduction.

Building age, floor area, and the number of PPV outlets were each observed to poorly predict PM reduction, with R^2 values of 0.16, 0.23, and 0.15, respectively. Roof material, wall material, and insulation location were also assessed; however, as these variables were nonnumerical rather than continuous and given the relatively small sample size, no statistically significant relationships could be identified.

TABLE 3: Temperature and humidity data.

Location	House no.	Temperature (°C)					RH (%)				
		Pre		Post		*Δ* mean	Pre		Post		*Δ* mean
		Mean	St dev	Mean	St dev		Mean	St dev	Mean	St dev	
Auckland	2	16	2.1	17	1.7	6%	73.7	4.3	67.3	4.2	**−9%**
	3	18.6	2	18.8	1.9	1%	68.8	4.2	64.7	4	**−6%**
	4	17.5	2.8	18.2	2.4	4%	73.4	6.1	63.3	4.1	**−14%**
	6	17.4	3.2	17.5	3.3	1%	69.2	8.4	63.8	7.5	**−8%**
	7	19.5	3	18.5	3.3	−5%	63.7	7.3	66.9	9.8	**5%**
	8	16	2.2	17.6	2.4	10%	74.2	5.2	65.5	5.2	**−12%**
Hamilton	1	19.8	2	19.3	2	−3%	62.7	5	60.5	3.7	**−4%**
	5	19.1	2.1	17.9	1.6	−6%	67.8	5.9	61.3	4.4	**−10%**

Note: Values in bold (negative values) indicate houses where there was a substantial reduction in mean RH values.

Additionally, the number of occupants appeared to have minimal influence on PM reduction, possibly due to the lack of variation, as all homes comprised either three or four residents.

Multilinear regression analysis was also conducted to identify any significant relationships between groups of building characteristics and PM reductions. A relationship developed between PM reduction, air exchange rate (AER), and house area was found to predict PM reduction with a high level of accuracy ($R^2 = 82\%$) when House 7 was excluded from the dataset. This revealed that larger homes generally show a greater reduction in PM, suggesting that larger homes may contribute to better air circulation and more effective dispersion of particulates, particularly after the installation of a PPV system. The larger volume of air in these homes likely allows for a more efficient distribution and removal of airborne particles, resulting in a greater overall decrease in particulate concentrations. This relationship could potentially be extrapolated to other scenarios. However, given the inherent complexities of IAQ, including variations in housing conditions, occupant behavior, and environmental factors, it is advisable to expand the analysis to include a larger dataset for greater reliability and applicability.

3.5. AQI. Despite the relatively low average $PM_{2.5}$ concentrations observed across the eight houses during both the pre-PPV installation and post-PPV installation periods, the measured values were further assessed against the USEPA AQI [73] for fine particle pollution ($PM_{2.5}$) to benchmark the results against recognized best practice standards and to have a better insight into the changes qualitatively. While the AQI is based on ambient air, it has been adopted for comparison in the absence of any guidance specific to indoor air or any other AQI officially adopted in New Zealand. The AQI is based on average daily $PM_{2.5}$ limits set to protect public health and designates categories corresponding to different ranges of $PM_{2.5}$ concentrations (micrograms/cubic meter) as follows: good (0–12), moderate (12.1–35.4), unhealthy for sensitive groups (35.5–55.4), unhealthy (55.5–150.4), very unhealthy (150.5–250.4), and hazardous (250.5–500).

Figure 5 shows the percentage of $PM_{2.5}$ samples for each house that fall within the different AQI categories, both pre-PPV installation and post-PPV installation.

The majority of houses experienced an increase of between 15% and 25% of samples ranked as "good" following installation of the PPV system. One house experienced an increase of 43%; however, this house started with relatively poor air quality, with only 19% of "good" samples pre-PPV installation. One house did not show any change in the percentage of "good" samples following PPV installation.

Post installation, two houses had all or nearly all measurements within the "good" range (99% and 100%). The majority of houses showed a postinstallation reduction in unhealthy levels ("unhealthy for sensitive groups," "unhealthy," or "very unhealthy"), ranging from 2% to 26%. Three houses showed little to no reduction (< 1%), one of which was House 7 which, as previously described, may have been due to faulty PPV performance. No houses registered hazardous levels of $PM_{2.5}$ either pre-PPV installation or post-PPV installation.

Figure 5 shows that for Houses 2 and 3, virtually all $PM_{2.5}$ measurements post-PPV installation remained within "good" levels. House 4 experienced the highest percentage of $PM_{2.5}$ concentrations in excess of the upper limit for "moderate" levels, both pre- and post-PPV installation.

3.6. Indoor/Outdoor $PM_{2.5}$ Ratio. The average I/O ratio for $PM_{2.5}$ under natural ventilation conditions (pre-PPV installation) in the urban houses ranged between 0.85 and 1.81, with an average of 1.27. A significant reduction in the I/O ratio was observed post-PPV installation, with an average of 0.54 (ranging between 0.08 and 1.01). The largest reductions in I/O were observed in Houses 2 and 3, with I/O values post-PPV installation of 0.08 each. For the rural houses (Houses 1 and 4), the average I/O ratio pre-PPV installation was 3.42 (1.09–5.75) while post-PPV installation was reduced to 2.28 (0.66–3.89).

These findings, for both urban and rural areas, are consistent with previous studies that have observed that mechanically ventilated buildings showed consistent reductions in I/O ratios for a range of air pollutants when compared with naturally ventilated buildings [34, 61, 67, 74].

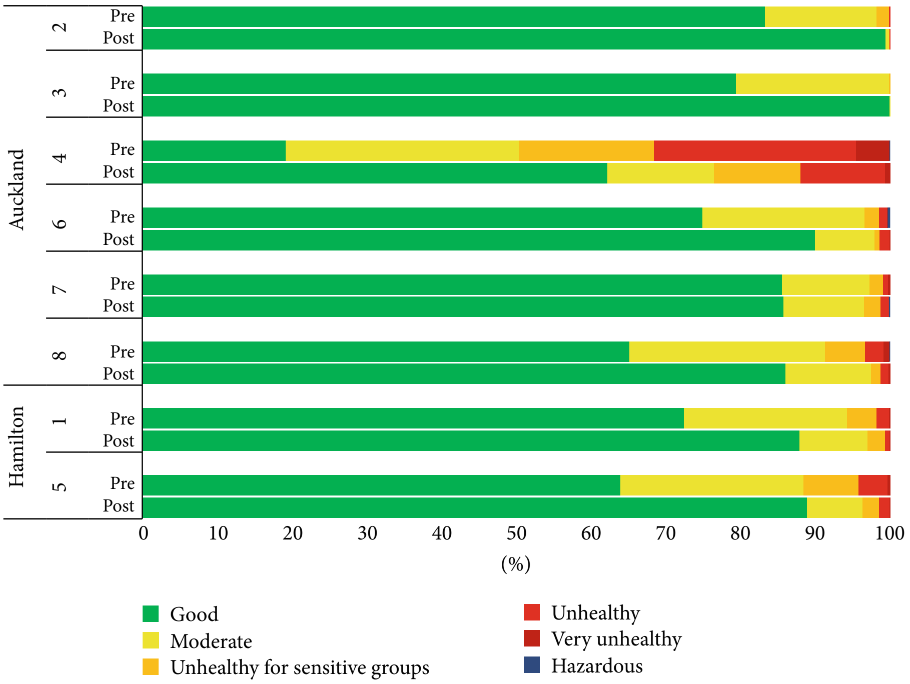

Figure 5: Evaluation of $PM_{2.5}$ concentrations against USEPA AQI.

Some of these studies also examined different types of MV (and indirectly AER) and highlighted the variability in filter efficiency and associated impacts on I/O [34, 58, 65].

3.7. COVID-19 Lockdown. Auckland first entered a strict (Level 4) lockdown in March 2020. The lockdown has been recognized as one of the most stringent worldwide [75], based on an assessment developed by the University of Oxford [76] of 21 government response measures. According to Patel [77], the lockdown led to a 60%–80% traffic reduction, while reductions in ambient concentrations of pollutants associated with vehicle emissions varied from 8% to 17% for $PM_{2.5}$ and 7%–20% for PM_{10}.

During this study, New Zealand experienced its second Level 4 lockdown, this time countrywide, in response to an outbreak of COVID-19 [78]. The lockdown meant that schools and all businesses were closed except for necessities (such as supermarkets and pharmacies) and essential services. All nonessential workers were requested to work from home, and travel was prohibited except for accessing necessities or essential services.

Figure 6 shows the monitoring period for each house pre-PPV installation and post-PPV installation and the overlap with the lockdown period, as shown by the blue arrow. The lockdown restrictions remained in place longer for Auckland than for the rest of the country.

To assess the impact that the lockdown had on IAQ as a result of increased occupancy (with PPV operational), the average indoor and outdoor $PM_{2.5}$ concentrations were compared for 1 week prelockdown and 1 week postlockdown.

Indoor $PM_{2.5}$ concentrations were found to increase in four of the houses (between 23% and 109%). While this increase is considered significant, it is recognized that $PM_{2.5}$ concentrations remained relatively low, keeping well within the USEPA AQI "good" to "moderate" ranges (i.e., below 35.4 $\mu g/m^3$). One house experienced an increase of 252%; however, $PM_{2.5}$ concentrations for this house were extremely low, on average equivalent to the sensor level of accuracy (1 $\mu g/m^3$), so the change was not relevant qualitatively.

One house exhibited no change in average indoor $PM_{2.5}$ concentrations. This residence, identified as a rural farmhouse, likely saw minimal impact on occupant behavior indoors due to the lockdown. Furthermore, prior research investigating the effects of COVID-19 on ambient PM concentrations has shown that, while PM in urban areas typically decreases significantly, reductions in rural PM levels tend to be relatively modest [79–81].

Two houses experienced reductions in $PM_{2.5}$ concentrations. In one case, the household included an essential worker, whose presence at home decreased due to the lockdown. For the other residence, although PM concentrations were initially low, there was no available information regarding changes in occupancy. It was noted that many Auckland residents relocated to their holiday homes in more remote areas to mitigate COVID-19 exposure, which might account for the observed improvement in IAQ.

The average I/O ratio across all eight houses was observed to increase from 0.42 for the week prior to lockdown commencement to 0.69 for the first week of lockdown. The I/O ratios pre- and postlockdown were significantly lower for both House 2 (0.04 and 0.2, respectively) and House 3 (0.05 and 0.07, respectively) compared with the other houses. Three houses showed an increase in I/O ratio from less than 1 for the week prior to lockdown to greater than 1 the week after lockdown. Increased occupancy rates due to the lockdown may explain this increase.

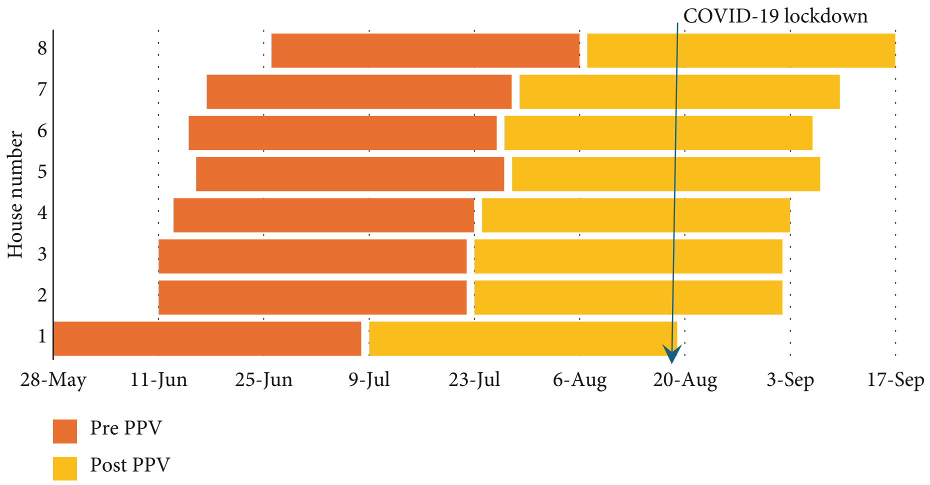

Figure 6: Data collection periods, showing COVID-19 lockdown.

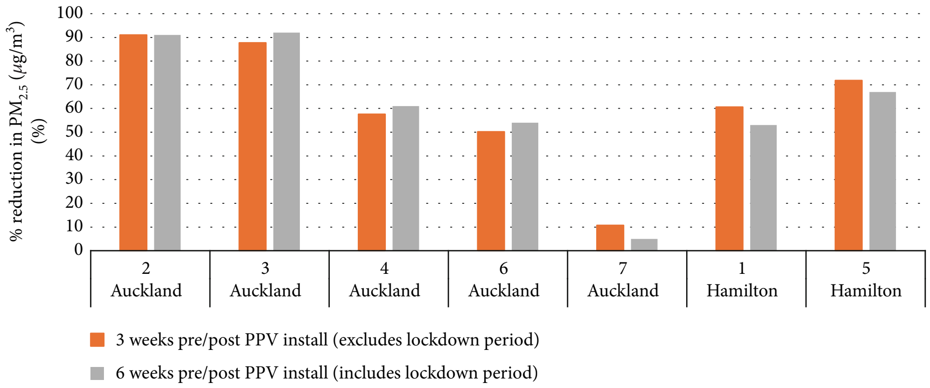

Figure 7: Percentage reduction in mean concentrations of indoor $PM_{2.5}$ following PPV installation.

3.7.1. Further Analysis (Excluding Impact of COVID-19). To isolate the impact of lockdown on IAQ from the effects of PPV installation, PM concentrations were analyzed for a 3-week period before and after PPV installation, that is, before any COVID-related restrictions were in place. PPV systems had been installed for at least 21 days prior to the COVID lockdown in all houses, with the exception of Houses 7 and 8, for which PPV systems had been installed 20 days and 11 days prior to lockdown, respectively. House 8 was excluded from the analysis as the PPV period was deemed insufficient for comparison with the other houses.

Mean indoor PM concentrations decreased following PPV installation by between 50% and 91% for all houses except for House 7, which saw a reduction of 11%. Figure 7 compares the percentage reductions in $PM_{2.5}$ for the entire study period against the reduced period excluding the COVID-19 lockdown. Houses 1, 5, and 7 showed greater reductions, while Houses 3, 4, and 6 showed slightly lower reductions, and House 2 showed a similar reduction. The average percentage reduction across all houses was 2% greater when the lockdown period was not included in the analysis.

4. Conclusions

By analyzing IAQ over a 6-week period before and after PPV installation, this study directly compared the effects of natural ventilation and MV within the same dwelling. The monitoring campaign was conducted under humid winter conditions and other environmental factors characteristic of Auckland's winter climate.

The installation of a PPV system was demonstrated to significantly reduce indoor PM concentrations across all eight study houses, by between 53% and 92%. There was a clear, but less substantial reduction in RH (6%–14%); however, there was no apparent influence of PPV operation on indoor temperatures.

Ninety-five percent of $PM_{2.5}$ measurements were classified as healthy (USEPA AQI "good" to "moderate" ranges) for seven of the eight study houses pre-PPV installation. This number increased to 98% post-PPV installation. PM reductions were generally found to be lower in the living rooms than in the bedrooms (6%–20%), potentially due to higher occupancy rates in living areas leading to increased human activity and PM generation. $PM_{2.5}$ I/O ratios were found to decrease significantly following the installation of PPV systems, from an average of 1.27 under natural ventilation conditions down to 0.54 with PPV installed.

The impacts of a COVID lockdown were analyzed and found to generally increase indoor PM concentrations. At the same time, outdoor PM concentrations decreased slightly (Auckland 20%, Hamilton 15%), possibly due to reduced outdoor human activity, especially vehicle use, resulting from the lockdown. An increase in I/O ratios after lockdown commenced is consistent with the supposition that occupancy rates increased.

Regression analysis revealed that none of the recorded building characteristics, when considered individually, could reliably predict PM reductions. However, multilinear regression analysis identified a strong relationship between AER, floor area, and PM reduction, with the model predicting PM reductions with high accuracy ($R^2 = 82\%$). Nevertheless, due to the limited sample size, future studies should consider a larger, more detailed investigation into the influence of building characteristics to enable a firmer conclusion.

5. Limitations and Future Research

The COVID-19 lockdown presented a unique opportunity to assess the impact of PPV systems on IAQ under conditions of heightened occupancy. However, anticipated increases in outdoor PM concentrations during winter, potentially driven by activities such as wood burning, were not observed. This lack of expected PM increase may be attributable to reduced outdoor activity during the lockdown, complicating the task of isolating the effects of occupancy changes on IAQ.

To enhance future research, it is recommended to incorporate comprehensive monitoring of outdoor PM concentrations at each residential location and to measure household AERs. Additionally, expanding the study to include diverse topographical and meteorological settings could provide a broader understanding of the findings. Intensifying the physical characterization of study homes by examining factors such as insulation and airtightness would further refine the assessment of IAQ dynamics.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* Appendix S1: Monitoring equipment details. Appendix S2: PPV system overview.

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