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Impact of positive pressure ventilation systems on indoor air quality in residential settings

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ABSTRACT

Effective ventilation is a key requirement in residential buildings to achieve healthy indoor air quality (IAQ) through the introduction of fresh air. Mechanical ventilation (MV) systems are designed to meet IAQ objectives by delivering regular air exchange and dilution of stale air. Positive pressure ventilation (PPV) systems commonly source air from the roof cavity and distribute it throughout the indoor environment.

This study evaluated the effects of PPV systems on IAQ in 10 single-family dwellings over a nine-month period across three seasons (winter, spring and summer) and including pre-and post-installation monitoring. Regular measurements of IAQ parameters including $PM_{2.5}$, PM_{10}, radon, fungal DNA, and heavy metals were collected from bedrooms, living areas, roof spaces and outdoors.

Mean indoor concentrations of $PM_{2.5}$ and PM_{10} each decreased by 44 % following PPV installation. Outdoor levels of $PM_{2.5}$ and PM_{10} increased over the same period, by 41 % and 37 %, respectively. Reductions in mean indoor concentrations were also observed for radon (53 %) and fungal DNA (64 %). Indoor concentrations of heavy metals also decreased, with chromium, copper, lead, nickel, and zinc decreasing by 28 % on average, while arsenic and cadmium were generally below detection limits.

Indoor $PM_{2.5}$ concentrations were 31 % higher than roof space concentrations, and weakly correlated (Spearman's coefficient, $r_s = 0.12$), suggesting limited influence from the roof cavity. Temperatures in the roof space were 7.1 °C lower, on average, than indoor temperatures. Analysis suggests that a higher temperature differential between roof and indoors is associated with higher levels of energy use, particularly at differentials above 4 °C.

1. Introduction

Poor IAQ has been associated with severe health impacts, such as lung cancer and asthma [1–5], as well as increased mortality [6–9]. Various studies have shown that exposure to indoor pollution tends to be more common than outdoor exposure [10–12]. This is further supported by evidence that people spend 90 % or more of their time indoors [13, 14].

Indoor pollutant levels often surpass outdoor concentrations, with common contaminants including fine particulate matter ($PM_{2.5}$), fungal spores, radon, and heavy metals [15]. These pollutants come from human activities (e.g., cooking, wood burning, smoking), building materials, household products, and structural issues such as leaks or cracks or secondary pollutants generated indoors [16,17]. Poor ventilation, particularly in airtight homes, can trap particulate matter (PM), leading to higher concentrations [18]. Mould thrives in damp, poorly ventilated spaces, growing on materials like plasterboard and wood [19–21]. Radon, a gas that infiltrates up from the ground through cracks in the building's foundation, poses a risk, especially in homes built on contaminated soil [22–24]. While radon levels in New Zealand homes are generally low [25,26], concentrations previously measured inside New Zealand homes have been found to exceed WHO and IAEA reference levels [25,27,28]. Heavy metals, which can accumulate from sources such as wood burning, household dust, plumbing systems, tobacco smoke, paint, pesticides and cleaning products, further impact IAQ [3,29,30]

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Ventilation plays an important role in maintaining healthy IAQ by diluting and flushing contaminants, and circulating fresh air throughout a building [31–33]. Indoor pollutant concentrations can be influenced by a variety of factors including outdoor air quality [34], internal pollutant sources, building airtightness and the efficiency of ventilation and passive removal processes [35]. Natural ventilation (NV), which relies on openings such as windows and doors to permit air exchange, provides an energy efficient alternative to mechanical systems. However, its effectiveness is often reduced during colder months, when windows and doors tend to be kept closed to maintain thermal comfort [36].

Modern insulation methods focus on creating airtight environments to minimise heat loss by forming a thermal barrier, sealing of gaps and cracks to prevent air exchange with outdoor air. de Groot & Leardini [2] identified that in New Zealand, while such practices elevate internal temperatures, they also restrict ventilation. Furthermore, New Zealand homes are commonly recognised for their dampness, likely reflecting high levels of outdoor humidity, a relatively poor housing stock, as well as inadequate heating and insulation [37–39]. These findings highlight the critical need for effective ventilation systems that achieve a balance between enhancing energy efficiency and maintaining healthy IAQ.

MV systems, in contrast, actively supply outdoor air into the indoor environment. PPV is a type of MV system which draws air from the roof cavity or outside, filters and distributes it through the home to create a positive pressure in the indoor environment, forcing out stale air. PPV systems have been widely adopted across various regions around the world, including Europe, USA, and New Zealand, due to their relative affordability and simplicity compared with more complex systems [40–42]. However, PPV systems drawing air from roof cavities (which may contain contaminants such as dust, mould, vermin, or even asbestos) into the indoor environment, have raised questions about their safety and long-term efficacy in removing pollutants [43]. Some countries, such as Spain and New Zealand, have introduced codes requiring that MV systems take air from outdoors to mitigate contamination risks, making many PPV systems non-compliant [44–48]. Furthermore, EU guidelines recommend sourcing air directly from outdoors to mitigate contamination risks [44,49].

PPV systems have been widely implemented in residential settings to improve IAQ and thermal comfort. The ability of PPV and other MV systems to reduce indoor pollutant concentrations is well-documented in the literature base [50–58]. These systems have shown consistent advantages over NV in terms of managing levels of various indoor pollutants, particularly in colder climates or more polluted urban environments. However, while the majority of such findings have emerged from cross-sectional studies comparing various ventilation strategies in different dwellings, the extent of literature comparing NV against MV within the same building is limited.

Rosbach et al. (2015) monitored PM concentrations inside 12 school classrooms during winter, before and after MV installation, reporting reductions in PM_{10} [59]. Montgomery et al. (2015) conducted $PM_{2.5}$ measurements in a 250m^2 open-plan office before and after an MV system was installed, noting reductions in $PM_{2.5}$ [60]. Vornanen-Winqvist et al. (2018) similarly reported decreases in $PM_{2.5}$ following installation of a PPV system, measured inside 12 school classrooms [61]. Ballerini et al. (2025) monitored PM and radon inside a school for 12 months, pre- and post-MV installation, however no notable changes were reported [62]. Kang et al. (2022), investigated the effects of different MV system types on IAQ in 40 homes, measuring PM levels for one week every three months of the 2.5 year study duration, observing decreases in $PM_{2.5}$ and PM_{10} I/O ratios post-installation [63]. Coggins et al. (2022) and Hassan et al. (2024) analysed $PM_{2.5}$ and radon concentrations for 3–4 months across 14 and 12 houses respectively, noting increases in $PM_{2.5}$, with no change in radon levels [64,65]. Much et al. (2024) conducted a repeat winter study in a single house, measuring $PM_{2.5}$, mould and relative humidity (RH) two weeks either side of the MV installation, noting RH decreased, $PM_{2.5}$ increased, with no change in radon level [18].

In New Zealand and Australia, PPV systems commonly draw intake air from roof cavities, which has the potential to bring contaminants inside the building. While existing studies have characterised roof space thermal conditions [66–69], a gap remains in studies investigating pollutant concentrations in roof cavity air and the associated impact on IAQ. The growing trend towards airtight building design to improve thermal efficiency has the potential to intensify the accumulation of indoor pollutants, making this gap particularly relevant. New studies investigating roof space air quality and its connection with IAQ would help to address this gap. Investigating the relationship between roof temperature, indoor temperature and heating demand could also prove beneficial.

This study aims to address some of these research gaps by comparing NV and MV conditions within the same building, with monitoring conducted over a continuous, nine-month period to identify seasonal patterns. This intervention-based approach has been applied across 10 single-family dwellings, focusing on a broad range of pollutants, including $PM_{2.5}$, PM_{10}, mould, radon, and heavy metals, as well as temperature and RH. Additionally, the study examines the quality of air drawn from roof cavities and the potential links with IAQ. Energy consumption is also analysed, alongside roof and indoor air temperatures, to assess the potential impact of PPV operation on energy use.

2. Methodology

2.1. Study design and overview

This study was designed to evaluate seasonal changes in IAQ and thermal comfort parameters before and after the installation of a PPV system in a selection of single-family dwellings situated in Auckland, New Zealand. The experimental campaign spanned three seasons (winter, spring and summer), from June 2023 to February 2024, including a six-week period either side of the scheduled installation.

The experiment related to four main visits. The first at the onset of winter involved installing IAQ monitors, assessing the house, collecting initial data, and taking dust samples. The second visit, in mid-winter, coincided with the installation of the PPV system and included further dust sampling. Six weeks post-installation, the third visit was conducted to assess the immediate impacts of the PPV, with additional dust collection. The final evaluation occurred six months later, at the end of summer, to analyse the long-term effects of the system, completing the cycle of data collection.

Additionally, air quality and temperature measurements were collected from within the roof cavities of selected homes to investigate the influence roof space air on air quality and thermal comfort indoors while the PPV system was operational. Household energy consumption data were analysed to determine whether temperature changes associated with the introduction of roof space air had any discernible effect on heating costs.

This experimental study was designed such that IAQ monitoring was conducted in the same dwellings, with the same occupants, across the same seasons, before and after PPV installation. This approach aimed to isolate the influence of the PPV system from other potential confounding factors such as weather, occupancy, or household activity, and reduce experimental uncertainty. Importantly, human behaviour and window/door opening were not actively controlled, as the objective was to observe the system's impact under typical domestic conditions. However, occupants were given clear instructions regarding system use and reported high compliance during the study period.

2.2. Selection of dwellings

In this study, 10 households were selected based on their scheduled installation of a new PPV system. The houses were chosen strategically to reflect the most common types within New Zealand's residential building stock. All houses were timber-framed, timber-clad, free-standing dwellings with single-glazed windows, comprising 2 to 5 bedrooms, an open plan kitchen/living area, 2.4 m ceilings and floor-plan area between 82 m^2 and 260 m^2. These features align closely with the typical size, layout and construction of New Zealand's detached housing stock [70–78]. Eight homes were single-storey, while two included a second-storey.

Selected households comprised 3 to 5 occupants, with at least two adults, and were all non-smoking, representing typical residential occupancy patterns and behaviours in New Zealand homes [79,80]. Only one home had an open fireplace, while all had kitchen extractor fans, and four had extractor fans in bathrooms. Locations of the selected houses are detailed in Fig. 1.

2.3. Positive pressure ventilation system

PPV systems were installed in all houses during the middle of winter. The PPV system operates automatically, using an algorithm to dynamically adjust airflow according to changes in indoor and outdoor temperatures. To ensure consistent and reliable ventilation performance under different environmental conditions, participants were instructed to not adjust the mode of operation for the duration of the study. Additionally, to achieve positive pressure was maintained and system performance optimised, occupants were instructed to keep all windows and doors closed while the PPV system was in use during winter months. Although the study did not actively monitor compliance with these instructions, the majority of occupants reported that they adhered to the request.

The PPV system features two main components: a fan and a filter. The fan is an alternating current centrifugal model with backward-curved blades, capable of delivering an airflow of 810 m^3/hour. The filter comprises a series of sheets, each formed by a web of fibres such as plastic, glass, paper, and wool, with an F8 efficiency grade, achieving 95 % removal of particles as small as 0.4 μm, according to Eurovent and ASHRAE standards [81,82].

The PPV retrofit involved mounting the fan and filter unit in the roof space, with insulated ducting connecting the unit to a ceiling-mounted diffuser. In most homes, minor alterations to the roof cavity (e.g. local modifications to roof insulation, sealing penetrations) were necessary to accommodate the ducting and ensure unobstructed airflow. However, these changes are not expected to have significantly altered the thermal or air leakage characteristics of these buildings.

In New Zealand, industry guidelines recommend a ventilation rate of three air changes per hour (ACH) be adopted when sizing MV systems [83]. This rate is intended to ensure a healthy level of IAQ is maintained. Each system was sized to deliver at least 3 ACH based on the internal volume of the dwelling, with additional (or higher speed) fans installed where necessary.

Fig. 2 depicts the typical airflow patterns associated with a PPV system.

2.4. Data collection and measurement

Time-resolved measurements were collected to assess indoor and outdoor air quality in residential homes. The study utilised three air quality monitors in each house – positioned in the master bedroom, the living area, and outdoors (Fig. 1) – to continuously monitor PM ($PM_{2.5}$ and PM_{10}), as well as temperature and RH, key parameters to assess thermal comfort. To ensure consistency, the PM instrumentation was placed approximately 1.5 m above floor level, and away from direct heat sources and windows, where possible. Air quality monitors measuring $PM_{2.5}$, PM_{10}, temperature and RH were also installed in the roof space of select houses during the post-PPV period to evaluate intake air. Household energy consumption data was obtained from monthly readings of individual household electricity meters.

Three different types of monitoring devices were deployed to collect air quality information during the experimental campaign: Airly PM [84], uRAD [85], and SunRadon [86]. These monitors gathered data on specific air quality parameters as detailed in Table 1.

Dust samples were collected from each home for fungal DNA and

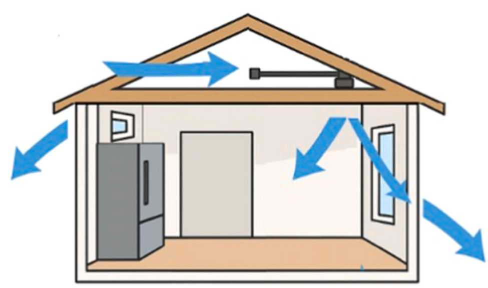

Fig. 2. PPV system and airflow.

Fig. 1. Study house locations across Auckland / Typical floorplan and sensor layout.

Table 1
Air quality monitor details.

Make/ Model	Location / Duration / Frequency	Parameter	Range / Accuracy	Sampling/ Measurement Method
Airly PM	Living Area, Outside: 12 weeks (pre/ post-PPV) Roof: 2 weeks (post-PPV) Every 5 min	Temp.	Range: −40 °C – +80 °C ± Accuracy: 0.1 °C	Uses a laser scattering sensor to measure PM. Field testing indicates strong correlation (R^2 for 5-min averages of 0.83, 0.92, and 0.89 for PM, Temp and RH respectively), high data recovery (>93 %) and low variability (0.29 μg/m^3 for $PM_{2.5}$) [87]
		RH	Range: 0 – 100 % Accuracy: ± 1 %	
		$PM_{2.5}$	Range: 0 – 1000 μg/ m^3 Accuracy: ±1 μg/m^3	
		PM_{10}	Range: 0 – 1000 μg/ m^3 Accuracy: ±1 μg/m^3	
Magnasci SRL uRADMonitor INDUSTRIAL (HW103)	Bedrooms 12 weeks (pre/post-PPV) Every 5 min	Temp.	Range: −40 °C – +125 °C Accuracy: ± 0.3 °C	Uses a laser scattering sensor to measure PM. Field evaluation indicates strong correlation (R^2 for 1-hr averages of 0.7–0.78 for $PM_{2.5}$), high data recovery (99 %) and moderate variability (19–25 % for $PM_{2.5}$) [88]
		RH	Range: 0 – 100 % Accuracy: ± 2 %	
		$PM_{2.5}$	Ramge: 0 – 1000 μg/ m^3 Accuracy: ±1 μg/m^3	
		PM_{10}	Range: 0 – 1000 μg/ m^3 Accuracy: ±1 μg/m^3	
SunRadon Model 1030 Radon Sentinel	Living room 2 weeks (pre/ post-PPV) Every 1 hour	Radon	Range: 0.1 - 9999 pCi/ l Accuracy: ±3 %	Utilises a solid-state photodiode detector with passive airflow diffusion to measure radon concentrations. Approved by the US National Radon Safety Board (NRSB) and under the National Radon Proficiency Program (NRPP).

heavy metals analysis, six weeks pre-PPV (to clean the sampling surface), immediately prior to installation (sample and clean), and six weeks after installation (sample). Fungal DNA dust samples were taken from the living area and master bedroom (60 cm^2 area from top of door frame). while heavy metals dust samples were collected from the living area only (100 cm^2 area from top of bookshelf). Dust samples were collected using sterile cotton swabs, sealed in individual plastic bags and sent to the laboratory for analysis. The entire surface was then wiped clean with sterile, distilled water after each sample.

Heavy metals analysis tested for arsenic, cadmium, chromium, copper, lead, nickel and zinc. These metals were selected as they are common combustion products from wood burning [89,90], and wood burning is a significant source of indoor pollution in New Zealand homes [91,92]. The analysis involved ICP-MS on the modified aqua regia digestion of the dust sample, based on NIOSH Method 7303, issue 1 (modified). Detection limits (μg/sample) were arsenic: 0.5; cadmium, copper and zinc: 0.03; chromium, nickel: 0.3; lead: 0.05.

Fungal DNA analysis was performed using qPCR (quantitative Polymerase Chain Reaction) on DNA extraction from the dust sample. DNA was extracted using DNeasy Plant Mini Kits (Qiagen, Germany, according to the manufacturer's instructions [93]) and amplified with primers 5.8 F1, 5.8R1 [94]. DNA extractions were quantified using real-time PCR (Bio-Rad CFX Connect, USA). Standard curves were established with fungal strains from International Collection of Microorganisms from Plants (ICMP), Landcare Research, New Zealand, cultured on potato dextrose agar (PDA) plates. qPCR was performed on Bio-Rad plates using SYBR Green super mix. Standard DNA templates were prepared in triplicate, with DNA copies calculated using Bio-Rad software.

2.5. Calibration of air quality monitors

Auckland Council air quality monitoring (AQM) station sensors served as reference sensors for calibrating all study sensors. Over a three-week period, a research-grade PM monitor (Aeroqual Dust Sentry Pro, which is MCERTs-certified and SCAQMD-pre-approved, [95]), and PM monitors (Airly PM and uRAD-Industrial) were co-located with an AQM station for cross-calibration and validation. All study sensors were then calibrated before and after the monitoring period using these cross-calibrated sensors at the Unitec Institute of Technology. Calibration involved two methods: (1) co-location with the Aeroqual Dust Sentry Pro, and (2) mutual co-location with the low-cost sensors as arbitrary references, aimed to reduce uncertainty and ensure consistency across devices. A similar approach has been adopted for other studies, including Kang et al. (2022) [63].

Correlation tests on the Aeroqual Dust Sentry Pro monitors, with an accuracy of ±5 μg/m^3 plus 15 % of the reading, showed strong correlations for $PM_{2.5}$ (R^2 = 0.89–0.95) and PM_{10} (R^2 = 0.92–0.96), consistent with previous studies [96–98]. In comparison, studies calibrating low-cost PM sensors against reference devices reported lower R^2 values (0.55–0.72) [99,100]. No significant differences were found between pre- and post-calibration R^2 values. Temperature and RH R^2 values were 0.85 and 0.95, respectively. Mutual co-location further confirmed strong linearity, with average R^2 values of 0.9 and 0.89 for $PM_{2.5}$ and PM_{10} respectively.

Following calibration, outliers were identified and removed using automated routines with the software package R [101] and through visual inspection to identify anomalous data points, including negative values. To help identify trends without distorting the data, a moving average filter was used to eliminate noise.

2.6. Analysis

Analysis of PM included both $PM_{2.5}$ and PM_{10}, however greater emphasis has been placed on $PM_{2.5}$ due to its stronger association with negative health impacts [102,103].

The pollutant measurement data were presented as mean, standard deviation (SD), 5th-95th percentile range for each house over the pre-PPV (winter), post-PPV (winter), spring and summer periods. Percentage change in time-averaged concentrations between each period was analysed to compare central tendencies.

Indoor-outdoor ratios were computed to account for infiltration effects and identify internal emission sources. Spearman's rank correlation [104] was applied to assess the extent of correlation between paired combinations of indoor, outdoor and roof space PM. The Wilcoxon signed rank test [105] was applied as a conservative measure to assess correlations and check consistency with the Spearman's rank results, while accounting for non-normal data distributions.

To further support the statistical analysis findings, a linear mixed-effects (LME) model was developed using R to evaluate the influence of the PPV system on indoor $PM_{2.5}$ concentrations over winter. A similar approach has been adopted in other IAQ studies [65,106]. The model included fixed effects for PPV status (pre/post-installation), outdoor $PM_{2.5}$ and outdoor temperature, with random intercepts and slopes by household to account for repeated measures and variability in intervention response. The dependent variable was log-transformed to approximate a normal distribution. Model reliability was confirmed by analysing Cook's Distance to identify influential data points, and inspecting BLUPs (best linear unbiased predictions) to ensure random effects followed the expected distribution.

Diurnal profiles were examined for each house to identify the presence and regularity of morning and evening peaks. For each house, average diurnal profiles for the pre and post-PPV periods were generated by calculating the mean concentration across the period at each time during of the day. The pre-PPV and post-PPV diurnals were then compared for each house, assessing the percentage change between the two profiles during peak and non-peak periods. The Wilcoxon signed-rank test was used to determine whether a statistically significant difference exists between the percentage changes calculated.

These analytical approaches help to mitigate possible uncertainties and strengthen the reliability of the reported findings.

3. Results and discussion

3.1. Indoor particulate matter

3.1.1. Pre/Post-Installation and seasonal trends

A summary of indoor PM measurements, collected pre- and post-PPV installation, is presented for all study houses in Table 2 and Table 3. The living room tends to be the most occupied area of a house [107,108]. Accordingly, living area concentrations were the focus of this analysis. Percentage change, as shown, is based on change over winter between the pre-PPV to post-PPV period, where negative values represent a reduction.

Pre-PPV mean winter $PM_{2.5}$ concentrations ranged from 1.7 μg/m³ to 7.9 μg/m³, except for Houses 2 (25.5 μg/m³) and 3 (48.8 μg/m³), which exceeded the World Health Organization's 24-hour exposure guideline of 15 μg/m³ [109]. Although pre-PPV PM levels were relatively low in many homes, these values are consistent with findings from previous studies on houses with NV [50,55,56,63,110]. Further analysis as outlined below highlights that House 3 in particular stands out as exhibiting overall poor air quality. Observations during site visits revealed that this house, despite being of average structural condition, exhibited a low level of cleanliness, signs of frequent cooking, candle-burning and pets, all of which can contribute to degraded IAQ. House 2 was also noted to be in poor condition and undergoing carpet replacement in the weeks before and after PPV installation, likely elevating PM levels due to resuspension.

Post-PPV installation, mean winter $PM_{2.5}$ concentrations decreased significantly in all but one house, with reductions ranging from 32 % to 71 %. House 6 showed a 7 % increase (0.2 μg/m³), which was deemed insignificant (beyond the limit of sensor accuracy). Post-installation concentrations ranged from 1.0 μg/m³ to 3.5 μg/m³ in eight houses. House 2 remained higher at 11.7 μg/m³ but still below the WHO guideline for 24-hour exposure. House 3 was the only house which remained above the WHO 24-hour limit, with post-PPV levels of 32.4 μg/m³.

These post-installation levels align with findings from previous studies on homes with MV [50,63,111], although Wang et al. (2016) [112] reported much higher indoor concentrations. The observed $PM_{2.5}$ reductions (excluding House 6) are consistent with Kang et al. (2022) [63]. During the site visit, the occupant of House 6 reported keeping windows and doors open most of the time, which can disrupt PPV system performance by preventing proper pressurisation, as noted by Chen et al. (2011) [113].

Pre-PPV mean PM_{10} concentrations followed a pattern similar to $PM_{2.5}$, with eight houses showing levels between 1.8 μg/m³ and 8.9 μg/

Table 2
$PM_{2.5}$ summary statistics for 5-minute indoor concentrations (living area).

House No.	Winter, pre-PPV				Winter, post-PPV				% change in mean	Spring				Summer			
	mean	SD	5th %ile	95th %ile	mean	SD	5th %ile	95th %ile		mean	SD	5th %ile	95th %ile	mean	SD	5th %ile	95th %ile
1	3.9	6.3	0.8	13.1	2.1	3.7	0.5	6.1	−45 %	1.7	2.5	0.6	4.8	1.5	1.4	0.7	3.1
2	25.5	79.4	0.7	115.6	11.7	38.0	0.6	50.4	−54 %	9.5	36.5	0.6	43.8	5.2	20.7	0.6	19.3
3	48.8	135.2	0.6	233.0	32.4	110.1	0.6	167.6	−34 %	26.9	100.3	0.6	129.7	7.2	33.8	0.6	25.8
4	2.9	3.5	0.6	9.6	1.6	2.5	0.5	5.5	−45 %	2.0	3.9	0.5	7.2	1.7	3.4	0.5	4.1
5	4.0	21.2	0.3	13.7	1.6	8.4	0.3	3.7	−59 %	1.6	8.0	0.3	3.9	0.8	2.1	0.3	2.2
6	3.3	8.2	0.6	11.2	3.5	7.7	0.6	11.5	7 %	1.6	4.2	0.6	3.3	1.6	7.0	0.6	2.6
7	7.9	31.0	0.6	20.6	2.3	8.1	0.6	5.5	−71 %	1.7	8.6	0.6	3.4	1.4	2.6	0.6	3.1
8	1.7	2.9	0.1	5.0	1.0	4.3	0.0	3.1	−41 %	0.7	2.0	0.0	2.1	0.8	0.8	0.0	2.1
9	4.5	16.3	0.4	14.0	3.0	10.1	0.4	11.1	−32 %	1.1	3.9	0.4	2.3	1.2	5.2	0.4	2.3
10	7.8	18.8	0.6	28.2	2.6	7.5	0.6	10.2	−66 %	2.1	8.1	0.6	5.7	2.2	7.8	0.6	6.9
Avg	11.0	32.3	0.5	46.4	6.2	20.0	0.5	27.5	−44 %	4.9	17.8	0.5	20.6	2.4	8.5	0.5	7.1

Table 3
PM_{10} summary statistics for 5-minute indoor concentrations (living area).

House No.	Winter, pre-PPV				Winter, post-PPV				% change in mean	Spring				Summer			
	mean	SD	5th %ile	95th %ile	mean	SD	5th %ile	95th %ile		mean	SD	5th %ile	95th %ile	mean	SD	5th %ile	95th %ile
1	4.0	6.2	0.8	11.3	2.3	3.8	0.5	5.2	−43 %	1.8	2.6	0.6	4.1	1.6	1.3	0.7	2.8
2	29.3	89.5	0.7	136.1	13.6	44.7	0.7	59.4	−54 %	11.0	42.2	0.7	51.5	6.0	24.4	0.7	22.1
3	54.4	146.0	0.7	270.6	36.1	119.8	0.7	192.4	−34 %	29.8	108.5	0.7	150.3	8.1	37.7	0.7	29.5
4	3.0	3.5	0.8	8.4	1.7	2.2	0.7	5.1	−44 %	2.0	3.5	0.7	6.5	1.9	3.8	0.7	3.7
5	6.8	34.7	0.8	22.3	3.0	13.7	0.8	6.0	−56 %	2.8	13.0	0.8	6.3	1.6	3.5	0.8	3.7
6	3.4	9.2	0.6	8.5	3.7	7.9	0.6	8.5	8 %	1.7	4.3	0.6	2.7	1.6	8.3	0.6	2.2
7	8.9	36.0	0.7	23.4	2.6	9.3	0.7	5.9	−71 %	1.8	9.8	0.7	3.6	1.5	3.0	0.7	3.3
8	1.8	3.2	0.2	4.7	1.0	4.1	0.0	2.9	−47 %	0.8	1.8	0.0	2.0	0.9	0.7	0.0	1.9
9	7.2	26.8	0.8	22.6	4.9	16.5	0.8	18.1	−32 %	1.8	6.3	0.4	2.3	1.9	8.5	0.8	3.4
10	8.7	21.8	0.7	32.2	2.9	8.8	0.7	11.4	−66 %	2.3	9.4	0.6	6.9	2.5	9.1	0.7	7.5
Avg	12.8	37.7	0.7	54.0	7.2	23.1	0.6	31.5	−44 %	5.6	20.1	0.6	23.6	2.7	10.0	0.6	8.0

m³, except for Houses 2 (29.3 μg/m³) and 3 (54.4 μg/m³). All houses were below the WHO 24-hour PM_{10} guideline of 45 μg/m³, except House 3. These levels aligned with previous studies on naturally ventilated homes [50,63], although other studies [55,56] reported levels 2–3 times higher. Post-PPV, PM_{10} concentrations decreased in nine homes over the winter period, with reductions ranging from 32 % to 71 % in nine houses; House 6 saw a slight increase of 8 %, consistent with $PM_{2.5}$ results. After installation, all houses had PM_{10} levels below the WHO limit, ranging from 1.0 μg/m³ to 4.9 μg/m³, except for House 2 (13.6 μg/m³) and House 3 (36.1 μg/m³). These post-PPV concentrations were consistent with research by Kang et al. [63] and Lim et al. [50] on homes with MV.

While standard deviation (SD) values for all houses indicate a generally high variability in PM concentrations (as expected, due to variation across the diurnal profile), SD values for $PM_{2.5}$ decreased following PPV installation, from an average of 32.3 μg/m³ down to 20.0 μg/m³ (PM_{10} decreased from 37.7 μg/m³ to 23.1 μg/m³). The progressive reductions in SD values observed for $PM_{2.5}$ and PM_{10} suggest that PPV systems may be having a stabilising effect on PM variability. Similar observations were made in previous studies Kang et al. [63] and Lim et al. [50]. Notably, while not necessarily exhibiting the highest percentage reductions, Houses 2 and 3, with the highest levels of pollutants initially, showed the greatest absolute reduction in $PM_{2.5}$ concentrations post-PPV (13.8 μg/m³ and 16.4 μg/m³ respectively). This suggests that the PPV system can effectively reduce high PM concentrations.

To evaluate the influence of the PPV system, while accounting for the effects of outdoor $PM_{2.5}$ and temperature, an LME model was developed. The indoor and outdoor $PM_{2.5}$ concentrations were log-transformed before using the model. Post-PPV installation was associated with a statistically significant reduction in indoor $PM_{2.5}$ concentrations (p-value 0.025, t-value −2.83), after adjusting for outdoor $PM_{2.5}$ and temperature. The estimated effect size was −0.26 (equating to a 22.9 % reduction on the original $PM_{2.5}$ scale), with a 95 % confidence interval between 4.2 % and 37.9 %. Model diagnostics used included Cook's Distance and BLUPs for random slopes. There were no significantly influential data points found. The random slopes aligned well with the observed effects across households, validating their inclusion. These model results together with the statistical analysis support the observed reductions in mean indoor $PM_{2.5}$ concentrations following the introduction of a PPV system.

3.2. Seasonal variation

In the spring, $PM_{2.5}$ levels averaged 1.5 μg/m³ across all houses, excluding Houses 2 and 3 (9.5 μg/m³ and 26.9 μg/m³, respectively). House 3 continued to experience relatively high levels, above the WHO 24-hour limit. In summer, $PM_{2.5}$ averaged 1.4 μg/m³, excluding Houses 2 and 3 (5.2 μg/m³ and 7.2 μg/m³, respectively). These concentrations are comparable with the results of Lim et al. [50] and were all below the WHO limit.

Percentage reductions in $PM_{2.5}$ observed between winter post-PPV period and spring averaged 29 % across all houses excluding House 4 (25 % increase). Further reductions of 29 % (average) occurred between spring and summer in seven houses. Houses 8, 9, and 10 showed increases of 15 %, 6 %, and 7 % respectively, however the net increase for each house was significantly less than 0.2 μg/m³ (i.e. beyond the level of sensor accuracy). PM_{10} reductions from winter post-PPV to spring averaged 29 % across all houses except House 4, which exhibited an increase of 22 %. An average reduction of 30 % was observed between spring and summer concentrations, excluding Houses 8, 9, and 10, showing increases of 14 %, 6 %, and 6 %, respectively (again, net increases were below 0.2 μg/m³). The PM reductions observed over spring and summer were likely influenced by periods of hybrid ventilation, where the PPV system operated concurrently with NV as temperatures increased. These findings for $PM_{2.5}$ and PM_{10} are consistent with those of previous studies which have reported general decreases from winter to spring and spring to summer [50,114].

3.2.1. Spatial and diurnal variability

Mean winter $PM_{2.5}$ concentrations were compared between the living area and master bedroom for each house to identify the degree of variability across the house.

Pre-PPV, mean winter $PM_{2.5}$ concentrations in living rooms were, in general, similar or slightly higher than master bedroom levels (within 3 μg/m^3). Notable exceptions were Houses 2 and 3, which had living room concentrations up to 25 μg/m^3 higher than the master bedroom. Post-PPV, living room concentrations were within 2 μg/m^3 of master bedroom levels. Again, Houses 2 and 3 were notable exceptions, with living room concentrations up to 20 μg/m^3 higher than those in master bedrooms. These variations are consistent with the findings of previous studies [114,115], identifying kitchen/living areas as typically the more polluted rooms, 2–3 μg/m^3 higher than the bedrooms, on average.

Similar to $PM_{2.5}$, mean winter concentrations of living room PM_{10} prior to PPV installation were generally similar or slightly higher than master bedroom levels (within 3 μg/m^3). Notable exceptions included Houses 2, 3 and 5, where living room concentrations were noted up to 30 μg/m^3 higher than in the master bedroom. Post-PPV, living room concentrations were similar or slightly higher than master bedroom levels (within 3 μg/m^3). Houses 2 and 3 exhibited somewhat higher concentrations in the living room, up to 23 μg/m^3 higher than in the master bedroom. These findings are comparable with those of Zhu et al. [114] which noted that wintertime mean PM_{10} concentrations were approximately 5 μg/m^3 higher in living areas than in bedrooms.

All homes included in this study featured open-plan living areas, making the living rooms more susceptible to higher concentrations of PM from kitchen activities such as cooking. This likely accounts for the elevated PM levels observed in the living areas in comparison with the bedrooms.

3.2.1.1. Diurnal variation. Diurnal profiles of indoor $PM_{2.5}$ concentrations were analysed for each house across each day of the pre-PPV and post-PPV winter periods. Diurnal patterns generally exhibited a morning and evening peak, consistent with typical domestic activities and outdoor pollution peaks linked to traffic times or burning wood for heating [116–118]. One house did not exhibit a regular, consistent morning or evening peak, and was therefore not included in the analysis. Weekends were also excluded as they typically reflect different household patterns and therefore different diurnal profiles.

For the remaining nine houses, the regularity of occurrence of diurnal peaks was assessed. Pre-PPV, morning peaks were observed to occur on between 82.8 % and 100 % of the days, and afternoon peaks 93.6 % to 97.0 %. Post PPV, morning peaks occurred 79.4 % to 97.3 % of the days (except one house, 61.3 %), and afternoon peaks 100 % (all houses).

For each house, significant reductions post-PPV installation were observed throughout the day for the majority of the houses. Reductions during peak intervals were noted to be the same or higher (up to 15 % more) than during non-peak intervals. These findings suggest that the PPV system can be effective at reducing concentrations during peak events, such as cooking, especially when compared with reductions in non-peak intervals. Due to the relatively low PM levels in most study houses initially, it is possible that the degree of reduction observed in non-peak concentrations has been impeded.

The Wilcoxon signed-rank test, comparing the calculated difference between pre- and post-PPV concentrations during peak and non-peak intervals for each house, indicate a significant difference ($z = -2.67$, $p = 0.009$), supporting the observation that $PM_{2.5}$ reductions over the post-PPV period were the same or higher for peak intervals than for non-peak intervals. Fig. 3 represents the average diurnal profile for the nine houses analysed, across all days for both the pre-PPV and post-PPV periods.

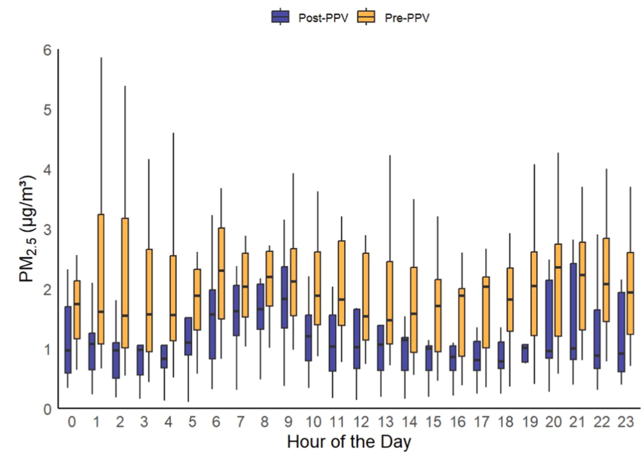

Fig. 3. Average diurnal profile of living room $PM_{2.5}$ concentrations, pre-PPV ('OFF') and post-PPV ("On").

3.2.2. Outdoor and roof space contributions

3.2.2.2. Indoor vs outdoor. Outdoor $PM_{2.5}$ concentrations measured across all sites averaged 3.8 μg/m^3, 2.2 μg/m^3 and 1.8 μg/m^3 over the winter, spring and summer periods, respectively. The highest measurements were recorded outside House 1 (1.5–2.5 times higher, but always within the WHO 24-hour limit), while the lowest were outside House 5 (37–81 % of the average). House 1 is located adjacent to a motorway, while House 5 is nestled within a large, forested parkland, potentially buffered from surrounding, more polluted areas [119]. These levels and seasonal trend are in line with historic daily averages measured at Auckland AQM stations [120]. By international standards, New Zealand is known to experience relatively low levels of outdoor $PM_{2.5}$ [67,121,122].

An increase of 41 % was noted between the pre- and post-PPV winter periods, potentially due to the cooler weather (average temperatures fell from 14.4 °C to 12.0 °C). Rises in ambient PM levels during cooler periods have been attributed to anthropogenic factors (e.g. wood burning, vehicle usage) and atmospheric factors (e.g. temperature inversion) [123,124]. Outdoor PM_{10} concentrations observed during this study followed similar values and trends to $PM_{2.5}$: 3.9 μg/m^3, 2.4 μg/m^3 and 2.0 μg/m^3 over winter, spring and summer, respectively.

Indoor vs outdoor relationships are presented in Fig. 4 and Table 4. Fig. 4 displays a typical time series distribution of mean daily indoor and outdoor $PM_{2.5}$ concentrations across the winter period. Table 4 summarises average seasonal indoor/outdoor (I/O) ratios for $PM_{2.5}$ concentrations alongside Spearman's Rank and Wilcoxon Test results.

I/O ratios pre-PPV were greater than one in six of the houses (Houses 2, 3, 5, 7, 9 and 10), i.e. indoor concentrations exceeded outdoor levels for these houses. In contrast, previous studies have consistently reported

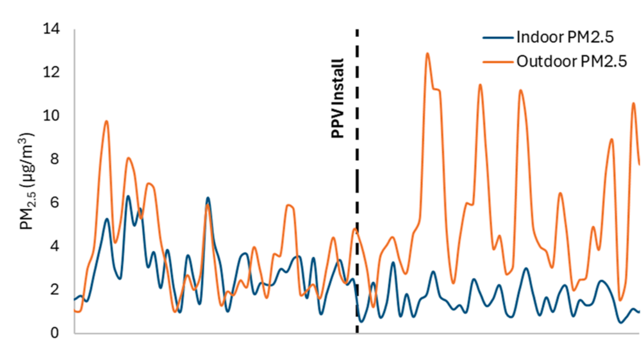

Fig. 4. Mean daily $PM_{2.5}$ concentrations (House 4).

Table 4
$PM_{2.5}$ Indoor/Outdoor ratios and correlation results.

House	I/O Ratio				Spearman's Rank			
	winter		spring	summer	winter		spring	summer
	pre-PPV	post-PPV	post-PPV	post-PPV	pre-PPV	post-PPV	post-PPV	post-PPV
1	0.5	0.2	0.5	0.5	0.8	0.5	0.8	0.7
2	6.5	2.4	3.7	2.4	0.1	0.1	0.0	0.1
3	21.5	9.1	15.8	4.4	0.1	−0.1	0.3	0.1
4	0.8	0.3	0.8	0.8	0.6	0.3	0.1	0.4
5	2.6	1.0	1.4	0.6	0.2	0.1	0.1	0.2
6	0.9	0.7	0.9	1.1	0.8	0.7	0.6	0.5
7	3.3	0.5	0.8	0.8	0.0	−0.1	0.2	0.4
8	0.7	0.3	0.3	0.6	0.7	0.4	0.3	0.5
9	2.4	0.9	1.2	0.5	0.1	−0.1	0.2	0.3
10	4.1	0.9	1.4	1.5	−0.1	0.2	0.1	0.0
House	Wilcoxon Test							
	winter				spring		summer	
	pre-PPV		post-PPV		post-PPV		post-PPV	
	p	Z	p	Z	p	Z	p	Z
1	<0.01	−19.48	<0.01	−25.44	<0.01	−32.95	<0.01	−28.2
2	<0.01	−12.6	<0.01	−10.65	0.04	−2.06	<0.01	−11.38
3	<0.01	−13.54	<0.01	−3.84	0.98	−0.03	<0.01	−11.05
4	<0.01	−14.05	<0.01	−20.8	<0.01	−12.52	<0.01	−7.72
5	<0.01	−11.18	<0.01	−20.84	<0.01	−30.68	<0.01	−33.17
6	<0.01	−9.51	<0.01	−17.19	<0.01	−32.02	<0.01	−30.04
7	0.01	−2.76	<0.01	−13.65	<0.01	−24.27	<0.01	−14.2
8	<0.01	−20.43	<0.01	−22.51	<0.01	−32.98	<0.01	−29.2
9	0.11	−1.62	<0.01	−4.86	<0.01	−21.22	<0.01	−26.65
10	<0.01	−5.93	<0.01	−15.23	<0.01	−14.27	<0.01	−6.36

p: p-value: probability of obtaining the observed results, assuming that the null hypothesis is true (equal concentration means during pre and post-PPV installation).
Z: Z-value: number of standard deviations a value is from the mean of a given distribution.

I/O ratios below one under NV conditions [50,53,63,112], which may be a reflection of the particularly low outdoor concentrations recorded in this study. By international standards, New Zealand experiences relatively low levels of outdoor $PM_{2.5}$ [67,121,122]. House 3 was noted to have an exceptionally high I/O ratio, reflecting elevated indoor PM concentrations, likely resulting from various indoor emission sources, as noted in Section 3.1.1. Post PPV installation, all I/O ratios were below one, except Houses 2 and 3, consistent with observations from previous studies that assessed the impact of MV systems [18,50,53,63,112].

I/O ratios in spring and summer were below/above 1.0 for six/four of the houses, respectively. spring I/O ratios increased by 40 % on average in comparison with winter post-PPV ratios, potentially due to an increased reliance on NV during the warmer period. Summer I/O ratios exhibited a very slight (3 % on average) decrease relative to spring ratios. Similar seasonal variations in I/O ratios were observed by Ścibor et al. [56].

Spearman's correlation for indoor vs outdoor $PM_{2.5}$, pre-PPV, was strong (> 0.7) for two houses, moderate (0.4 – 0.7) for two houses, and very weak (< 0.2) for six houses. Post PPV, correlations weakened for eight houses, leaving just one house strongly correlated and one house moderately correlated. Post-PPV correlations averaged 0.24, in contrast to a study by Mucha et al. [18], which reported correlations ranging from 0.73 to 0.90. While some increases in correlation were noted in subsequent seasons, the majority of houses remained weakly (0.2 – 0.4) to very weakly correlated. These results suggest that infiltration may be contributing to indoor concentrations prior to PPV installation, and that the PPV system effectively reduces the influence of outdoor air on the indoor environment.

Using the Wilcoxon test, p-values below 0.01 were consistently reported for both, pre and post PPV periods. Consistent with previous studies [18,56,63,125], these results indicate that the observed differences between indoor and outdoor concentrations are statistically significant, both pre PPV and post PPV. An increase in the absolute value of these Z-values in most houses, post PPV, suggests the PPV system effectively reduced indoor $PM_{2.5}$. However, a decrease detected in a few houses indicates a lesser impact. Z-values during spring fluctuated widely; House 3 shows a minimal Z-value of −0.03, indicating a lesser difference between indoor and outdoor $PM_{2.5}$ concentrations. In contrast, Houses 1 and 5 have large negative Z-values (−32.95 and −30.68, respectively), suggesting larger differences between indoor and outdoor levels. This pattern of negative Z-values continued over summer.

These results of the correlation analysis indicate that the observed differences between indoor and outdoor $PM_{2.5}$ concentrations are statistically significant, both pre- and post-PPV (Wilcoxon test, $p < 0.01$). However, the Spearman's correlation results show that the strength of association between indoor and outdoor $PM_{2.5}$ varied across houses and generally weakened after PPV installation. This suggests that while indoor and outdoor $PM_{2.5}$ levels were always statistically different, their relationship (how closely indoor levels followed outdoor levels) changed after the intervention.

The LME model was run both with and without outdoor $PM_{2.5}$ contribution to assess the impact of outdoor $PM_{2.5}$ levels on indoor concentrations. When outdoor $PM_{2.5}$ was included in the model as a fixed effect, the estimated effect of PPV is greater −0.26 (22.9 % reduction) than when it was excluded −0.19 (17.8 %). This difference indicates that controlling for outdoor pollution strengthens the estimated effect of PPV, i.e. observed changes in IAQ improved with PPV even though outdoor air quality evolved in the opposite direction. These results support the findings of the I/O ratios, Spearman's correlation and Wilcoxon tests, suggesting that the PPV system reduces indoor $PM_{2.5}$ concentrations, weakens the relationship between indoor and out levels, and reduces pollutant infiltration from outdoors.

3.2.2.3. Roof space particulate matter. Roof space monitoring took place in seven of the 10 houses. Mean indoor concentrations were higher than roof concentrations for five of the seven houses, with four of these ranging between 14 % and 51 % higher and one (House 3) showing a 160 % higher value. Compared with outdoors, mean indoor concentrations were lower for the majority of houses (2 % to 71 % lower). House 3 indoor concentrations are noted to be 166 % higher than outdoors. Roof space concentrations were below (5 % to 52 %) outdoor concentrations for six houses. House 3 roof concentrations were 2 % higher than outdoor levels. These findings indicate that the roof space appears to be generally less polluted than outdoor air (measured as $PM_{2.5}$). Possible causes for this difference could include the roof structure acting as a physical barrier to outdoor pollutants.

Spearman's rank analysis between indoor, outdoor and roof space $PM_{2.5}$ concentrations in the seven houses was conducted. Indoor and outdoor concentrations showed a very weak relationship, with correlation factors below 0.2 for all houses, indicating that indoor concentrations do not align strongly with outdoor levels. The relationship between roof space and outdoor concentrations was, in general, strong to very strong. Although a strong correlation indicates a connection between roof and outdoor concentrations, it does not imply that pollution levels in the roof space match those outdoors. Four houses showed correlations between 0.82 and 0.97, suggesting roof concentrations are influenced by outdoor levels in these houses.

The relationship between indoor and roof space $PM_{2.5}$ concentrations was notably weak to very weak, with the majority of houses showing correlation values below 0.2, while Houses 3 and 6 showed moderate correlation (0.29 and 0.4, respectively). The higher concentrations of $PM_{2.5}$ in indoor air than in roofs, plus the weak correlation between the roof and indoors suggests that the roof does not have a significant influence on indoor concentrations.

3.3. Thermal comfort parameters and energy implications

Following PPV installation, indoor temperatures decreased by 4 % on average (0.6 °C), with six houses showing decreases (0.9 °C to 2 °C), three with increases (0.5 °C to 0.8 °C) and one no change. From winter to spring, all houses recorded increases of 17 % on average (0.4 °C to 3.7 °C), with further increases in summer of 16 % (2.0 °C to 4.6 °C) across nine houses, with one house unchanged. These observations are in line with previous studies investigating temperature impacts of MV [50,51,63].

RH decreased in nine houses over winter following PPV installation, with an average relative reduction of 5.5 % (absolute reductions from 0.5 %RH to 7.3 %RH), while one house showed no change. These findings are consistent with previous studies on MV impacts on RH [50,51], while Kang et al. [63] observed an increase in RH. Further reductions were observed from winter to spring in seven houses, with average relative reduction of 2.8 % (absolute reductions between 0.4 % RH and 3.5 %RH), while two houses recorded slight increases, and one remained stable. In summer, seven houses experienced average relative reductions from spring of 3.8 % (0.3 %RH to 11.1 %RH), two experienced slight increases, and one showed no change. These seasonal observations contrast with previous findings [50,51].

3.3.1. Indoor vs outdoor temperature & relative humidity

Average indoor temperatures were 3 °C to 5 °C higher than outdoor temperatures across the study period. Winter average outdoor temperatures were 12.8 °C, while average indoor temperatures were 18.1 °C pre-PPV and 17.5 °C post-PPV. Spring and summer outdoor temperatures were 15.8 °C and 20.7 °C, respectively, while average indoor temperatures were 20.2 °C and 23.3 °C for the corresponding periods.

Outdoor RH levels were 77 % over winter, 11 % higher than average indoor levels (in terms of absolute percentage). During spring, outdoor levels decreased to 73 %, 16 % higher than average indoor RH. Summertime outdoor RH remained at 73 %, 12 % higher than average indoor levels.

Spearman's correlation was used to assess the relationship between indoor and outdoor parameters. Winter temperatures were moderately correlated (0.36 pre-PPV; 0.37 post-PPV), while spring and summer temperatures were very strongly correlated (both 0.9). RH was found to be moderately correlated during winter and summer (0.5 and 0.4, respectively) and strongly correlated in spring (0.78). The stronger correlations observed in spring and summer may be a result of hybrid ventilation occurring during these months.

3.3.2. Temperature control and energy consumption

Roof space temperatures were measured for two weeks in early spring. One monitor failed during this period and was excluded from the analysis. To explore the influence of roof space temperature on the indoor environment, roof space, indoor and outdoor mean temperatures were analysed and compared against changes in household energy consumption (where energy data was available). Fig. 5 shows the change in energy consumption (between the six-week periods pre- and post-PPV installation) against the temperature differential between the roof space and the living room. This indicator was chosen based on the hypothesis that a higher temperature differential will result in an increase in energy consumption as the occupants heat the house more in response to the introduction of cooler roof space air.

Roof space temperatures were found to be cooler than those indoors (living area) for the majority of the time, and were, on average, 7.1 °C cooler than indoors and 1.1 °C cooler than outdoor temperatures. This suggests that for the duration of the roof space monitoring period, cooler air from the roof space was supplied into the indoor environment. This is aligned with observations made by Zhao et al. [51], attributing reductions in indoor temperature in homes with MV to the introduction of lower temperature air. Building characteristics, such as insulation and construction materials, were examined for potential links to temperature differentials, though no clear patterns emerged.

The average temperature difference between outdoor and indoor temperatures was 8 °C (cooler outdoors), with the exception of House 6 (1.5 °C). As discussed in Section 3.1.1, occupants of House 6 reported keeping doors and windows open which may have contributed to the similarity between indoor and outdoor temperatures. Energy consumption was observed to increase for all houses over the post-PPV period.

Analysing the difference between roof space and indoor temperatures against the change in energy consumption, post-PPV, it was observed that minimal additional energy was consumed in houses where the temperature difference was below 4 °C (House 6). For the remaining houses, a more substantial increase in energy consumption was noted. Houses 2 and 3 exhibited the most significant temperature differences (11.1 °C and 11.5 °C, respectively) coupled with the largest increases in energy consumption (839 kW.hr and 526 kW.hr, respectively). These findings suggest that the PPV system itself does not necessarily use a significant amount of electricity relative to overall household consumption. However, where roof space temperatures are more than 4 °C below indoor temperatures, more electricity may be required for heating to maintain comfort levels. A previous study examining changes in energy use with MV reported heating energy consumption increased by 19.4 kWh/m^2 (more than double the results observed in our study) where outdoor air was supplied at an average temperature of 17.5 °C below indoor air [126]. Similarly, Ben-David & Waring [127] found that

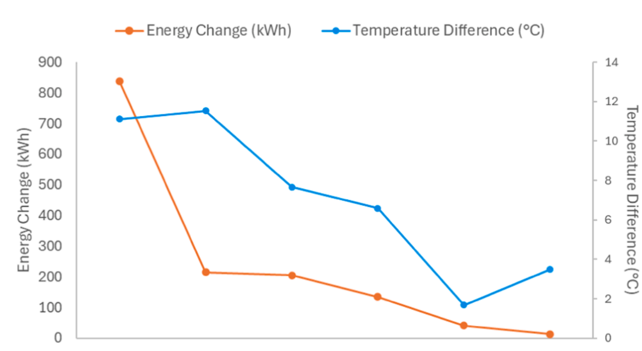

Fig. 5. Roof space-indoor temperature differences vs change in energy consumption.

NV tended to consume less energy for heating than MV.

3.4. Chemical and biological pollutants

This section presents an assessment of radon, heavy metals, and fungal DNA concentrations pre- and post-PPV installation during the winter period to provide a more comprehensive evaluation of IAQ impacts associated with PPV operation.

3.4.1. Radon

Mean pre-PPV radon concentrations averaged 11.9 Bq/m^3 across nine houses, ranging from 4.3 Bq/m^3 to 26.7 Bq/m^3, with House 2 exhibiting a significantly higher concentration of 52.8 Bq/m^3. Maximum 1-hour concentrations averaged 45.5 Bq/m^3 (ranging from 11.1 Bq/m^3 to 122.1 Bq/m^3). These concentrations are consistent with findings from a national survey of indoor radon in homes across New Zealand, which reported median concentrations in Auckland homes of 15 Bq/m^3 [25]. Meanwhile, the observed levels are relatively low compared to those reported in other studies for indoor radon in naturally ventilated homes [128–130].

Following PPV installation, despite initial low levels, mean concentrations across eight houses showed an average reduction of 53 %, while Houses 1 and 3 increased by 25 % and 21 %, respectively. Maximum concentrations decreased across six houses, with reductions averaging 47 %, however three houses showed increases of 167 %, 80 % and 14 % respectively, while one house saw no change. Previous studies have reported reductions of 70–75 % in houses with MV [131,132].

Post-PPV mean concentrations averaged 5.1 Bq/m^3 across eight houses. However, Houses 1 and 2 had substantially higher levels of 14.1 Bq/m^3 and 29.4 Bq/m^3, respectively. Maximum concentrations averaged 25.9 Bq/m^3 across nine houses, with House 3 having a relatively higher value of 74.0 BQ/m^3. The elevated radon levels in House 1 may be attributable to its proximity to a motorway, where vibrations could facilitate radon release from the soil through cracks in the building foundations [23,133]. House 3 was noted to have well-worn timber floorboards, which may have contributed to elevated radon levels within the home.

These results align with similar studies on MV impacts on indoor radon [111,129,134]. All concentrations were below the WHO reference level for indoor radon of 100 Bq/m^3 [28], except for one pre-PPV measurement in House 2.

3.4.2. Heavy metals

Arsenic and cadmium were below detection limits for all samples. Fig. 6 summarises the pre- and post-PPV results for the other metals analysed.

Results were highly variable across the ten study houses, where copper, lead and zinc concentrations decreased in four houses, by an average of 65 %, 67 % and 28 %, respectively, while chromium and nickel decreased by 71 % and 73 % in three houses. Conversely, lead increased in five houses (323 %), chromium and copper in three (231 % and 251 %), and nickel and zinc in two (129 % and 38 %). The highest chromium concentration measured across all houses was significantly lower than levels reported by Lioy et al. (2002). All lead results observed were well below the Australian Standard clearance level for surface dust lead [135,136].

In general, greater reductions were observed where initial concentrations were high. Five houses had higher metal concentrations post-PPV. Notable increases included House 1 (copper, lead), and House 7 (chromium, copper, lead and zinc). The occupants of House 1 reported using the fireplace as their primary mode of heating during winter. In addition, during the field visits, it was observed that treated timber was being used in the fireplace. Extensive wood burning was noted in the neighbourhood of House 7 during the field visits. The occupants of this house stated that this was a common practice in the area during winter.

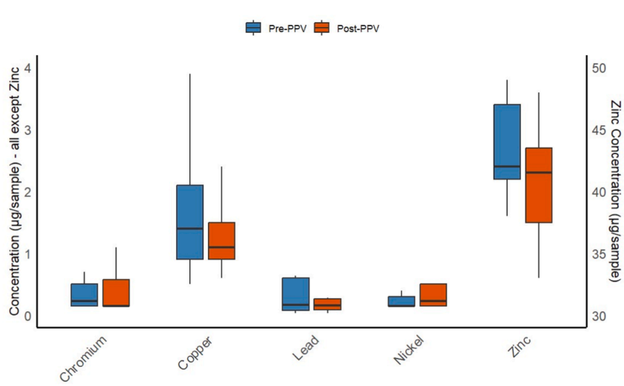

Fig. 6. Heavy metal concentrations pre/post-PPV installation.

3.4.3. Fungal DNA (mould)

Dust samples were analysed for fungal DNA concentration to evaluate the potential impacts of the PPV system on mould. Fig. 7 illustrates the distribution of data from the sample analysis.

Fungal DNA concentrations exhibited similar levels across both rooms in the majority of the houses and generally decreased in all houses following PPV installation.

Prior to PPV installation, fungal DNA levels ranged between 4015 CE/m^2 and 828,704 CE/m^2. Reductions in concentrations ranged between 24 % and 99 %. Post-PPV (winter) concentrations ranged from CE 374/m^2 to 181,931 CE/m^2. House 6 recorded notably higher pre- and post-PPV concentrations of 3414,073 CE/m^2 and 6504,781 CE/m^2 respectively, representing an increase of 91 %. In general, these reductions are in line with the observed reductions in PM concentrations over winter following PPV installation.

The observed reductions are in line with previous research [137,138], highlighting the advantages of MV systems over NV in controlling mould levels. Holme [138], investigating 205 homes in Norway, found viable mould spores present in more than twice the number of homes with NV than MV. Brambilla & Sangiorgio [137] posits that MV is more effective than NV due to better control of air flow, improved dehumidification potential, and air filtration, going on to highlight that the average size of bioaerosol particles which transport fungi and bacteria (5.5 – 5.9 µm) can be efficiently removed by residential ventilation systems.

Spearman's rank analysis was used to examine the relationship between reductions in fungal DNA concentrations against relative reductions in RH. A very weak correlation of 0.12 indicates that while RH consistently decreased across all homes following PPV installation, the reduction was insufficient to facilitate associated reductions in mould levels. Similar findings were reported by Fletcher et al. [139].

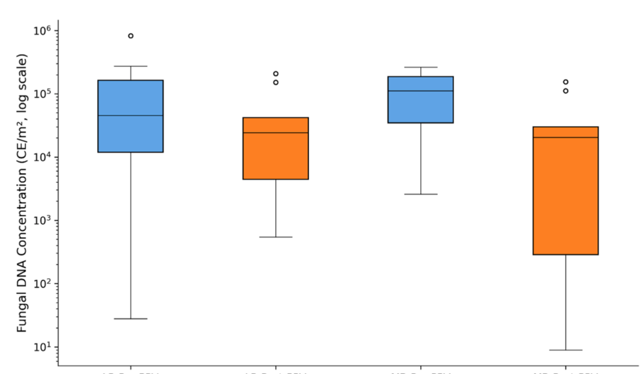

Fig. 7. Mould concentrations, pre- and post-PPV (LR = living room, MB = master bedroom).

4. Limitations and future work

While this study had some limitations, they offer important opportunities for future research to enhance and extend these findings.

Some of the limitations encountered included: limited sample size due to challenges of needing repeat access to homes and long-term cooperation from participants; difficulty obtaining energy consumption data for some houses; lack of access to permanent power supply for roof monitoring, limiting the monitoring period to battery life.

Future studies would benefit from including: a greater number of houses in the study sample; monitoring of additional parameters that could influence indoor pollutant concentrations (e.g. indoor sources, ventilation activity and thermal control); increasing the roof space monitoring duration; evaluation of room-specific concentrations during periods of typical use (e.g. daytime for living areas, nighttime for bedrooms).

5. Conclusions

PM and fungal DNA concentrations both experienced notable declines post-PPV installation, with PM levels indoors often falling below outdoor concentrations. Radon levels decreased, although they were generally very low initially, and remained below healthy levels. However, the system's influence on heavy metal concentrations was limited, particularly in homes affected by localised sources like fireplaces or wood-burning activities.

This study demonstrated that the PPV system can effectively reduce indoor PM concentrations independent of initial levels. Descriptive statistics and mixed-effects modelling both supported this finding, with the model confirming a statistically significant decrease in indoor pollution after controlling for outdoor $PM_{2.5}$ and temperature. Observed reductions following PPV installation ranged between 32 % and 71 %. Notably, one house with high initial concentrations and significant emission sources still achieved a 32 % reduction in $PM_{2.5}$. Despite its overall effectiveness, the PPV system showed minimal impact in homes with frequent door and window openings, where pollutant reductions were minimal.

The study further revealed spatial differences in pollutant concentrations, with living rooms exhibiting similar-to-slightly higher pollutant levels than bedrooms. This is potentially due to the influence of occupancy patterns and proximity to pollution-generating activities like cooking. The indoor-outdoor pollutant ratio demonstrated a marked decrease (to below 1 for most houses) in winter post-PPV installation, while slight increases were noted during warmer seasons. Meanwhile, the PPV system was shown to effectively reduce diurnal peak concentrations as well as background levels during winter, with reductions in peaks up to 15 % greater than non-peak reductions.

Seasonal variations played a critical role, with PPV being particularly effective during winter when NV was minimised. However, in spring and summer, hybrid ventilation practices are likely to have obscured the system's effectiveness due to increased reliance on NV.

Pollutant concentrations in the roof space, where PPV systems draw from, were found to be lower than outdoor levels, potentially due to the cavity's sheltering effect. Indoor concentrations were not well correlated with roof space air, indicating minimal direct influence of roof air on indoor concentrations, suggesting that the PPV filter is effective in preventing pollutants from the roof space from entering indoors. Temperature observations suggested that PPV systems might contribute to cooling effects in certain cases, which can lead to increased energy consumption due to changes in heating operation.

This study highlights the significant impacts of PPV systems on IAQ in residential settings, emphasising its potential to mitigate a range of indoor pollutants. However, their performance is contingent on environmental conditions, occupant behaviours and pollutant sources, necessitating a nuanced approach to their deployment and evaluation.

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CRediT authorship contribution statement

German Hernandez: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rafael Borge:** Writing – review & editing, Supervision, Conceptualization. **Dan Blanchon:** Writing – review & editing. **Terri-Ann Berry:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

German Hernandez reports financial support was provided by Cristal Air International Limited. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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