The impact of increased occupancy on particulate matter concentrations in mechanically-ventilated residential buildings in a subtropical climate.

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ABSTRACT

Indoor air pollution can pose a serious threat to human health and can increase the risk of early mortality. Studies have shown that human exposure to indoor pollution is more common than to outdoor pollution, especially where people spend the majority of their time indoors at home. Heating, ventilating, and air conditioning (HVAC) systems are used in buildings to regulate internal climate to improve the comfort level for occupants. In addition, ventilation rates are often increased to maintain appropriate Indoor Air Quality (IAQ). Inadequate ventilation can limit the removal of substances from inside the building, leading to an accumulation of pollutants resulting from internal sources (e.g., building materials, furnishings, and personal care products). Minimum ventilation rates for buildings are prescribed in standards published by organisations such as the European Committee for Standardization and ASHRAE. However, unlike outdoor air quality, there is currently no common standard or index for IAQ.

The aim of this study is to investigate the impact of high occupancy levels, caused by stay-at-home orders under a COVID-19 lockdown, on IAQ in mechanically-ventilated residential buildings. The study focuses on particulate matter ($PM_{2.5}$ and PM_{10}) in six residential buildings across Auckland, New Zealand's largest city, which has a subtropical climate with characteristic high humidity in the winter. Monitoring took place over a six-week period during winter: three weeks pre-COVID-19 lockdown and three weeks into the lockdown.

Indoor concentrations of $PM_{2.5}$ and PM_{10} were found to increase during the lockdown period in the majority of the houses (64% and 40% respectively). In contrast, outdoor $PM_{2.5}$ and PM_{10} concentrations decreased by 34% and 31%, suggesting internal sources were largely responsible for indoor concentrations.

KEYWORDS

Indoor Air Quality, Mechanical Ventilation, Increased Occupancy, COVID-19 lockdown, Particulate Matter

1 INTRODUCTION

Indoor air pollution can be detrimental to human health (Cohen et al., 2005; Donaldson et al., 2001) and can lead to increased mortality rates (Dockery et al., 1993; Hales et al., 2012). Numerous studies have shown that human exposure to indoor pollution is often more common than exposure to outdoor pollution (Logue et al., 2011, 2012; Weschler, 2006), especially where people spend most of their time indoors at home (Klepeis et al., 2001). A 2016 study found that New Zealanders on average spend 68.9% of their time at home indoors (Khajehzadeh & Vale, 2017). The control of indoor air quality (IAQ) inside homes is therefore an important factor for the health and wellbeing of residents.

Inadequate ventilation can prevent escape of substances from within the home and lead to an accumulation of physical pollutants arising from internal sources (e.g., building materials, furnishings, personal care products, pesticides, and household cleaners). The term "Sick Building Syndrome" describes the relationship between the IAQ and its potential effects on occupants (Bernstein et al., 2008), such as headache, respiratory infection, and cognitive function (Taptiklis et al., 2017; Tookey et al., 2019). Ventilation rates are often increased to maintain appropriate IAQ and to reduce the risk of sick building syndrome (ASHRAE, 2013; Fisk et al., 2009; Sundell et al., 2010).

Due to the growing awareness of global warming and climate change, many governments have applied pressure to reduce energy consumption and increase energy efficiency. This has motivated the building industry to innovate and improve technology, leading to more environmentally sustainable buildings. However, energy efficient buildings over the last decade have been shown to increase the concentration of some pollutants (USEPA, 2017). Similarly, despite trying to maintain or improve IAQ with ventilation, some building characteristics can negatively impact IAQ. While ventilation can help reduce concentrations of indoor pollutants, indoor concentrations of pollutants originating from outside can actually increase due to higher ventilation rates (Rackes & Waring, 2016; Weschler & Shields, 2000). A PPV (positive pressure ventilation) system uses mechanical ventilation to extract relatively dry air from the roof space, filter it and blow it into the house, creating a slight positive pressure inside. This positive pressure drives out old, stale air via gaps and cracks in the building fabric.

The Coronavirus disease (COVID-19) pandemic led to the implementation of strict lockdown policies by many countries around the world, including New Zealand, in an attempt to stem transmission of the virus. These lockdowns resulted in (with the exception of essential service workers and businesses) the general public spending the majority of their time at home. This increased occupancy has the potential to elevate concentrations of indoor air pollutants such as PM and VOCs generated by household activities such as cooking and cleaning (Cowell et al., 2023; Laltrello et al., 2022), while also increasing the likelihood of exposure to harmful pollutant levels (Adam et al., 2021; Morawska et al., 2020; Stabile et al., 2021).

New Zealand is an island country in the southwestern Pacific Ocean, divided into two main land masses (North and South Islands) with a total area of approximately 268,000 km^2. The population is approximately 5.2 million residents with a housing stock of approximately 2 million houses (Stats NZ, 2020a, 2023). Visible mould larger than A4 size is always present in 4.3% of New Zealand homes, while 20% of New Zealand homes suffer from damp (Stats NZ, 2019). 13% of New Zealanders suffer from asthma (Asthma Foundation NZ, 2023). Auckland is New Zealand's largest city (by population and land mass) and one of the most remote in the world. The city is located in an isthmus in the northern part of the country and has a population of over 1.6 million. Auckland has a humid, subtropical climate with warm, humid summers and mild winters (Hessell, 1988).

Numerous IAQ studies have investigated the effects of increased occupancy on IAQ, however these primarily focus on buildings which rely on natural ventilation. To improve understanding of the effects of occupancy on indoor pollutant concentrations, in particular where mechanical ventilation systems are installed, this study analysed IAQ parameters ($PM_{2.5}$, PM_{10}) in homes in Auckland, before and during a COVID-19 lockdown.

2 METHODOLOGY

2.1 Residential Data Collection, Study Location, Eligibility & Recruitment

As part of a longitudinal study, IAQ parameters were monitored for a selection of mechanically-ventilated residential homes across Auckland. The study was conducted over a three-week period prior to the COVID-19 lockdown, followed by a further three weeks during the lockdown period. Six Auckland households fitted with PPV systems were selected for this study. For standardisation, houses were selected with floor areas ranging between 120 and 273 m^2, comprising three to four bedrooms. Houses were selected where the number of occupants reflected the national average (three to four) (Khajehzadeh & Vale, 2017).

2.2 Air Quality Measurements

Three monitors were located indoors to measure $PM_{2.5}$ and PM_{10}: in the master bedroom, another bedroom and the living area. Outdoor PM measurements were obtained from nearby council-owned air quality monitoring stations. Indoor monitors were positioned 1.0 m above floor level (where possible) and data was collected at five-minute intervals. Details of the monitors used are as follows:

- Type A monitors (designed and created in-house at Unitec). Type A uses a PM sensor to measure $PM_{2.5}$ and PM_{10} (range 0 - 1,000 $\mu g/m^3$, with an accuracy of ±15%).
- Type B monitors measure $PM_{2.5}$ and PM_{10} (range 0 – 500 $\mu g/m^3$). They were field-tested by the Air Quality Sensor Performance Evaluation Centre (AQ-SPEC) in California, and calibrated with regulatory-grade (Federal Equivalent Method) equipment.

2.3 Quality Control

The low-cost sensors used in this study were pre-calibrated against two commercial grade PM monitors (Aeroqual Dust Sentry Pro, ±5$\mu g/m^3$ +15% of reading (Aeroqual, 2023)) before the monitoring period. A linear correlation assessed accuracy and provided an equation to offset the monitors, if required. Post-calibration was completed after the monitoring period, using the same monitors (Dust Sentry Pro). The equipment was isolated and co-located for one week. This data was used to run correlation tests between the low-cost sensors and the robust monitors. $PM_{2.5}$ was well correlated with our standard monitoring equipment, yielding R^2 values in the 0.89 – 0.96 range.

3 RESULTS AND DISCUSSION

3.1 Household Environment, Occupancy Rates and Activity

All six houses were single-storey, open-plan timber construction, with floor and roof insulation. All windows were single-glazed. All houses had some form of heating to the main living areas (heat pumps the most common), while three houses also had heating to the bedrooms. Two households kept indoor plants (in the living and bedrooms). All households comprised at least two adults (two had three adults), while two households included two children, and two included one child. All participants reported that their homes were typically only occupied outside of business hours (prior to lockdown) and were generally occupied full time during lockdown.

Ventilation rates, based on PPV system installed and house size, varied between 3 and 4 air exchanges per hour. Larger houses require additional fan units to guarantee this air exchange rate. The system uses a deep-pleat nano-fibre filter (F8), with filter media laminated to a nylon monofilament mesh. The filter removes all particles greater than 0.4µm, and has been tested to meet international (Eurovent and ASHRAE) standards. The PPV system is controlled centrally using an internal algorithm that regulates fan speeds according to the temperature differential measured between rooms and the roof-space. PPV systems were set up to adjust automatically during the study period. Participants confirmed that they did not alter the controls or open windows during the study period.

Potential indoor sources of PM identified included one house with an open fire, one with a heating stove, four houses had greater than 50% floor area carpeted, and four kept dogs or cats. Two houses burned candles or similar naked flame devices indoors, while one household had smoking indoors. All occupants reported they increased the frequency of PM-inducing activities during lockdown such as cooking and vacuuming. All households had an extractor fan in the kitchen and reported using it regularly while cooking.

3.2 Indoor Particulate Matter ($PM_{2.5}$, PM_{10})

The average PM concentrations (measured in the living area) across the three-week periods before and during lockdown are presented in Table 1. Three of the residential buildings (D, E and F) showed an increase in $PM_{2.5}$ of between 25% and 62%.

Table 1 – Average indoor concentrations of $PM_{2.5}$ and PM_{10}

Parameter	House:	A	B	C	D	E	F
$PM_{2.5}$ (µg/m^3)	pre-lockdown	0.55	0.73	20.62	4.20	4.96	4.37
	during lockdown	0.80	1.73	21.21	5.24	8.01	5.78
PM_{10} (µg/m^3)	pre-lockdown	0.93	1.08	23.51	4.69	5.52	6.05
	during lockdown	0.58	0.36	21.50	6.13	9.00	7.71

This is consistent with findings by (Laltrello et al., 2022) and (Cowell et al., 2023). One house showed a substantial increase in $PM_{2.5}$ of around 136%, while two houses showed minimal change. The change in $PM_{2.5}$ levels for House A was close to the limit of the sensor accuracy. House C was identified as a rural/farming house, where the level of occupational activity outside the home was not affected by the lockdown. This house had the highest indoor concentration of $PM_{2.5}$ both pre and post lockdown. In Auckland, the average household normally spends the majority of its food budget on takeaway meals (32%) (Stats NZ, 2020b). The impact of the lockdown arguably led to many more meals prepared at home than usual (due to the closure of all restaurants and takeaway food outlets), which is likely to have contributed to the observed increases in $PM_{2.5}$.

Indoor PM_{10} concentrations increased following lockdown for three of the houses, between 27% and 63%, which is consistent with Laltrello et al. (2022) and Cowell et al. (2023). This may indicate the primary sources of PM_{10} were internal for these houses. Internal PM_{10} sources can include smoking, woodfire burning, unflued heaters and burning of candles. House F, for example, contained a fireplace. The other two houses where PM_{10} increased were geographically sheltered from the nearest roads, so internally generated PM_{10} is more likely to be the main component of indoor concentrations for these houses, and accordingly increase with occupancy. For the other three houses, the magnitude of change in PM_{10} was relatively minor (< 1 μg/m^3) for two of these, while the third house was the farmhouse mentioned previously, where day to day activities were not affected by the lockdown.

Average indoor $PM_{2.5}$ concentrations for two selected houses for the weeks immediately prior to and following COVID-19 lockdown are shown in Figure 1a and Figure 1c. These show that diurnal $PM_{2.5}$ peaks during lockdown were higher than those prior to lockdown. Figure 1b and Figure 1d show diurnal profiles for a typical day. The main diurnal peak occurred between 6 and 8pm, with a secondary peak around midday (Figure 1d). These peaks could be created during food preparation which has led to increased internal $PM_{2.5}$ levels (Laltrello et al., 2022). Background levels of $PM_{2.5}$ remained relatively low during the lockdown period as expected for people working from home, spending much of the day seated and limiting $PM_{2.5}$ emissions.

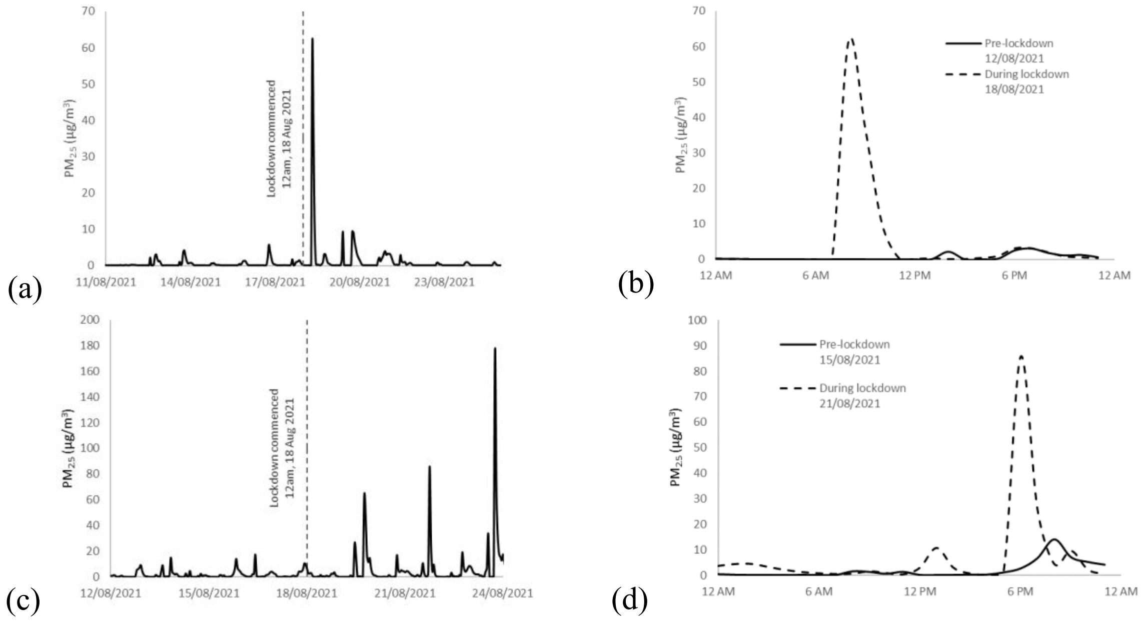

Figure 1 - Indoor $PM_{2.5}$ concentrations (a) House A, 1-week pre/post lockdown; (b) House A typical diurnal profiles; (c) House D, 1-week pre/post lockdown; (d) House D typical diurnal profiles.

Figure 2a and Figure 2c show indoor PM_{10} concentrations for two selected houses for the weeks immediately prior to and following COVID-19 lockdown. For the same two houses, Figure 2b and Figure 2d show that diurnal concentration peaks during lockdown were of similar magnitude to those prior to lockdown. In general, these occurred during mid-morning and evening time, reflecting peak traffic volumes.

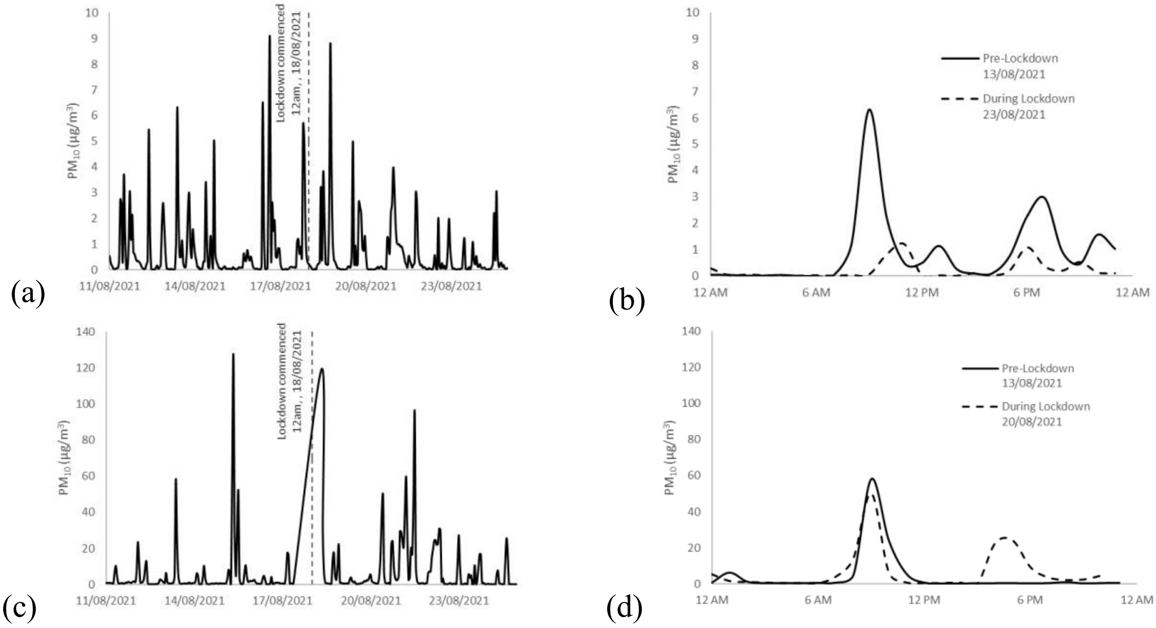

Figure 2 - Indoor PM_{10} concentrations (a) House B, 1-week pre/post lockdown; (b) House B typical diurnal profiles; (c) House F, 1-week pre/post lockdown; (d) House F typical diurnal profiles.

Average daily $PM_{2.5}$ and PM_{10} concentrations for each house were compared with the corresponding WHO Air Quality Guidelines (AQG) (15 $\mu g/m^3$ and 45 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}, respectively). In general, the $PM_{2.5}$ limit was exceeded more frequently than the PM_{10} limit. Similar studies (Algarni et al., 2021; Cowell et al., 2023) have shown that WHO limits are typically exceeded with increased occupancy, but these mostly apply to homes which only have natural ventilation. Prior to lockdown, House C exceeded the $PM_{2.5}$ limit on 16 of the 21 days, while the only other exceedance was one day in House E. During lockdown, House C exceeded the $PM_{2.5}$ limit 11 days out of the 3-week period, House E exceeded on two days, while Houses B and D both exceeded one day. The PM_{10} limit was only exceeded twice, two different houses, each on a different day, both during lockdown. House C was identified as comprising residents who regularly smoked cigarettes indoors. Cigarette smoking has been shown to increase indoor concentrations of $PM_{2.5}$ up to 28 times that for non-smoking households (Algarni et al., 2021).

The variability in indoor PM concentrations across the household was investigated by comparing PM concentrations between living areas and bedrooms. As expected, PM in bedrooms tended to be lower than in the living areas (60% lower prior to lockdown, 75% lower during lockdown), potentially due to people spending more of their time in the living areas.

3.3 Indoor Vs Outdoor PM

Outdoor PM measurements were obtained from three nearby council-owned urban air quality monitoring stations located across central Auckland. Average PM concentrations were calculated for the three-week periods immediately prior to and following COVID-19 lockdown. Average $PM_{2.5}$ concentrations decreased by 34% (from 7.7 $\mu g/m^3$ to 5.1 $\mu g/m^3$), ranging between 30% and 37% for the three stations. PM_{10} decreased by 31% (from 17.3 $\mu g/m^3$ to 11.9 $\mu g/m^3$), ranging between 10% and 39%. Decreases in PM_{10} and $PM_{2.5}$ were expected due to reduced traffic volumes and restrictions on non-essential commerce and industry during lockdown (Laltrello et al., 2022). Figure 3a and Figure 3b compare indoor and outdoor $PM_{2.5}$ and PM_{10} levels for a typical house and AQ monitoring station, one week prior to and one week immediately after COVID-19 lockdown. Despite a gradual decrease in outdoor PM concentrations, indoor concentrations increased during the lockdown. Mechanical ventilation has been shown to substantially reduce indoor concentrations of outdoor-generated pollutants when compared with natural ventilation (Martins & Carrilho da Graça, 2018; Ren et al., 2017), which suggests that internally-generated pollutants are a major contributor to indoor PM concentrations.

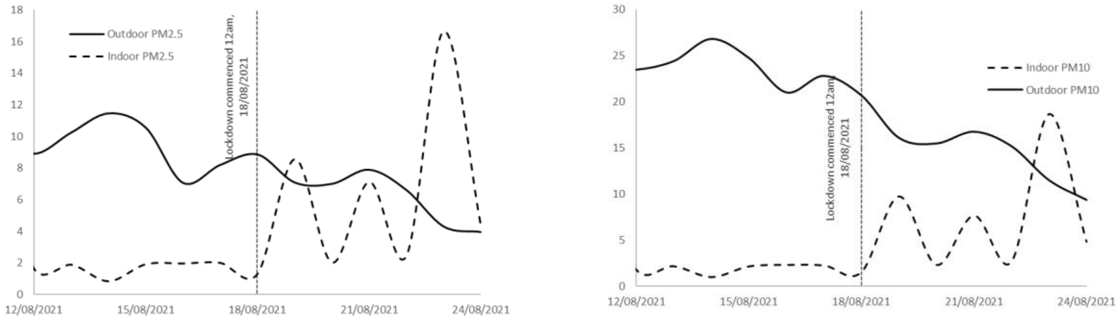

Figure 3 – Indoor vs outdoor PM concentrations, 1-week pre/post lockdown (House D) (a) $PM_{2.5}$; (b) PM_{10}

Average daily $PM_{2.5}$ and PM_{10} concentrations for each outdoor monitoring station were compared with WHO (AQG) limits, with only one site exceeding the PM_{10} AQG for one day over the six-week study period.

$PM_{2.5}$ indoor/outdoor ratios (I/O) were calculated, and prior to lockdown, all but one of the houses had I/O <1. The one house with I/O >1 was notable for having pets (two dogs and four cats) and being occupied by smokers, factors which are likely to have elevated indoor PM concentrations. During lockdown, I/O ratios increased in four houses, with three houses having I/O ratios >1. An I/O ratio of one or less is an indicator that internal sources of PM are not likely to be significant (Lomboy et al., 2015; Yang Razali et al., 2015; Zhou et al., 2016). Where mechanical ventilation with a well-performing filter is installed, the system removes PM from the influent air to offset potential internally-generated PM (Quang et al., 2013; Wang et al., 2006). Increased I/O ratios observed during the lockdown were expected due to the increased occupancy as reported previously, consistent with previous studies (Martins & Carrilho da Graça, 2018).

4 CONCLUSIONS

This study investigates the impact of changes in occupancy rates on IAQ in homes where mechanical ventilation is installed. Outdoor concentrations of $PM_{2.5}$ generally decreased during lockdown (34%, on average compared with pre-lockdown levels). Despite this, indoor $PM_{2.5}$ concentrations were generally found to be between 25% and 62% higher during the lockdown period, suggesting the influence of internal sources relates to occupancy. Furthermore, mechanical ventilation has been shown to substantially limit penetration of outdoor pollutants indoors, suggesting that internal concentrations are even more likely to have originated from internal sources. Diurnal peaks were also observed to be higher during lockdown, with highest peaks typically occurring during evenings. Increased cooking activities at home may be responsible for evening $PM_{2.5}$ spikes.

Indoor PM_{10} concentrations generally increased during lockdown (40% average) compared with outdoor concentrations, which decreased by 31% on average. Reduced traffic emissions and industrial activity during lockdown may have been directly responsible for reduced outdoor concentrations of PM_{10} and $PM_{2.5}$. Increased indoor PM_{10} concentrations are therefore likely to be due to internal sources, mainly from combustion activities. With the exception of House C, average daily PM concentrations rarely exceeded WHO Air Quality Guideline limits for short term exposure. Average daily $PM_{2.5}$ concentrations inside House C exceeded the WHO limit 76% of the time prior to lockdown and 52% of the time during lockdown. Average PM concentrations in House C were five times greater than the other houses. House C was identified as a smoking household which is consistent with these results. All six of the mechanically ventilated homes were able to maintain indoor PM levels below the WHO guidelines throughout the duration of the trial, despite the increased levels of occupancy.

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