An intervention study of $PM_{2.5}$ concentrations measured in domestic kitchens

Catherine O'Leary[1], Benjamin Jones[*1], and Ian Hall[2]

1 University of Nottingham
B12 Paton House,
Department of Architecture and Built Environment,
University of Nottingham, NG7 2RD, UK
*Corresponding author:
Benjamin.Jones@nottingham.ac.uk

2 Division of Respiratory Medicine,
School of Medicine,
University of Nottingham
Nottingham, NG7 2UH, UK.

ABSTRACT

Exposures to elevated concentrations of fine particulate matter with diameter ≤2.5µm ($PM_{2.5}$) are linked to multiple acute and chronic health effects, including increased risk of cardiovascular and respiratory disease. As people spend up to 70% in their own homes, exposures to pollutants indoors could have a greater impact on health than exposure outdoors. Cooking is a primary emission source of $PM_{2.5}$ in dwellings, and is of interest as it is an activity conducted several times a day in most households. Therefore, occupants are at risk of exposure to elevated levels of $PM_{2.5}$ emitted during cooking if these particles are not removed at source. This is particularly important in high occupancy dwellings, such as student housing, where cooking periods are likely to be longer or more frequent than average.

We studied the changes between $PM_{2.5}$ concentrations measured during two one-week periods in the kitchens of non-smoking, high occupancy dwellings in Nottingham, UK. The dwellings were occupied by students and there were between 2 and 6 occupants per household. The measurements were made during the heating season between 2016 and 2018.

During the first week, temporal changes in $PM_{2.5}$ concentrations were measured and the occupants of the dwellings were only informed that air quality parameters were being monitored, and so this period represents typical occupant behaviour. Before the second week of monitoring, the same occupants were shown the measured concentrations from week 1 and informed of the potential risks to their health that elevated $PM_{2.5}$ concentrations may pose. Occupants recorded details of cooking activity throughout both weeks.

During week 2 the occupants were also asked to make any intervention that they felt was appropriate, such as activating a range hood or opening a window or door. Specific guidance was not given and so this represents changes made by non-experts and may also indicate the approaches used by much of the population.

The concentrations recorded during each period were investigated independently, and compared to assess whether simple interventions are effective in reducing $PM_{2.5}$ concentrations due to cooking and if expert guidance and mitigation measures are required. The results suggest $PM_{2.5}$ concentrations in student housing in the UK are high. Across all houses, measured concentrations exceeded the WHO daily mean threshold (25µg/m^3) at least 14% of the time for Week 1, and 10% for Week 2. However, behavioural intervention was only found to reduce concentrations in one of the five houses investigated. This highlights the limitation of outsourcing ventilation decisions to non-experts, and automated ventilation systems should be considered.

KEYWORDS

house, dwelling, range hood, cooking

1 INTRODUCTION

In the UK, people spend over 70% of their time inside their own homes (Lader *et al.*, 2006). Buildings contain airborne pollutants emitted internally by building material and furnishings and by activities undertaken in the building, and also those emitted externally. There is a growing awareness that some bio-accumulating semi-volatile organic compounds and ultrafine particles may negatively affect the health of occupants (Logue *et al.*, 2011) and so building air quality is a cause for concern. The most dangerous pollutant is estimated to be particulate matter with a diameter of ≤2.5μm ($PM_{2.5}$) (Logue *et al.*, 2011). The particles are small enough to bypass biological defences, and exposure has been linked to increased risk of chronic respiratory and cardiovascular diseases, and cancer (Lewtas, 2007). The WHO (2005) recommends mean maximum $PM_{2.5}$ concentrations of 25μg/m^3 per day and 10μg/m^3 per year. In the USA the inhalation of $PM_{2.5}$s in dwellings is estimated to be responsible for approximately 1000 disability adjusted life years lost per year per 100,000 people (Logue *et al.*, 2011).

Primary $PM_{2.5}$ sources in dwellings are cooking and tobacco smoking, but also candle and incense burning, open and stove fires, gas fires, hobs and ovens, and spray aerosols (Afshari *et al.*, 2005). Of these sources, cooking is of particular interest because it is an essential activity undertaken in most dwellings. It is likely that the scale of the cooking activity increases with the size of the household and so the risk of exposure to cooking related $PM_{2.5}$ could be higher in high occupancy dwellings. Student housing is one example of high density, multiple occupancy dwellings. Behaviour may differ as, unlike a household composed of a single family unit, each resident is likely to operate independently.

Due to the nature of cooking, means of mitigation are limited, as total source removal is not possible. A key strategy to reduce $PM_{2.5}$ concentrations is through use of ventilation. Possible ventilation methods include an extract fan, vent or window, which allows full mixing within the space, or a cooker hood, which offers direct extraction before mixing. Cooker hoods can either extract all air to the outside, or recirculate it after passing it through a filter. In the UK, the statutory Approved Document F (ADF) (HM Government, 2010) prescribes intermittent kitchen ventilation rates of 30 l/s through a cooker hood or 60 l/s elsewhere, or a continuous rate of 13 l/s. These are required for new dwellings, but for renovations of existing dwellings it is only necessary to maintain existing systems (HM Government, 2010). Additionally, the basis for these standards is to effectively control humidity levels (HM Government, 2010), and there is no discussion of recirculating cooker hoods.

It is clearly important to have suitable ventilation systems in a kitchen. However, these systems can only reduce pollutant concentrations in kitchen if they are used appropriately. Accordingly, this study uses a simple intervention study to investigate the ability of occupants to use their kitchen ventilation systems to reduce $PM_{2.5}$ concentrations. This will show whether it is possible to outsourcing expert ventilation decisions to non-experts, or if other mitigation strategies are required. Section 2 introduces the methods, and Section 3 presents the results, which are discussed in Section 4.

2 METHOD

Table 1 outlines the characteristics of the 5 multiple occupancy, student dwellings in Nottingham, UK, investigated here. All households were selected to be non-smoking, however, after monitoring, House D was revealed to include a regular user of electronic cigarettes (e-cigs). As each use was recorded, House D was not excluded. No conventional cigarettes were smoked.

All tests were conducted during the heating seasons between October 2016 and April 2018. The occupants of student houses can be in fuel poverty, and so it is expected that occupants would be less inclined to use ventilation methods in order to conserve heat. This represents a worst case behaviour scenario. Furthermore, houses A, D and E can be considered leaky because they were constructed before 1930, which represents a best case infiltration scenario.

Houses B and C are modern apartments constructed after 2000 and so are considered to be much more airtight.

Table 1: House summary information

House	Dwelling type	No of occupants	Open plan kitchen?	Kitchen volume (m^3)	Cooker type	Extractor fan?
A	Semi-detached	6	Yes	77	Gas stove, electric oven	Cooker hood (faulty)
B	Ground floor apartment	2	No	-	Electric	Wall mounted, automated
C	2nd floor apartment	5	Yes	-	Electric	Cooker hood, unknown
D	End terrace	6	Yes	94.9	Gas stove, electric oven	Cooker hood, recirculating
E	Detached	4	No	24.1	Gas	Cooker hood, external vent

The available cooking facilities varied between houses, as can be seen in Table 1. Each house had either an electric or gas stove-top, and an oven. UK ovens typically have a grill option, where food is cooked using only radiant heat from the upper heating element. Additionally, student kitchens would be expected to have a toaster, kettle and microwave, although the exact details were not recorded for each house.

2.1 Equipment

One SidePak™ AM510 Personal Aerosol Monitor (TSI Inc., Shoreview, MN, USA), fitted with a 2.5μm impactor, was used to monitor $PM_{2.5}$ concentrations. Concentrations were time averaged and logged at 1 minute intervals, because of the limited storage capacity of the SidePak. Optical sensors, such as the SidePak, require a calibration factor (CF) when converting to mass concentrations (Dacunto *et al.*, 2013). The CF was set to the default 1.0, as no concurrent gravimetric sampling was available, therefore all mass concentrations reported are approximations. In addition, an IAQ-Calc Indoor Air Quality Meter (Model 7545, TSI Inc., Shoreview, MN, USA) monitored indoor temperature, CO_2 and CO concentrations, and relative humidity.

The SidePak™ and IAQ-Calc were positioned together, in the kitchen, out of direct sunlight and away from heat sources. The aim was to measure $PM_{2.5}$ concentrations in mixed air, therefore the equipment was positioned away from sources of $PM_{2.5}$ and water vapour, such as the stove and kettle. The exact position varied between dwellings, and was restricted by the need for both devices to be connected to a power supply. In houses A, C and D, with open plan kitchens, the equipment was located in the kitchen area of the room.

2.2 Monitoring

In each household, one occupant was briefed on the aims of the study, instructed how to set up and use the equipment, and instructed how to brief the other occupants. During Week 1, only this occupant was aware that $PM_{2.5}$ concentrations related to cooking were being investigated, however, all occupants were asked to record cooking behaviour in a household cooking log. This included a record of cooking start and end times, and notes describing the cooking activity taking place. It was intended that occupants would not be asked to record the use of specific ventilation systems and openings during the first week, as this might modify their behaviour. However, in two cases, Houses A and E, their notes included the use of kitchen ventilation in Week 1.

At the end of Week 1, the data was downloaded, and the initial findings discussed with the same occupant. They were given an overview of the concentrations, and provided with plots and instructions on how to direct the other occupants before commencing Week 2 measurements. Occupants were informed of the risks associated with exposure to $PM_{2.5}$, shown the concentrations from Week 1 with reference to the WHO (2006) daily and annual mean guidelines, and informed that increasing the ventilation rate might improve indoor air quality. Suggested methods included use of the extractor fan, or opening external doors or windows during or after cooking, but no specific direction was given nor was there any indication of which strategies might be more effective. Alongside the cooking log, all households were asked to record use of ventilation.

2.3 Post-processing of Data

The monitoring data was collated and it was analysed using bespoke MATLAB code (MathWorks, 2016). Each monitored week was truncated to include only the first 7 complete days, missing $PM_{2.5}$ data points were removed, as were those where RH exceeded 70%, as optical measurements such as the SidePak™ may be influenced by high humidity (Dacunto *et al.*, 2013). In the case of House D, neither week had a full 7 days of recorded data, so both were truncated to 6 days 12 hours, the shorter of the two weeks. Finally, this study was only concerned with $PM_{2.5}$ from cooking sources and e-cigs are a possible source of $PM_{2.5}$. Therefore, to isolate cooking emissions, in House D, data points corresponding to the recorded e-cig use were removed. The same process was used to split concentrations into cooking and non-cooking, which worked by separating the data points between the recorded start and end time of each event

To consider the changes between the two weeks of data, two statistical tests were used. Firstly, the non-parametric Kolmogorov-Smirnov (K-S) test was used to see whether the concentrations from each week are likely to be sampled from the same continuous distribution. Secondly, the effect size, a measure of the size of the difference between two samples, was calculated using Glass's Δ, according to Equation 1 (Ferguson, 2009).

$$\Delta = \frac{(\mu_2 - \mu_1)}{SD_{control}} \tag{1}$$

The control data set, with mean μ_1 and standard deviation $SD_{control}$, was considered to be the concentrations measured during Week 1, and μ_2 the mean concentration in Week 2.

3 RESULTS

Three questions were considered in analysing the results. Firstly, did cooking activity result in increased concentrations? Second, was there any evidence of behavioural change as a result of the intervention? And finally, did the intervention result in lower concentrations during Week 2?

3.1 The Influence of Cooking on Concentrations

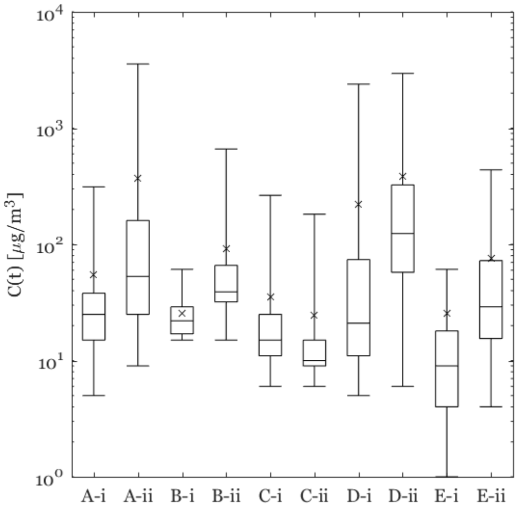

Figure 1: Week 1 concentrations for houses A-E for (i) non-cooking and (ii) cooking periods

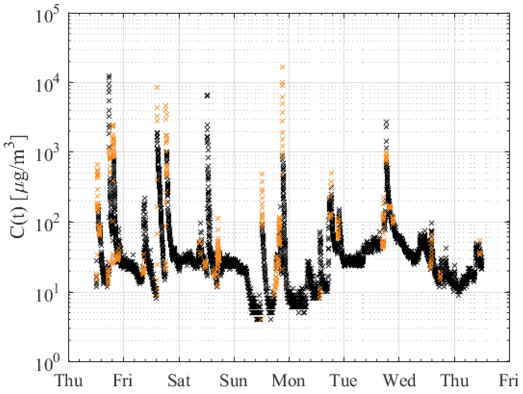

Figure 2: House A concentrations with cooking periods indicated in orange

Week 1 data and recorded cooking times were used to investigate whether cooking led to elevated kitchen $PM_{2.5}$ concentrations. Figure 1 indicates higher concentrations during cooking in all houses except House C. However, this comparison is limited by the quality of the recorded cooking logs, and the method of parsing the data purely based on cooking times means the decay period following emissions may not be captured as cooking data, as shown in Figure 2. For these reasons, subsequent analyses do not distinguish between concentrations measured during and outside of cooking periods.

3.2 Cooking and Ventilation Behaviour

The number of recorded cooking events and the total time spent cooking varied between houses and between Weeks 1 and 2 for each house, see Table 2. Additionally, whilst ventilation was used during Week 2, it was not used during all cooking events. Here, Table 2 shows that the number of cooking events is not equal to the number of ventilation events.

In houses A and E, where ventilation use was recorded in the first week, ventilation was used more frequently in the second week. In Week 2, ventilation was not used during all cooking events; its use was recorded during 53% events for Houses D and E and 75% House A events. Where ventilation was used, it was not generally noted for how long, with the exception of House E Week 2, where the ventilation mechanisms were left in use after cooking had ceased on 4 occasions.

Table 2: Cooking event count and duration

House	**Total time cooking (minutes)**		**Cooking Events**		**Cooking Events with ventilation**	
	Week 1	**Week 2**	**Week 1**	**Week 2**	**Week 1**	**Week 2**
A	554	525	34	28	5	21
B	672	725	*	*	-	†
C	422	517	*	*	-	†
D	377	397	23	32	-	17
E	401	697	30	47	5	25

*unavailable as cooking times were aggregated into 3 meals per day
† not recorded

Mitigation strategies usually involved a cooker hood, often in combination with open windows or doors. House B was an exception, as its wall mounted extractor fan was activated by a sensor and so was used as a mitigation strategy during weeks 1 and 2, but an external window was opened during Week 2.

3.3 $PM_{2.5}$ Concentrations

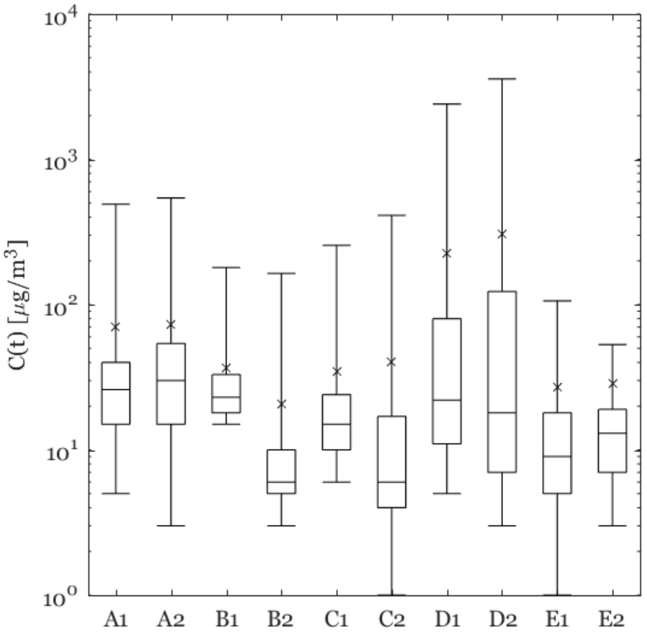

Figure 3: Kitchen $PM_{2.5}$ Concentrations for all houses, week 1 and week 2

The concentrations measured during Week 1 and Week 2 are summarised in Figure 3 and Table 3. Only House B shows a decrease in the mean concentration in Week 2, indicated by the mean and median, although Glass's Δ suggests that the effect is *small*. However, the K-S test indicates a statistically significant difference in the Week 1 and 2 distributions for all houses. The effect size suggests a very small to negligible positive effect (a very small increase in concentration) in all houses except House B. This suggests the intervention was only successful in reducing concentrations for one of the 5 cases, House B.

Table 3: Summary Concentrations (μg/m^3) and

	House A		**House B**		**House C**		**House D**		**House E**	
	W 1	**W 2**	**W 1**	**W 2**	**W 1**	**W 2**	**W 1**	**W 2**	**W 1**	**W 2**
2 centile	5	3	15	3	6	1	5	3	1	3
25 centile	15	15	18	5	10	4	11	7	5	7
50 centile	26	30	23	6	15	6	22	18	9	13
75 centile	40	54	33	10	24	17	80	123	18	19
98 centile	490.4	542	179.9	164	255.8	411.2	2399	3575	106	53.0
Mean	70.6	72.8	36.9	20.7	34.7	40.5	226.3	307.9	26.8	28.4
Std. Dev.	400.1	248.9	79.7	96.8	81.7	178.0	847.9	1079	147.5	193.6
K-S*	Rejected ($p \ll 0.05$)		Rejected ($p \ll 0.05$)		Rejected ($p \ll 0.05$)		Rejected ($p \ll 0.05$)		Rejected ($p \ll 0.05$)	
Effect Size	0.0055		-0.2028		0.0705		0.0962		0.0112	

* tests the null hypothesis that week 1 and 2 samples are from the same distribution

4 DISCUSSION

The concentrations reported here are generally higher than those measured in previous studies. Stranger *et al.* (2009) found indoor $PM_{2.5}$ concentrations with median 27.2 µg/m^3 and 41.1 µg/m^3 across two sets of dwellings in Antwerp, Belgium. Wallace *et al.* (2006) measured concentrations of similar magnitudes in 36 North Caroline residences, with an overall mean of 29.8 µg/m^3 and a maximum average 56.8 µg/m^3 in non-smoking households. As did Chan *et al.* (2017), with mean concentrations ranging from 1.6µg/m^3 to 64.1 µg/m^3 across 18 California apartments. These are generally lower than the mean concentrations of between 20.7 µg/m^3 and 309.4 µg/m^3 reported in Table 3. One common feature of these studies that differs from this investigation, is that the sampling location was not exclusively the kitchen, but was instead located in the kitchen or dining room. By sampling in the kitchen, concentrations might be expected to be higher. However, in a study of 15 domestic Brisbane kitchens during autumn and winter, Morawska *et al.* (2003) measured overall mean $PM_{2.5}$ concentrations of 15.5 µg/m^3 during activity and 11.1 µg/m^3 otherwise. These concentrations are also significantly lower than those given in Table 4, but many factors may contribute to this difference, including household and dwelling characteristics, activity types, and the SidePak CF. Additionally, these studies are not of UK house, and dwelling characteristics and occupant behaviour vary considerably between countries.

For this study, the factory default CF 1.0 was used as no gravimetric sampling was available and because the primary purpose was to compare concentrations between the two measurement weeks. It was assumed, therefore, that the CF was similar over both measurement weeks. Dacunto *et al.* (2013) and Jiang *et al.* (2011) found SidePak CFs ranging between 0.41 and 0.70 for a variety of cooking sources, therefore the true mass concentrations are likely lower than those reported. This is an important consideration, and limitation, when comparing the findings to standards or other studies.

The mean concentration for all houses and test weeks, except for House B during Week 2, exceeded the WHO 24-hour mean guideline of 25 µg/m^3, although this is not a fair comparison because of the differences in the averaging periods. If the 7 day average exceeds the threshold, it is likely that most days will also exceed it. However, as the SidePak calibration factor of 1.0 likely overestimates the measured concentrations, comparisons to guidelines can only indicate a potential issue with elevated concentrations during the heating season. If we apply CF=0.3 to the mean concentrations, a worst case scenario, only House D exceeds the WHO 24-hour guideline. For CF=1.0, given the limitations of this assumption, measured concentrations exceeded the WHO daily threshold at least 14% of the time in Week 1, and 10% in Week 2.

The potential for the intervention to reduce concentrations was limited by two key factors: (i) the ventilation systems available and (ii) occupant decisions on how and when to use ventilation. Only Houses A and E were fitted with externally venting cooker hoods, although a subsequent investigations in House A revealed damaged ductwork, so extracted air was probably partly recirculated without filtration. It was not possible to access the hood in House C. If the filter in recirculating hoods is poorly maintained, it is unlikely to remove pollutants effectively.

The decision to use ventilation depends on expertise. Someone with knowledge who decides to reduce $PM_{2.5}$ concentrations might prioritise cooking events that are more likely to have higher emission rates, such as oil based or dry processes (Torkmahalleh *et al.*, 2017) rather than those that use boiling or steaming. However, the recorded behaviour did not reflect this.

Instead, occupants primarily used ventilation during stove-top cooking. For example, in House D Week 2, the cooker hood was turned on and a window opened during all stovetop cooking events, but they were only used for just 1 of 5 events of grilling events and for 0 of 8 oven events. Here, He *et al*. (2004) show that frying and grilling are significant sources of emissions. Therefore it is interesting that occupants chose to use ventilation whilst using hot water to cook couscous and not whilst grilling sausages.

The concentrations measured in House E indicate that there may have been significant behavioural change during Week 2. The main peak in $PM_{2.5}$ concentrations during Week 1corresponds with the only recorded use of the oven and this was discussed with the instructor-occupant. As the oven appeared to be the most significant source of $PM_{2.5}$, the occupants seem to have responded, using the cooker hood during 10 of the 11 occasions the oven was on during Week 2. Nevertheless, the two highest peaks in concentration during Week 2 were 6500 $\mu g/m^3$ and 2656 $\mu g/m^3$, and both corresponded to the use of the oven with the cooker hood on and the external door open. It is possible that using multiple ventilation systems and openings in combination may not lead to increased benefits, although using the fan with one or more ventilation openings was the most popular choice for all households. Here, it may desirable to depressurize the kitchen and to ensure that air only flows into it from other zones.

A potential limitation of the findings is that cooking behaviour varied between the two weeks. Cooking behaviour is semi-random, where the exact frequency, duration and emission rates all vary. Table 2 shows how the total time spent cooking increased in Week 2 in all Houses, except House A. An improved method to separate cooking associated concentrations from those from other activities would be to include the subsequent decay periods, say until concentrations return to background similar to Chan *et al.* (2017). This may reduce any confounding effect of cooking behaviour. However, cooking methods and period lengths may also influence emissions. For example, in House B, the time spent using the toaster, oven and grill increased from 271 minutes in Week 1 to 343 minutes in Week 2. A similar effect was observed in House C, where the time using these appliances increasing from 112 minutes to 204 minutes. These appliances all use dry or oil based cooking process, which have been linked to higher particle emissions (Torkmahalleh *et al.*, 2017).

Finally, of the five houses investigated, a reduction in concentrations during Week 2 was only observed in House B. This was achieved using natural ventilation opening, as the installed extractor fan was controlled by a sensor, and so could not be used as part of the intervention. Additionally, the longevity of any behavioural changes was not investigated. It is possible that occupants regress to Week 1 behaviour over time.

These results suggest that concentrations of $PM_{2.5}$ in student housing in the UK are high and that they could affect the health of their occupants. One solution might be to use range hoods that capture emissions at their source and that automatic switch on when they detect elevated $PM_{2.5}$ concentrations. A public awareness campaign might also encourage population behavioural change. In the medium term, the UK building regulations should be reviewed, and a ventilation system of some kind should be mandatory. However, work is required to identify appropriate ventilation rates to dilute $PM_{2.5}$ once they have mixed in a space and systems should be identified to achieve them. An extracting cooker/range hood is currently the best known and quickest remediation measure but further work is required to identify suitable airflow rates and capture efficiencies for it.

5 CONCLUSIONS

This paper uses a simple intervention study to investigate the potential to reduce kitchen $PM_{2.5}$ concentrations using existing ventilation methods. $PM_{2.5}$ concentrations were monitored in five student households for two weeklong periods. Student households were selected as high occupancy dwellings whose occupants may be in fuel poverty. During the first week of measurements, normal behaviour was assumed. Prior to 2nd week of measurements, occupants were informed of the risks associated with exposure to $PM_{2.5}$ and given suggestions of ventilation methods that might reduce the concentrations.

Results suggest that $PM_{2.5}$ concentrations in student housing in the UK might be high. Across all houses, measured concentrations exceeded the WHO daily mean threshold ($25\mu g/m^3$) at least 14% of the time for Week 1, and 10% for Week 2. However, there is considerable uncertainty in the measured concentrations as an optical device was used without corresponding gravimetric sampling. Future work should aim to include such measurements to provide a better understanding of the concentrations experienced in student dwellings.

The intervention only successfully reduced concentrations in one of the five dwellings considered, despite evidence of behavioural change. Statistical tests suggest the concentration distributions differ before and after the intervention in all five houses. These changes were small, and suggested concentrations increased post-intervention in four of the five houses. However, the comparison between the two weeks is limited, due to the variation in the frequency and duration of cooking events, and the cooking methods used. Therefore, future work should improve the method of isolating cooking events, so that only the concentrations attributable to cooking can be analysed.

The intervention may also have been limited by occupant decisions regarding ventilation methods. This highlights the limitations of out-sourcing expert decisions to non-experts, and so automated mechanical extract ventilation should be considered as standard. This should be considered during the next review of UK Building Regulations. Finally, a public awareness campaign might encourage population behavioural change in the kitchen, leading to reduced exposures and a reduction in health care costs.

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