Residential cooking-related $PM_{2.5}$: Spatial-temporal variations under various intervention scenarios

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Abstract

Some cooking events can generate high levels of hazardous $PM_{2.5}$. This study assesses the dispersion of cooking-related $PM_{2.5}$ throughout a naturally-ventilated apartment in the US, examines the dynamic process of cooking-related emissions, and demonstrates the impact of different indoor $PM_{2.5}$ mitigating strategies. We conducted experiments with a standardized pan-frying cooking procedure under seven scenarios, involving opening kitchen windows, using a range hood, and utilizing a portable air cleaner (PAC) in various indoor locations. Real-time $PM_{2.5}$ concentrations were measured in the open kitchen, living room, bedroom (door closed), and outdoor environments. Decay-related parameters were estimated, and time-resolved $PM_{2.5}$ emission rates for each experiment were determined using a dynamic model. Results show that the 1-min mean $PM_{2.5}$ concentrations in the kitchen and living room peaked 1–7 min after cooking at levels of 200–1400 μg/m^3, which were more than 9 times higher than the peak bedroom levels. Mean (standard deviation) k_t for the kitchen, ranging from 0.58 (0.02) to 6.62 (0.34) h^{-1}, was generally comparable to that of the living room (relative difference < 20%), but was 1–5 times larger than that of the bedroom. The range of $PM_{2.5}$ full-decay time was between 1–10 h for the kitchen and living room, and from 0 to > 6 h for the bedroom. The $PM_{2.5}$ emission rates during and 5 min after cooking were 2.3 (3.4) and 5.1 (3.9) mg/min, respectively. Intervention strategies, including opening kitchen windows and using PACs either in the kitchen or living room, can substantially reduce indoor $PM_{2.5}$ levels and the related full-decay time. For scenarios involving a PAC, placing it in the kitchen (closer to the source) resulted in better efficacy.

Keywords: Cooking, $PM_{2.5}$, emission rate, range hood, window opening, portable air cleaner

1. Introduction

People spend 60-70% of their time in their residences [1, 2], where the concentrations of hourly residential $PM_{2.5}$ (particles with an aerodynamic diameter less than 2.5 μm) can be larger than 300 $\mu g/m^3$ with the presence of cooking events [3]. Longitudinal studies have found associations between long-term exposure to cooking fumes and lung cancer risk, especially in poor ventilation situations [4-8]. Cross-sectional studies have measured biomarkers after short-term exposure to cooking fumes in occupational health scenarios among cooks in restaurant environments [9-12]. These studies suggest that exposure to cooking fumes is associated with increased oxidative damage [9, 10] and decreased lung function [11, 12].

As cooking fumes disperse in residences, occupants in locations besides kitchens are also exposed to cooking-related air pollution. A growing number of studies have illustrated the strikingly high $PM_{2.5}$ concentrations and emission rates in kitchens during some cooking scenarios (e.g., frying) [13-16]. In contrast, only a few studies have examined the dispersion of cooking-related $PM_{2.5}$ from kitchens to living rooms in residences [14, 17, 18]. For instance, one study conducted in Korean residences examined the dispersion of $PM_{2.5}$ from open kitchens to living rooms before, during, and after cooking events, and found comparable $PM_{2.5}$ concentrations in living rooms relative to kitchens during cooking despite using different cooking and ventilation scenarios [14]. Overall, limited measurements have been carried out regarding the $PM_{2.5}$ dispersion in residences, especially from kitchens to bedrooms, where the doors may be closed during cooking.

A key parameter of the cooking-related $PM_{2.5}$ emission is the emission rate. Several studies have estimated the $PM_{2.5}$ emission strength from some cooking scenarios by assuming a constant emission rate during the cooking process [13, 19]. However, the emission rates can vary significantly with many factors, such as food temperature. Thus, a nonlinear fitting of the $PM_{2.5}$ increasing curve by assuming a constant emission rate over the full process could lead to a large bias. Using more discreet time steps can potentially result in more accurate estimates for different times during and after the cooking process.

Using a kitchen range hood or opening the kitchen windows is a common method to mitigate indoor $PM_{2.5}$ during cooking events. Chen et al. examined the efficacy of range hoods during some typical cooking scenarios in a Chinese residential kitchen, showing a removal efficiency of over 40% [13]. Gao et al. examined indoor PM during cooking with different door and window status combinations, indicating that indoor $PM_{2.5}$ declined by over 40% with a window open compared to a window-closed scenario [20]. Brett et al. conducted a series of experiments to examine the pollutant capture efficiency of kitchen range hoods in test chambers and California homes. They found a wide range in the capture efficiency from <15% to 98% [21-24]. Zhao et al. evaluated the efficacy of multiple intervention strategies, including range hood, face mask, personal portable fan, and air cleaner, to reduce $PM_{2.5}$ exposure in a Chinese kitchen [25]. They found that using a range hood with an equivalent air exchange rate of 7.5–10.9 h^{-1} and wearing a face mask during cooking reduced 90–95% and 79–84% $PM_{2.5}$ exposure for the cook, respectively [25]. Additionally, a recent study evaluated the efficacy of using portable air cleaners (PACs) during cooking events in six US homes [3]. Results showed that PAC filtration significantly reduced hourly indoor $PM_{2.5}$ levels by 15–31% compared with non-filtration scenarios. However, as this was a free-living study, and partcipants were allowed to cook as this wish (i.e., varying cooking methods and food items) in the study, cooking was not controlled and statistical adjustments only for periods of cooking were included in the comparison between filtration and non-filtration scenarios. None of these studies have compared the efficacy of these strategies for mitigating cooking-related $PM_{2.5}$ in US residences. Moreover, in the case of using a PAC, it remains unclear how the placement of it in different rooms impacts the mitigating effectiveness.

Unlike previous studies that have examined the cooking-related emissions from the mixture of fuel (e.g., natural gas) combustion and food fumes (including oils and ingredients), the present study focuses on $PM_{2.5}$ emissions from food fumes by utilizing an electric range. By collecting measurements for multiple scenarios in a US residence, this study aims to 1) illustrate the dispersion of cooking-related $PM_{2.5}$ throughout the residence; 2) examine the dynamic process of cooking-related $PM_{2.5}$ concentrations and emission rates; and 3) demonstrate the impact of different mitigating strategies (i.e., opening kitchen windows, using a range hood, or utilizing a PAC in various indoor locations) on indoor $PM_{2.5}$ levels.

2. Methods

2.1. Experimental site

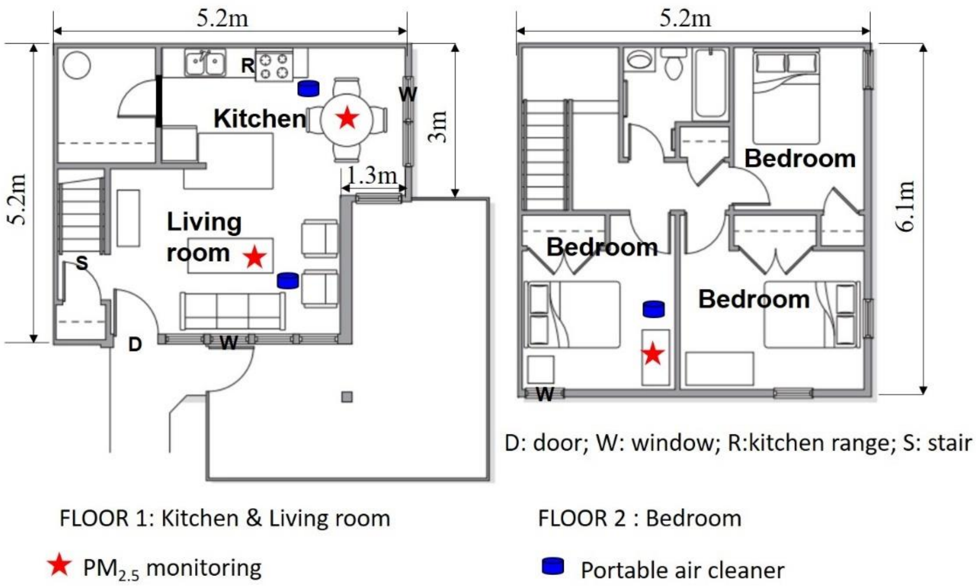

Fig. 1. The layout of the experimental site. The size (length and width) is marked on the plot. The height of each story is 2.5 m.

The experiments were conducted in an apartment in Seattle, Washington State, US, from August 6 to September 16, 2019. The apartment, built in 2003, had no mechanical ventilation systems or air conditioners. As shown in Fig.1, the duplex apartment had two stories, with the open kitchen (including the dining area) and living room in the first story and all three bedrooms in the second story. The two stories were connected via internal stairs with no door or barrier. The kitchen, living room, and bedrooms all only had one openable window each. The kitchen had an electric range (Hotpoint, GE Appliances, US) which offered ten temperature options (i.e., *OFF*, and *1–9* from low to high levels) and four burners. One of the front burners was used in this study. A range hood (length × width × height: 0.76 × 0.44 × 0.15 m; Broan BUEZ2, US), which had a nominal airflow of 90 liters/s and a sound level of 6 sones (~54 dB), was located about 0.6 m above the range.

2.2. Cooking scenarios

As pan-frying is one of the most particle-emitting cooking methods [13], pan-frying steak and asparagus were selected for the standardized cooking recipe. We strictly followed the same protocol for each experiment to buy, prepare, and cook the food. The detailed protocol for preparing and cooking the food is described in the Appendix. Specifically, the same type of steak and asparagus for two persons were purchased at a local grocer 1–2 days before each experiment and stored in a fridge (above 0 °C). The mean (standard deviation, SD) weights of each serving of steak and asparagus were 230 (17) g and 227 (25) g, respectively. The asparagus was rinsed and drained for each experiment, and the steak was seasoned with black pepper, salt, and sunflower oil (~10 g) before the electric range was turned on. At the start of cooking (time = 0), the pre-cleaned nonstick frying pan on the electric-range burner was heated for 2 min at the temperature *level 9*. The steak was then added to the pan with both sides fried for 1 min at the same temperature level, respectively. With the temperature adjusted to *level 5* and ~56 g butter added to the pan, both sides of the steak were then fried for another 2 min, respectively. While removing the steak out of the pan, the temperature was adjusted to *level 8*. After heating the pan for 30 s, the prepared asparagus was added to the pan and fried for 7 min and flipped at 1-min intervals. The asparagus was then fried with salt added for one more minute before the range was turned off. It was followed by removing the asparagus from the pan and leaving the uncovered pan on the same burner to cool for 1 h. The whole time with the range on lasted about 17 min. Given the remaining oil in the pan after steak frying, no more oil was added during asparagus frying. There were no other cooking activities throughout each experiment.

Table 1. Summary of experimental scenarios.

Date (mm/dd/yy)	Scenario	Number of Trials	Range hood	Kitchen window	PAC
09/16/20	1	1	off	closed	off
08/07/20, 08/12/20	2	2	off	open	off
08/08/20, 08/09/20	3	2	on	closed	off
08/13/20, 08/15/20	4	2	on	closed	KC
08/16/20, 09/15/20	5	2	on	closed	LR
08/26/20, 08/28/20	6	2	on	closed	BR
08/29/20, 08/30/20	7	2	on	closed	KC + LR + BR

Definition of abbreviations: PAC = portable air cleaner; KC = kitchen; LR = living room; BR = bedroom.

Seven experimental scenarios were conducted with one trial for Scenario 1 and two trials for the other scenarios (Table 1). For all scenarios, all doors and windows in the living room and bedrooms were kept closed unless specified. In Scenario 1, the range hood and PAC were off, and the kitchen window was closed. This was considered to be the worst-case scenario for cooking-related indoor air quality. Because the measured indoor $PM_{2.5}$ levels were too high and decayed slowly (see more in the Results section), we opened the kitchen window and main door of the apartment about 1 h after cooking ended and closed them again after 5 min. Also, to avoid extremely excess exposure and potential adverse health impacts of the occupants, we did not conduct more trials of Scenario 1. In Scenario 2, the kitchen window was opened at least 30 min before cooking until all measurements were taken, while the range hood and PAC remained off. This scenario was used to examine the efficacy of opening kitchen windows during and after cooking. In Scenarios 3–7, the range hood was turned on at the start of cooking (time = 0) and turned off 1 min after cooking due to the noise issue, while the kitchen window was kept closed. Scenario 3, where the PAC was still off, was used to examine the efficacy of range hood during cooking.

In contrast, Scenarios 4–6 involved the use of a PAC in the kitchen, living room, and one of the bedrooms, respectively (Fig. 1). The PAC was turned on about 10 min before cooking and kept on until all measurements were taken. The three scenarios were used to examine the efficacy of PAC use in different indoor locations. Additionally, we conducted a scenario (Scenario 7) with the combined use of PACs in all three locations. This was considered to be the best-case scenario for cooking-related indoor air quality. In this study, we utilized PACs containing a high-efficiency particulate air (HEPA) filter (Air Purifier 2000i, Philips, US). With a rated clean air delivery rate (CADR) of 179 m^3/h for smoke, the PAC offers both manual and auto operation modes. In the auto operation mode, the PAC automatically adjusts its fan speed level based on $PM_{2.5}$ measurements made by an integrated particle sensor. This auto-mode feature has been widely used in residences due to its convenience. The effectiveness and benefits of auto operation mode in reducing indoor $PM_{2.5}$ levels have been evaluated elsewhere [3]. In Scenarios 4–7, the PACs were all running in auto operation mode.

2.3. Instrumentation

We utilized real-time $PM_{2.5}$ monitors (Appendix Fig. A1) to measure the $PM_{2.5}$ mass concentrations in the kitchen, living room, and bedroom (Figure 1) at 1-min intervals from about 30 min before and 4 h after cooking. This $PM_{2.5}$ monitor, consisting of an optical particle sensor (Plantower PMSA003, Beijing Ereach Technology, China), was used in many previous studies [3, 26-28]. The well-validated Plantower PMSA003 sensor is capable of measuring both ambient and residential $PM_{2.5}$ [3, 29, 30]. A previous study compared Plantower PMS A003 with the gravimetric-based method when exposed to multiple particle sources. The overall accuracies of Plantower PMS A003 with residential air and cooking aerosols were 92% and 96%, respectively [30]. Prior to the main experiments, we calibrated the monitors against a factory-calibrated reference monitor (Grimm Portable Laser Aerosol Spectrometer Model 1.109, Grimm Aerosol Technik GmbH & CO. KG, Germany) in a scenario similar to Scenario 1 in the same residence. US Environmental Protection Agency has approved an updated version of the Grimm monitor (Grimm EDM 180) as a federal equivalent method (FEM) [31]. The normalized root mean squared errors (NRMSE) [32] of the post-calibrated monitors were 6–7%, indicating reasonably accurate measurements (see more details of the calibration process in Appendix Fig. A2 and Table A1). Hourly outdoor $PM_{2.5}$ concentrations, mostly < 10 $\mu g/m^3$, were obtained from the nearest governmental air quality monitoring station about 10 km away from the residence [33]. The CO_2 concentration was measured in the kitchen using a factory-calibrated Q-Trak (Model 7575, TSI Inc., US) at 1-min intervals. All instruments were placed on a table, about 1 m above the ground, as shown in Fig. 1.

2.4. Data analysis

While examining the $PM_{2.5}$ spatial-temporal variations under different intervention scenarios, we assessed $PM_{2.5}$ concentrations, decay-related parameters, and emission rates. A p-value < 0.05 indicated statistical significance for all statistical tests in this study. All calculations were made in R Version 3.3.0 [34], integrated into RStudio Version 1.1.456.

2.4.1. Concentrations

First, the $PM_{2.5}$ concentrations were compared for periods before, during, and after cooking. The time when the electric range was turned on was set as Minute 0. Minutes (-10)–(-1), 0–16, and 17–75 were then defined as before-, during-, and after-cooking periods, respectively. The $PM_{2.5}$ concentrations after Minute 75 were not directly compared because the window and door statuses were changed at Minute 76 in Scenario 1. Second, the $PM_{2.5}$ concentrations were compared among different locations, i.e., the kitchen, living room, bedroom, and outdoor environment, by assuming the outdoor $PM_{2.5}$ levels unchanged during each hour. Lastly, the $PM_{2.5}$ concentrations among different scenarios were compared by averaging all the trials in each scenario. The $PM_{2.5}$ concentrations in each period, location, and scenario were not normally distributed according to the Shapiro-Wilk tests. Thus, the Wilcoxon rank-sum tests, which can be applied for unpaired comparisons, were conducted to compare the $PM_{2.5}$ levels from different periods. The Wilcoxon signed-rank tests, which can be applied for paired comparisons, were conducted to compare the $PM_{2.5}$ levels from different locations and scenarios.

2.4.2. Decay-related parameters

Assuming the air was well mixed in the kitchen, living room, and bedroom, respectively, the $PM_{2.5}$ levels in each location after cooking (no emission source) can be described as Eq. (1) [19, 35]:

$$C_{in}(t_2) = C_{in}(bg) + \left(C_{in}(t_1) - C_{in}(bg)\right) \cdot e^{-k_t \cdot (t_2 - t_1)} \qquad (1)$$

where $C_{in}(t_1)$ and $C_{in}(t_2)$ are the indoor $PM_{2.5}$ concentrations at time t_1 and t_2, μg/m^3, respectively; $C_{in}(bg)$ is the background indoor $PM_{2.5}$ level measured before cooking, μg/m^3; k_t is the total $PM_{2.5}$ decay rate from ventilation, deposition, and PAC use, h^{-1}.

The total decay rate, k_t, can be estimated with an exponential fitting of the $PM_{2.5}$ decay curve after cooking. The decay curves were fitted for each location in each experiment during periods in compliance with the criteria: 1) ≥ 10 min after cooking; 2) no altered conditions of windows and doors; 3) no range hood or other air cleaning equipment besides the PACs were in use; 4) the curve was visually smooth and exhibiting a decreasing trend; 5) a time window of at least 30 min. The fitting assumes the background level, $C_{in}(bg)$, remained unchanged during the experimental process. Considering the negligible variation in the low outdoor $PM_{2.5}$ levels (see more in the Results), this assumption is reasonable.

The air exchange rate (AER) in the first story (kitchen and living room) was determined using the CO_2 tracer gas method [36]. The approach is described in detail in the Appendix. Given the open design of the kitchen and the relatively small space on each floor (~25 m^2), the air in the kitchen and living room were assumed to be well mixed. However, this AER did not apply to the bedroom since the door was kept closed. The assumptions were confirmed by the measured $PM_{2.5}$ levels in the three locations (see more in the Results).

The indoor $PM_{2.5}$ level decayed gradually after cooking. Theoretically, it takes infinite time to decay to the background level based on Eq. (2). Thus, instead of taking the measured background levels before cooking (maximum: 10.5 μg/m^3; see Appendix Table A2) as a target concentration, we chose 11 μg/m^3 as the reference background level, which was slightly larger than the actual measured concentration. In this study, the indoor $PM_{2.5}$ concentrations decayed to the reference background levels within 4 h after cooking in some scenarios, especially for those with PAC use. For those scenarios where indoor levels did not decay to the reference background level, we estimated the full-decay time after cooking using Eq. (2):

$$T_{FD} = \frac{-ln\left(\frac{C_{in}(ref) - C_{in}(bg)}{C_{in}(t_e) - C_{in}(bg)}\right)}{k_t} + t_e - 16 \tag{2}$$

where T_{FD} is the full-decay time after cooking, min; $C_{in}(ref)$ is the $PM_{2.5}$ reference background level, μg/m^3; t_e is the end time of $PM_{2.5}$ measurement; $C_{in}(t_e)$ is the indoor $PM_{2.5}$ level at time t_e, μg/m^3.

2.4.3. Emission rates

During cooking, the dynamic mass balance model for indoor $PM_{2.5}$ can be expressed as Eq. (3):

$$\frac{dC_{in}(t)}{dt} = p \cdot AER \cdot C_{out}(t) + \frac{S(t)}{V} - k_t \cdot C_{in}(t) \tag{3}$$

where $C_{in}(t)$ and $C_{out}(t)$ are indoor and outdoor $PM_{2.5}$ concentrations at time t, μg/m^3, respectively; p is the penetration factor of $PM_{2.5}$ (unitless), set as 0.97 and 1 when windows were closed and open, respectively [37]; *S(t)* is the $PM_{2.5}$ emission rate from cooking at time *t*, μg/h; V is the volume of the indoor space, m^3; *AER* and k_t are defined as above, h^{-1}.

Assuming the AER, p, and k_t remain constant over the time step Δt, Eq. (3) can be solved as [35, 38]:

$$C_{in}(t) = \frac{p \cdot AER \cdot C_{out}(t)}{k_t} + \frac{S(t)}{k_t \cdot V} + \left(C_{in}(t - \Delta t) - \left(\frac{p \cdot AER \cdot C_{out}(t)}{k_t} + \frac{S(t)}{k_t \cdot V}\right)\right) \cdot e^{-k_t \cdot \Delta t} \quad (4)$$

Thus, *S(t)* can be solved as Eq. (5):

$$S(t) = \frac{C_{in}(t) - \frac{p \cdot AER \cdot C_{out}(t)}{k_t} - \left(C_{in}(t - \Delta t) - \frac{p \cdot AER \cdot C_{out}(t)}{k_t}\right) \cdot e^{-k_t \cdot \Delta t}}{1 - e^{-k_t \cdot \Delta t}} \cdot k_t \cdot V \quad (5)$$

During cooking (Minutes 0–16), the increase in $PM_{2.5}$ concentrations in the bedroom was negligible compared to those in the kitchen and living room based on our measurements. Thus, the cooking-related total $PM_{2.5}$ emission rates can be estimated using averaged $PM_{2.5}$ concentrations and total decay rates in the kitchen and living room. The estimated emission rates for Scenarios 3–7 reflect the net emission rates with the range hood use.

3. Results

3.1. Overview

Fig. 2 shows the profile of 1-min outdoor and indoor (kitchen, living room, and bedroom) $PM_{2.5}$ levels for each experimental scenario and trial. Outdoor $PM_{2.5}$ concentrations were assumed to remain constant during each hour. Despite the differences in magnitudes and time phases, the $PM_{2.5}$ concentration mostly displayed a similar pattern. Specifically, the outdoor levels were relatively stable and low (< 15 μg/m^3). The kitchen and living-room levels were relatively consistent and started to increase 2–4 min after the range was turned on (0–2 min after the steak was added). While peaking 1–7 min after the cooking ended (Table 2) at levels of 200–1400 μg/m^3, the concentrations gradually decayed to the background levels within a wide range of time (ranging from < 1 to > 6 h). In contrast, the variation in bedroom concentrations showed a significant time lag. Notably, in the scenarios with PAC use, no significant increase was observed in the bedroom.

Significant differences can be found in indoor $PM_{2.5}$ concentrations during and after cooking among various scenarios. For instance, keeping the kitchen window open (Scenario 2) substantially reduced the indoor $PM_{2.5}$ levels compared with Scenario 1. Additionally, using a PAC in the kitchen (Scenario 4) resulted in overall lower indoor $PM_{2.5}$ concentrations compared with using it in the living room (Scenario 5) and bedroom (Scenario 6). On the other hand, there were variations between the two trials for some scenarios. For example, the two trials in Scenario 2 exhibited different indoor $PM_{2.5}$ concentrations. The underlying reasons can be the large variations in AERs with the kitchen window open. The contrasts in spatial-temporal variations of cooking-related $PM_{2.5}$ concentrations among different scenarios and between repeated trials were further investigated below.

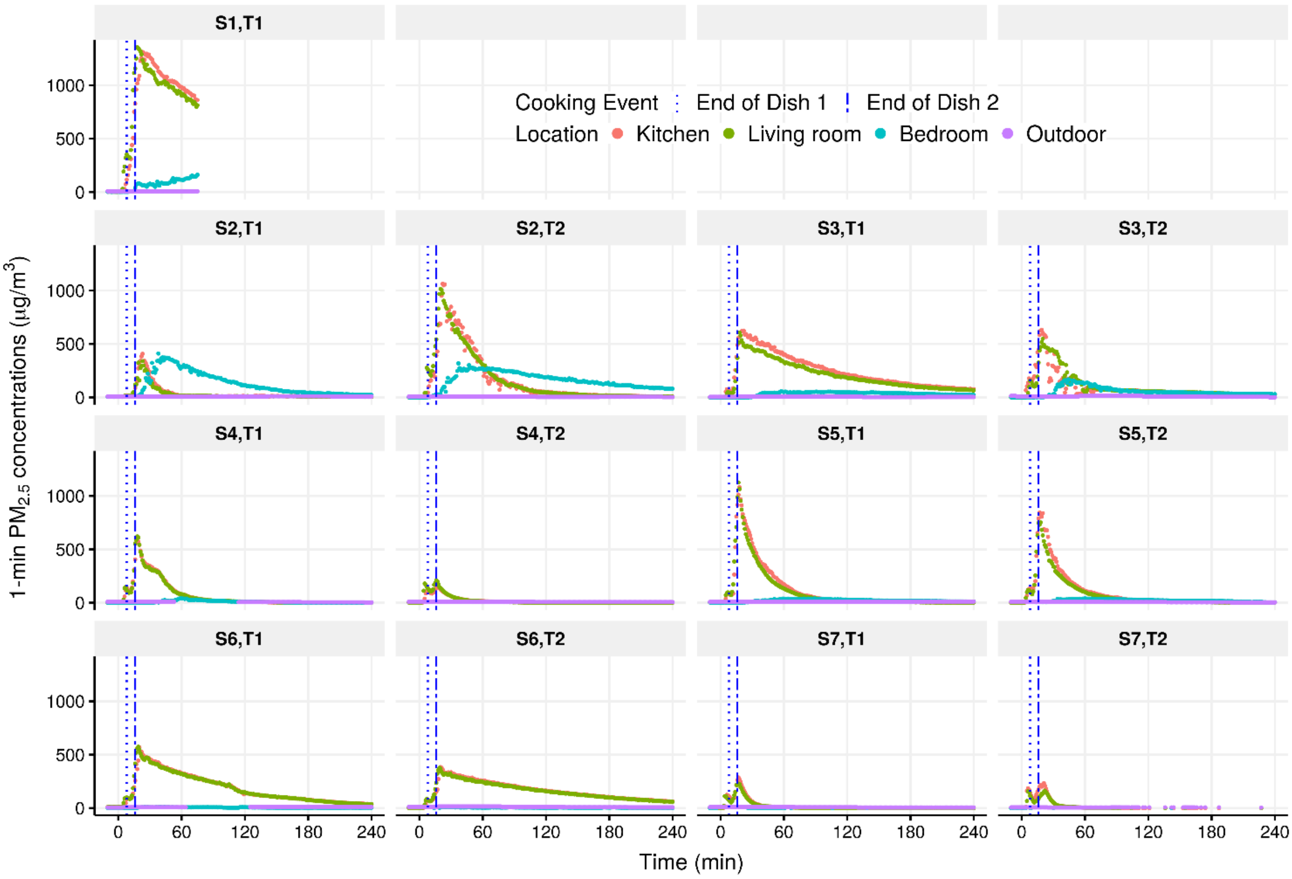

Fig. 2. Time-series plots of 1-min outdoor and indoor (kitchen, living room, and bedroom) $PM_{2.5}$ concentrations for each experimental scenario and trial. *S1–7* represents Scenarios 1–7, and *T1–2* represents *Trial* 1–2.

Table 2. The peak time of indoor $PM_{2.5}$ concentration after cooking.

Scenario	Trial 1 (min)			Trial 2 (min)		
	Kitchen	Living room	Bedroom	Kitchen	Living room	Bedroom
1	7	2	Not available	Not applicable		
2	7	7	22	6	4	21
3	6	2	41	3	4	28
4	2	2	44	1	0	Not measured
5	2	1	73	1	2	44
6	4	3	24	4	3	11
7	1	1	0	5	6	0

3.2. Concentrations

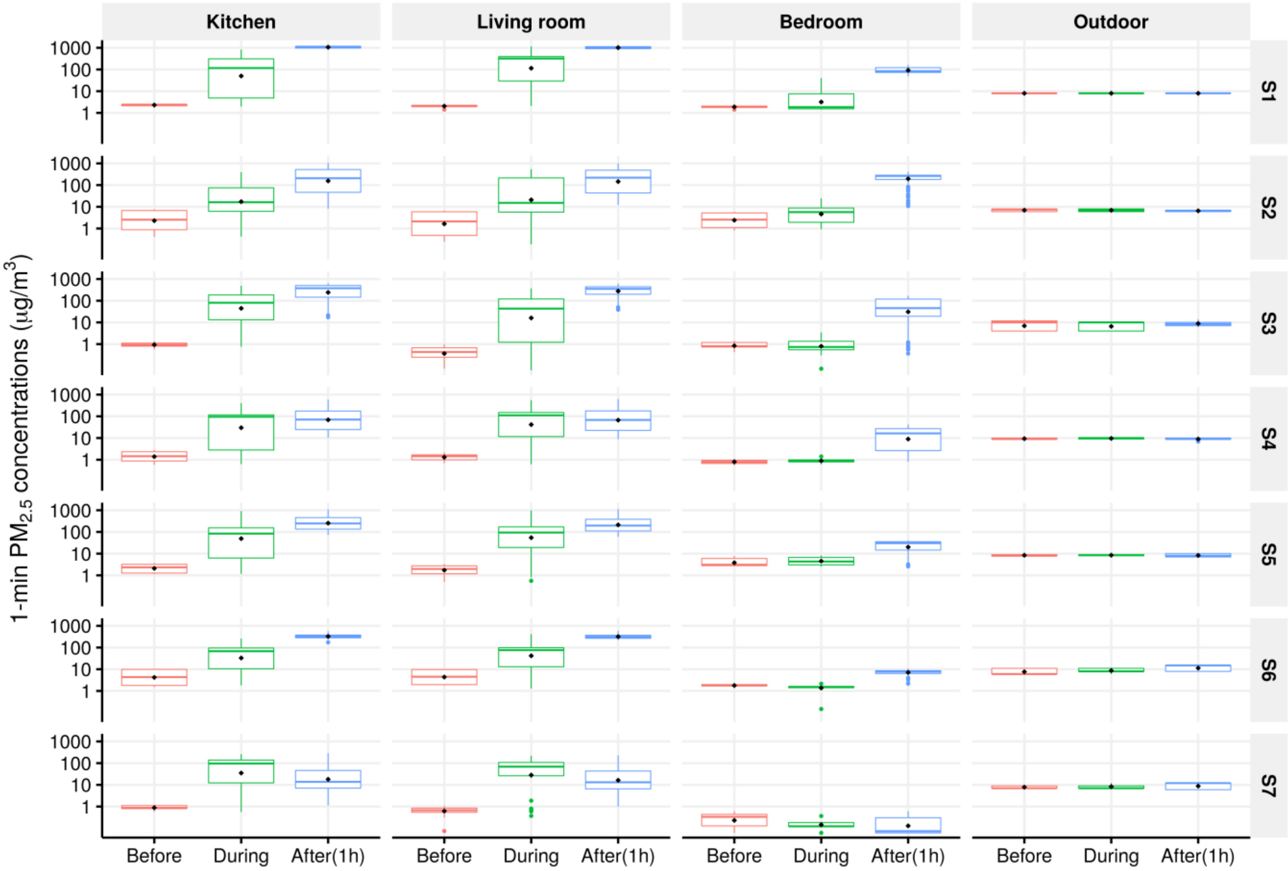

Fig. 3. Pooled boxplot of 1-min indoor (kitchen, living room, and bedroom) and outdoor $PM_{2.5}$ levels 10-min before, during, and 1-h after cooking in each scenario. *S1–7* represents Scenarios 1–7. The scale of the y axis is log10 transformed.

Pooling the data for each scenario, Fig. 3 shows the boxplot of 1-min outdoor and indoor (kitchen, living room, and bedroom) $PM_{2.5}$ levels 10-min before, during, and 1-h after cooking. As mentioned earlier, the outdoor $PM_{2.5}$ concentrations were relatively low during the experimental period, with a mean (standard deviation, SD) of 7.1 (2.9) μg/m^3 and a maximum of 15.0 μg/m^3. Also, there were not large variations in the indoor $PM_{2.5}$ levels before cooking among all the scenarios (range: 0.3–5.8 μg/m^3). Thus, the variations in indoor $PM_{2.5}$ levels mainly reflect the time-varying indoor emission sources and sinks. Overall, the $PM_{2.5}$ levels in the kitchen and living room increased to a high level during and 1 h after cooking compared with the before-cooking concentrations. By comparison, the bedroom $PM_{2.5}$ levels did not change much during cooking, but varied largely 1 h after cooking among different scenarios.

In the scenario with no $PM_{2.5}$ mitigating strategies (Scenario 1), the mean $PM_{2.5}$ levels in the kitchen, living room, and bedroom were nearly equivalent and lower than the outdoor levels before cooking. In contrast, the $PM_{2.5}$ levels during cooking increased enormously in the kitchen and living room (p-value < 0.01) but slightly in the bedroom (p-value = 0.92). Specifically, the mean (SD) $PM_{2.5}$ levels in the kitchen and living room were 217.1 (267.3) and 373.4 (377.8) μg/m^3, respectively, 35.8 and 62.3 times higher than those in the bedroom (5.9 [9.5] μg/m^3). In the first hour after cooking, the mean indoor concentrations were significantly higher than those during cooking (p-value < 0.01), with increases of 3.8, 1.6, and 15.4 times in the kitchen, living room, and bedroom, respectively. Among these three indoor locations, the mean concentrations in the kitchen (~1071 μg/m^3) and living room (~1023 μg/m^3) were comparable, approximately 9 times higher than those in the bedroom (~97 μg/m^3).

Compared with Scenario 1, the window-open scenario (Scenario 2) significantly reduced the $PM_{2.5}$ levels in the kitchen and living room during and after cooking, but increased the bedroom levels after cooking. Specifically, the mean levels in the kitchen during and 1 h after cooking decreased by 157 μg/m^3 (72%) and 761 μg/m^3 (71%), respectively. These reductions were comparable to those in the living room, i.e., 267 μg/m^3 (72%) and 727 μg/m^3 (71%) during and 1-h after cooking, respectively. In contrast, the bedroom levels did not change much (6.9 μg/m^3 versus 5.9 μg/m^3) during cooking, but increased by 140 μg/m^3 (145%) on average 1 h after cooking. Although the bedroom levels were still lower than the kitchen and living-room levels, the relative concentration differences between the first and second floors became smaller than those in Scenario 1, indicating that the cooking-emitted $PM_{2.5}$ diffused faster indoors with the kitchen window open. The AERs in Scenario 2 were much larger than those in Scenario 1; thus, the airflow velocities and pollutant diffusion rates in Scenario 2 were higher as well (see more details of AERs in Section 3.3).

Keeping the range hood on during cooking (Scenario 3) significantly reduced the indoor $PM_{2.5}$ levels during and after cooking, compared with Scenario 1. Specifically, the mean levels in the kitchen and living room during cooking decreased by 81 $\mu g/m^3$ (37%) and 294 $\mu g/m^3$ (79%), respectively. The larger reductions in the living room reflect that the range hood captured a fraction of cooking fumes before they were dispersed to the living room. As the range hood was turned off 1 min after cooking, the reduction in the mean levels in the kitchen and living room 1 h after cooking were comparable (69% versus 68%), similar to Scenario 2. Contrary to Scenario 2, the bedroom levels decreased by 32 $\mu g/m^3$ (33%) 1 h after cooking compared with those in Scenario 1 (p-value < 0.01).

Compared with Scenario 3, using the PAC in the kitchen (Scenario 4) significantly reduced the average kitchen $PM_{2.5}$ levels during and 1 h after cooking by 47 $\mu g/m^3$ (35%) and 200 $\mu g/m^3$ (61%), respectively. Although the living-room levels 1 h after cooking decreased by 195 $\mu g/m^3$ (60%), there was an increase of 35 $\mu g/m^3$ (44%) during cooking. This increase may be partly due to the PAC's impacts on indoor airflows and other varying factors, e.g., AERs. Also, the PAC use reduced the bedroom $PM_{2.5}$ levels by 48 $\mu g/m^3$ (74%) 1 h after cooking (p-value < 0.01). Compared with Scenario 4, using the PAC in the living room (Scenario 5) consistently increased the mean $PM_{2.5}$ levels in the kitchen, living room, and bedroom during and 1 h after cooking by 49–156%. By contrast, using the PAC in the bedroom (Scenario 6) increased the mean kitchen and living-room levels 1 h after cooking by ~155%, and decreased the 1-h-after-cooking bedroom levels by 56%, compared with Scenario 4.

When using the PACs in the kitchen, living room, and bedroom simultaneously (Scenario 7), the kitchen levels during cooking slightly increased by 5% compared with Scenario 4. Except for this minor increase, overall large reductions, ranging 35–99%, were observed for the three locations during and 1 h after cooking compared to Scenario 4.

The statistical description of outdoor and indoor (kitchen, living room, and bedroom) $PM_{2.5}$ levels for each scenario and trial are shown in Appendix Table A2. There were some variations between the two trials in each scenario. Taking Scenario 2 as an example, the kitchen and living-room levels during and 1 h after cooking for Trial 1 were 79–89% lower than those for Trial 2, reflecting the large variation in AERs while the kitchen window was open. Because there can be variations in some underlying factors that impacted the indoor $PM_{2.5}$ levels, such as AERs, we further determined the decay-related parameters and $PM_{2.5}$ emission rates, as shown below.

3.3. k_t and T_{FD}

Table 3 shows the $PM_{2.5}$ total decay rate (k_t) and full-decay time (T_{FD}) for each location and scenario. No eligible measurements were available to estimate k_t for the bedroom in Scenarios 1 and 6–7. Mean (SD) k_t for the kitchen, ranging from 0.58 (0.02) to 6.62 (0.34) h^{-1}, was generally comparable to that of the living room (relative difference < 20%), but 1–5 times larger than that of the bedroom. Because the bedroom door was closed during the experiments, the airflow between the living room and bedroom was mostly blocked, resulting in the relatively large differences in k_t. In contrast, the living room was connected to the kitchen via a large opening; thus, the k_t values for those rooms were relatively similar. k_t in Scenario 1 were 0.58 (0.02) and 0.49 (0.02) h^{-1} for the kitchen and living room, respectively. Among all the intervention scenarios, Scenario 7 (three PACs used), unsurprisingly, resulted in the largest k_t in the kitchen and living room on average (~6 h^{-1}). Scenario 2 (opening kitchen windows) resulted in the second-largest k_t in the kitchen and living room on average (~4 h^{-1}), indicating that such a mitigating strategy could be very effective. In the scenario of using a PAC, placing it closer to the source (i.e., in the kitchen), seemed to lead to a larger reduction in $PM_{2.5}$ levels. Notably, using the PAC in the bedroom had a minimal effect on k_t for the kitchen and living room.

Table 3. The total decay rate and full-decay time of indoor $PM_{2.5}$ concentrations in each scenario.

Scenario	Location	k_t (h^{-1})		T_{FD} (min)	
		Trial 1	Trial 2	Trial 1	Trial 2
1	Kitchen	0.58 (0.02)	NA [a]	543 [d]	NA [a]
1	Living room	0.49 (0.02)	NA [a]	618 [d]	NA [a]
1	Bedroom	NA [b]	NA [a]	>380 [e]	NA [a]
2	Kitchen	6.60 (0.20)	1.85 (0.08)	51 [f]	197 [f]
2	Living room	5.20 (0.15)	1.80 (0.04)	80 [f]	191 [f]
2	Bedroom	1.08 (0.01)	0.41 (0.01)	333 [d]	496 [d]
3	Kitchen	0.62 (0.00)	2.00 (0.12)	438 [d]	295 [d]
3	Living room	0.61 (0.00)	2.36 (0.09)	427 [d]	294 [d]
3	Bedroom	0.45 (0.00)	0.90 (0.02)	380 [d]	337 [d]
4	Kitchen	2.44 (0.10)	3.41 (0.05)	99 [f]	56 [f]
4	Living room	2.25 (0.13)	3.76 (0.07)	104 [f]	50 [f]
4	Bedroom	1.69 (0.04)	NA [c]	96 [f]	NA [c]
5	Kitchen	2.41 (0.04)	2.58 (0.04)	139 [f]	133 [f]
5	Living room	2.78 (0.02)	2.57 (0.03)	135 [f]	122 [f]
5	Bedroom	0.67 (0.01)	0.60 (0.01)	226 [f]	187 [f]
6	Kitchen	0.73 (0.01)	0.49 (0.00)	494 [d]	455 [d]
6	Living room	0.68 (0.01)	0.46 (0.00)	449 [d]	458 [d]
6	Bedroom	NA [b]	NA [b]	0 [f]	0 [f]
7	Kitchen	5.69 (0.25)	6.62 (0.34)	40 [f]	33 [f]
7	Living room	4.79 (0.19)	7.09 (0.37)	39 [f]	32 [f]
7	Bedroom	NA [b]	NA [b]	0 [f]	0 [f]

[a] Not applicable because the trial was not conducted. [b] Not applicable because no eligible periods were found for the fitting. [c] Data were not recorded. [d] Estimated based on Eq. (2). [e] Estimated based on Trial 1 in Scenario 3 since the air exchange rates between these two experiments were comparable; [f] Based on the measured data.

Appendix Table A3 summarizes the AERs and AER/k_t ratio for each scenario, where k_t refers to the average k_t for the kitchen and living room. For all experiments, the overall mean (SD) window-closed AERs were 0.49 (0.37) h^{-1}, ranging from 0.22 (0.11) to 1.24 (0.52) h^{-1}. In contrast, the mean (SD) window-open AERs were 3.23 (2.68) h^{-1}, ranging from 1.33 (1.55) to 5.12 (2.25) h^{-1}, significantly larger than the window-closed ones. With windows closed and no PACs in use, ventilation contributed to 49% (10%) of k_t, indicating that ventilation and particle deposition contributed comparably in total decay under such scenarios. When the windows were open (Scenario 2), the ratio increased to 80% (10%), demonstrating that ventilation was the dominant factor for $PM_{2.5}$ decay. By comparison, the ratio decreased to 10% (4%) in Scenario 4, implying that the kitchen PAC removal acted as the primary role in such scenarios because ventilation and deposition contributed comparably.

The kitchen and living room $PM_{2.5}$ concentrations decayed to the background levels (11 μg/m^3) in Scenarios 2, 4, 5, and 7, and so did the bedroom levels in Scenarios 4–7, within 4 h after cooking. In Scenario 1, T_{FD} was ~ 10 h for the kitchen and living room, and > 6 h for the bedroom. Keeping the kitchen window open effectively reduced T_{FD} to 1–3 h for the kitchen and living room, but less useful for the bedroom (6–8 h). This difference can be explained by two reasons. First, the bedroom AER was not as large as the kitchen AER in Scenario 2 because the bedroom door was closed. Thus, the total decay rate of $PM_{2.5}$ for the bedroom was much smaller than that for the kitchen. Second, the cooking-emitted $PM_{2.5}$ diffused faster indoors with the kitchen window open, as mentioned above, and thus led to higher bedroom concentrations and a longer decay time. In contrast to the other locations, using the PAC in the kitchen resulted in the shortest T_{FD} for the kitchen and living room (1–2 h). Unsurprisingly, T_{FD} was down to 30–40 min for the kitchen and living room, and 0 min for the bedroom in Scenario 7.

3.4. Emission rates

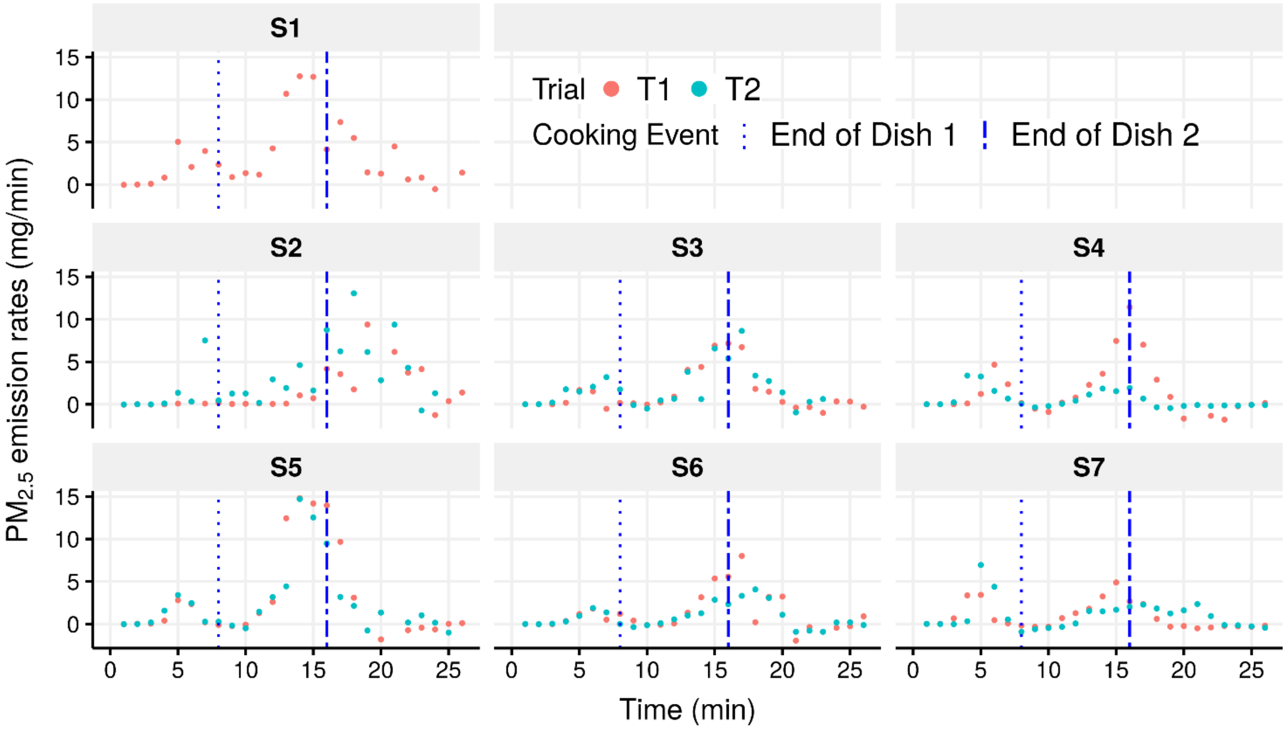

Fig. 4. Time-series plots of 1-min cooking-related $PM_{2.5}$ emission rates for each experimental scenario and trial. *S1–7* represents Scenarios 1–7, and *T1–2* represents Trials 1–2. Dishes 1 and 2 refer to the steak and asparagus, respectively.

Fig. 4 displays the time-varying $PM_{2.5}$ emission rates for each experimental scenario and trial. Generally, the emission rates started to increase from Minute 4 (about 2 min after the steak was added), peaked at Minutes 5–6 and 14–18, and then declined to 0 gradually about 5 min after cooking. The mean (SD) $PM_{2.5}$ emission rates during (Minutes 0–16) and 5 min after cooking (Minutes 17–21) without the kitchen range hood in use (Scenarios 1–2) were 2.3 (3.4) and 5.1 (3.9) mg/min, respectively (see more details in Appendix Table A4). In contrast, the corresponding emission rates with the range hood in use (Scenarios 3–7) were 1.9 (3.2) and 1.4 (3.0) mg/min, respectively. Comparing the average during-cooking emission rates, the capture efficiency of the range hood was ~17%. The results also reveal that there were continuous emissions that lasted ~5 min after cooking. One potential reason for the after-cooking emissions is that the $PM_{2.5}$ measurement in the kitchen and living room may not reflect the real-time cooking emissions since the monitors were 1–3 m away from the burner. However, based on the time-varying patterns in the $PM_{2.5}$ emission rates and cooking procedure (e.g., the measured emission rate started to increase about 2 min after the steak was added), the time lag should not be as long as 5 min. On the other hand, the after-cooking emissions may come from the food residuals in the hot pan.

4. Discussion

4.1. Concentrations

This study illustrates the strikingly high indoor $PM_{2.5}$ levels emitted from pan-frying cooking fumes, independent of fuel combustion. Under such scenarios, the 1-min mean $PM_{2.5}$ concentrations in the kitchen and living room rose to > 1300 μg/m^3, generally much higher than the ambient levels worldwide. Keeping the room door closed during and after cooking has the potential to block most cooking fumes and sustain the $PM_{2.5}$ levels in that room substantially (e.g., 90% in this study) lower than those in the kitchen. This is consistent with a previous study, which concluded that the position of the internal doors had a strong influence on the air movement [39]. On the other hand, although cooking time can be short (< 1–2 h), the effect of cooking could linger for many hours (> 10 h in this study), potentially leading to considerably excess $PM_{2.5}$ exposures for occupants.

4.2. Emission rates

Previous studies have assumed a constant $PM_{2.5}$ emission rate during the cooking process [13, 19].

However, this study revealed large temporal variations in $PM_{2.5}$ emission rates during the pan-frying cooking events. Hence, assuming a constant emission rate in place of a more appropriate nonlinear $PM_{2.5}$ increasing curve could lead to a large bias. The approach of using a more discreet time step (i.e., 1 min), as in the current study, will also likely yield more accurate estimates.

This study found comparable $PM_{2.5}$ emissions during and within several minutes after cooking. Therefore, it is meaningful to take some measures to reduce such emissions not only during but after cooking. In the present study, we turned off the range hood after we removed the dish out of the pan, about 1 min after cooking ended, due to the noise issue, which did not reduce the after-cooking emissions. Despite the noise, it may be beneficial to keep the range hood on, covering the pan, removing the pan from the burner, or cleaning the pan immediately after cooking.

In this study, we established a standard operating procedure for cooking, aiming to control the variations in $PM_{2.5}$ emission rates across different trials. However, the results suggested that it is challenging to control the emissions from pan-frying scenarios. This finding is also supported by a previous study with three trials for each cooking scenario [13]. The variation in underlying factors specific to a food item (e.g., the fat content and shape of the food materials) is difficult to control, even if the food weight and pan temperature are well managed. With such inevitable variability present, directly comparing the emission rates with and without the range hood may not be the best way to determine range hood effectiveness. A previous study estimated the capture efficiency of range hoods by utilizing a CO_2-based approach from fuel combustion [23], but this cannot be used for electric ranges. A possible way to determine the range hood efficacy with electric ranges is to measure the net emission rates (mg/min) based on indoor $PM_{2.5}$, as presented in the present paper, and the exhaust rates (mg/min) based on the $PM_{2.5}$ in the exhaust air and the flow rates. The sum of these two parts can make up the total emission rate, and the proportion of the exhaust rate to the total emission rate can be deemed the range hood efficacy. In this way, the variability in $PM_{2.5}$ emission rates can be assessed. However, the approach is not applicable in the current study since we did not directly measure the range hood exhaust rates.

4.3. Intervention strategies

This study illustrated that three different intervention strategies could result in meaningful reductions in indoor $PM_{2.5}$ levels despite the difference in magnitude. Opening kitchen windows can be a very cost-effective way to reduce the overall indoor $PM_{2.5}$ levels, taking Trial 1 of Scenario 2 as an example. However, the effects can be less significant when the window-open AERs are smaller due to the meteorological variations (Trial 2 of Scenario 2). Based on a recent review study [40], the residential window-open AERs varied largely with housing stock features, climate, weather, and occupancy. The reported mean AERs were ~0.5 h^{-1} in the lower end and ~4 h^{-1} in the higher end [40]. Generally, the window-open AERs were larger for single-family houses than apartments, dwellings with earlier construction years and more windows/doors, and scenarios with larger outdoor wind speeds or indoor-outdoor temperature differences [40]. The two window-open examples in the present study represent scenarios with medium-to-large window-open AERs. On the other hand, this strategy might substantially increase the bedroom $PM_{2.5}$ levels, as illustrated above. If occupants spend most of their time in the bedroom, their time-weighted exposure may be elevated compared to a window-closed scenario. The present study was conducted in Seattle of Northwest US, where the ambient $PM_{2.5}$ levels are generally lower than 20 μg/m^3 except for certain periods, such as wildfire episodes [28]. Thus, introducing ambient air to dilute indoor pollutants during and after cooking is generally effective.

Nevertheless, this strategy may not apply to regions or scenarios with high ambient $PM_{2.5}$ levels [41, 42] or scenarios where keeping windows or doors open is physically infeasible.

In contrast, PAC use during and after cooking is more flexible, although it comes with the cost of the unit. This study found that placement of the PAC closer to the PM source might improve overall efficacy in reducing indoor $PM_{2.5}$. In other words, placing it in the kitchen might be more effective than in other rooms. Herein, the efficacy refers to the reduction of indoor $PM_{2.5}$ levels. As for time-weighted exposure, placing the PAC closer to occupants should result in lower exposure, but this requires frequently moving the PAC. An alternative is to use multiple PACs, as illustrated in Scenario 7 of this study, when the excess cost is not a concern.

With proper power and airflow, the kitchen range hood should considerably mitigate cooking-related emissions as it is usually close to the source [21-24]. Based on a previous study [24], the capture efficiency of a range hood that has the same nominal airflow (90 liters/s) and sound level (6 sones) was ~20% with the use of the front burner, consistent with our results (~17%). The efficiency can be higher with the back burner use and higher airflow range hoods [24]. However, the large noise (~70 dB) during use remains a common issue that prevents some people from using it for a long time.

This study does not favor one intervention strategy over any other, but provides a sense of the magnitude of the reduction in indoor $PM_{2.5}$ levels and related full-decay time that may be achieved by utilizing one or more strategies. All three strategies evaluated here can produce meaningful reductions in indoor $PM_{2.5}$ levels generated by cooking, based on results from this study and previous studies. The choice that individuals make for a suitable intervention strategy involves financial and behavioral factors. For instance, if a range hood in a home is not very effective, it may be more practical to use a PAC or open windows during and after cooking than replace the range hood with a better one. Some high-end range hoods can cost several thousand US dollars, while a PAC costs only a few hundred US dollars. On the other hand, people may utilize both a high-end range hood and PACs in various indoor locations if the cost is not a concern.

4.4. Limitations

First, we did not fully control the variations in $PM_{2.5}$ emission rates from pan-frying cooking events across different trials, although we followed the same standard operating procedure. As mentioned above, the variation in underlying factors specific to a food item (e.g., the fat content and shape of the food materials) is difficult to control, even if the food weight and pan temperature are well managed. Future studies will benefit from a more controllable emission source. Second, we did not include the second floor when estimating the total $PM_{2.5}$ emission rates from cooking. It makes negligible impacts on the during-cooking emission rate estimates since the during-cooking bedroom levels did not increase significantly compared with the before-cooking levels. However, the after-cooking emission rates (Minutes 17–21) could be underestimated, especially in Scenario 2, where obvious bedroom-level elevation occurred. Nonetheless, such underestimates do not change our conclusion that it is meaningful to take some measures to reduce such emissions not only during but after cooking. Third, in the window-open scenario, we only consider the kitchen window. Nevertheless, occupants may open the windows elsewhere and the main building door as well, which would alter the indoor airflows and, as a result, spatial distributions of indoor air pollutants. Finally, the quantitative results obtained in the current study are specific to the selected cooking scenarios and the apartment where the experiments were conducted, despite the findings supporting expected results based on previous studies. Future studies with more housing units and cooking scenarios (i.e., different combinations of cooking methods, food items and weights, oil usage, and cooking time [13]), using an approach similar to that used in the present study, are warranted.

Despite the limitations, to our knowledge, the present study is the first to examine the dynamic process of cooking $PM_{2.5}$ emission rates, and the first to compare the efficacy of various strategies for mitigating cooking-related $PM_{2.5}$ in US residences.

5. Conclusions

This study reveals the large spatial-temporal variations in indoor $PM_{2.5}$ levels and emission rates during and after pan-frying cooking events. In this study, the 1-min mean $PM_{2.5}$ concentrations in the kitchen and living room peaked 1–7 min after cooking at levels of 200–1400 $\mu g/m^3$. Keeping the room door closed during and after cooking has the potential to achieve substantially lower $PM_{2.5}$ levels in that room (e.g., ~90% in this study) than those in the kitchen. Without intervention strategies, the effect of cooking lingered for more than 10 h, although the cooking time was short (~17 min). Large variations were found in the 1-min $PM_{2.5}$ emission rates from such pan-frying events, with means of 2.3 and 5.1 mg/min during and 5 min after cooking, respectively. The results indicate that the $PM_{2.5}$ emission rates during cooking cannot be taken as a constant. Also, proper measures are needed to reduce the after-cooking emissions from the food residuals in the hot pan. Compared with no-intervention scenarios, the mean $PM_{2.5}$ concentrations during and 1 h after cooking in the kitchen and living room reduced by ~70% with the kitchen window open, but the corresponding bedroom levels 1 h after cooking increased by ~150%. In contrast, the $PM_{2.5}$ concentrations in the kitchen, living room, and bedroom decreased by 30–80% with a range hood used during cooking. Utilizing a PAC in the kitchen along with the range hood on during cooking further reduced the average $PM_{2.5}$ concentrations in the kitchen, living room, and bedroom 1 h after cooking by an additional 60–70%. In comparison, utilizing the PAC in the living room or bedroom increased the mean kitchen and living-room levels 1 h after cooking by 50–160%. The findings provide useful information on how to reduce cooking-related $PM_{2.5}$ exposure via readily accessible intervention strategies.

Declaration of competing interest

The authors declare they have no actual or potential competing financial interests.

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Appendix

The Appendix is provided.

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Appendix

Residential cooking-related $PM_{2.5}$: Spatial-temporal variations under various intervention scenarios

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Cooking protocol

The standard operating procedures of pan-frying steak and asparagus are as follows:

1) Days (-2)–(-1): purchase the same type of steak and asparagus at a local grocer 1–2 days before each experiment;
2) Days (-2)–(-1): store the steak and asparagus in a fridge (above 0 °C);
3) Minute (-30): on an experimental day, rinse and drain the asparagus about 30 min before the electric range on;
4) Minute (-10): season the steak with black pepper, salt, and sunflower oil (~10 g) about 10 min before the electric range on;
5) Minutes 0–1: heat the pan for 2 min at the temperature *level 9*;
6) Minute 2: add the steak to the pan, and fry one side (Side A) for 1 min at the temperature *level 9*;
7) Minute 3: flip the steak, fry the other side (Side B) for 1 min at the temperature *level 9*;
8) Minutes 4–5: adjust the temperature to *level 5*, add ~56 g butter to the pan, fry Side A for 2 min at the temperature *level 5*;
9) Minutes 6–7: flip the steak, fry Side B for 2 min at the temperature *level 5*;
10) Minute 8: remove the steak out of the pan;
11) Minute 8: adjust the temperature to *level 8*, heat the pan for 30 s;
12) Minute 8: add the prepared asparagus to the pan;
13) Minutes 9–15: fry the asparagus for 7 min while flipping it at 1 min interval;
14) Minute 16: add salt, and fry the asparagus for 1 min;
15) Minute 17: turn off the range (adjust the temperature to *level OFF*);
16) Minute 17: remove the asparagus out of the pan;
17) Minutes 18–77: leave the uncovered pan on the same burner to cool for 1 h;
18) Minutes 78–85: clean the pan.

Air exchange rate

With an occupant in the first story of the apartment, the dynamic mass balance model for the first-story CO_2 concentrations can be expressed as [1]:

$$\frac{dC_{in}(t)}{dt} = AER \cdot \left(C_{out}(t) - C_{in}(t)\right) + \frac{\mathrm{FR}}{V} \tag{A1}$$

where $C_{in}(t)$ and $C_{out}(t)$ are indoor and outdoor CO_2 levels at time t, ppm, respectively; *AER* is the air exchange rate, h^{-1}; FR is the human emission rate of CO_2, cm3/h; V is the volume of the first story, m3.

The change of CO_2 concentration (ΔC) during the time interval (Δt) can be described with a differential equation as:

$$\Delta C = C_{in}(t + \Delta t) - C_{in}(t) = \left(AER \cdot \left(C_{out}(t + \Delta t) - C_{in}(t + \Delta t)\right) + \frac{\mathrm{FR}}{V}\right) \cdot \Delta t \quad \text{(A2)}$$

Thus, the AER can be calculated as:

$$AER = \frac{C_{in}(t + \Delta t) - C_{in}(t)}{\Delta t} - \frac{\mathrm{FR}}{V} / \left(C_{out}(t + \Delta t) - C_{in}(t + \Delta t)\right) \quad \text{(A3)}$$

According to the ASHRAE Handbook Fundamentals [2], an empirical equation for human CO_2 emission rate is:

$$FR = RQ \frac{0.00276 \times 0.202 H^{0.725} W^{0.425}}{(0.23RQ + 0.77)} M \times 1000/3600 \quad \text{(A3)}$$

where *RQ* is respiratory quotient (dimensionless); *H* and *W* are human height (m) and weight (kg), respectively; *M* is the human metabolic rate (met).

Based on data on human nutrition in the US, specifically the ratios of fat, protein, and carbohydrate intake, *RQ* equals about 0.85 [3]. M was set as 1.3 met based on the activity level [3]. Outdoor CO_2 concentrations were relatively stable during the experiments. Based on our measurements, C_{out} was about 450 ppm.

The AERs were then calculated based on the CO_2 measurements made during periods meeting the following criteria: 1) no altered conditions of windows and doors; 2) a time window of at least 30 min. For those selected periods without human occupancy, FR was set as 0.

Figures

Profile　　　　Inner structure

Fig. A1. Profile and structure of the $PM_{2.5}$ monitor used in this study.

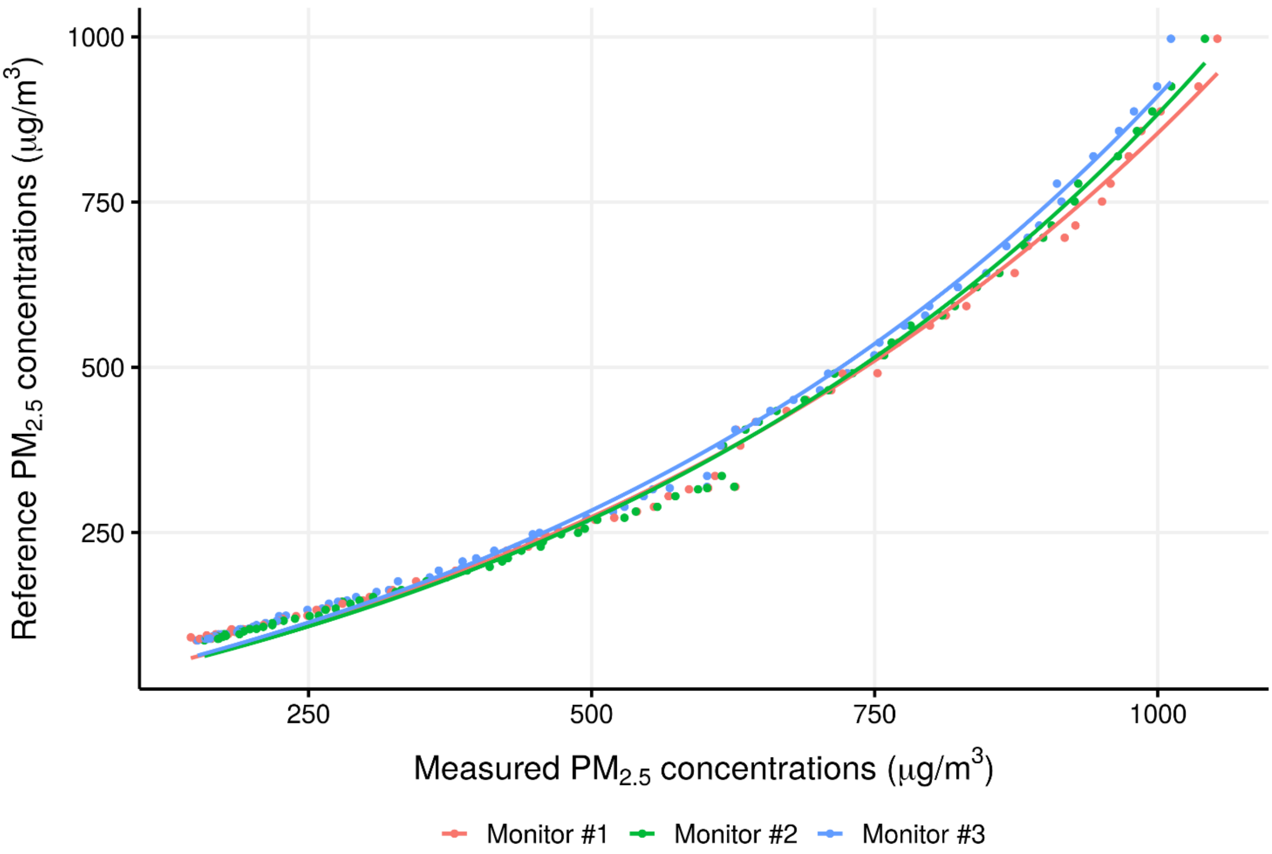

Fig. A2. Calibration curves of the $PM_{2.5}$ monitors used in this study.

Linear models are commonly used for low-cost sensor calibration. However, in the present study, the $PM_{2.5}$ concentrations were so high (up to 1000 µg/m^3) that a linear model does not work well for the high-concentration range. We evaluated the performance of both linear and exponential calibration models for the dataset. The summary of the model evaluations is shown in Appendix Table A1. Although the linear models have reasonable performance with R^2 of 0.96 and NRMSE of 24–26%, the exponential models are apparently much better with NRMSE of 6–7% and much smaller AICs and BICs. Thus, we applied the exponential calibration models to the main experimental datasets. Note that the model selection is specific to this study which covered a wide range of indoor $PM_{2.5}$ concentrations. In other scenarios with lower concentrations, a linear model or other models may be sufficient or work better.

Tables

Table A1. Calibration model evaluation summary for the $PM_{2.5}$ monitors.

Model	**Monitor ID**	**RMSE ($\mu g/m^3$)**	**NRMSE (%)**	**R^2**	**AIC**	**BIC**
Linear	Monitor #1	75	24	0.96	921	926
Linear	Monitor #2	79	26	0.96	941	946
Linear	Monitor #3	75	24	0.96	933	938
Exponential (used in this study)	Monitor #1	21	7	*NA*	717	724
Exponential (used in this study)	Monitor #2	19	6	*NA*	714	721
Exponential (used in this study)	Monitor #3	19	6	*NA*	711	718

Definition of abbreviations:: RMSE = root mean square error; NRMSE = normalized root mean square error [4]; AIC = Akaike information criterion; BIC = Bayesian information criterion; NA = not available.

Table A2. Descriptive summary of 1-min $PM_{2.5}$ levels and environmental conditions before, during, and after cooking for each experimental scenario.

Scenario	Trial	Location	Period	$PM_{2.5}$ (μg/m^3)			
				Min	Median (IQR)	Mean (SD)	Max
1	1	KC	Before	1.9	2.4 (0.4)	2.3 (0.2)	2.6
1	1	KC	During	2	116.4 (304.1)	217.1 (267.3)	828.1
1	1	KC	After (1h)	858.1	1041.0 (209.5)	1071.0 (129.5)	1311.2
1	1	LR	Before	1.4	2.0 (0.3)	2.1 (0.3)	2.6
1	1	LR	During	2.1	320.3 (364.4)	373.4 (377.8)	1156.8
1	1	LR	After (1h)	797.5	1007.6 (215.5)	1022.7 (146.0)	1354.7
1	1	BR	Before	1.4	1.9 (0.3)	1.9 (0.2)	2.3
1	1	BR	During	1.4	1.8 (6.0)	5.9 (9.5)	40.1
1	1	BR	After (1h)	48.8	84.1 (48.2)	96.5 (30.3)	161.2
1	1	OD	Before	8	8.0 (0.0)	8.0 (0.0)	8
1	1	OD	During	8	8.0 (0.0)	8.0 (0.0)	8
1	1	OD	After (1h)	8	8.0 (0.0)	8.0 (0.0)	8
2	Pooled	KC	Before	0.4	3.5 (5.8)	3.8 (3.1)	7.5
2	Pooled	KC	During	0.4	16.2 (71.9)	60.0 (92.2)	392.1
2	Pooled	KC	After (1h)	8.2	207.3 (474.0)	309.7 (286.1)	1063.8
2	Pooled	LR	Before	0.2	3.1 (5.4)	3.2 (2.8)	6.5
2	Pooled	LR	During	0.2	15.2 (208.5)	106.2 (152.3)	543.4
2	Pooled	LR	After (1h)	12.4	220.0 (440.9)	296.1 (281.8)	1014.6
2	Pooled	BR	Before	0.8	3.0 (4.1)	3.2 (2.2)	5.9
2	Pooled	BR	During	0.9	5.7 (6.8)	6.9 (6.1)	24.4
2	Pooled	BR	After (1h)	10.8	264.2 (103.3)	236.0 (97.6)	410.7
2	Pooled	OD	Before	6	7.5 (2.0)	7.0 (1.0)	8
2	Pooled	OD	During	6	7.0 (2.0)	7.0 (1.0)	8
2	Pooled	OD	After (1h)	6	6.5 (1.0)	6.5 (0.6)	8
2	1	KC	Before	5.8	6.7 (0.6)	6.7 (0.5)	7.5
2	1	KC	During	5.7	15.5 (11.0)	17.6 (19.8)	89.1
2	1	KC	After (1h)	8.2	46.2 (150.1)	106.6 (116.4)	407.6
2	1	LR	Before	5.5	5.9 (0.5)	6.0 (0.4)	6.5
2	1	LR	During	4.8	13.8 (9.3)	21.2 (28.2)	118
2	1	LR	After (1h)	12.4	43.0 (107.1)	84.2 (93.1)	338.9
2	1	BR	Before	4.4	5.3 (0.5)	5.3 (0.5)	5.9
2	1	BR	During	5.3	6.4 (2.3)	7.1 (2.0)	11.4
2	1	BR	After (1h)	10.8	284.8 (114.1)	254.0 (110.0)	410.7
2	1	OD	Before	8	8.0 (0.0)	8.0 (0.0)	8
2	1	OD	During	8	8.0 (0.0)	8.0 (0.0)	8
2	1	OD	After (1h)	7	7.0 (0.0)	7.1 (0.3)	8
2	2	KC	Before	0.4	0.9 (0.2)	0.8 (0.2)	1.1
2	2	KC	During	0.4	45.0 (187.6)	102.5 (115.4)	392.1
2	2	KC	After (1h)	126.3	523.4 (431.6)	512.9 (260.1)	1063.8
2	2	LR	Before	0.2	0.4 (0.2)	0.5 (0.2)	0.8
2	2	LR	During	0.2	217.4 (275.6)	191.2 (178.0)	543.4

Scenario	Trial	Location	Period	PM$_{2.5}$ (μg/m^3)			
				Min	Median (IQR)	Mean (SD)	Max
2	2	LR	After (1h)	162.4	488.3 (377.3)	508.1 (245.2)	1014.6
2	2	BR	Before	0.8	1.1 (0.3)	1.1 (0.2)	1.5
2	2	BR	During	0.9	1.7 (9.1)	6.8 (8.5)	24.4
2	2	BR	After (1h)	19.4	260.8 (89.9)	218.1 (80.3)	318.9
2	2	OD	Before	6	6.0 (0.0)	6.1 (0.3)	7
2	2	OD	During	6	6.0 (0.0)	6.0 (0.0)	6
2	2	OD	After (1h)	6	6.0 (0.0)	6.0 (0.0)	6
3	Pooled	KC	Before	0.6	0.9 (0.3)	1.0 (0.2)	1.3
3	Pooled	KC	During	0.8	80.9 (167.1)	136.2 (140.4)	490.9
3	Pooled	KC	After (1h)	17.4	376.4 (355.9)	330.5 (198.2)	632.2
3	Pooled	LR	Before	0.1	0.4 (0.4)	0.4 (0.3)	1
3	Pooled	LR	During	0.1	43.3 (119.2)	79.7 (94.4)	368.9
3	Pooled	LR	After (1h)	38.6	351.9 (241.0)	323.5 (145.7)	606.8
3	Pooled	BR	Before	0.4	0.8 (0.5)	0.9 (0.3)	1.4
3	Pooled	BR	During	0.1	0.7 (0.8)	1.0 (0.7)	3.5
3	Pooled	BR	After (1h)	0.4	45.4 (99.8)	64.3 (52.9)	168.6
3	Pooled	OD	Before	4	10.0 (8.0)	8.1 (4.3)	14
3	Pooled	OD	During	4	10.0 (6.0)	7.2 (2.9)	10
3	Pooled	OD	After (1h)	6	8.5 (3.0)	9.2 (2.6)	14
3	1	KC	Before	0.6	0.8 (0.2)	0.8 (0.2)	1.1
3	1	KC	During	0.8	59.5 (80.7)	106.6 (141.8)	490.9
3	1	KC	After (1h)	338.5	486.0 (145.3)	472.2 (83.3)	624.1
3	1	LR	Before	0.1	0.2 (0.1)	0.2 (0.1)	0.4
3	1	LR	During	0.1	39.0 (49.9)	68.2 (101.0)	368.9
3	1	LR	After (1h)	287.6	389.7 (118.6)	399.2 (76.3)	606.8
3	1	BR	Before	0.4	0.7 (0.2)	0.6 (0.2)	0.8
3	1	BR	During	0.1	0.5 (0.2)	0.5 (0.2)	0.7
3	1	BR	After (1h)	0.4	41.6 (38.7)	31.0 (19.9)	54.7
3	1	OD	Before	4	4.0 (0.0)	4.0 (0.0)	4
3	1	OD	During	4	4.0 (0.0)	4.4 (1.0)	7
3	1	OD	After (1h)	6	7.0 (0.0)	7.0 (0.1)	7
3	2	KC	Before	0.9	1.1 (0.3)	1.1 (0.2)	1.3
3	2	KC	During	1.2	160.1 (132.2)	165.7 (136.7)	444.1
3	2	KC	After (1h)	17.4	144.4 (179.0)	188.7 (177.2)	632.2
3	2	LR	Before	0.3	0.7 (0.2)	0.6 (0.2)	1
3	2	LR	During	0.4	100.7 (130.7)	91.1 (89.0)	326.2
3	2	LR	After (1h)	38.6	198.2 (332.3)	247.8 (159.3)	548
3	2	BR	Before	0.7	1.2 (0.3)	1.2 (0.2)	1.4
3	2	BR	During	0.7	1.3 (0.2)	1.5 (0.7)	3.5
3	2	BR	After (1h)	1.6	119.8 (91.1)	97.6 (54.7)	168.6
3	2	OD	Before	10	12.0 (4.0)	12.0 (2.0)	14
3	2	OD	During	10	10.0 (0.0)	10.0 (0.0)	10
3	2	OD	After (1h)	10	10.0 (4.0)	11.4 (1.9)	14
4	Pooled	KC	Before	0.6	1.5 (1.5)	1.6 (0.8)	2.8

Scenario	Trial	Location	Period	PM2.5 (μg/m³)			
				Min	Median (IQR)	Mean (SD)	Max
4	Pooled	KC	During	0.6	95.3 (113.1)	88.8 (88.7)	406
4	Pooled	KC	After (1h)	10.3	70.8 (150.4)	130.1 (143.8)	579.2
4	Pooled	LR	Before	0.7	1.5 (0.7)	1.4 (0.4)	2.2
4	Pooled	LR	During	0.6	111.2 (136.1)	114.5 (107.5)	552.9
4	Pooled	LR	After (1h)	8.8	68.0 (155.5)	128.6 (144.0)	620.4
4	Pooled	BR	Before	0.6	0.8 (0.3)	0.8 (0.2)	1.1
4	Pooled	BR	During	0.6	0.9 (0.2)	0.9 (0.2)	1.4
4	Pooled	BR	After (1h)	0.8	16.4 (24.3)	16.7 (13.7)	41.5
4	Pooled	OD	Before	9	9.0 (1.0)	9.4 (0.5)	10
4	Pooled	OD	During	9	10.0 (1.0)	9.6 (0.5)	10
4	Pooled	OD	After (1h)	7	9.0 (1.0)	9.0 (1.2)	10
4	1	KC	Before	0.6	0.9 (0.3)	0.9 (0.2)	1.2
4	1	KC	During	0.6	101.1 (138.0)	107.6 (114.4)	406
4	1	KC	After (1h)	39.5	177.2 (254.2)	218.7 (155.8)	579.2
4	1	LR	Before	0.7	1.0 (0.5)	1.0 (0.3)	1.4
4	1	LR	During	0.6	97.3 (132.3)	117.8 (138.3)	552.9
4	1	LR	After (1h)	37.6	173.5 (231.5)	214.0 (158.1)	620.4
4	1	BR	Before	0.6	0.8 (0.3)	0.8 (0.2)	1.1
4	1	BR	During	0.6	0.9 (0.2)	0.9 (0.2)	1.4
4	1	BR	After (1h)	0.8	16.4 (24.3)	16.7 (13.7)	41.5
4	1	OD	Before	9	10.0 (1.0)	9.6 (0.5)	10
4	1	OD	During	10	10.0 (0.0)	10.0 (0.0)	10
4	1	OD	After (1h)	10	10.0 (0.0)	10.0 (0.0)	10
4	2	KC	Before	1.8	2.3 (0.4)	2.3 (0.3)	2.8
4	2	KC	During	1.6	88.7 (94.8)	70.0 (49.0)	138.9
4	2	KC	After (1h)	10.3	24.4 (39.6)	41.4 (38.0)	149.3
4	2	LR	Before	1.5	1.7 (0.3)	1.7 (0.2)	2.2
4	2	LR	During	1.5	122.0 (60.3)	111.3 (68.4)	208
4	2	LR	After (1h)	8.8	22.1 (42.7)	43.1 (44.6)	199.3
4	2	OD	Before	9	9.0 (0.0)	9.0 (0.0)	9
4	2	OD	During	9	9.0 (0.0)	9.0 (0.0)	9
4	2	OD	After (1h)	7	9.0 (2.0)	8.1 (1.0)	9
5	Pooled	KC	Before	1.1	2.4 (2.0)	2.3 (1.0)	3.7
5	Pooled	KC	During	1.2	84.1 (148.0)	182.9 (255.4)	915.7
5	Pooled	KC	After (1h)	72.5	246.2 (321.3)	333.6 (249.1)	1082.8
5	Pooled	LR	Before	0.5	2.0 (1.5)	2.0 (0.9)	3.3
5	Pooled	LR	During	0.6	93.9 (148.8)	191.4 (255.5)	987.8
5	Pooled	LR	After (1h)	59.6	196.1 (271.5)	283.1 (230.6)	1125.2
5	Pooled	BR	Before	2.6	3.1 (3.4)	4.2 (2.1)	7.8
5	Pooled	BR	During	2.5	4.4 (3.6)	4.9 (2.0)	8.3
5	Pooled	BR	After (1h)	2.6	30.4 (20.8)	24.9 (12.3)	40.6
5	Pooled	OD	Before	8	8.0 (1.0)	8.4 (0.5)	9
5	Pooled	OD	During	8	8.5 (1.0)	8.5 (0.5)	9
5	Pooled	OD	After (1h)	7	8.0 (3.0)	8.4 (1.5)	10

Scenario	Trial	Location	Period	PM$_{2.5}$ (μg/m^3)			
				Min	Median (IQR)	Mean (SD)	Max
5	1	KC	Before	2.7	3.3 (0.7)	3.2 (0.4)	3.7
5	1	KC	During	2.5	78.6 (85.1)	183.9 (285.4)	915.7
5	1	KC	After (1h)	84.9	300.2 (342.0)	375.8 (263.7)	1082.8
5	1	LR	Before	1.9	2.7 (0.5)	2.7 (0.4)	3.3
5	1	LR	During	2	90.5 (157.8)	203.7 (289.4)	987.8
5	1	LR	After (1h)	71.5	229.5 (324.5)	329.3 (263.6)	1125.2
5	1	BR	Before	2.6	2.9 (0.4)	3.0 (0.3)	3.5
5	1	BR	During	2.5	3.0 (0.2)	3.1 (0.4)	3.8
5	1	BR	After (1h)	2.6	22.9 (22.3)	22.2 (12.2)	38.2
5	1	OD	Before	8	8.0 (0.0)	8.0 (0.0)	8
5	1	OD	During	8	8.0 (0.0)	8.0 (0.0)	8
5	1	OD	After (1h)	8	10.0 (0.0)	9.8 (0.6)	10
5	2	KC	Before	1.1	1.3 (0.4)	1.4 (0.3)	2
5	2	KC	During	1.2	122.9 (148.1)	181.8 (230.3)	789.6
5	2	KC	After (1h)	72.5	194.8 (300.9)	291.5 (227.9)	844.7
5	2	LR	Before	0.5	1.1 (0.6)	1.2 (0.4)	2
5	2	LR	During	0.6	100.9 (121.8)	179.0 (224.8)	747.5
5	2	LR	After (1h)	59.6	171.9 (216.8)	236.8 (183.0)	751.9
5	2	BR	Before	7.1	7.3 (0.4)	7.4 (0.3)	7.8
5	2	BR	During	4.9	6.7 (1.3)	6.8 (0.9)	8.3
5	2	BR	After (1h)	5	33.6 (18.3)	27.6 (12.0)	40.6
5	2	OD	Before	9	9.0 (0.0)	9.0 (0.0)	9
5	2	OD	During	9	9.0 (0.0)	9.0 (0.0)	9
5	2	OD	After (1h)	7	7.0 (0.0)	7.0 (0.3)	9
6	Pooled	KC	Before	1.5	5.6 (8.0)	5.8 (4.2)	10.5
6	Pooled	KC	During	1.8	67.8 (84.2)	66.2 (60.5)	256.6
6	Pooled	KC	After (1h)	174.3	322.5 (96.3)	334.4 (76.5)	568.3
6	Pooled	LR	Before	1.8	5.6 (7.7)	5.8 (4.0)	10.4
6	Pooled	LR	During	1.3	76.3 (85.3)	87.2 (90.0)	416.1
6	Pooled	LR	After (1h)	221.4	311.4 (104.3)	327.0 (80.9)	574.3
6	Pooled	BR	Before	1.5	1.8 (0.2)	1.8 (0.2)	2.1
6	Pooled	BR	During	0.1	1.5 (0.2)	1.5 (0.4)	2.1
6	Pooled	BR	After (1h)	2.2	7.8 (2.2)	7.4 (1.8)	10.8
6	Pooled	OD	Before	6	6.0 (5.0)	8.0 (2.5)	11
6	Pooled	OD	During	6	8.0 (3.0)	8.9 (1.9)	11
6	Pooled	OD	After (1h)	8	15.0 (7.0)	11.8 (3.5)	15
6	1	KC	Before	9.2	9.8 (0.6)	9.9 (0.4)	10.5
6	1	KC	During	9.2	80.2 (83.4)	76.4 (70.8)	256.6
6	1	KC	After (1h)	285.8	370.9 (109.1)	384.4 (70.6)	568.3
6	1	LR	Before	8.8	9.7 (0.9)	9.7 (0.6)	10.4
6	1	LR	During	8.1	89.0 (82.8)	103.8 (109.2)	416.1
6	1	LR	After (1h)	276.8	364.5 (104.7)	380.1 (76.8)	574.3
6	1	BR	Before	1.5	1.8 (0.2)	1.8 (0.2)	2.1
6	1	BR	During	1.3	1.5 (0.2)	1.6 (0.2)	2.1

Scenario	Trial	Location	Period	PM$_{2.5}$ (μg/m^3)			
				Min	Median (IQR)	Mean (SD)	Max
6	1	BR	After (1h)	2.2	8.2 (1.2)	8.1 (1.3)	10
6	1	OD	Before	6	6.0 (0.0)	6.0 (0.0)	6
6	1	OD	During	6	8.0 (2.0)	7.4 (0.9)	8
6	1	OD	After (1h)	8	8.0 (0.0)	8.0 (0.0)	8
6	2	KC	Before	1.5	1.8 (0.3)	1.8 (0.2)	2
6	2	KC	During	1.8	67.3 (73.7)	56.0 (48.1)	154.5
6	2	KC	After (1h)	174.3	280.8 (60.9)	284.4 (41.7)	383.7
6	2	LR	Before	1.8	1.9 (0.2)	2.0 (0.2)	2.3
6	2	LR	During	1.3	67.5 (73.7)	70.6 (64.7)	235.8
6	2	LR	After (1h)	221.4	265.5 (58.2)	273.8 (39.5)	376.8
6	2	BR	During	0.1	0.1 (0.0)	0.1 (NA)	0.1
6	2	BR	After (1h)	2.3	6.4 (2.6)	6.6 (1.9)	10.8
6	2	OD	Before	11	11.0 (0.0)	11.0 (0.0)	11
6	2	OD	During	11	11.0 (0.0)	11.0 (0.0)	11
6	2	OD	After (1h)	11	15.0 (0.0)	15.0 (0.4)	15
7	Pooled	KC	Before	0.6	0.9 (0.3)	0.9 (0.2)	1.2
7	Pooled	KC	During	0.6	96.4 (126.5)	93.1 (70.5)	262.4
7	Pooled	KC	After (1h)	1.1	13.8 (39.1)	46.5 (69.2)	286.5
7	Pooled	LR	Before	0.1	0.7 (0.3)	0.7 (0.3)	1.1
7	Pooled	LR	During	0.4	68.8 (78.9)	74.9 (58.8)	217.1
7	Pooled	LR	After (1h)	1	13.1 (36.8)	38.1 (52.4)	227.5
7	Pooled	BR	Before	0.1	0.3 (0.3)	0.3 (0.2)	0.6
7	Pooled	BR	During	0.1	0.1 (0.1)	0.2 (0.1)	0.4
7	Pooled	BR	After (1h)	0.1	0.1 (0.2)	0.2 (0.2)	0.6
7	Pooled	OD	Before	7	7.0 (2.0)	7.9 (1.0)	9
7	Pooled	OD	During	7	7.0 (2.0)	8.5 (1.9)	12
7	Pooled	OD	After (1h)	6	12.0 (6.0)	9.2 (2.9)	12
7	1	KC	Before	0.8	1.0 (0.3)	1.0 (0.2)	1.2
7	1	KC	During	0.7	96.4 (101.9)	91.9 (74.5)	262.4
7	1	KC	After (1h)	4.5	14.7 (41.6)	49.0 (70.4)	286.5
7	1	LR	Before	0.5	0.7 (0.2)	0.7 (0.2)	1.1
7	1	LR	During	0.6	86.0 (59.9)	86.7 (65.8)	217.1
7	1	LR	After (1h)	4.4	14.7 (34.4)	41.4 (56.7)	227.5
7	1	BR	Before	0.1	0.1 (0.1)	0.1 (0.1)	0.2
7	1	BR	After (1h)	0.1	0.1 (0.3)	0.2 (0.2)	0.6
7	1	OD	Before	9	9.0 (0.0)	9.0 (0.0)	9
7	1	OD	During	9	9.0 (3.0)	10.2 (1.5)	12
7	1	OD	After (1h)	8	12.0 (0.0)	11.7 (1.1)	12
7	2	KC	Before	0.6	0.8 (0.2)	0.8 (0.2)	1.1
7	2	KC	During	0.6	101.2 (144.0)	94.4 (68.6)	184.6
7	2	KC	After (1h)	1.1	12.1 (35.9)	44.1 (68.5)	233.3
7	2	LR	Before	0.1	0.7 (0.4)	0.7 (0.3)	1.1
7	2	LR	During	0.4	66.6 (88.9)	63.0 (50.2)	156.2
7	2	LR	After (1h)	1	11.6 (36.4)	34.8 (47.9)	162.8

Scenario	Trial	Location	Period	PM$_{2.5}$ (μg/m^3)			
				Min	Median (IQR)	Mean (SD)	Max
7	2	BR	Before	0.1	0.4 (0.2)	0.4 (0.2)	0.6
7	2	BR	During	0.1	0.1 (0.1)	0.2 (0.1)	0.4
7	2	BR	After (1h)	0.1	0.1 (0.0)	0.1 (NA)	0.1
7	2	OD	Before	7	7.0 (0.0)	7.0 (0.0)	7
7	2	OD	During	7	7.0 (0.0)	7.0 (0.0)	7
7	2	OD	After (1h)	6	6.0 (0.0)	6.1 (0.3)	7

Definition of abbreviations: S1–7 = Scenarios 1–7; T1–2 = Trials 1–2. KC = kitchen; LR = living room; BR = bedroom; OD = outdoor; Temp = temperature; RH = relative humidity; IQR = interquartile range; SD = standard deviation.

Table A3. Scenario-trial-specific means (standard deviations) of $PM_{2.5}$ total decay rate and air exchange rate for the first floor.

Scenario	**Trial**	k_t **(h^{-1})**	***AER*** **(h^{-1})**	***AER*/k_t (%)**
1	1	0.53 (0.01)	0.28 (0.12)	52 (23)
2	1	5.90 (0.12)	5.12 (2.25)	87 (38)
2	2	1.83 (0.04)	1.33 (1.55)	73 (85)
3	1	0.62 (0.00)	0.23 (0.16)	37 (25)
3	2	2.18 (0.08)	1.24 (0.52)	57 (24)
4	1	2.34 (0.08)	0.24 (0.07)	10 (3)
4	2	3.58 (0.04)	0.36 (0.14)	10 (4)
5	1	2.59 (0.02)	0.41 (0.18)	16 (7)
5	2	2.58 (0.02)	0.74 (0.08)	29 (3)
6	1	0.70 (0.01)	0.22 (0.11)	31 (15)
6	2	0.48 (0.00)	0.22 (0.13)	46 (27)
7	1	5.24 (0.16)	0.31 (0.13)	6 (2)
7	2	6.86 (0.25)	1.12 (0.15)	16 (2)
Window closed [a]	Pooled	1.11 (0.93)	0.58 (0.57)	49 (10)
Window open (Scenario 2)	Pooled	3.87 (2.88)	3.23 (2.68)	80 (10)

[a] Including Scenarios 1 and 3 where the range hood was turned off 1-min after cooking.

Table A4. Scenario-trial-specific mean (standard deviation) of indoor $PM_{2.5}$ emission rate.

Scenario	**Trial**	**Emission rate (mg/min)**			
		Dish 1 (Minutes 2–8)	**Dish 2 (Minutes 9–16)**	**During (Minutes 0–16)**	**5-min after (Minutes 17–21)**
1	1	2.0 (1.9)	6.0 (5.2)	3.9 (4.4)	4.0 (2.6)
2	Pooled	0.7 (2.0)	1.8 (2.4)	1.2 (2.2)	5.6 (4.4)
2	1	0.1 (0.1)	0.8 (1.4)	0.4 (1.0)	3.7 (4.5)
2	2	1.4 (2.7)	2.8 (2.7)	2.0 (2.7)	7.5 (3.9)
3	Pooled	1.0 (1.1)	2.5 (2.8)	1.7 (2.3)	2.5 (3.1)
3	1	0.4 (0.8)	3.0 (3.1)	1.7 (2.5)	2.0 (2.8)
3	2	1.5 (1.1)	2.1 (2.7)	1.7 (2.1)	3.0 (3.5)
4	Pooled	1.3 (1.6)	1.9 (3.2)	1.5 (2.5)	0.6 (2.7)
4	1	1.2 (1.8)	3.0 (4.3)	2.1 (3.3)	1.3 (3.8)
4	2	1.3 (1.5)	0.8 (0.9)	1.0 (1.2)	-0.1 (0.4)
5	Pooled	1.0 (1.2)	6.5 (6.3)	3.7 (5.3)	0.6 (4.2)
5	1	0.8 (1.2)	7.4 (7.0)	4.0 (6.0)	0.9 (5.6)
5	2	1.2 (1.3)	5.6 (5.9)	3.3 (4.8)	0.3 (3.0)
6	Pooled	0.7 (0.7)	1.5 (1.9)	1.0 (1.5)	2.3 (2.9)
6	1	0.7 (0.7)	2.0 (2.4)	1.3 (1.9)	2.5 (3.8)
6	2	0.6 (0.8)	0.9 (1.2)	0.8 (1.0)	2.1 (2.0)
7	Pooled	1.4 (2.3)	1.2 (1.5)	1.2 (1.8)	1.1 (1.2)
7	1	1.1 (1.6)	1.7 (1.8)	1.4 (1.7)	0.4 (1.2)
7	2	1.6 (2.9)	0.7 (1.1)	1.0 (2.1)	1.9 (0.5)
Range hood off (1–2)	Pooled	1.2 (2.0)	3.2 (4.0)	2.3 (3.4)	5.1 (3.9)
Range hood on (3–7)	Pooled	1.1 (1.4)	2.7 (4.0)	1.9 (3.2)	1.4 (3.0)

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