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Characterization of cooking-related ultrafine particles in a US residence and impacts of various intervention strategies

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Abstract

Interventions that improve air exchange or filter the air have the potential to reduce particle exposures from residential cooking. In this study, we evaluated the effect of using a range hood, opening kitchen windows, and using portable air cleaners (PACs) in various home locations on the concentrations of ultrafine particles (UFPs) at different times and in different rooms during and after cooking. All experiments were conducted using a standardized cooking protocol in a real-world naturally-ventilated apartment located in the northwest United States. Real-time UFP measurements collected from the kitchen, living room, and bedroom locations were used to estimate parameters of a dynamic model, which included time-varying particle emission rates from cooking and particle decay. We found that 1-min mean UFP number concentrations in the kitchen and living room mostly peaked within 0–10 min after cooking ended at levels of 150000–500000 particles/cm^3. In contrast, the bedroom UFP concentrations were consistently low except for the window-open scenario. While varying considerably with time, the 1-min UFP emission rates were comparable during and within 5-min after cooking, with means (standard deviations) of 0.8 (1.1) $\times 10^{12}$ and 1.1 (1.2) $\times 10^{12}$ particles/min, respectively. Compared with the no-intervention scenario, keeping the kitchen windows open and using a kitchen range hood reduced the mean indoor average UFP concentrations during and 1 h after cooking by ~70% and ~35%, respectively. Along with the range hood on, utilizing a PAC in the kitchen during and after cooking further reduced the mean indoor average UFP levels during and 1 h after cooking by an additional 53%. In contrast, placing the PAC in the living room or bedroom resulted in worse efficacy, with additional

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CRediT authorship contribution statement

Jianbang Xiang: Conceptualization, Methodology, Software, Data collection and curation, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Jiayuan Hao**: Data collection, Writing – review & editing. **Elena Austin**: Conceptualization, Methodology. **Jeffry Shirai**: Writing – review & editing. **Edmund Seto**: Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of interests

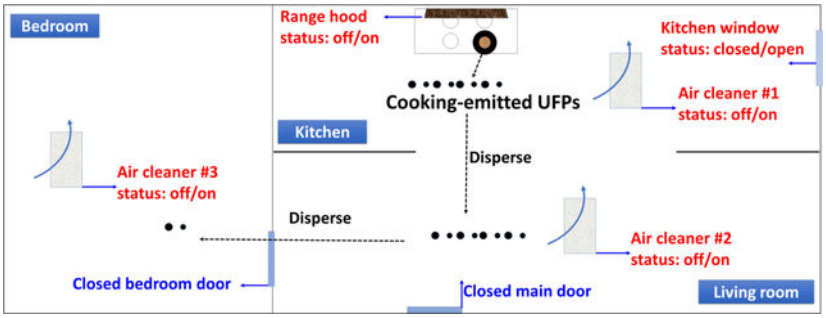
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

The Appendix is provided.

2–13% reductions. These findings provide useful information on how to reduce cooking-related UFP exposure via readily accessible intervention strategies.

Graphical Abstract



Keywords

cooking; ultrafine particle; emission; range hood; window opening; portable air cleaner

1. Introduction

Residential cooking activities can produce a wide range of hazardous particles and gaseous organic compounds (Chen et al., 2018; Huang et al., 2021; Wallace et al., 2004; Xiang et al., 2017). Exposure to such cooking-related pollutants has been associated with adverse health effects (Gabdrashova et al., 2021; Ke et al., 2009; Neghab et al., 2017; Pan et al., 2008; Singh et al., 2016), even lung cancer risks (Gao et al., 1987; Seow et al., 2000; Wang et al., 1996; Wu-Williams et al., 1990; Zhong et al., 1999). Among the cooking-related pollutants, ultrafine particles (UFPs; particles with an aerodynamic diameter ≤ 100 nm) dominate the particle number concentrations (Wallace et al., 2004). Based on a review study by Zhao et al. (Zhao and Zhao, 2018), the residential UFP concentrations during some cooking events, e.g., pan-frying and stir-frying, can exceed 10^6 particles/cm^3, up to 70–100 fold of typical urban levels (Presto et al., 2021) and 5–10 fold of on-road levels (Austin et al., 2021; Xiang et al., 2020).

Although cooking activities mainly occur in kitchens, occupants in other rooms may also be exposed to cooking-related UFPs due to cooking-fume dispersion. Some studies have demonstrated the remarkably high UFP levels and emission rates in kitchens in certain cooking scenarios (e.g., frying) (Chen et al., 2018; Lunden et al., 2015; Wan et al., 2011). However, few studies have investigated the dispersion of cooking-related UFPs from kitchens to other rooms in homes (Wan et al., 2011). In particular, it is unclear how cooking impacts UFP levels in other rooms with their doors open or closed, such as an open living room or a closed bedroom.

Several studies have measured the UFP or UFP emission rates from certain cooking scenarios by assuming a steady emission strength during cooking (Chen et al., 2018; Wallace et al., 2004). Specifically, the UFP concentration time-series curves were nonlinearly fitted for the entire increasing stage by assuming a constant emission rate.

However, this assumption may lead to large biases because the UFP emission rates can be time-varying with oil and food temperature. A difference method with more discreet time steps should yield more accurate estimates.

Utilizing a kitchen range hood during cooking is a common way to mitigate the dispersion of cooking fumes. Brett et al. evaluated the pollutant (e.g., CO_2) capture efficiency of various types of kitchen range hoods in California homes (Delp and Singer, 2012; Lunden et al., 2015; Singer et al., 2012; Singer et al., 2017), showing that the capture efficiency varied widely (from <15% to >98%). When the range hood is not very effective, people may open kitchen windows or use a portable air cleaner (PAC) during and after cooking to reduce indoor pollutant levels. However, it remains unclear how these strategies impact the time-varying profiles of indoor UFP levels in different locations in the residence. While using a PAC, it is not evident how the placement impacts the overall effectiveness. Moreover, no studies have compared the effectiveness of these strategies for reducing cooking-related UFPs in residences.

The present study is part of a larger study, which assesses cooking-related $PM_{2.5}$, UFPs, and size-resolved particles ranging from 0.3 to 10 μm. In contrast to a previous analysis, which assessed the characteristics of cooking-related $PM_{2.5}$ (Xiang et al., 2021a), the present study examines the profiles of cooking-related UFPs. Instead of examining the pollutant mixture from both fuel combustion and food fumes, as illustrated in the studies mentioned above (Chen et al., 2018; Lunden et al., 2015), the current study focuses on UFP emissions from food fumes using an electric range. Through multi-scenario field measurements in a US home, this study aims to 1) illustrate the time-varying profiles of cooking-related UFPs in different locations in the residence; 2) demonstrate the dynamic process of cooking-related UFP emission rates; and 3) evaluate the impact of different intervention strategies (i.e., utilizing a range hood, opening kitchen windows, or using a PAC in various indoor locations) on indoor UFP number concentrations.

2. Methods

2.1. Experimental site

The experimental methods were reported in greater detail elsewhere (Xiang et al., 2021a). Briefly, we conducted the experiments in a naturally ventilated apartment in Sand Point, Seattle, Washington State, United States (US), from August 6 to September 16, 2019. As shown in Appendix Fig. A1, the duplex apartment had an open kitchen (including a dining area) and living room on the first floor, and all three bedrooms on the second floor. There was an internal staircase, without a door or barrier, connecting the two floors. Openable windows were in the kitchen, living room, and bedrooms. Cooking was conducted on one of the front burners of the electric kitchen range (Hotpoint, GE Appliances, US) with 10 temperature options (i.e., *OFF*, *1–9* from low to high levels). In cooking scenarios involving the range hood (Broan BUEZ2, US), the exhaust hood with a nominal airflow of 90 liters/s over the electric range was used to vent the kitchen air outside.

2.2. Cooking scenarios

Pan-frying steak and asparagus were chosen as the primary cooking recipe since pan-frying is a common and high-emitting cooking method (Chen et al., 2018). We followed the same protocol to purchase, prepare, and cook the food for each experiment, as described in detail in the Appendix. Fig. 1 shows the timeline of the cooking protocol for each experiment. In brief, the same amount of food materials (mean ± standard deviation [SD]: 230 ± 17 g for steak and 227 ± 25 g for asparagus) were prepared about 30 min before cooking for each experiment. At the start of cooking (Minute 0), the electric range was turned on at the temperature *level 9* with the pre-cleaned nonstick frying pan on one front burner. After 2 min, the steak was added to the pan and fried for 6 min. After removing the steak from the pan, we reheated the pan for 30 s and then fried the prepared asparagus for 8 min. That step was followed by turning off the range (Minute 17) and removing the asparagus from the pan. The uncovered pan was left on the same burner to cool for 1 h before being cleaned. No smoking, cleaning, candle burning, or other cooking activities but the designed cooking during Minutes 0–16 occurred during each experiment. Only the experimenters (1–2 persons) were present in the apartment during the experiments, when they mostly stayed in the kitchen during cooking and in the living room/bedroom after cooking.

We conducted seven experimental scenarios with various combinations of range hood, kitchen window, and PAC statuses as follows: 1) kitchen window closed + range hood off + PAC off, 2) kitchen window open + range hood off + PAC off, 3) kitchen window closed + range hood on + PAC off, 4) kitchen window closed + range hood on + kitchen PAC on, 5) kitchen window closed + range hood on + living-room PAC on, 6) kitchen window closed + range hood on + bedroom PAC on, and 7) kitchen window closed + range hood on + kitchen PAC on + living-room PAC on + bedroom PAC on. Because the measured indoor UFP levels in Scenario 1 were extremely high and decayed slowly, we opened the apartment's main door and the kitchen window about 1 h after cooking to avoid acute exposure and closed them again after 5 min. Also, no repeated trials were conducted in Scenario 1 because of the extremely high exposure. In contrast, two trials were conducted for all the other scenarios (Scenarios 2–7). In Scenario 2, we opened the kitchen window at least 30 min before cooking until the end of all measurements. In Scenarios 3–7, we turned on the range hood at the start of cooking (Minute 0) and turned it off 1 min after cooking (Minute 18) due to the noise issue. In the scenarios involving PAC use, we turned on the PACs about 10 min before cooking and kept them on until the end of all measurements. One of the three bedrooms was chosen when the PAC was used in the bedroom, as illustrated in Appendix Fig. A1. We kept all doors and windows closed in the living room and bedrooms for all scenarios unless specified.

The PACs utilized in this study (Air Purifier 2000i, Philips, US) contain a high-efficiency particulate air (HEPA) filter, with a rated clean air delivery rate (CADR) of 179 m^3/h for smoke. In Scenarios 4–7, we used the PACs' auto operation mode, automatically adjusting its fan speed level based on an integrated particle sensor. This auto-mode feature, widely used in real-world settings due to its convenience, has been discussed in greater detail elsewhere (Huang et al., 2021; Xiang et al., 2021b; Xiang et al., 2021c).

2.3. UFP and CO_2 measurement

We utilized P-Trak (Model 8525, TSI Inc., MN) condensation nuclei particle counters to measure the UFP number concentrations in the kitchen, living room, and bedroom at 1-min intervals from about 30 min before and 4 h after cooking. Note that the living-room UFPs in Scenario 1 were not measured due to the instrument unavailability. P-Trak monitors have been widely used for UFP measurement in previous studies (Austin et al., 2021; Liu et al., 2010; Xiang et al., 2020). Prior to the current study's experiments, the P-Trak monitors were factory calibrated by TSI. Also, we conducted a relative calibration among the three monitors (choosing one of the monitors as the reference monitor) in a scenario similar to Scenario 1 with all three monitors co-located to ensure consistent measurements from the three monitors (see more details in Appendix Fig. A2). The normalized root mean squared errors (Xiang et al., 2020) of the post-calibrated monitors were 8–17%, indicating reasonably consistent measurements. Besides, we measured CO_2 concentration in the kitchen with a factory-calibrated Q-Trak (Model 7575, TSI Inc., US) at 1-min intervals to assess air exchange rate (AER) as described below.

2.4. Data analysis

While investigating the UFP variations under various intervention scenarios, we evaluated the UFP number concentrations, decay-related parameters, and emission rates. To minimize the biased comparison attributed to window-closed air exchange rate (AER) variations among different scenarios, we selected one of the two trials in Scenarios 3–7, which had comparable window-closed AERs to that in Scenario 1. Also, we selected one of the two trials in Scenario 2 (window open) that had complete measurements in the three indoor locations. All calculations were made in R (Version 3.3.0) (R Core Team, 2013).

2.4.1. Concentrations—Besides the location-specific concentrations, we calculated the indoor average concentrations by averaging the first-floor (kitchen and living room) and second-floor (bedroom) concentrations (see more details in the footnotes of Appendix Table A1). We then conducted the following analyses. First, we calculated the UFP level increases during and after cooking compared with the before-cooking levels to adjust for the daily variations in the indoor UFP background levels. As defined earlier, the time when we turned on the electric range was Minute 0. Minutes (−10)–(−1), 0–16, and 17–75 were defined as before-, during-, and after-cooking periods, respectively. The UFP levels after Minute 75 were not compared since the door and window statuses were altered at Minute 76 in Scenario 1. Second, the UFP level increases were compared among different indoor locations, i.e., the kitchen, living room, and bedroom. Finally, the UFP level increases were compared across different scenarios to determine the effectiveness of these intervention strategies. Scenarios 2 and 3 were compared with Scenario 1 to reveal the effects of keeping the kitchen window open and utilizing the range hood, respectively. Scenarios 4–7 were compared with Scenario 3 to demonstrate the efficacy of using a single PAC and multiple PACs in various locations.

2.4.2. Estimation of decay-related parameters—The UFP levels in the kitchen, living room, and bedroom after cooking (no emission source) can be described as Eq. (1)

(Sun et al., 2019; Wallace et al., 2004; Xiang et al., 2021a), assuming the air was well mixed in each location.

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

The model describes the dynamics of indoor UFP number concentration $C_{in}(t)$ in units of particles/cm^3 as a function of two times, t_1 and t_2. The total particle decay is modeled via the exponential function, with rate parameter k_t in units of h^{-1}. The background particle concentration indoors (i.e., before cooking) is represented by $C_{in}(bg)$.

The total decay rate, k_t, accounts for decay from ventilation, deposition, and PAC use. As shown in Eq. (1), we assume an exponential decay with time, and fit the parameter empirically to the monitored UFP concentrations as they decreased after each experiment's cooking period, according to the following criteria: the decay curve showed a clear decreasing trend and was visually smooth over at least a 30 min period, at least 10 min had elapsed since the end of cooking, and the period over which the decay parameter was fit did not include any change in door or window openings or range hood use.

An approach based on CO_2 tracer gas (Li et al., 2014) was used to estimate the AER for the first story (kitchen and living room) as described elsewhere in detail (Xiang et al., 2021a). We assumed that the AER applied to the open and connected kitchen and living areas, but not the upstairs bedroom behind the closed door. The UFP concentrations reported in the results for the different areas suggest that this assumption was valid. More details about the AER estimation were shown in the Appendix.

2.4.3. Estimation of emission rates—The dynamic model for indoor UFPs during cooking is described by Eq. (3):

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

In this model, the change in indoor UFP number concentrations $dC_{in}(t)/dt$ in units of particles/cm^3 is a function of the current indoor concentration $C_{in}(t)$, which is subject to decay as described in the previous section for k_t, but also driven by the UFP emission rate at that time, $S(t)$ from cooking, which is distributed over the indoor volume, V in units cm^3. The model also assumes non-negligible infiltration of UFP from the outdoors, subject to the outdoor UFP concentration $C_{out}(t)$, the AER, and the penetration factor p (unitless). Based on previous studies, we set p to 0.47 and 1 when windows were closed and open, respectively (Stephens and Siegel, 2012).

Eq. (3) can be solved using a difference method, assuming the AER, p, and k_t remain constant over the time step Δt, as described in other studies (Bennett and Koutrakis, 2006; Sun et al., 2019):

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

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

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

The outdoor UFP levels during the experiments were not continuously measured due to instrument unavailability. We estimated the outdoor UFP concentrations using the measured before-cooking UFP concentrations in the kitchen in Scenario 2 and a steady-state model (see more details in the Appendix). In Scenario 2, the kitchen windows were opened at least 4 h before the UFP measurement, and no events generating amounts of particles (e.g., cooking, smoking, incense burning, and vacuuming) occurred within 4 h before the UFP measurement. Thus, the indoor sources' impacts on indoor UFPs were assumed to be minimal. Based on the steady-state model, the average outdoor UFP concentrations were ~3000 particles/cm^3. Austin et al. measured the ambient UFP levels in Sand Point of Seattle (~1.5 km from our experimental site) during May–July 2018 and found the mean levels of 5200 particles/cm^3 (Austin et al., 2019; Austin et al., 2021), similar to our results. Given the two studies were both conducted in the warm season within two years, the UFP levels at this urban background site between these two periods should be similar. Considering that the measurements by Austin et al. involved more days, we took their measurements, i.e., 5200 particles/cm^3, as the input of the outdoor UFP concentration in this study.

The increase in bedroom UFP levels during cooking (Minutes 0–16) was negligible compared to those in the kitchen and living room based on our measurements (see more details below). Thus, the cooking-related total UFP emission rates can be estimated using average UFP number concentrations and total decay rates in the kitchen and living room via Eq. (5). As the living-room UFPs were not measured in Scenario 1, the emission rates were calculated using the UFP concentrations and decay rates in the kitchen instead.

3. Results and Discussion

3.1. Overview

Fig. 2 shows the profile of 1-min indoor average and location-specific UFP levels for each scenario. In spite of the varying magnitudes, the UFP levels across all scenarios mostly exhibited a similar time-varying pattern. Throughout all the experiments, the mean (SD) background indoor UFP levels (before cooking) were 6100 (4300) particles/cm^3 in this apartment, with relative differences of less than 20% among the kitchen, living room, and bedroom levels. The average indoor levels were slightly higher than ambient concentrations (~5200 particles/cm^3 on average), possibly due to the secondary organic

aerosols generated from indoor ozone-initiated chemical reactions (Weschler, 2016; Xiang et al., 2016). Previous studies have shown that ozone can react with unsaturated indoor organic compounds (e.g., terpenes from building materials and cleaning products; squalene and unsaturated fatty acids from occupants' skin oil), resulting in secondary organic aerosol (SOA) formation (Weschler, 2016; Xiang et al., 2016). The UFP levels in the kitchen and living room started to rise 0–2 min after the steak was added (Minutes 2–4). The peak concentrations mostly occurred 0–10 min after cooking ended, at levels of 150000–500000 particles/cm^3, comparable to those reported in previous studies for pan-frying cooking events (Zhao and Zhao, 2018). The kitchen and living-room UFP levels then gradually declined to the background levels after at least 4 h after cooking. An after-cooking spike occurred in Scenario 3, potentially resulting from the fluctuations of AERs and outdoor ozone concentrations. Similarly, a spike of indoor UFP concentrations dominated by the increasing outdoor ozone concentrations was previously reported by Xiang et al. (2016). Compared with the kitchen and living room, the bedroom UFP levels during and after cooking were consistently low except for Scenario 2, in which the kitchen window was open, and the bedroom levels were even higher than the two first-floor rooms during Minutes 40–150.

3.2. Concentrations

Fig. 3 shows the means (SDs) of 1-min indoor UFP level increases during and 1-h after cooking compared with before-cooking levels for each scenario (see Appendix Fig. A3 for the boxplots and Table A1 for the statistical summary). In Scenario 1 (no intervention strategies), the indoor average mean (SD) UFP levels during and 1-h after cooking increased by 82000 (55400) and 123300 (54200) particles/cm^3, respectively, compared with the before-cooking levels. Comparing indoor locations, the pooled during-and-after (D&A) UFP concentration in the kitchen increased by 211300 (113300) particles/cm^3, which was approximately 12 times higher than the mean bedroom-level increase (16800 particles/cm^3). The living-room levels were not measured in this scenario due to instrument unavailability.

In Scenario 2 (kitchen window open), the mean (SD) indoor average UFP level increase in the pooled D&A period was 34400 (17100) particles/cm^3, about 80000 particles/cm^3 (70%) lower than that in Scenario 1. The mean kitchen level increase in the D&A period was 169000 particles/cm^3 (80%) lower, while the bedroom increase was 15000 particles/cm^3 (87%) higher than seen in Scenario 1. Comparing indoor locations, the kitchen level increases in the D&A period were 10000 particles/cm^3 (30%) higher than those for the living room, and 11000 particles/cm^3 (35%) higher than those for the bedroom. The kitchen-bedroom concentration differences in the D&A period in Scenario 2 were minor compared to those in Scenario 1. The substantial increase in bedroom UFP levels in Scenario 2 suggests that keeping the kitchen window open significantly increased the diffusion rates of the cooking-emitted UFPs because of the large AERs in this scenario (see more results of AERs in Section 3.3).

In Scenario 3 (range hood on during cooking), the mean (SD) indoor average UFP level increase in the pooled D&A period was 73600 (29200) particles/cm^3, about 40000 particles/cm^3 (35%) lower than that in Scenario 1. The mean kitchen and bedroom level

increases in the D&A period were about 69000 particles/cm^3 (33%) and 7000 particles/cm^3 (42%) lower than those in Scenario 1, respectively. Comparing the indoor locations, the kitchen level increases in the D&A period were 10000 particles/cm^3 (8%) higher than those for the living room, and 133000 particles/cm^3 (14 times) higher than those for the bedroom. The kitchen-bedroom concentration differences in the D&A period in Scenario 3 were larger than those in Scenario 1. While less effective than Scenario 2, the range hood utilization consistently reduced the cooking-related UFP levels for multiple indoor locations compared with Scenario 1. Larger concentration reductions for the bedroom reveal that the range hood captured a substantial amount of cooking-related UFPs before they migrated to the upstairs bedroom.

In Scenario 4 (PAC in the kitchen), the mean (SD) indoor average UFP level increase in the pooled D&A period was 34700 (30600) particles/cm^3, about 39000 particles/cm^3 (53%) lower than that in Scenario 3. The mean kitchen, living room, and bedroom level increases in the D&A period were about 78000 particles/cm^3 (54%), 72000 particles/cm^3 (54%), and 3000 particles/cm^3 (32%) lower than those in Scenario 3, respectively. Comparing the indoor locations, the kitchen level increases in the D&A period were 4000 particles/cm^3 (7%) higher than those for the living room, and 58000 particles/cm^3 (9 times) higher than those for the bedroom. In contrast, using the PAC in the living room (Scenario 5) and bedroom (Scenario 6), the mean indoor average UFP level increases in the pooled D&A period were 2% and 17% lower than those in Scenario 3, respectively, but 107% and 76% higher than those in Scenario 4. The sheer difference of the mean indoor average UFP level increases in the pooled D&A period among Scenarios 4–6 highlights the importance of the PAC placement location (see more results and discussion below). When using PACs in all three rooms (Scenario 7), the mean indoor average UFP level increases in the pooled D&A period were 49% lower than those in Scenario 3 but 9% higher than those in Scenario 4. Theoretically, Scenario 7 should yield better efficacy in mitigating indoor UFP levels than Scenario 4 if all experimental conditions except PAC usage were the same. However, there were likely variations in cooking-related UFP emission rates across the different scenarios, impacting UFP decay rates and explaining the higher UFP levels seen in Scenario 7 compared to Scenario 4. In light of this, we further evaluated the decay-related parameters and UFP emission rates below.

3.3. Decay-related parameters

Table 1 shows the location-specific UFP total decay rate (k_t) and first-floor AERs for each scenario. As described in the *Methods*, the AERs were measured based on a CO_2-based approach. The decay rates (k_t) for the kitchen and living room were comparable across all the scenarios, with a mean relative difference of 15% (range: 0–30%). Thus, k_t for these two locations were aggregated into the first-floor k_t, ranging from 1.10 (0.02) h^{-1} (Scenario 1) to 7.16 (0.24) h^{-1} (Scenario 7). In contrast, k_t for the first floor was 256% larger than that for the bedroom on average. The large difference in k_t between the bedroom and first floor suggests that the bedroom door, or equivalent barrier, can substantially reduce the UFP decay rates between the spaces. The first-floor k_t (range: 1.10–1.26 h^{-1}) and AERs (range: 0.23–028 h^{-1}) in the scenarios with windows closed and no PACs in use (i.e., Scenarios 1 and 3) were consistent with those reported in Wallace et al., where the median k_t measured

in 74 Canadian homes was 1.26 h^{-1} with a median AER of 0.23 h^{-1} (Wallace et al., 2013). In the window-open scenario (Scenario 2), k_t for the first floor increased markedly due to the increased AER, consistent with a previous study that evaluated the importance of window opening conditions on indoor UFPs in a full-scale test building (Rim et al., 2013). Scenario 7 with three PACs yielded the largest k_t for the first floor among all the intervention scenarios, about 6 times larger than that in Scenario 1 and 63%–497% larger than those with a single PAC in use (Scenarios 4–6). In the scenarios using a single PAC, placing it in the kitchen (Scenario 4) led to a much larger k_t for the first floor. Notably, using the PAC on the first floor had a minimal effect on k_t for the bedroom, and vice versa. Ventilation contributed to 18–26% on average of total UFP decay rates for the first floor when the windows were closed and no PACs were in use. In contrast, the AER/k_t ratio increased substantially with the kitchen window open, and decreased to below 10% with a PAC used in the kitchen. The varying ratios further reveal the relative importance of each UFP decay pathways in each scenario.

3.4. Emission rates

Fig. 4 displays the time-varying UFP emission rates during and after cooking for each scenario (see Appendix Table A2 for the statistical summary). Remaining negligible during Minutes 0–3, the emission rates began to increase from Minute 4 (about 2 min after the steak was added), peaked at Minutes 6–8 (Dish 1) and 15–18 (Dish 2), and then declined to 0 gradually about 5–10 min after cooking. The time-varying pattern confirms our hypothesis that the cooking-related UFP emission rates varied considerably with time. Hence, the emission rates cannot be estimated via a statistical fitting approach by assuming a constant value during cooking. The method of using a more discreet time step (i.e., 1 min), as in the present study, will likely yield more accurate estimates.

Results also revealed significant UFP emissions within several minutes after cooking. The mean (SD) emission rates during (Minutes 0–16) and 5-min after cooking (Minutes 17–21) in Scenarios 1–7 were 0.8 (1.1) $\times 10^{12}$ and 1.1 (1.2) $\times 10^{12}$ particles/min, respectively. The after-cooking emissions possibly came from food residue in the hot pan. Thus, it would likely be beneficial to take some mitigating measures to reduce emissions not only during but after cooking. In this study, the range hood was turned off shortly after cooking due to the noise issue, so it could not reduce the after-cooking UFP emissions. Some measures, such as keeping the range hood on, covering the pan, removing the pan from the burner, or cleaning the pan immediately after cooking, may reduce the indoor UFP levels after cooking.

The mean (SD) UFP emission rates during (Minutes 0–16) and 5-min after cooking (Minutes 17–21) with the range hood off and kitchen window closed (Scenario 1) were 1.0 (1.3) $\times 10^{12}$ and 1.7 (1.7) $\times 10^{12}$ particles/min, respectively. The during-cooking emission rates in Scenario 2 were about 70% lower than those in Scenario 1, which suggests that larger ventilation rates or airflow velocities can reduce cooking-related emissions. Further investigation is needed to understand the underlying reasons for this observation, which may in turn help setting up control strategies to reduce cooking-related UFP emissions at the source.

On the other hand, the results of this study suggest that it is challenging to control the emissions from pan-frying cooking events given the significant emission variations across Scenarios 3–7 (e.g., emission rates in Scenario 7 were twice those seen in Scenario 6), even though a standard cooking operating procedure was followed. This finding is also supported by a previous study with three repeated experiments for each cooking scenario (Chen et al., 2018). Even when the pan temperature and food weight were kept consistent, the underlying factors specific to a food item, such as the fat content and shape of the food materials, are difficult to control. The emission variations due to such food-specific variability also explain why the mean indoor average UFP level increases in the pooled D&A period in Scenario 7 (PACs used in three locations) were higher than those in Scenario 4 (PAC only used in the kitchen). As shown in Appendix Table A2, the mean (SD) UFP emission rates during and 5-min after cooking in Scenario 7 were 1.3 (1.3) $\times 10^{12}$ particles/min, approximately 60% higher than those in Scenario 4 on average. Thus, the concentration increases in Scenario 7 were 9% higher than those in Scenario 4, although the UFP decay rates for the first floor in the former scenario were ~60% larger (Table 1). Still, similar experiments utilizing homogenous foods (e.g., processed foods) may provide useful insight into the effectiveness of different mitigation strategies.

3.5. Comparison with $PM_{2.5}$ results

In a companion paper (Xiang et al., 2021a), we assessed the characteristics of cooking-related $PM_{2.5}$ in the apartment and the impacts of various interventions. Overall, the varying patterns and the impacts of these interventions were consistent for $PM_{2.5}$ and UFPs. In the no-intervention scenario (Scenario 1), the bedroom concentrations were > 90% lower than the first-floor concentrations for both pollutants. Both studies revealed large variations in pollutant emission rates during cooking and substantial pollutant emissions within 5 min after cooking. Also, both studies found that opening kitchen windows during and after cooking reduced the first-floor pollutant concentrations substantially but increased the bedroom levels after cooking. As for scenarios involving using a PAC, placing it in the kitchen led to better efficacy in reducing indoor $PM_{2.5}$ or UFP concentrations. Nonetheless, $PM_{2.5}$ is larger in size and mass than UFPs and thus has the potential to behave differently than the UFPs described in this paper. In the comparison of the two studies, larger decay rates were found for UFPs than $PM_{2.5}$ in all window-closed scenarios (Appendix Fig. A4), consistent with a previous study that measured $PM_{2.5}$ and UFP decay rates in 74 Canadian homes and found the total decay rates for $PM_{2.5}$ were ~17% greater than those for UFPs (Wallace et al., 2013). As a result of the larger decay rates, the lingering effects of cooking on indoor UFPs lasted for a shorter period than $PM_{2.5}$. Taking Scenario 3 as an example, the lingering effects on UFPs and $PM_{2.5}$ lasted for ~4 h and ~7 h, respectively.

3.6. Selection of cooking-related UFP mitigation strategies

This study illustrated the impacts of several commonly-used cooking fume mitigation strategies on cooking-related indoor UFP concentrations. Overall, opening kitchen windows can substantially and cost-effectively reduce indoor UFPs attributed to cooking. However, the efficacies vary with the actual window-open AERs, and thus, can be less significant when the AERs are low (see more discussion on window-open AERs elsewhere (Nazaroff, 2021; Xiang et al., 2021a)). Also, the kitchen windows may be physically unopenable in

some dwellings or not opened when ambient PM levels are high (Xiang et al., 2021d; Xiang et al., 2019). On the other hand, the efficacies of kitchen range hoods vary widely with brands and styles, e.g., from <15% to >98% based on previous studies (Delp and Singer, 2012; Lunden et al., 2015; Singer et al., 2012; Singer et al., 2017). The relatively low efficiency and large noise (as high as 70 dB) of some range hoods may prevent people from running them for a long time. All the above issues may lead to a relatively low frequency of range hood use and window opening during cooking in real-world settings. This is consistent with a recent study, which investigated residential cooking and kitchen ventilation behaviors in 132 Canadian households and found that only 27% of the cooking activities were conducted with added ventilation (range hood use 10%, window opening 15%, and both 2%) (Sun and Wallace, 2021).

By contrast, the use of PACs is more flexible despite the availability of effective range hoods and openable windows, or the condition of meteorology. This study revealed that the single PAC use resulted in an additional 2–53% reduction of the mean indoor average UFP levels in the pooled D&A period. Remarkably, the placement location impacted the overall efficacy of PAC use. Specifically, placing the PAC in the kitchen, i.e., closer to the source, reduced indoor average UFP concentrations more significantly. However, further investigation on how the placement of a PAC impacts occupants' time-weighted exposure is needed as exposure is also dependent on people's time-activity patterns.

3.7. Limitations

This study has several potential limitations. First, the second floor was not included when we estimated the total cooking-related UFP emission rates since we did not measure the AERs in the bedroom. However, the impacts on the emission rate estimates during cooking (Minutes 0–16) should be negligible because the bedroom level increase during cooking was minimum. Although the after-cooking emission rates (Minutes 17–21) could be underestimated, especially in Scenario 2 (open kitchen window), where UFP levels in the bedroom clearly occurred, 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. Second, we did not measure ambient UFP levels, which could result in some biases in estimating the UFP emission rates. Nonetheless, as explained in the Methods, our estimates of outdoor UFP concentrations were similar to those measured ~1.5 km away from the experimental site. Third, the variations in UFP emission rates from pan-frying cooking scenarios across different trials were not fully controlled, although the same standard operating procedure was followed. Future studies will benefit from a more controlled emission source. Fourth, in the window-open scenario (Scenario 2), we did not examine similar situations where the windows elsewhere in the apartment (e.g., bedroom) or main entry door were open (Scenario 2), both of which could significantly alter the indoor airflow and, thus, the spatial distribution of indoor air pollutants. Lastly, the quantitative results obtained in the present study are specific to the pan-frying cooking scenario and the apartment where the experiments were conducted. Future studies with more cooking scenarios and housing types are warranted.

In spite of these limitations, this study provides useful information on the characteristics of cooking-related UFP levels with high-emitting cooking activities (e.g., pan-frying and stir-frying) in a residence and a sense of the magnitude of the reduction in indoor UFP levels that may be achieved by utilizing one or more strategies.

4. Conclusions

This study illustrates the large variations in indoor UFP levels and emission rates during and after pan-frying cooking events. The 1-min mean UFP number concentrations in the kitchen and living room peaked at levels of 150000–500000 particles/cm^3. In contrast, the bedroom UFP concentrations were consistently low except for the window-open scenario. Related, the lingering effects of cooking on indoor UFPs lasted for up to 4 h, despite cooking time being short (< 20 min in this study). Large variations in the 1-min UFP emission rates were found from the cooking events, with a mean (SD) of 0.8 (1.1) $\times 10^{12}$ and 1.1 (1.2) $\times 10^{12}$ particles/min during and with 5 min after cooking. Given the substantial UFP emissions in both periods, it would likely be beneficial to take some mitigating measures to reduce emissions not only during but after cooking. Compared with the no-intervention scenario, keeping the kitchen windows open and using a kitchen range hood reduced the mean indoor average UFP concentrations during and 1 h after cooking by ~70% and ~35%, respectively. Along with the range hood on, utilizing a PAC in the kitchen during and after cooking further reduced the mean indoor average UFP levels during and 1 h after cooking by an additional 53%. In contrast, placing the PAC in the living room or bedroom resulted in worse efficacy, with additional 2–13% reductions. These findings provide useful information on how to reduce cooking-related UFP exposure via readily accessible intervention strategies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Highlights

- The time-varying profile of cooking-related UFPs in a residence was examined.
- The effect of various cooking-fume intervention ways on indoor UFPs was evaluated.
- Large variations were found in 1-min UFP emission rates during and after cooking.
- Opening kitchen windows can reduce indoor average UFP concentrations by 70%.
- Placing an air cleaner in the kitchen resulted in better efficacy than other locations.

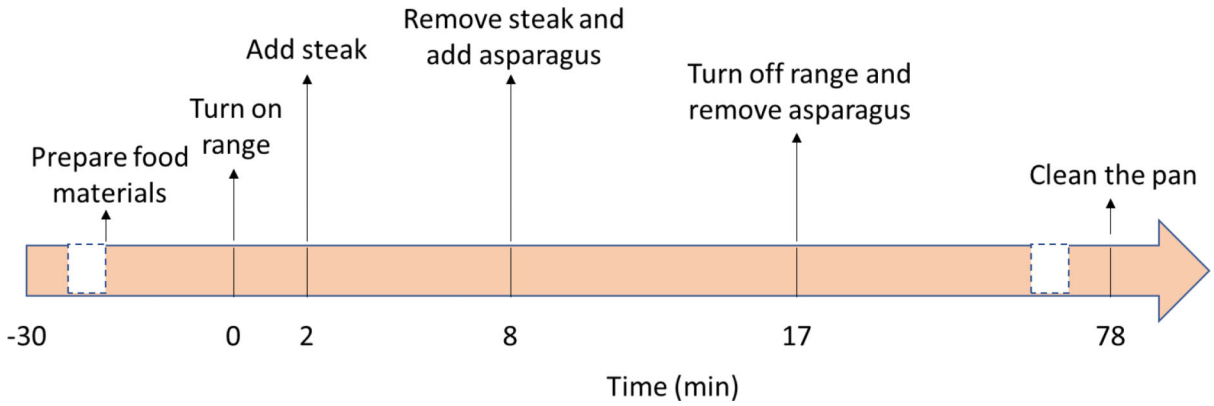

Fig. 1.
Timeline of the cooking protocol.

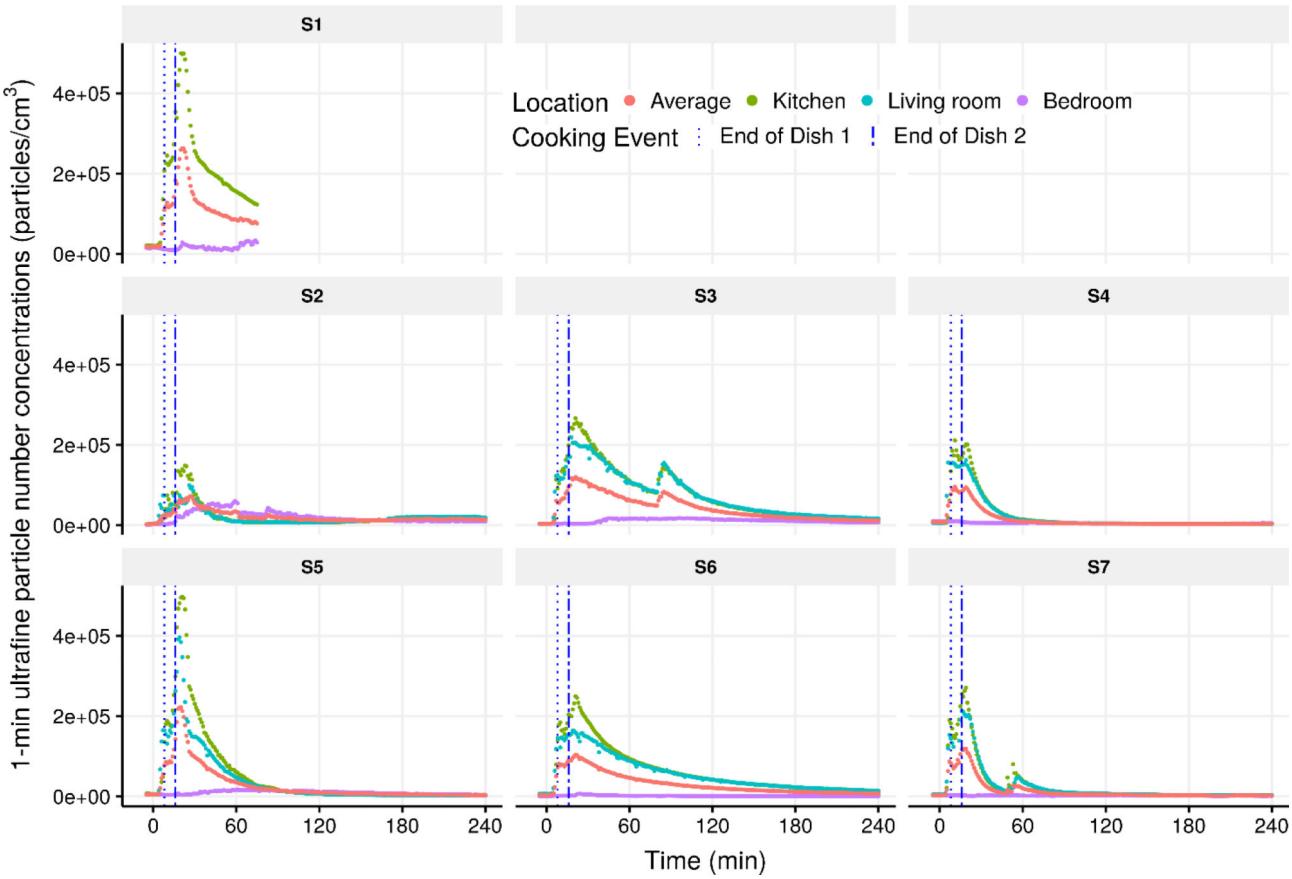

Fig. 2.

Time-series plots of 1-min indoor ultrafine particle number concentrations for each scenario. "S1–7" represents Scenarios 1–7. "Average" refers to indoor mean concentration. Note that the living-room UFPs in Scenario 1 were not measured due to the instrument unavailability.

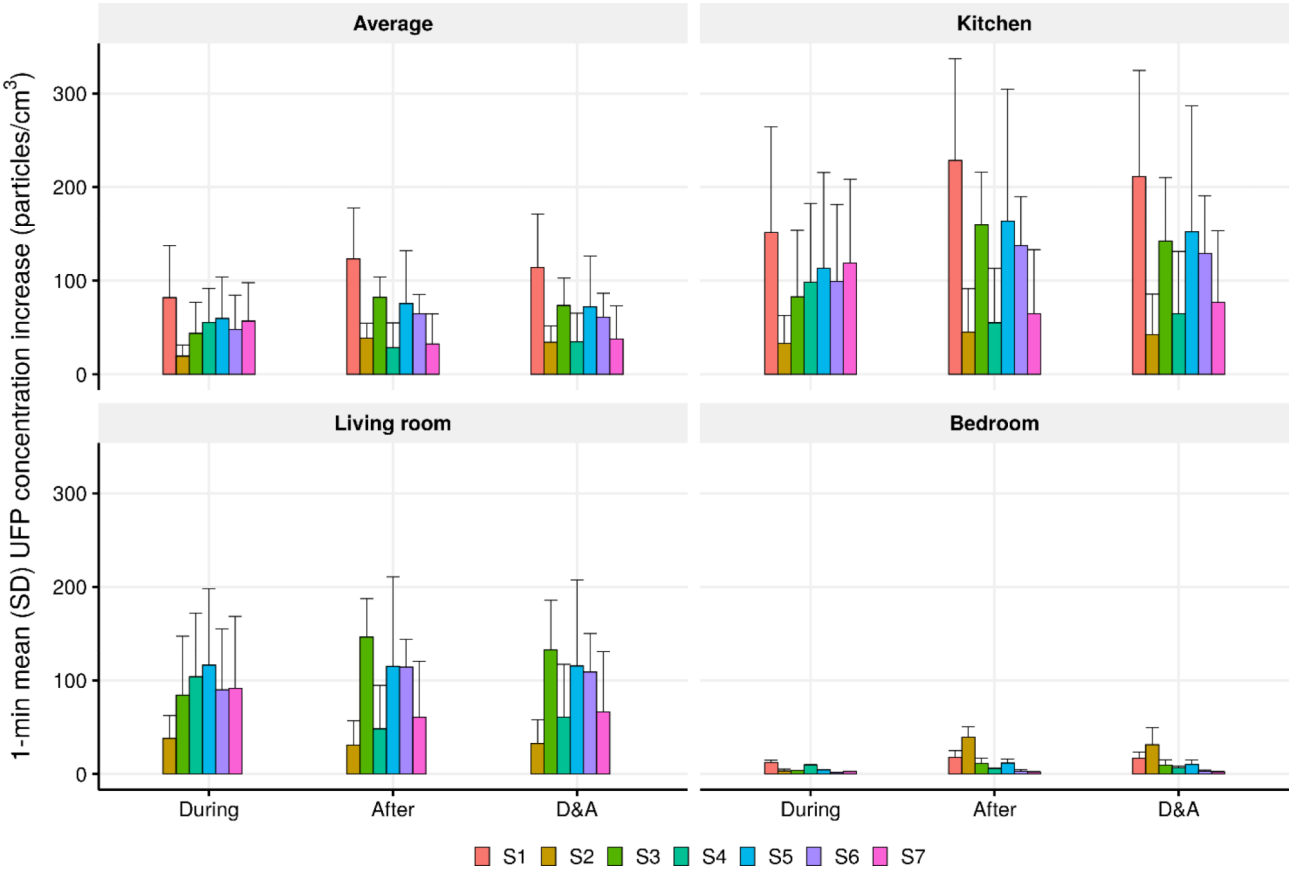

Fig. 3.

Means (standard deviations) of 1-min indoor ultrafine particle concentration increases during and 1-h after cooking compared with before-cooking levels in each scenario. “S1–7” represents Scenarios 1–7. “During”, “After”, and “D&A” refer to during cooking, 1-h after cooking, and pooled period, respectively. “Average” refers to indoor mean concentration. Note that the living-room UFPs in Scenario 1 were not measured due to the instrument unavailability.

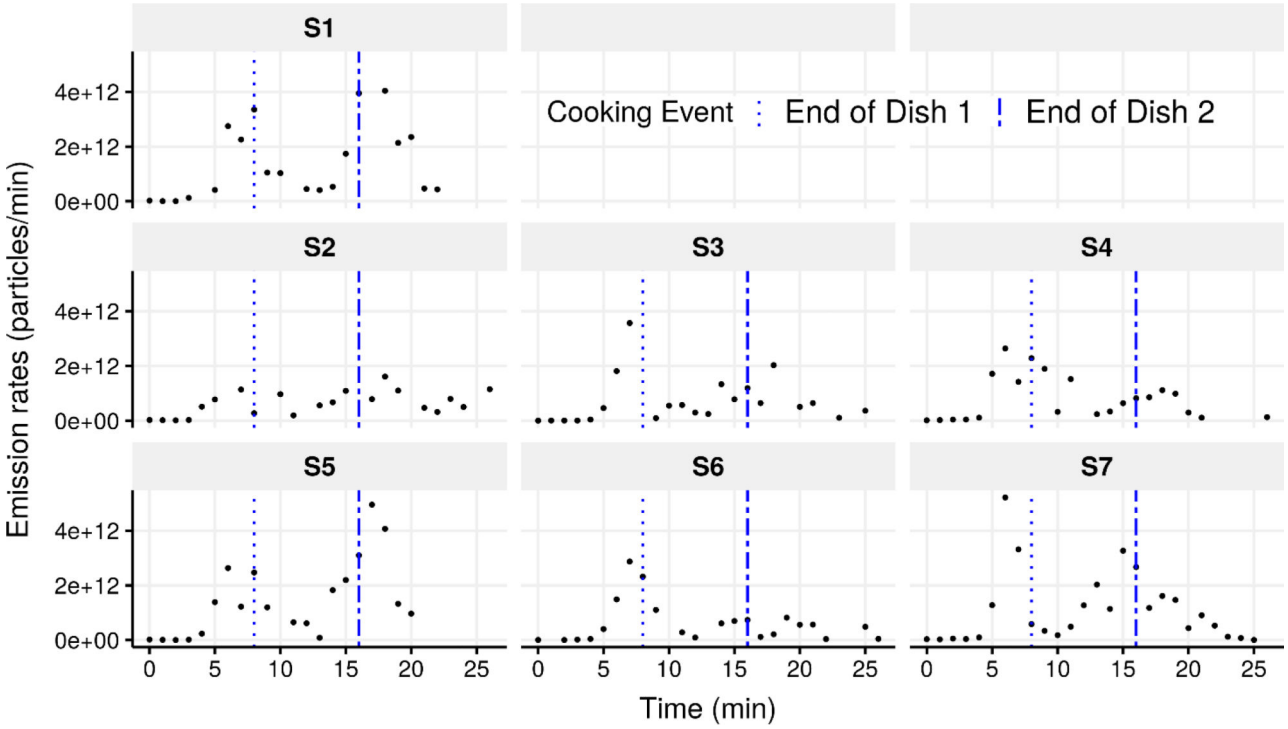

Fig. 4.

Time-series plots of 1-min cooking-related ultrafine particle emission rates for each scenario. “S1–7” represents Scenarios 1–7. Dishes 1 and 2 refer to the steak and asparagus, respectively.

Table 1.

The total decay rate of indoor UFP number concentrations and air exchange rate in each scenario.

Scenario	k_t (h^{-1})				AER (h^{-1})	$\frac{AER}{k_t(F_1)}$ (%)
	Kitchen	Living room	Bedroom	F1 [a]		
S1	1.10 (0.02)	NM [b]	1.64 (0.10)	1.10 (0.02)	0.28 (0.17)	26 (15)
S2	5.09 (0.12)	4.75 (0.15)	0.71 (0.03)	4.92 (0.24)	5.12 (3.18) [c]	104 (65)
S3	1.42 (0.02)	1.10 (0.04)	0.69 (0.01)	1.26 (0.23)	0.23 (0.22)	18 (18)
S4	4.41 (0.04)	4.40 (0.03)	0.80 (0.07)	4.40 (0.01)	0.36 (0.20)	8 (5)
S5	2.80 (0.02)	2.13 (0.06)	0.42 (0.02)	2.46 (0.48)	0.41 (0.25)	17 (11)
S6	1.29 (0.02)	1.12 (0.03)	2.26 (0.08)	1.20 (0.11)	0.22 (0.18)	19 (15)
S7	7.32 (0.08)	6.99 (0.11)	NA [d]	7.16 (0.24)	0.31 (0.18)	4 (3)

[a] Floor 1, which includes the kitchen and living room.

[b] Not measured.

[c] Because of the relatively large measurement error of window-open AER, the AER was even larger than k_t.

[d] Not applicable because no eligible periods were found for the fitting.