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Cooking aerosols in all-electric flat and studio accommodations: event-scale emissions, transport, and exposure assessments using low-cost sensors

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Cooking generates short and intense pollutant spikes in indoor environments, while event-scale dynamics studies in compact, all-electric homes are rare. Our observational field study deployed calibrated low-cost sensors (LCSs) to 11 UK flat and studio accommodations, inhabited by occupants with varying cultural backgrounds. The LCS pods captured particulate matter (PM, including PM_1, $PM_{2.5}$ and PM_{10}) and gas-phase species (CO_2, NO_2 and O_3) levels at a 2-min time resolution, recording 247 individual cooking events over ~1 year, and quantifying emissions for 125 quality-assured events. Traditional frying and braising dominated $PM_{2.5}$ peaks, emission rates and exposures, whereas water-based, oven and air-fryer emissions were lowest. Increased ventilation by using range hoods and/or opening windows reduced the transmission of kitchen peak $PM_{2.5}$ to the living room by 3–20% and the closed bedroom door sharply cut $PM_{2.5}$ transport from kitchen to bedroom (~68% peak; 78% exposure; 91% elevated-time) with a 79-min lag. The accumulated inhaled dose of cooking-generated $PM_{2.5}$ across 125 events during 81 monitored days was in the range of 1.7 to 4.7 mg, annualising to ~6–17 mg for an assumed 300 cooking days. LCS-reported NO_2 increases were small and infrequent, with only slight O_3 dips. However, NO_2 detection with LCSs is challenging; hence, we focus on the PM analysis. Our findings support low-burden controls, including preventing oil smoking, running well-maintained hoods during and after cooking with windows open, and keeping bedroom doors closed, to significantly reduce the inhabitants' exposures.

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Environmental significance

Short, intense cooking plumes can dominate event-scale $PM_{2.5}$ exposure in flats and contribute significantly to 24-h exposure (mean ~15% and up to ~80%). Using calibrated low-cost sensors in 11 homes, we captured 125 real-world events and quantified propagation from kitchen to living and sleeping areas. High-heat and oil-rich cooking dominated exposure to pollutants, and door-closing substantially curtailed impacts in bedroom air quality, with extractor use and window opening providing the largest additional reductions and faster clearance. Event-scale exposure metrics enable simple operational advice, such as extending extraction after cooking, ventilating effectively, and isolating sleeping spaces, which offers immediate inexpensive benefits. The framework is scalable for community campaigns and policy pilots aiming to reduce indoor pollution exposure where retrofits are constrained.

1 Introduction

Indoor air quality (IAQ) is increasingly recognised as a major determinant of human health, particularly in urban areas where people spend over 80% of their daily lives indoors, while pollutant concentrations often exceed outdoor levels.[1,2] Although the World Health Organization (WHO) has identified indoor air pollution from combustion sources as a leading contributor to global disease burden, electric cooking can also generate substantial aerosol emissions from heated oils and foods, contributing to respiratory and cardiovascular morbidity and mortality, especially for vulnerable groups.[3–8] Fuel combustion, oil use and thermal food processing can emit particulate matter (PM), ultrafine particles (UFPs), and gaseous pollutants, including nitric oxide (NO) and nitrogen dioxide (NO_2) (together referred to as NO_x), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), and ozone (O_3), which can accumulate indoors and exceed health-based guideline values.[9–13]

Recent evidence suggests that in urbanised environments, cooking-related emissions can be comparable or even surpass outdoor traffic contributions to indoor exposure.[14–17] Exposure is associated with acute health effects, such as eye and airway irritation, and chronic outcomes, including asthma exacerbations, impaired lung development in children, and elevated long-term cardiovascular risk,[4,5,7,13,18] with emerging evidence linking indoor air pollution to broader health outcomes, such

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as sleep disruption, skin-related outcomes and psychological distress.[19–23] These findings underscore the need for refined characterisation of pollutant profiles and exposure pathways in diverse indoor settings.

Cooking is a highly variable activity influenced by fuel type, appliance design, food ingredients, oil properties, cooking temperature and ventilation conditions, resulting in complex emission patterns.[1,13,24,25] Multiple studies have documented sharp increases in $PM_{2.5}$, UFPs, and black carbon during cooking events,[1,13,26] and oil type can strongly affect emissions: soybean oil generates substantially higher PM and aldehyde concentrations than rapeseed oil under identical conditions.[24,27,28] Gas stoves also elevate NO_2 and CO, with NO_2 frequently exceeding WHO guidelines.[18,29,30] Substantial studies and our previous work have highlighted cooking as a source of VOC mixtures, including aldehydes, ketones, and aromatics, that can contribute to secondary pollutant formation indoors.[31–34]

A growing number of studies have linked cooking emissions to human exposure in different residential and occupational settings. Field campaigns in dormitories, canteens, and university housing often report exceedances of WHO $PM_{2.5}$ guidelines during peak cooking hours,[35,36] and large-scale household studies in sub-Saharan Africa report disproportionately higher exposure among women and children in biomass-using homes.[37] Exposure profiles vary substantially by building type and ventilation: poorly ventilated canteens frequently exhibit $PM_{2.5}$ levels exceeding 200 to 300 μg m^{-3} during peak cooking, which are several times higher than in residential kitchens,[38,39] and studies in high-rise buildings show stratified pollutant distributions due to limited dispersion.[16,36,40] Personal monitoring research also reports that cooking events contributed 60% of daily indoor particle dose,[41] and even in all-electric homes, peaks of $PM_{2.5}$ concentrations at 100–150 μg m^{-3} have been observed.[36] Beyond particles, indoor O_3 formation can be enhanced through VOC-NO_x chemistry, and cooking-related VOC exposures can include potentially carcinogenic compounds, such as benzene and PAHs.[34,42–46] Cooking adds to other indoor sources and can dominate daily indoor exposure for many populations.[42,47–50]

In recent years, low-cost sensors (LCSs) have become a powerful tool for indoor air quality studies.[17,51–53] In comparison to traditional reference instruments, LCSs are relatively inexpensive, compact, portable, and easy to deploy in real-world environments, enabling large deployments to capture spatio-temporal variability across wider regions, which is rarely feasible with outdoor monitoring stations or single high-grade instruments.[36,51–54] Their high temporal resolutions (seconds to minutes) combined with minimal installation requirements make them useful for observing short-lived indoor events such as cooking, smoking and candle lighting. Their portability has also supported citizen science and community monitoring projects, as well as personal exposure research, which increases accessibility to air quality information at the local scale.[53,55] Nevertheless, noticeable limitations of LCSs remain: optical particle counters (OPC), which often featured in LCSs for PM monitoring, are influenced by relative humidity and particle composition, while electrochemical gas sensors frequently show cross-sensitivity, baseline drift, and higher detection limits for key species, such as NO_2 and O_3.[51,55] As a result, calibration against reference instruments is essential to ensure data reliability.[53,56] These challenges limit their reliability for regulatory compliance, but they remain invaluable for exploratory and large-scale exposure studies.

Evidence on cooking-related indoor air pollution in the UK remains limited, particularly in compact dwellings with electric hobs and culturally diverse cooking practices. Here, we use calibrated LCSs to monitor PM, CO_2, NO_2 and O_3, across multiple rooms in all-electric UK homes under real-life occupant behaviours, and translate measurements into event-scale exposure metrics (peak, AUC-based exposure, elevated-time (*i.e.* exposure duration with concentration higher than guidance)) with attention to persistence and inter-room transport. The novelty is not that cooking emits PM, but that compact, all-electric UK dwellings create a distinctive exposure geometry: studios behave as a single mixed microenvironment where source and receptor are co-located, whereas in one-bedroom flats a single interior door can substantially decouple bedroom exposure from the source zone; when baseline indoor $PM_{2.5}$ is low, the cooking contribution to daily exposure can remain high even at lower absolute concentrations. We therefore evaluate low-burden interventions (door status, hood use, window opening) that are practical where retrofit options are constrained. Thus, this work offers timely insight that complements laboratory experiments and informs strategies for healthier urban living environments.

2 Experimental

2.1 Materials and methods

2.1.1 Sampling site. The field measurements were conducted in residential environments to capture realistic indoor cooking emissions. A total of 11 dwellings were included, comprising six flats and five studio accommodations, each housing up to three adults and no children, in Birmingham, UK. The flats have a combined kitchen-living area with a separate bedroom divided by a door, whereas the studios incorporate kitchen, living, and sleeping functions within a single open-plan space. None of the dwellings had a balcony. Most of the dwellings are located on the eighth floor or higher, while the other lower-floor accommodations face internal communal gardens or residential green spaces rather than roadside directions, which minimise the influence of outdoor traffic emissions on indoor air quality.

The indoor volumes of the flats and studios range 95–126 and 47–53 m^3, respectively, excluding ancillary spaces such as storage rooms, laundry rooms, toilets and bathrooms. All kitchens are of open-plan design and equipped with electric hobs (either ceramic hotplates or induction units) installed at standard worktop height (approximately 0.9 m). An overhead range hood is present above each hob. The monitoring campaign spanned June 2024 to April 2025, with measurement periods scheduled to avoid known highly polluted events such as Guy Fawkes Night, Christmas, New Year, Diwali, and Chinese

New Year, when fireworks and bonfires typically cause substantial short-term particulate pollution outdoors.

A total of 16 occupants were aged 21 to 35 years old, representing the target population (*i.e.* university students and early-career residents). Participants self-identified their cultural backgrounds as African, British, Chinese (Northern/Southern), Indian, and Thai, and several households were multicultural, accommodating more than one background. This diversity was included to reduce bias toward a single cuisine/cooking style and to contextualise cooking practices, rather than to enable subgroup comparisons. This information was noted only for sample description, and no analyses were conducted by cultural backgrounds. By intentionally including a broad spread of customary cuisines and cooking styles, the study aims to minimise the risk of over-representing any single cooking practice and thereby mitigate method- and lifestyle-driven bias as far as possible with the available number of sites and participants.

2.1.2 Instrumentation and deployment. The Persium sensor pod (Persium Ltd, UK) is a compact multi-pollutant monitor that integrates several sensing technologies. Particulate matter (PM_1, $PM_{2.5}$ and PM_{10}) is measured by a proprietary optical particle counter: an internal fan draws ambient air into a chamber illuminated by a focused 635 nm laser diode, and a photodiode detects the light scattered by each particle. The scattering signals are interpreted using Mie scattering theory to compute mass concentrations and particle counts in defined size bins. Carbon dioxide (CO_2) is measured using a ZyAura ZG09 dual-beam non-dispersive infrared (NDIR) module, which covers the full range 0–10,000 ppm with an accuracy of about $\pm$ (50 ppm + 3% of reading), *via* a digital interface. Nitrogen dioxide (NO_2) and ozone (O_3) are detected by SemeaTech electrochemical sensors with analogue outputs, and those raw signals are temperature-compensated using a fourth-order polynomial in the cloud backend. In addition to pollutants, the sensor pod records ambient temperature, barometric pressure and relative humidity. All channels are sampled every 15 s and a time-weighted average (with more weight on recent samples) is computed, and the averaged values are transmitted *via* Wi-Fi to Persium's cloud server at *ca.* 2-min intervals. These transmitted 2-min values were used for analysis.

In each household, two sensors were deployed to record the indoor air pollutants and characterise spatial differences. In flats, monitoring ran for 20 days, while measurements were performed for only 10 days in studios owing to the absence of a separate sleeping room. Sensor A (source-side) was fixed in the kitchen for the entire period, positioned 10–30 cm from the edge of the hob and 150–170 cm above the floor to approximate the breathing zone of a standing cook. Sensor B (receptor-side) was placed on the dining table in the living area, with at least 1.5 m from the hob, for 10 days. In flats only, Sensor B was then relocated to the separate bedroom for a further 10 days.

Sensors were collocated with reference analysers at the Birmingham Air Quality Supersite (BAQS) (Palas FIDAS 200E for PM, ABB-LGR GLA331 MCEA1 for CO_2, Teledyne API 500U for NO_2, and Thermo Scientific 49i for O_3) during 2–30 May 2024 and 9–19 May 2025 (pre- and post-deployment). Raw LCS data were first compensated for temperature and relative humidity (manufacturer's algorithm; fourth-order polynomial) prior to calibration. Channels with adequate co-variation (Pearson $r \geq 0.8$) were calibrated using ordinary least-squares regression ref $= \alpha + \beta$ LCS. The fitted slope (β) and intercept (α) were then applied to the full low-cost sensor (LCS) time series. Channels with insufficient correlation were excluded from quantitative analysis. The CO_2 channel was not calibrated as its raw data were used solely to estimate ventilation rates and were not included in further pollutant analyses. As a result, $PM_{2.5}$ was selected for detailed analysis owing to its public-health relevance and satisfactory agreement with the BAQS reference (high Pearson correlation and accuracy, with clear improvements on performance after calibration), whereas the gaseous pollutants (NO_2 and O_3) are presented descriptively given their health relevance but generally low indoor abundance, despite good temporal co-variation with the reference. Full calibration details are provided in SI Section S1.

2.1.3 Cooking activities recording. A detailed log of cooking activities was maintained to correlate emissions with specific events. For each cooking activity, the following information was recorded: the timing and duration of the event, the number of dishes and their cooking methods, use of the range hood, the open/closed status of the living room window and (for flats) the bedroom door, and any other notable activities (*i.e.* smoking, cleaning, use of perfume or candle burning). Volunteers were instructed to behave and cook as they normally would. The use of the range hood was therefore left to the cook's discretion, although participants were advised to select the highest fan setting, and the same guidance was applied to window operation. A detailed survey form for recording cooking activities and definitions of each cooking method is provided in the SI (Fig. S3 and Table S2, respectively).

As the study assessed air pollutants only in kitchens, living rooms, and bedrooms, participants were advised to keep the doors to other ancillary spaces closed during cooking. The conditions of living room windows and bedroom doors (in flats) were required to remain unchanged during cooking and for at least 30 minutes after cooking finished to ensure consistency in the ventilation context. In addition, the flats' bedroom windows were advised to be kept closed during cooking and for at least 60 minutes afterwards. In these flats/studios, windows were fitted with safety restrictors, so "window open" denotes opening the window to the maximum restrictor-limited position (a small opening gap), rather than a fully open casement. However, these instructions were not always strictly followed in practice, likely due to occasional personal choices or weather conditions, and such instances appeared to be uncommon. As with most field studies, minor inadvertent deviations may occur in day-to-day living. We therefore inspected each event time series during data cleaning and excluded events showing clear mid-event departures from the recorded activity notes (*e.g.*, abrupt step changes or marked shifts in behaviour).

In total, 247 cooking events were logged during the study period. Following data quality checks (to ensure valid sensor data and complete activity records), 125 events from a total of 81 days were deemed valid and included in the emissions analysis.

Events with missing data, incomplete records, or overlapping activities, such as smoking, cleaning, or candle use, were excluded. None of the participating dwellers smoked or vaped; however, occasional smoking occurred when guests visited. To ensure a clean background level of indoor air, both the smoking period itself and the subsequent 12 hours were removed from the dataset. The majority of valid events involved common home-cooking practices, ensuring that the analysed dataset is representative of typical household exposure scenarios. All activity records were compiled in a spreadsheet, and each cooking event was assigned a unique identifier for cross-referencing with the pollutant concentration time series.

2.2 Emission assessment

To quantify the indoor emissions and personal exposure from cooking, we derived several parameters from the measurement data. These include the air exchange rate of the kitchen, the particulate matter emission rates and emission factors for cooking events and estimates of human exposure to $PM_{2.5}$. The following subsections describe the calculation methods and equations used for each parameter. All emission and decay calculations in this study use the kitchen sensor (Sensor A), while the living/bedroom sensor (Sensor B) is used only to characterise spatial gradients and time lags.

2.2.1 Air exchange rate. The air exchange rate (AER, also known as air change rate (ACR)) of the kitchen was determined to characterise ventilation conditions. A tracer-decay method was applied using indoor CO_2 concentrations.[57,58] As the presence or absence of occupants and the ventilation conditions outside cooking periods (*i.e.* door or window positions) were not systematically recorded, the AER estimation relied on identifying periods in the time series that exhibited clear exponential decay towards background levels. This behaviour is mathematically described by eqn (1),

$$C_{(t)} = C_{(0)} \times e^{-a \times t} \quad (1)$$

where $C_{(0)}$ is the initial concentration, $C_{(t)}$ is the concentration at time t (approaching the background level after decay), a is the air exchange rate (min^{-1}), and t is the elapsed time (min). Consequently, the derived AER values are presented for contextual reference only and were not incorporated directly into the emission/exposure analysis calculations. Ranges of estimated AER values in unoccupied periods of the dwellings are provided in SI Fig. S4.

2.2.2 PM emission rate and emission factor. Emission rates (ER) of $PM_{2.5}$ were derived using an area-under-the-curve (AUC) approach, integrating excess concentrations above background across the cooking period and the subsequent decay. This avoids assuming a constant emission rate and provides a robust estimate of total source strength, which has been adopted in a previous indoor cooking emission study by O'Leary, Kluizenaar[11] which reported the cook-window formulation, expressed as eqn (2),

$$\overline{ER} = \lambda V \overline{C(t_{cook})} + \frac{V C(t_{cook})}{t_{cook}} \quad (2)$$

where $\overline{ER}$ is the event-average emission rate ($\mu g\ min^{-1}$) over the cooking period t_{cook} (min), V is the effective volume (m^3) of the space, λ is the first-order total removal rate (min^{-1}) obtained from the post-cooking log-linear decay, $\overline{C(t_{cook})}$ is the average concentration ($\mu g\ m^{-3}$) over the cooking period, and $C(t_{cook})$ is the concentration ($\mu g\ m^{-3}$) at the end of the cooking activity (hob/appliance switched off). The second term in eqn (2) is a storage correction that accounts for pollutant mass remaining in the room when integration is terminated at t_{cook}. Selected decay segments were verified to show near-exponential decay (log-linear behaviour) before estimating the first-order removal rate λ.

In our study, we integrated increased concentration from the start of cooking through the post-cooking decay to background. Because the residual stock at the end of cooking has already been counted within the post-cooking integral, no additional storage term is required. Then, the total emitted mass, E_{tot} (μg), is calculated as in eqn (3):

$$E_{tot} = V\lambda \cdot AUC_{ex.tot} = V\lambda \int_{t_{start}}^{t_{end}} (C_t - C_{bg}) dt \quad (3)$$

where $AUC_{ex.tot}$ is increased exposure ($\mu g\ m^{-3}$ min), as well as the time integral of the window of increased concentration from t_{start} (start of cooking) to t_{end} (the end of the post-cooking decay to background level), C_t is real-time concentration at the time t, C_{bg} is the 10-minute averaged pre-cook background concentration ($\mu g\ m^{-3}$). λ was estimated from the longest monotonic log-linear segment of the post-cooking.

The emission rate was then derived as eqn (4):

$$ER = \frac{E_{tot}}{T_{cook}} \quad (4)$$

The ER is reported as an event-average emission rate ($\mu g\ min^{-1}$) for a cooking event.

The emission factor per dish (μg per dish) was computed as eqn (5):

$$EF_{dish} = \frac{E_{tot}}{N_{dish}} \quad (5)$$

with N_{dish} representing the number of dishes in the cooking event.

2.2.3 PM personal exposure estimation. To examine the potential health impact of cooking emissions on occupants, we estimated the personal exposure to $PM_{2.5}$ in the open-plan kitchen (which served as a combined cooking, dining, and living space). Personal exposure was quantified as the inhaled $PM_{2.5}$ dose, and this was extrapolated to an annual total dose. Given the limitations in tracking occupants' exact presence or absence in their homes, we defined three exposure scenarios to capture a range of potential personal intakes during cooking events:

Scenario A (lower bound): the occupant remains only for the cooking period and then leaves the area immediately (*i.e.* moves to a separate room or outside the flat) to avoid post-cooking exposure. This represents a lower-bound case with no exposure to the decay phase.

Scenario B (intermediate): the occupant stays for the cooking period and 60 minutes afterwards (typical of eating and tidying). If the post-cooking decay ends sooner than 60 minutes, exposure is counted until returning to background; for such short-decay events, Scenario B collapses to Scenario A.

Scenario C (upper bound): the occupant remains in the kitchen area from the start of cooking until $PM_{2.5}$ returns to background. This is the worst-case exposure, capturing the full cooking and post-cooking decay. It is plausible in studios, or in flats when the bedroom door is open, so pollutants can readily transfer.

These scenarios focus on the incremental $PM_{2.5}$ exposure due to cooking. For each cooking event, the increased exposure was calculated, and the resulting inhaled dose for that event was obtained for each scenario. The exposures from all individual dishes over the monitoring campaign were then summed to represent the total cooking-related $PM_{2.5}$ exposure during the 81-day study period. Participants from multiple cultural backgrounds carried out a total of 125 cooking events in this open-plan kitchen space.

To estimate an annual personal exposure from these data, we assumed that home cooking occurs on $N_{days} = 300$ days per year as an upper-central scenario estimated based on UK surveys which reported most adults cook at home for at least 5 days a week.[59,60] We used an average inhalation rate of approximately 0.011 m^3 min^{-1} for individuals aged 16 to 50 reported by U.S.EPA,[61] which is appropriate for light activity during cooking and applicable to UK adults due to the activity-based physiological rate. The annual inhaled $PM_{2.5}$ dose (D) from cooking is calculated using eqn (6),

$$D_{annual} = AUC_{ex}\ IR\ N_{days} \quad (6)$$

where D_{annual} is the annual dose (μg), AUC_{ex} is the increased exposure by integration of $PM_{2.5}$ concentrations above background (also referred to cooking-generated exposure), IR is inhalation rate (m^3 min^{-1}), and N_{days} is the number of cooking days per year. Alternative annualisation scenarios varying N_{days} and IR are provided in the SI (Section S4, Tables S3–S4).

In addition, we report the duration for which $PM_{2.5}$ exceeded 15 μg m^{-3} (aligned with the WHO[3] 24-h guideline) as an elevated exposure time metric.

2.2.4 Statistical analysis. Group comparisons used non-parametric tests (Kruskal–Wallis with post-hoc Dunn) given skewed distributions. Correlations were assessed by Pearson or Spearman depending on normality; significance was set at $p < 0.05$. Analyses were conducted in IBM SPSS Statistics v30.0 and Origin 2025; descriptive summaries were prepared in Microsoft Excel.

3 Results and discussion

3.1 Particulate matter (PM)

We present PM results along the exposure pathway in compact dwellings: (i) source strength by cooking method, (ii) transport controls (windows/hoods/doors), and (iii) event-integrated exposure duration and dose.

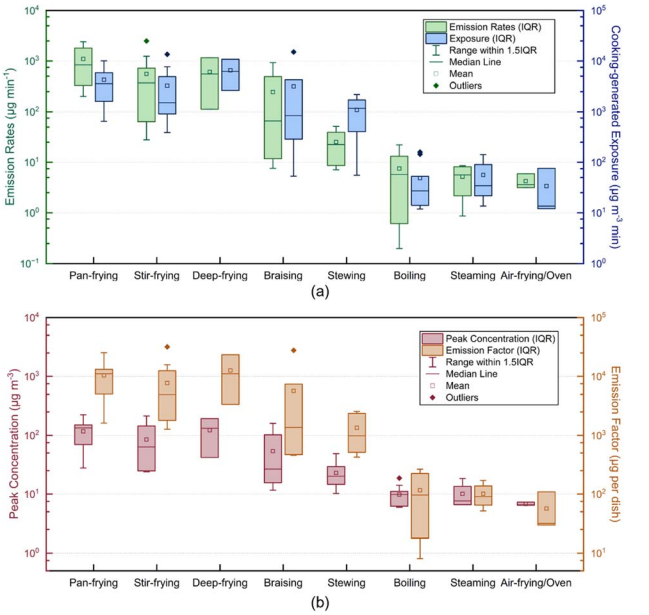

Fig. 1 Particulate matter metrics by cooking method from single-dish events (pan-frying, $N = 14$; stir-frying, $N = 15$; deep-frying, $N = 3$; braising, $N = 7$; stewing, $N = 7$; boiling, $N = 11$; steaming, $N = 4$; air-frying/oven, $N = 3$). (a) Emission rate (left, green; μg min^{-1}) and cooking-generated exposure, AUC_{ex} (right, blue; μg m^{-3} min), integrated from cook start to return to background. (b) Peak $PM_{2.5}$ concentration (left, burgundy; μg m^{-3}) and emission factor per dish (right, orange; μg per dish).

3.1.1 Cooking methods. The $PM_{2.5}$ emissions are generally reported by their (1) peak concentrations (μg m^{-3}), (2) cooking-generated exposure (μg m^{-3} min), defined as the increased exposure above pre-event background from cooking start until return to background, (3) event-average emission rates (ER, μg min^{-1}), and (4) emission factors per dish (EF, μg per dish). Fig. 1 summarises the PM outcomes for single-dish events across pan-frying, stir-frying, deep-frying, braising, stewing, boiling, steaming, and air-fryer/oven cooking (combined due to small numbers). As expected, oil-based, high-temperature methods (pan-/stir-/deep-frying and braising) produced the highest $PM_{2.5}$, while water-based methods and air-frying/oven cooking were lowest.[25,34,62]

Frying methods show higher medians and wider interquartile ranges (IQRs) for emission rates, cooking-generated exposure and emission factors than boiling and steaming, which mirrors studies when frying and grilling yield markedly higher number and mass emissions of particles than water-based cooking methods.[62,63] Braising and stewing sit between frying and water-based categories on the medians, but braising is notably skewed as its median EF lies at 1.4 mg per dish while occasional high emission braises pull the mean to 7.8 mg per dish, suggesting embedded high-heat steps (*i.e.* initial searing, fat rendering and reducing the braising soup to a glaze) within nominally 'wet' recipes. This type of within-method variability likely reflects differences in oil temperature, food moisture/forms, and cooking surface strongly affect emissions.[64] Air-frying and oven cooking events generally track closer to the

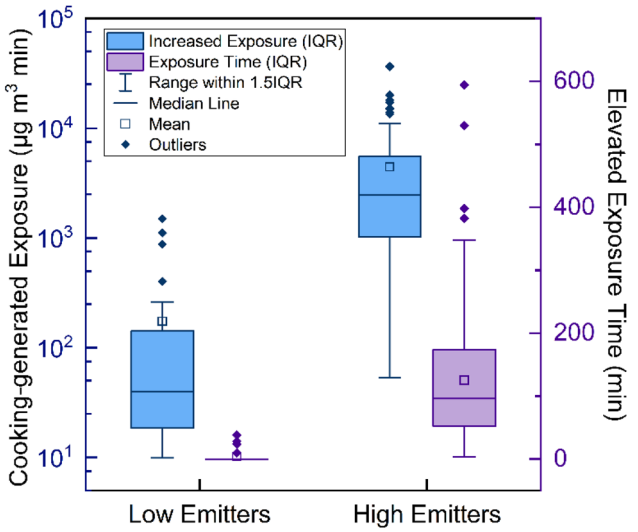

Fig. 2 Cooking-generated $PM_{2.5}$ exposure (left, blue; μg m^{-3} min) and elevated exposure time (right, purple; minutes with $PM_{2.5}$ > 15 μg m^{-3}, WHO 24-h guideline) for low- *vs.* high-emitter events across the recorded cooking activities. High emitters are events involving any frying or braising (pan-/stir-/deep-frying, braising; N = 93); low emitters include events without these methods (N = 32).

water-based group than to frying, although variability remains appreciable, plausibly reflecting the fat content and cooking temperatures again, which also agrees with prior comparisons showing that enclosure and lower oil use reduce aerosol generation.[63,65,66]

Normality checks on log-transformed outcomes remained significant (Shapiro–Wilk, all $p \leq 0.015$), so we used non-parametric tests. Kruskal–Wallis showed strong method effects for ER, cooking-generated exposure, peak concentration and EF (H = 43.4–46.6, all $p < 0.001$; ε^2 = 0.65–0.72). Dunn post-hoc tests with Bonferroni adjustment indicated that pan- and stir-frying were consistently higher than boiling and steaming across outcomes (*i.e.* pan-frying *vs.* boiling, adj $p \leq 0.001$ for all four metrics). Pan-frying also exceeded air-frying/oven (adj p = 0.010–0.019) and steaming (adj p = 0.003–0.010) across multiple metrics. Deep-frying was higher than boiling for cooking-generated exposure, peak concentration and EF (adj p = 0.007–0.033), whereas many fry-vs-fry contrasts were not significant after adjustment. Braising showed intermediate medians with wide variability, yielding few adjusted pairwise differences.

To capture the heavy tail explicitly, we classified cooking events as high-emitter or low-emitter using the single-dish EF distributions as the reference. Cooking methods that cluster at low EF, including boiling, steaming, air-frying, oven cooking and stewing, were defined as the low-emitter group, while methods associated with higher EF (pan-/stir-/deep-frying and braising) were defined as the high-emitter group. Applied to the full dataset, including multi-dish events, any event that included any high-emitter method was labelled high emitter, and those with no high-emitter methods were low emitters. This yielded 93 high-emitter and 32 low-emitter events. Their cooking-generated exposure and elevated exposure time (minutes with $PM_{2.5}$ > 15 μg m^{-3}; WHO 24-h guideline[3]) were compared and presented in Fig. 2.

Fig. 2 shows that high-emitter events dominate exposure. Their means of cooking-generated exposure values are 4450.7 μg m^{-3} min, and their elevated exposure times are correspondingly longer, often extending well beyond 15 μg m^{-3} with their mean at 125.2 min. For low-emitter events, the mean of cooking-generated exposure only falls at 174.7 μg m^{-3} min and the averaged elevated exposure time at 3.9 min, with 27 out of the 32 low-emitter events showing no time of $PM_{2.5}$ concentration higher than 15 μg m^{-3}. The distributional shape is equally informative: low emitters cluster tightly with short tails, whereas high emitters exhibit broad IQRs and long right tails. This reflects both routine high-output frying and occasional very large episodes. These observations echo the heavy-tailed emission factors and size-resolved emission rates reported across frying/grilling experiments, where a small proportion of events account for a large proportion of emitted particles.[39,62,67] Because cooking-generated exposure, calculated by subtracting background level from measured concentrations to determine the excess area-under-the-curve (AUC_{ex}), integrates PM concentrations over time, only a small number of high-emission

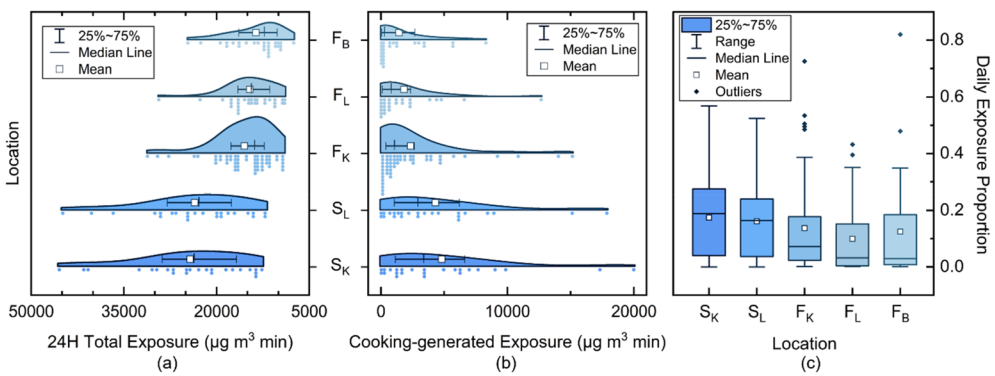

Fig. 3 Spatial distributions of $PM_{2.5}$ exposure by dwelling type and room (studio cooking days, N = 24; flat cooking days, N = 58). (a) 24-h total exposure (μg m^{-3} min), (b) cooking-generated exposure (μg m^{-3} min; time-integrated excess above background from cook start until return to background), and (c) daily cooking-attributable exposure fraction (cooking-generated/24-h total) at five locations: S_K (studio kitchen), S_L (studio living/sleeping), F_K (flat kitchen), F_L (flat living room), F_B (flat bedroom).

Table 1 Living/kitchen reductions ($1 - L/K$) in peak concentration of $PM_{2.5}$, cooking-generated exposure, and elevated exposure time (≥15 μg m^{-3}), the living room peak time lag relative to the kitchen, and average particle decay rate at kitchen by ventilation condition

Living room ventilation condition (N events)	Peak concentration	Cooking-generated exposure	Elevated exposure time	Peak time lag (min)	Particle decay rate (h^{-1})
No vent (34)	3.3%	3.3%	5.3%	1.1	0.47
Only window open (15)	3.3%	15.1%	10.6%	3.7	1.09
Only extractor on (28)	17.2%	8.3%	7.1%	3.4	0.81
Full vent (11)	19.1%	20.6%	15.8%	3.0	1.52

events can contribute a substantial share of cumulative dose over weeks of monitoring, which is a pattern reinforced by high-resolution cooking studies showing sharp, high-intensity peaks and prolonged tails.[13,63]

3.1.2 Spatial patterns and ventilation trade-offs. Cooking-generated PM was not confined to the source zone, while interzone transmission depended strongly on ventilation. Fig. 3 shows spatial gradients in both 24-h total exposure and cooking-generated exposure and Table 1 values represent reduction rates between kitchen (K) and (a) living room (L), (b) bedroom (B). In studios (S), kitchen (S_K) and living space (S_L), which is also the sleeping area, distributions are nearly indistinguishable for both panels (Fig. 3a and b), indicating an effectively single-zone exposure environment during both plume and decay. In flats (F), the ordering of exposure is kitchen (F_K) ≥ living space (F_L) >> bedroom (F_B), showing that a single interior door can substantially decouple bedroom exposure from the kitchen/living zone.

Cooking contributed the largest fraction of daily exposure in kitchens and a lower fraction in living spaces (Fig. 3c). In flats, the bedroom cooking fraction could exceed that of the kitchen/living area despite lower absolute concentrations, consistent with a lower non-cooking background in the more isolated bedroom.[68] Pre-cooking background $PM_{2.5}$ was low and broadly similar across rooms (kitchen 5.2–12.6, living room 5.4–11.5, bedroom 5.8–10.9 μg m^{-3}; >92% of values below 15 μg m^{-3}), supporting attribution of subsequent peaks to cooking, rather than persistent background or outdoor access due to locations of the study sites, such as high floor, being far from major roads and/or facing green space.[16,50,69,70]

These spatial patterns follow indoor mass-balance expectations and have been observed in prior residential studies, where cooking particles disperse rapidly through connected spaces, especially in open-plan layouts.[71] Field and research-home studies regularly report near-synchronous kitchen/living peaks and short lags when doors are open or spaces are connected, with the range hood and/or window affecting and decay rather than preventing spread.[72–74] For example, Xiang, Hao[73] observed 1 to 7 minutes delays on peak and kitchen/living 1-min peaks of 200–1400 μg m^{-3} during pan-frying, which was nine times higher than bedroom peak levels when isolated. The heavy-tailed exposure distributions we observed also suggest that a minority of high-emission events drives much of day-to-day indoor dose in homes, as shown in population representative and test home studies (including HOMEChem).[50,74]

Our contribution here is to quantify how strongly compact layout and simple behaviours shape exposure: studios behaved as near single-zone environments (SK ≈ SL), whereas in flats the bedroom was strongly protected by door closure, producing large reductions (~68% peak, ~78% cooking-generated exposure, ~91% elevated-time) and long lags (~79 min) even when kitchen decay rates were similar (Tables 1 and 2). The bedroom findings quantify a practical principle that closing interior doors substantially attenuates and delays PM transport to receptor rooms. This highlights that source-room clearance and receptor-room protection are not the same outcome, and that

Table 2 Bedroom/kitchen reductions ($1 - B/K$) in peak concentration of $PM_{2.5}$, cooking-generated exposure, and elevated exposure time (≥15 μg m^{-3}), the bedroom peak time lag relative to the kitchen, and average particle decay rate at kitchen by ventilation condition

Bedroom ventilation condition (N events)	Peak concentration	Cooking-generated exposure	Elevated exposure time	Peak time lag (min)	Particle decay rate (h^{-1})
Bedroom door open (18[a])	21.9%	17.4%	26.0%	16.8	0.82
No vent (4)	5.5%	12.4%	20.9%	18.8	0.30
Only window open (2)	29.6%	14.8%	N/A[b]	17.0	1.06
Only extractor on (6)	27.7%	11.7%	26.4%	16.3	0.63
Full vent (5)	32.3%	27.6%	27.8%	15.2	1.39
Bedroom door closed (19)	67.8%	77.6%	90.9%	79.1	0.83
No vent (3)	45.8%	91.7%	N/A[b]	69.3	0.38
Only window open (3)	65.2%	80.6%	87.3%	75.3	1.04
Only extractor on (9)	67.7%	77.0%	87.5%	83.8	0.66
Full vent (4)	86.3%	93.0%	96.0%	78.5	1.41

[a] A total of 18 events were recorded with the bedroom door open; however, ventilation information was unavailable for one event, so the subsets sum to 17. [b] N/A denotes that the $PM_{2.5}$ concentration did not meet or exceed 15 μg m^{-3} at any point in the event.

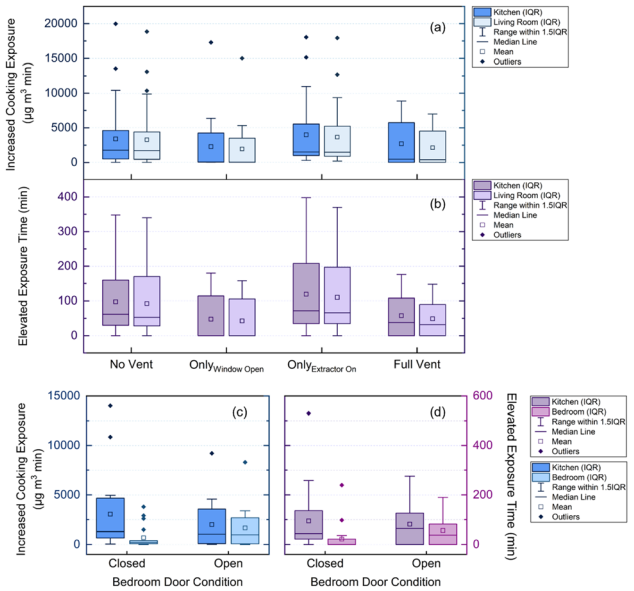

Fig. 4 Ventilation and bedroom-door effects on cooking exposure and elevated exposure time. (a and b) Kitchen *vs.* living room under four ventilation states: no Vent, window only, extractor only, full vent (hood + window). (c and d) kitchen *vs.* bedroom by door condition (closed/open).

door position can dominate bedroom exposure in multi-room homes.[71]

Detailed ranges of cooking-generated exposure and the exposure time with higher than 15 μg m^{-3} $PM_{2.5}$ levels in kitchens, living rooms and bedrooms are presented in Fig. 4. Given that bedroom windows were advised to be closed during cooking and for 60 minutes post-cooking, all ventilation conditions noted here refer to the living room/kitchen zone. From Table 1, under no-vent (extractor off, window closed), the average reductions in living room were small for peak concentrations (3.33%) and cooking-generated exposure (3.29%), with a short peak lag (1.13 min), indicating near well-mixed behaviour between kitchen and living space, with rapid transport. Opening only the window yielded similarly small reductions for peaks (3.31%) but a clearer drop in exposure (15.08%) and a longer lag (3.71 min), consistent with faster dilution at source and slightly delayed propagation. Running only the extractor produced larger reductions (17.15% peak, 8.30% exposure, lag 3.38 min). The full-vent (*i.e.* extractor + window) condition, produced the largest kitchen-to-living reduction overall (19.09% peak, 20.64% exposure, lag 3.00 min). In other words, the living area was rapidly impacted under open-plan connectivity, and reductions relative to the kitchen increased as ventilation improved.

The average particle decay rates in kitchen stepped up from 0.47 h^{-1} (no-vent) to 0.81 h^{-1} (extractor only) and 1.09 h^{-1} (window only), with full-vent highest at 1.52 h^{-1}, presented in Table 1, and similar results found in the group of kitchen-bedroom monitoring events in Table 2. Meanwhile, air exchange also contributes to particle removal and therefore to the observed decay rates.[58] We estimated AER from CO_2 decay tests conducted when dwellings were unoccupied and no cooking was underway. Results are summarised as two ranges (low *vs.* high ventilation), with a box plot provided in SI Fig. S4. Hoods mainly reduced peaks (source capture), window opening increased clearance (dilution/air exchange), and together produced the largest benefits. The doubling-to-tripling of decay rates with window opening/full ventilation is consistent with previous findings by a Canadian multi-home analysis and the indoor aerosol theory.[75,76]

When looking into the particle removal performance of extractors, only two out of the 11 accommodations were equipped with vented hoods, which extracted indoor air using ducting leading to the outside, while the others were all using recirculating hoods, removing particles by a filter (generally a charcoal filter). Four events were recorded while operating the vented extractor and these showed high kitchen decay rates ranging 1.86–2.16 h^{-1} when the window was also open (full-vent) and 1.46 h^{-1} with window closed; these values were all above the study-wide means. This aligns with controlled tests which demonstrated that ducted hoods can achieve much higher capture/removal of cooking particles than recirculating units, whose performance is sensitive to filter condition (*i.e.* cleanliness and age); reported reductions for recirculating systems are often modest (*e.g.* ~30% $PM_{2.5}$ with fresh carbon filters, degrading within weeks).[72,77–79]

Bedroom transmission depends chiefly on whether the door is open or closed with reduction rates shown in Table 2 and Fig. 4c and d. With the door open, median reductions were ~22% (peak concentration), ~17% (exposure) and ~26% (time ≥ 15 μg m^{-3}) with a peak lag ~17 min, although the bedroom still experienced ~70–80% of kitchen peaks and exposures with a moderate delay. Under no-vent and door-open conditions, peak reduction was minimal (5.47%) which suggested well-mixed air and was also due to low absolute concentrations close to background levels in three of the four samples from low emission methods. When the door was closed, reductions were much larger and the averaged lags were longer, reflecting the protocol instructing occupants to keep the door closed for at least 60 minutes after cooking. Within the closed-door subset, full vent produced the largest reduction in kitchen-to-bedroom $PM_{2.5}$ (see Fig. 4c and d). Kitchen decay rates in the door-closed cases (~0.38–1.41 h^{-1}) were similar to those with the door open, indicating that compartmentation, not faster kitchen clearance, is the dominant driver of bedroom protection.

Besides the layout of the accommodations and interior door status, the dwelling type and form factors, such as studio *versus* flats and overall volume, also play a critical role. Studios were smaller (47–53 m^3) with limited window provision, whereas flats were larger (95–125.5 m^3 total; 66–92 m^3 kitchen per living) and typically had more windows, even though their opening widths were limited as well, supporting cross-ventilation.[80,81] These differences likely contribute to higher absolute exposures and larger cooking-attributable fractions in studios (Fig. 3).[76,82,83]

3.1.3 Emission dynamics. Fig. 5 summarises the $PM_{2.5}$ emission dynamics of three representative events with their operational settings embedded in the traces. In Fig. 5a, a flat with an open-plan kitchen/living area underwent deep-frying followed by pan-frying, resulting in two peaks (106.0 and

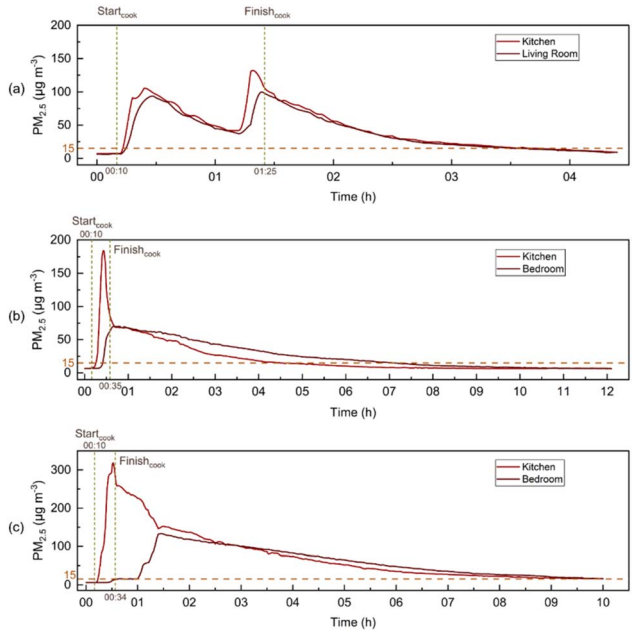

Fig. 5 Samples of $PM_{2.5}$ emission dynamics, with the vertical dotted lines indicating the time points of cooking start and finish, from left to right, respectively. (a) Deep-frying followed by pan-frying, with extractor on and window closed during cooking; (b) pan-frying, with extractor on, window open and bedroom door open during cooking; (c) pan-frying, with extractor on, window open and bedroom door closed during cooking.

135.4 μg m^{-3}). The range hood was on during cooking and off immediately afterwards, with at least one of the living room windows open. The recording shows almost synchronous peaks in the kitchen and living area with only a small lag of a couple of minutes. The concentrations jump rapidly once ingredients come in contact with the hot oil, then drop quickly as the heat is reduced, followed by a slow decay. The dashed 15 μg m^{-3} line shows that $PM_{2.5}$ remained above the WHO 24-h guideline for several hours, indicating substantial post-cooking exposure even with window dilution.

In Fig. 5b, a one-bedroom flat experienced pan-frying with the hood on during cooking and off as soon as the cooking activity finished. The bedroom door was open throughout, and the windows in the living room were also open. The $PM_{2.5}$ concentration peaked first at 193.4 μg m^{-3} in the kitchen, then the peak in the bedroom was observed at 70.9 μg m^{-3}, which was 12 minutes after the peak in the kitchen. After the door-enabled connectivity was established, the two rooms exhibited similar decay constants during the first hour, which was consistent with a well-mixed zone. However, a possible closure of bedroom door and/or opening of the additional living room window after the first hour of decay was deduced due to the quicker decay rate in kitchen while the bedroom's remained unchanged.

Fig. 5c presents another flat during pan-frying with the hood on, and is also a representative example of evening high-emitter cooking in a compact dwelling where limited post-cook ventilation and door status can extend elevated $PM_{2.5}$ into typical sleep hours. The bedroom door was initially closed, possibly briefly opened and re-closed at around the 34th minute, then left open from the 64th to 86th minute before closing it again. The living room window was open during cooking and closed right after cooking, with the bedroom window closed all the time. The brief opening near the end of cooking finished time triggered a rapid rise in the bedroom concentrations as the kitchen concentration was approximately at the peak value. Once the door was left open, the bedroom approached the kitchen level within about 20 minutes. Thereafter, the kitchen cleared faster, potentially owing to the open living-room window, whereas the bedroom concentration decayed more slowly due to a lower air-exchange rate due to the closed window. Because this event started after 19 : 00, $PM_{2.5}$ concentrations in the bedroom remained above the WHO 24-h guideline (15 μg m^{-3}) for around 9.5 hours, extending into the night until morning. This implies that occupants were exposed during sleep, which highlights the particular importance of evening peaks and raised health concerns. Furthermore, this is not uncommon in our dataset: evening cooking occurred frequently (*i.e.* 91/247 logged events after 18 : 00), and prolonged elevated exposure ($PM_{2.5} \geq 15$ μg m^{-3}) was repeatedly observed for high-emitter events under poorer ventilation and/or non-isolated sleeping areas (*i.e.* 30/93 high-emitter events > 140 min; 12/93 > 240 min).

These patterns are consistent with rapid propagation of cooking fumes through connected spaces, minute-scale lags between kitchen hobs and living areas, and extended decay tails governed by air exchange rates and deposition.[58,71,73] In addition to the cooking process, sharp initial rises may also occur before ingredients are added, as hot oil in the heated cookware emit PM, especially ultrafine particles, which inflate the early phase of the episode.[1,34,48,64]

3.1.4 Event-integrated personal exposure and elevated exposure time. Table 3 presents the estimated inhaled cooking-attributable $PM_{2.5}$ dose (above background) under three behavioural scenarios, using the kitchen monitor as the exposure proxy given limited time-activity records. Summed across the 125 valid events, the inhaled $PM_{2.5}$ dose attributable to cooking was 1.73 mg if exposure is limited to the cooking period only (scenario A), 2.76 mg if the occupant remains another 60 minutes post-cooking (scenario B), and 4.66 mg if the occupant is present for the entire event until return to background level (scenario C). Annualised using 300 days of cooking per year (N_{days}) as an upper-central scenario estimated based on UK surveys,[59,60] these correspond to 6.42, 10.22 and 17.25 mg per year, respectively. Annualised values under alternative N_{days} and IR assumptions are reported in the SI (Tables S3–S4).

Table 3 Estimated inhaled $PM_{2.5}$ dose (μg) from cooking by behavioural scenario. Scenarios: A = cooking only, B = cooking + 60 min post-cooking, C = entire event until return to background

	Scenario A	Scenario B	Scenario C
Total	1734	2762	4661
High emitter	1695	2707	4599
Low emitter	39	55	62
Annual total estimation	6417	10 219	17 245

For context, an independent personal exposure study which converted full-day exposures, including all microenvironments and all sources, to estimate the total inhaled $PM_{2.5}$ dose reported at around 0.94 mg per day (~343 mg per year) for urban adults.[84] The orders of magnitude were much larger than our estimates, because they included ambient and non-cooking indoor exposure, while our values isolated cooking-incremental intake only. In studies on school-age and adult daily-dose, they typically report total inhaled $PM_{2.5}$ masses from tens to more than 1000 μg per day, depending on ambient levels, activity and ventilation.[85,86] Although our annualised cooking-incremental intakes are a modest share of annual totals, they are important at the event scale, because high-emitter cooking drives most of the cooking-related intake.[87]

Personal exposure evidence similarly indicates that cooking can dominate short-term $PM_{2.5}$ peaks and contribute a substantial fraction of daily integrated exposure. For example, in a 7-day panel study of non-smoking adults, cooking was identified as the strongest predictor of personal $PM_{2.5}$ peaks, and two representative cooking episodes accounted for approximately 14% and 40% of a day's integrated exposure.[17] Controlled house and field campaigns likewise report repeated mealtime-driven indoor peaks followed by multi-hour decay tails, meaning that a relatively short activity can contribute disproportionately to daily dose.[38,41,50,74] Review and synthesis papers also emphasise that frying can generate event-level peaks of hundreds to >1000 μg m^{-3} with high inter-event variability, producing heavy-tailed exposure distributions in which a minority of episodes contributes most of the cumulative cooking-attributable exposure.[48,88]

Across our dataset, more than 30% of the cooking events were observed to result in the elevated exposure time (≥15 μg m^{-3}) of more than two hours, including seven cases lasting more than five hours, in kitchens, with living-room time scales typically similar to those of the kitchens due to the open-plan spaces, and bedroom durations depended strongly on door status (near zero when doors are closed and similar to kitchen durations when doors are open), as shown in Fig. 2, 4b and d.

Notably, evening cooking means that exceedances can extend into sleep hours; ~10% of our bedroom assessments recorded elevated exposure for >6 h during high-emitter cooking. This is relevant because short-term $PM_{2.5}$ increases have been linked to acute cardiovascular responses (including same-day myocardial infarction within hours) and to sleep-related cardiometabolic effects such as higher night-time blood pressure and blunted nocturnal dipping.[6,22,89–91] Personal exposure studies also report reduced heart-rate variability with higher $PM_{2.5}$, consistent with autonomic imbalance that can persist into the sleep period.[92,93]

3.1.5 Recommendations for PM exposure reduction. From a practical and cultural standpoint, exposure can be reduced by limiting high-emitter intensity and reducing time near the source during the decay tail (*i.e.* avoiding scenario-C-like behaviour). This can be achieved through source capture and dilution: avoid oil smoking, use a lid/splatter screen, run the extractor early and keep it on after cooking, keep pans within the capture zone, favour low-emitter methods where feasible, and open windows during and after cooking. Where possible, choose or configure homes with an operable kitchen window and a closable door separating kitchen and living/sleeping areas; keep the window open for at least an hour after cooking and keep the door closed except for brief movements to reduce pollutant transport and exposure. These measures align with evidence that effective ducted hoods and cross-ventilation reduce peaks and persistence, whereas recirculating hoods with aged filters provide only modest removal.[75,80,81] For evening cooking, prioritising extraction/ventilation and closing bedroom doors can shorten elevated exposure duration and reduce risks linked to nocturnal haemodynamics and sleep quality.[91,92,94]

3.2 NO_2 and O_3

Significant changes in concentrations of and exposure to NO_2 and O_3 during cooking activities were found in 61 and 52 out of the 125 total cooking events, and are presented in Tables 4 and 5 for NO_2 and O_3, respectively. In terms of NO_2, across all valid events, the increases in concentration were small, with the median at 0.71 and ranged 0.11 to 2.73 μg m^{-3}. Corresponding cooking-generated NO_2 exposure had a median of 21.98 μg m^{-3} min, contributing a median 0.23% of the daily NO_2 exposure. Grouped by emission class, high-emitter events produced more cooking-generated NO_2 exposure overall (median 23.7 μg m^{-3} min) than low-emitters (median 16.9 μg m^{-3} min). This occurred despite their slightly lower median concentration increase (0.70 *vs.* 1.07 μg m^{-3}), indicating that high-emitters tend to last longer and sustain elevated levels, which drives up total exposure. Ozone typically declined during cooking, with the median in decreased concentrations at 0.46 μg m^{-3} and exposure at 58.11 μg m^{-3} min. A modest inverse association was observed between NO_2 increase and O_3 decrease (Pearson $r = -0.34$, $p = 0.007$), suggesting fast NO–O_3–NO_2 titration chemistry in low-NO_x indoor air.[95]

For context, the background levels (pre-event baselines) in our accommodations were low, with NO_2 ranging from 2.25 to 17.22 (median at 6.69) μg m^{-3}, and O_3 ranged from 19.08 to 26.86 (median at 20.87) μg m^{-3}. These values lie within typical residential ranges reported internationally, where indoor NO_2

Table 4 Increased NO_2 concentration (μg m^{-3}), increased exposure (μg m^{-3} min) and fraction of 24-h exposure of cooking generated NO_2. Values are shown as range (median) for all, PM high-emitters, and PM low-emitters

	Increased concentration	Increased exposure	Cooking/24H exposure
All ($N = 61$)	0.11–2.73 (0.71)	1.38–82.89 (21.98)	0.03–1.04% (0.23%)
PM high emitter ($N = 44$)	0.11–2.73 (0.70)	8.09–82.89 (23.65)	0.14–1.04% (0.22%)
PM low emitter ($N = 17$)	0.14–2.19 (1.22)	1.38–81.54 (15.17)	0.03–0.86% (0.24%)

Table 5 Decreased O_3 concentration (μg m^{-3}) and decreased O_3 exposure (μg m^{-3} min) during cooking events. Values are shown as range (median) for all, PM high-emitters, and PM low-emitters

	Decreased concentration	Decreased O_3 exposure
All ($N = 52$)	0.02–2.74 (0.46)	12.53–201.46 (58.11)
PM high emitter ($N = 38$)	0.02–2.74 (1.10)	12.53–201.46 (58.98)
PM low emitter ($N = 14$)	0.02–2.15 (0.20)	39.00–118.43 (57.17)

in homes without gas combustion is often lower than 40 μg m^{-3}, and indoor O_3 commonly sits in the low-tens μg m^{-3}.[29,30,69,77,96] The low in-home backgrounds suggest limited outdoor pollutant access during monitoring, which therefore ensures that reporting increased metrics tends to be more appropriate for our specific dataset.[18,46]

These weak NO_2 signals align with the absence of indoor combustion while cooking. Field and intervention studies consistently show that gas stoves elevate indoor NO_2 by tens of μg m^{-3} over hours, while switching to electric or induction hobs eliminates the combustion source and significantly reduces the household NO_2 exposure.[18,30,97] Our increased NO_2 medians (*ca.* 0.7 μg m^{-3}) are significantly lower than those found in homes with gas stoves (*ca.* 39.5 μg m^{-3}) as reported by Paulin, Williams.[98] The co-occurring ozone dips and negative NO_2/O_3 correlation fit established indoor air chemistry: ozone is primarily of outdoor origin indoors and is readily removed by surface deposition and reactions with NO/NO_2 and cooking-emitted volatile organic compounds (VOCs), with modest decreases during cooking frequently observed.[13,46,96]

Occasional small NO_2 increases under electric cooking may arise from nitrogen-containing ingredients (*i.e.* cured meats, high-protein items, processed potatoes, *etc.*) and/or thermal decomposition of kitchen nitrates, as noted in some kitchen chemistry studies, but such contributions are typically minor relative to gas combustion.[32,99–101] The slightly higher median of increased NO_2 under PM low-emitter groups, which largely included water-based or water-rich cooking methods, than the PM high-emitters could reflect relative humidity effects on the electrochemical NO_2 sensor response and/or on heterogeneous indoor chemistry, as humidity can modulate both sensor signal and gas-phase/heterogeneous reaction pathways.[46,56] All observed backgrounds and concentrations during cooking were well below the health-based benchmarks commonly used for indoor air quality assessment, *i.e.* 25 μg m^{-3} of 24-hour NO_2 and 100 μg m^{-3} of 8-hour O_3 by WHO.[3] Together with the electric hob context, this supports the interpretation that our homes exhibited low NO_2 and O_3 pollution and that day-to-day variability was dominated by background infiltration and indoor chemistry, instead of cooking combustion.

3.3 Limitations of the study

Using low-cost sensors (LCSs) in lived-in homes enables observation of cooking emissions and the transport of pollutants under natural conditions and behaviours, but it also introduces uncertainties. Although we co-located sensors for calibration and applied manufacturer compensation on temperature and relative humidity, the electrochemical channels for NO_2 and O_3 and optical PM sizing inevitably carry residual bias. Accordingly, we prioritised changes/excess over background and avoided over-interpreting absolute values of the gaseous pollutants. Despite the observational design and heterogeneous behaviours, robustness is supported by the number of recorded events ($N = 125$) across multiple homes and our use of non-parametric comparisons with effect-size reporting for skewed outcomes. Where subgroup sizes are small (*e.g.* less common cooking methods), findings are treated as exploratory and interpretation focuses on consistent directional patterns and aggregated groupings (*e.g.* high- *versus* low-emitter classification), while recognising that absolute magnitudes vary with dwelling configuration, hood condition and occupant practice.

We also note that 2-min weighted averaging may slightly smooth very sharp peaks. Room concentrations near an active kitchen are highly sensitive to local mixing and short-lived thermal plumes, as well as ventilation that varies with outdoor conditions (*i.e.* weather), window use, as well as building fabric, condition and maintenance. In flats, the living room and bedroom were not monitored simultaneously, so kitchen-bedroom contrasts inevitably include day-to-day variability in activities and airflow. Also, hood technology and maintenance were not standardised (most locations had recirculating units with filters, but often not recently cleaned), so part of the variability in decay and inter-room transport likely reflects hood type/cleanliness as well as user practice. In addition, behavioural data were collected with a light touch approach to avoid over-burdening volunteers and also to protect privacy, so we did not require volunteers to log off-cook window/door states or detailed dish characteristics.

Finally, this is a small, all-electric cohort of dwellings occupied by young adults in Birmingham (UK), so broader generalisability (*i.e.* other layouts, demographics, fuel types, *etc.*) should be tested in future work. Nevertheless, open-plan or small-volume homes are likely to experience near whole-space exposure during cooking, whereas multi-room dwellings can protect sleeping areas *via* door closure; combining source capture (hood) with dilution (window/air exchange) provides the most reliable reduction in event-integrated exposure. Therefore, looking ahead, future deployments that pair simultaneous multi-room logging with event-specific AER, light-touch behaviour sensors for door/window/hood state, and a simple check of hood flow/cleanliness would sharpen possible inferences without compromising natural behaviour. Accordingly, extrapolation beyond young-adult studio/flat residents (*e.g.*, families, children, older or clinically vulnerable populations) should be made cautiously and warrants dedicated follow-up deployments.

4 Conclusion

Our study used calibrated Persium low-cost sensors to observe real-world cooking emission dynamics, inter-room transport and decay, in lived-in UK homes with electric stoves. Cooking was identified as a major, but highly variable, source of indoor PM. Oil-rich and high-temperature cooking methods (pan-/stir-/deep-frying and braising) produced the highest PM peak concentrations and largest cooking-generated exposure, while water-based methods and air-frying/oven events were consistently lower. These high-emitter episodes also dominated dose and elevated exposure time (duration when $PM_{2.5}$ concentrations are higher than 15 μg m^{-3}), with multi-hour tails, raising concerns about exposure-related health impacts, especially from evening cooking events which frequently extended high concentration exposure into typical sleep periods. Spatially, the kitchens bore the greatest burden of pollutants, followed by open-plan spaces (living room for flats, and living/sleeping spaces for studios) that were affected within minutes, while the bedrooms of flats were strongly protected by door closure. Ventilation, including use of range hoods and window opening, enhanced the pollutant decay in the kitchens and yielded modest kitchen-to-living reductions, with the combination of window opening and hood extraction performed best. Summed inhaled $PM_{2.5}$ mass across 125 events was *ca.* 1.7–4.7 mg, depending on the exposure time, annualising to *ca.* 6–17 mg per year assuming 300 cooking days, which was relatively small in annual terms, but concentrated in short, high-dose periods aligned with peaks and also produced long tails post-cooking. Gaseous pollutant elevation under electric cooking was minor, with fewer than half of the events reporting small NO_2 increases and slight O_3 dips against low background levels. Practically, daily life strategies, such as preventing oil smoking, using a lid/splatter screen, operating a well-maintained (ideally ducted) hood with good pan placement, opening windows when feasible, keeping flats' bedroom doors closed during and after cooking, and minimising the time spent in the kitchen and in open-plan spaces, would significantly benefit indoor air quality and reduce exposure.

Author contributions

Conceptualisation was performed jointly by R. T. and C. P.; funding acquisition, supervision, and project administration were carried out by C. P.; study design, analysis plan, and metric definition were developed by R. T. with input from C. P.; resources (low-cost sensors) were provided by C. P.; field operations, including volunteer recruitment, sensor deployment, and participant instruction, were conducted jointly by R. T. and B. Y., and B. Y. additionally organised and digitised paper survey records from participants; low-cost sensor collocation and calibration, formal data curation, analysis, visualisation, and validation, and drafting of the original manuscript were carried out by R. T.; reviewing and editing of the manuscript were performed jointly by C. P., R. T., and B. Y.

Conflicts of interest

The authors declare no conflicts of interest.

Data availability

The data supporting this article have been included as part of the supplementary information (SI) and the full data sets supporting the conclusions of the study will be made available by the corresponding author upon request. Latest indoor research will be made available at https://github.com/IndoorAir. Supplementary information: cooking-activity survey materials, cooking-method definitions, sensor calibration details (incl. collocation plots and performance metrics), air-exchange-rate estimation and sensitivity tables for annual dose assumptions. See DOI: https://doi.org/10.1039/d5va00442j.

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