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How Routine Fragrance Product Use Elevates Indoor $PM_{2.5}$ Exposure in London Households

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Abstract

Fragrance products are ubiquitous in UK homes, yet the associated indoor $PM_{2.5}$ exposure remains poorly quantified under real residential conditions. Using high time-resolution measurements from 112 London homes between 2022 and 2024, together with a source-resolved framework, our study found that fragrance use markedly elevated indoor $PM_{2.5}$ exposure, with hourly peaks up to 1293 $\mu g/m^3$ for incense, 858 $\mu g/m^3$ for oil diffusers, and 622 $\mu g/m^3$ for candles. Across homes using those fragrance products, incense and oil diffusers each accounted for nearly 50% of bedroom $PM_{2.5}$ exposure, whereas candles contributed 14%. Exceedance of the WHO 24-h guideline (15 $\mu g/m^3$) was frequent, with a median exceedance rate of 40% in candle-using homes, and in some incense-using households, exceedances occurring on the majority of monitored days. Exposures were highest in compact dwellings and under inadequate room ventilation. As UK housing moves toward greater airtightness, these findings identify fragrance products as a dominant indoor $PM_{2.5}$ source and provide empirical evidence relevant to source-aware ventilation design and Net Zero housing assessments.

Keywords: indoor $PM_{2.5}$; fragrance product use; residential exposure; source-aware ventilation; airtight dwellings

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1. Introduction

The fragrance industry utilizes approximately 3,000 odoriferous compounds to formulate fragrance products widely recognized for promoting relaxation and improving sleep quality (de Groot and Frosch, 1997; Field et al., 2008). These products commonly range from combustible products such as incense and candles to non-combustible products such as air fresheners and fragrance diffusers (Ahn et al., 2015; Wolkoff and Nielsen, 2017; Zhang et al., 2024). Despite their perceived benefits, fragrance products are increasingly recognized as important indoor sources of fine particulate matter ($PM_{2.5}$). Exposure to fragrance-product-derived $PM_{2.5}$ has been associated with adverse respiratory and cardiovascular effects, but the risks under real residential conditions remain poorly characterized (Dimitroulopoulou et al., 2015; Hien et al., 2022; Trantallidi et al., 2015; Wolkoff and Nielsen, 2017; Yadav et al., 2024).

The evidence based on fragranced products in occupied dwellings is limited compared with the substantial experimental work on their emissions. Chamber and test-room studies have shown that combustible products such as candles and incense can be potent indoor particle sources; specifically, candles predominantly generate ultrafine particles, while incense produces $PM_{2.5}$ at concentrations several times higher than those from cigarette smoke or ambient background levels (Andersen et al., 2021; Hien et al., 2022; Lee and Wang, 2004; Mannix et al., 1996; Ofodile et al., 2024; Wang et al., 2007). Non-combustion oil diffusers have been examined to emit substantial $PM_{2.5}$ mass, with fragrance-derived terpenes acting as precursors to secondary organic aerosols (SOA) through reactions with indoor oxidants (Angulo Milhem et al., 2020; Huang et al., 2012; Nørgaard et al., 2014; Schwartz-Narbonne et al., 2021). Despite these mechanistic insights, real-world residential studies of indoor $PM_{2.5}$ have focused chiefly on dominant sources such as cooking and smoking, leaving the impact of fragranced products marginalized (Wallace and Ott, 2011; Yadav et al., 2024; Zheng et al., 2026) . Existing field studies remain limited in scope: a Danish study with roughly two days of monitoring in 56 homes showed that candles can dominate integrated particle exposure, but the short monitoring fails to capture the stochastic nature and longer-term fragrance-related $PM_{2.5}$ exposures (Bekö et al., 2013). A recent study in California examined incense burning in a single vacant house, providing detailed emission factors and organic $PM_{2.5}$ composition but no long-duration $PM_{2.5}$ time series or exposure metrics for occupied homes (Ofodile et al., 2024). A recent UK study of plug-in oil diffusers in 60 homes in Ashford focused on indoor volatile organic compounds (VOCs), leaving particulate emissions unquantified (Warburton et al., 2023). This limited residential evidence base on $PM_{2.5}$ is notable because fragranced products, particularly incense, are widely used in western countries with ethnically and religiously diverse populations, such as the United States and the United Kingdom (Jetter et al., 2002; Roberts, 2016).

There is also a lack of long-term and high time-resolution $PM_{2.5}$ datasets capable of detecting and characterizing fragrance-related episodes in situ. Existing indoor monitoring campaigns that include fragranced products typically span only hours to a few days per dwelling, and thus offer limited constraint on frequency, duration and determinants of fragrance-related $PM_{2.5}$ peaks. Chamber-derived emission factors and short-term monitoring, while informative about instantaneous emissions, cannot substitute for long-duration home measurements because they do not capture household-specific behaviours, ventilation regimes and loss processes that dictate event

frequency and persistence (Goodman et al., 2020; Lamplugh et al., 2020; Liu et al., 2004). To our knowledge, no previous work has integrated multi-week continuous $PM_{2.5}$ monitoring with systematic identification of fragrance-source events in a sizeable and diverse sample of occupied dwellings, leaving a significant gap in quantifying short-term $PM_{2.5}$ exposure burden linked to routine fragrance use.

These evidence gaps are increasingly salient as the UK Net Zero strategy reshapes the housing stock toward higher airtightness and lower carbon intensity (Treasury, 2021). In the UK, over 24 million homes account for approximately 40% of total carbon emissions in 2021 (Treasury, 2021). Furthermore, as around two-thirds of the current building stock is expected to still be in use by 2050, decarbonization pathways emphasize enhanced insulation and a transition to low-carbon heating systems (Abdalla and Peng, 2021; Climate Change Committee, 2020; Gupta and Kapsali, 2015). As building envelopes become more airtight, background ventilation rates decrease, potentially amplifying the influence of episodic, spatially localized indoor sources (Climate Change Committee, 2025). Fragrance products are therefore poised to become dominant determinants of indoor air quality in future dwellings. A clear and quantitative assessment of their contribution to current indoor air quality across different types of dwelling is essential to support credible indoor air quality projections under decarbonization scenarios and to reconcile energy efficiency with occupant well-being.

In response to these gaps, this study utilizes indoor measurements from the West London Healthy Home and Environment Study (WellHome), a transdisciplinary, community-based study of 112 households in socio-economically and ethnically diverse urban communities in London (Varaden et al., 2025). Using multi-month, high time-resolution $PM_{2.5}$ data and detailed questionnaires on fragrance product use, we systematically identify source events from incense, candles and oil diffusers; estimate source-specific $PM_{2.5}$ relative emission rates and their contributions to indoor $PM_{2.5}$ mass; quantify short-term exceedances of the WHO 24-h guideline associated with different fragrance products; and assess the dwelling-level drivers of fragrance-related $PM_{2.5}$ exposure. By situating these real-world findings within the broader experimental evidence, we provide an integrated assessment of fragrance-related $PM_{2.5}$ emissions and their implications for indoor exposure, mitigation strategies and the transition to low-carbon, airtight housing.

2. Methods

Fig. 1 outlines the methodological framework of this study. The analysis comprised five main stages: (1) collection and preparation of model inputs, including indoor measurements, household questionnaire data, building information, and outdoor air pollution and meteorological data; (2) estimation of time-resolved indoor $PM_{2.5}$ emission rates; (3) identification of fragrance emission events; (4) attribution of fragrance-source emission rates; and (5) quantification of source contributions to indoor $PM_{2.5}$. Each stage is described in detail in the following sections.

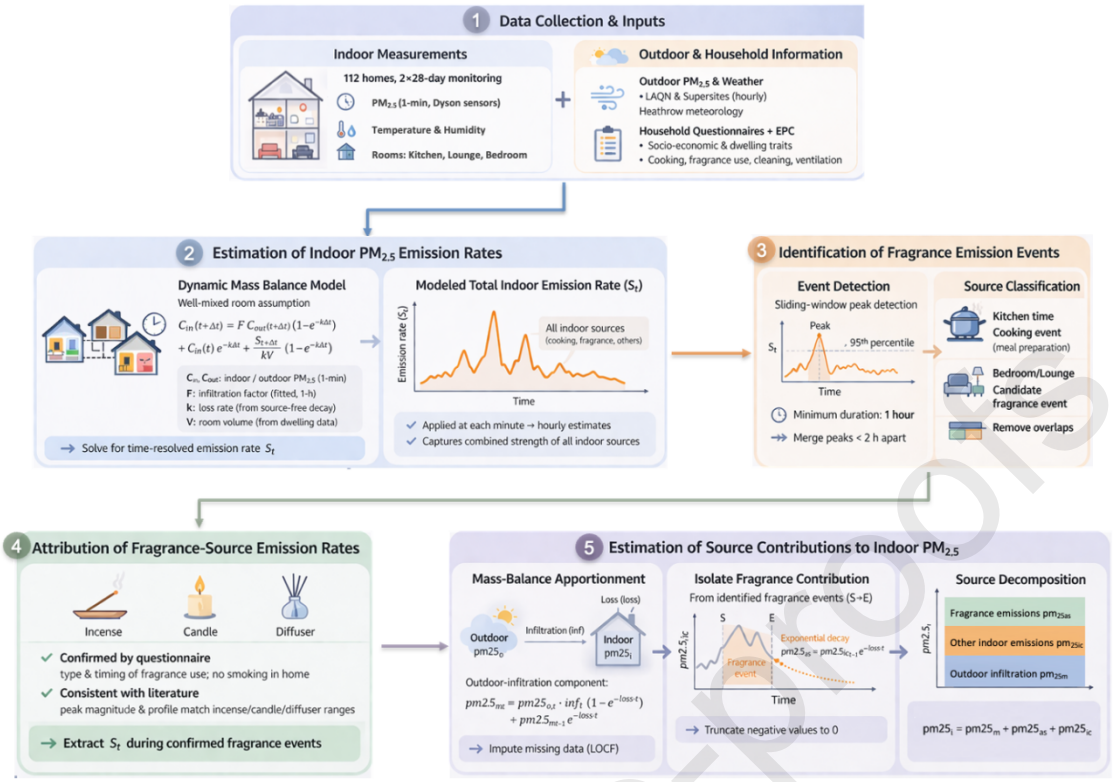


Fig. 1. Methodological framework for identifying fragrance emission events and estimating fragrance-source contributions to indoor $PM_{2.5}$.

2.1. Description of Household Characteristics

Residents of 112 homes were recruited for the West London Healthy Home and Environment Study (WellHome), a transdisciplinary community-based study. The spatial distribution of participating households within Greater London is shown in Fig. S1. Participants were randomly selected based on specific criteria: resident in the home for at least 12 months, a non-smoking household (defined as no use of combustible tobacco, e-cigarettes, or vaping devices), and the presence of at least one child with asthma. Among the 112 households, 78 are flats, 18 are mid-terrace houses, 8 are maisonettes, 6 are end-terrace houses, 1 is a detached house, and 1 is a semi-detached house. The average floor area is 77 m^2, ranging from a one-bedroom flat of 30 m^2 to a detached house of 261 m^2. The number of residents in each household ranged from 1 to 9, with an average of 4 occupants. Notably, 77 out of 112 households reported that at least one occupant stayed at home full-time.

The WellHome study was approved by the Imperial College Research Ethics Committee (ICREC Reference: 21IC7385, 22 June 2022), and written informed consent was obtained from all participating households. Full details of the study design and ethical procedures are available in a previous publication (Varaden et al., 2025).

2.2. Indoor and Outdoor Measurement

Indoor air quality and environmental measurements were obtained from the WELLHOME Real-Time Sensor Network, which operated from October 2022 to July 2024 across 112 homes in the WellHome community. In each home, kitchens, lounges, and bedrooms were monitored continuously during two separate 28-day periods, spaced approximately 3 to 6 months apart. The network employed CO_2 sensors recording at 15-minute intervals, alongside high-resolution Dyson sensors that collected per-minute data on $PM_{2.5}$, nitrogen dioxide (NO_2), total volatile organic compounds (TVOCs), formaldehyde (HCHO), temperature, and humidity. Sensors were placed in each room following consultation with the household to avoid proximity to known emission sources, including cooking appliances, fragrance products, and windows, ensuring that measurements reflected general room conditions. Sensors were calibrated against reference instruments at the start and end of the monitoring campaign. A two-stage calibration approach was applied to account for non-linear sensor response at high $PM_{2.5}$ concentrations, using factors derived from controlled ambient and high-concentration experiments. Details on the air pollution monitoring network and the rigorous quality assurance and quality control procedures applied to the data are available in a previous publication (Varaden et al., 2025).

Outdoor $PM_{2.5}$ data were incorporated into the indoor air quality analysis using measurements from multiple sources, including the London Air Quality Network (LAQN) (LAQN, 2024) and UKRI research "Supersites" at Marylebone Road and Honor Oak Park (Defra, 2024). Meteorological data was also obtained from Heathrow Airport (Met, 2024).

2.3. Household Questionnaires

Questionnaires were conducted with participating households throughout the study period and categorized into three main groups: (1) basic information on the household's cultural and socio-economic background; (2) dwelling construction characteristics and energy use for cooking and heating; and (3) household behaviours before and during the monitoring periods, including cooking habits, use of fragrance products (product type and usual weekly frequency; Table S1), cleaning practices, and ventilation preferences (both natural and mechanical). To further characterize the physical attributes of the dwellings, each household address was linked to the England and Wales Energy Performance Certificate (EPC) database (Government, 2017). This provided standardized information on dwelling type, floor area, energy rating, and related property features. Collectively, these data enabled integrated assessment of both social and physical determinants of indoor air quality and environmental conditions in the study population.

2.4. Estimation of Indoor $PM_{2.5}$ Emission Rates

To estimate the strength of indoor emission sources for $PM_{2.5}$, we applied a dynamic mass balance model assuming that indoor air is well-mixed within each room. The well-mixed assumption has been applied in previous residential indoor air quality

modelling studies and is more appropriate when concentrations are evaluated over periods longer than the characteristic room-mixing time. For residential rooms of similar dimensions, air mixing has been reported to occur within minutes (Vu et al., 2022). Although near-source concentration gradients may occur during active emission from point sources, these gradients are expected to decrease as particles disperse throughout the room, assuming more appropriate during the post-emission decay phase, which accounts for a substantial proportion of the overall exposure period. The temporal evolution of indoor $PM_{2.5}$ concentration, $C_{in}(t + \Delta t)$, was modeled according to a backward-difference formulation (Vu et al., 2022):

$$C_{in}(t+\Delta t) = F\,C_{out}(t+\Delta t) \cdot (1 - e^{-k\,\Delta t}) + C_{in}(t)e^{-k\,\Delta t} + \frac{S_{t+\Delta t}}{kV} \cdot (1 - e^{-k\,\Delta t}) \quad (1)$$

Where F is the particle infiltration factor (min^{-1}), k is the effective total $PM_{2.5}$ loss rate (min^{-1}), representing removal through air exchange, deposition, evaporation and chemical reactions, V is the volume of the room (m^3), and $S_{t+\Delta t}$ represents the emission rate of indoor $PM_{2.5}$ sources (μg/min). The time step Δt was set to 1 minute, consistent with the temporal resolution of the $PM_{2.5}$ measurements.

Rearranging equation 1 yields an explicit expression for the emission rate, described by equation 2:

$$S_{t+\Delta t} = [C_{in}(t+\Delta t) - F\,C_{out}(t+\Delta t) \cdot (1 - e^{-k\,\Delta t}) - C_{in}(t) \cdot e^{-k\,\Delta t}] \cdot \frac{\kappa V}{1 - e^{-k\,\Delta t}} \quad (2)$$

Indoor (C_{in}) and outdoor(C_{out}) $PM_{2.5}$ concentrations were obtained from synchronized monitoring data, and room volume (V) information was derived from the dwelling characteristics reported in the Household Questionnaires. The loss rate k was inferred from the decay of indoor $PM_{2.5}$ during periods identified indoor emissions and represents the combined effect of air exchange and other particle-removal processes across the particle-size distribution present during each decay episode (Vu et al., 2022). F was obtained by fitting the mass-balance model to paired indoor–outdoor $PM_{2.5}$ data and was re-fitted at each 1-h interval to capture hourly variations in air exchange conditions; within each interval, the fitted values were applied to the 1-minute resolution observations. This method was applied to each hourly time step, providing dynamic estimates of indoor source strength throughout the monitoring period. The resulting S_t series represents the combined contribution of all indoor sources, including cooking, fragrance products, and other occupant activities, and serves as the foundation for subsequent event identification and source attribution.

2.5. Identification of Fragrance Source-Related Emission Events

Candidate emission events were first detected using a sliding-window algorithm designed to identify short-duration indoor source activities. A peak was defined as any period where the modelled emission rate (S_t) exceeded the 95th percentile of its local 5 h background window, with the window shifted forward in 1-h increments while peak detection was conducted using the 1-min emission rate series. This 5-h time scale corresponds to the typical total duration of an indoor source episode, encompassing both the active emission phase and the subsequent particle decay phase, and is sufficiently long to distinguish such episodes from background noise. The 1-h interval

therefore refers to the updating of the background window rather than a minimum duration requirement for individual source events. Adjacent peaks separated by less than 2 h were merged into a single event to avoid over-segmentation of multi-phase episodes. The resulting event list was subsequently screened according to the room in which each event was detected and its temporal overlap with kitchen events.

Detected $PM_{2.5}$ emission events were subsequently classified according to the room in which they were recorded and their temporal context to distinguish fragrance-related activities from other indoor sources. Events occurring in kitchens during identified meal preparation periods were categorized as cooking-related events. Events detected in bedrooms or lounges, which were pre-identified as potential fragrance-use areas, were retained as candidate fragrance-source events. To minimize the risk of misclassification, any non-kitchen event that temporally overlapped with a kitchen event, defined as an overlap in start or end times within the same time window, was excluded if the corresponding kitchen event exhibited a higher average emission rate. This filtering ensured that retained non-kitchen events represented independent emission activities unrelated to cooking, providing a robust basis for subsequent fragrance-source attribution.

2.6. Attribution of Fragrance-source Emission Rates

Household questionnaire data were used to cross-validate fragrance-source attribution by confirming the types and frequencies of fragrance product use (e.g., incense, candles, oil diffusers) and any changes in usage patterns between or during monitoring campaigns. The questionnaires also confirmed that the monitored residences were free from tobacco use, thereby ensuring that fragrance-related signals were not confounded by smoking emissions. For each potential fragrance event, emission peaks were cross-referenced with the fragrance product types and typical usage patterns reported by each household. Furthermore, the magnitude and temporal profiles of observed peaks were quantitatively compared against emission rate ranges reported in controlled chamber and field studies for comparable products (e.g., incense, candles, or oil diffusers) (Andersen et al., 2021; Lee and Wang, 2004; Schwartz-Narbonne et al., 2021; Uhde and Schulz, 2015). Only events consistent with both questionnaire records and characteristic source ranges were retained as confirmed fragrance-related episodes. Their corresponding S_t values were extracted as fragrance-source emission rates. In practice, confirmed events were predominantly associated with households reporting frequent product use (multiple times per week or daily), providing additional consistency between the algorithm-driven detection and questionnaire-reported usage patterns. Households reporting infrequent use (≤1 time per week) rarely yielded events that satisfied all retention criteria, consistent with the lower probability of capturing sporadic use within the two 28-day monitoring windows. This multi-criteria cross-validation, combining time-resolved modelling, questionnaire evidence, and literature-based emission rate values, ensured robust identification of fragrance-source emissions and minimized the potential for misclassification with other indoor activities.

To illustrate the methodological framework, Fig. 2 presents a representative example from a household reporting daily oil-diffuser use. Fig. 2a shows the time series of $PM_{2.5}$ concentrations in the bedroom and kitchen over a continuous 9-days window

within the full monitoring campaign, together with outdoor and infiltrated $PM_{2.5}$. Fig. 2b shows one accepted bedroom oil-diffuser event identified within this period, providing a detailed example of the multi-criteria cross-validation used to confirm fragrance-related episodes. Additional representative cases for incense and candle events are shown in Fig. S2 and Fig. S3.

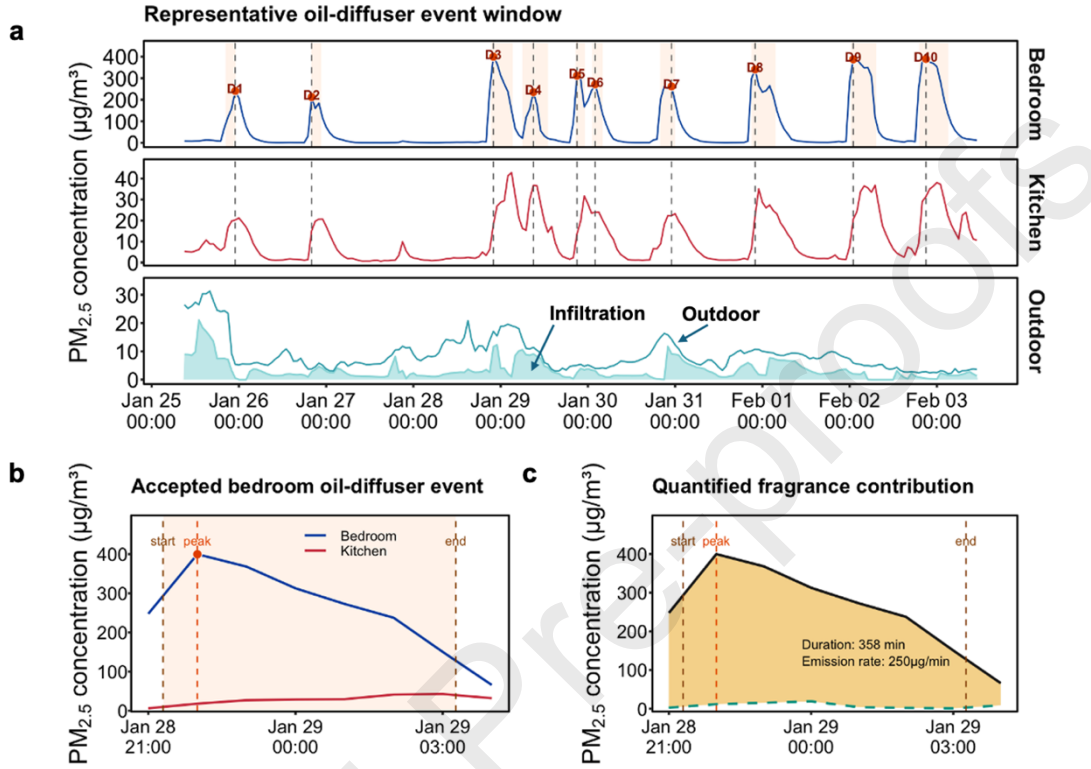


Fig. 2. Representative event identification and estimation of fragrance-contributed $PM_{2.5}$ in the bedroom of an oil-diffuser use household. (a) Time series of hourly $PM_{2.5}$ concentrations in the bedroom and kitchen during a representative monitoring window, with outdoor and infiltrated $PM_{2.5}$ shown in the outdoor panel; accepted bedroom fragrance events and their peak times are marked. (b) Time series of hourly $PM_{2.5}$ concentrations in the bedroom and kitchen during one accepted bedroom oil-diffuser event. (c) Illustration of fragrance-contributed $PM_{2.5}$ for the same accepted event, showing the event window used for estimating emission and contribution.

2.7. Estimation of Source Contributions to Indoor $PM_{2.5}$ concentrations

To quantify the contributions of fragrance emissions, other indoor sources, and outdoor infiltration to indoor $PM_{2.5}$ (denoted as pm25i), a dynamic mass-balance approach was applied under the assumption of a well-mixed indoor environment. Outdoor $PM_{2.5}$ concentration was represented by pm25o, while infiltration (inf) and loss (loss) coefficients were used to describe indoor–outdoor particle exchange and indoor decay processes, respectively (Vu et al., 2022). Missing values in these variables were imputed using a bidirectional last observation carried forward method to ensure temporal continuity (Vu et al., 2022). The indoor $PM_{2.5}$ attributable to outdoor infiltration (pm2.5m) was estimated by iteratively solving the indoor concentration at

each time step t as:

$$pm2.5m_t = pm25o_t \cdot inf_t(t) \cdot (1\text{-}e^{-loss \cdot t}) + pm2.5m_{t-1} \cdot e^{-loss \cdot t} \quad (3)$$

where the first term represents outdoor penetration and the second term denotes indoor persistence from the previous time step.

The residual indoor concentration increments due to indoor activities (pm2.5ic) was obtained as:

$$pm2.5ic_t = pm25i_t - pm2.5m_t \quad (4)$$

To isolate the fragrance-induced component ($pm2.5as$) of indoor $PM_{2.5}$, periods corresponding to fragrance use were identified using event markers ("S" for start, "E" for end), with the start and end times derived from the previously estimated emission rate dataset. During the decay phase following the end of each fragrance event, the remaining $PM_{2.5}$ concentration was modelled as an exponential loss (Vu et al., 2022):

$$pm2.5as_t = pm2.5ic_{t-1} \cdot e^{-loss \cdot t} \quad (5)$$

The residual pm2.5ic after subtracting pm2.5as represented $PM_{2.5}$ from other indoor sources. Negative values were truncated to zero.

This framework thus decomposes indoor $PM_{2.5}$ into three additive components:

$$pm25i = pm25m + pm25as + pm25ic \quad (6)$$

enabling quantitative attribution of indoor $PM_{2.5}$ concentrations to outdoor infiltration, fragrance emissions, and other indoor activities. Fig. 2c shows the event-based estimation of source contributions to indoor $PM_{2.5}$ for the same case described above, illustrating how fragrance-contributed $PM_{2.5}$ was quantified relative to the background concentration over the event period.

2.8. Assessment of Short-term $PM_{2.5}$ Exposure

The World Health Organization (WHO) recommends an indoor 24-hour average $PM_{2.5}$ Air Quality Guideline (AQG) level of 15 μg/m^3, defined as the 99th percentile (equivalent to 3-4 exceedance days per year) of the annual distribution of 24-hour means (WHO, 2021). The 99th percentile is intended to limit the adverse health effects associated with short-term $PM_{2.5}$ exposure. The WHO $PM_{2.5}$ guideline was developed primarily from epidemiological evidence on ambient $PM_{2.5}$ exposure worldwide. In the absence of a separate indoor-specific guideline, the WHO guideline value is used here as a health-protective benchmark for assessing $PM_{2.5}$ concentrations in indoor environments. Using this benchmark, we calculated the number of exceedance days for each fragrance-use household, defined as days when the daily average indoor $PM_{2.5}$ concentration exceeded 15 μg/m^3 in at least one monitored room. Daily average $PM_{2.5}$ concentrations were calculated separately for each room (bedroom, kitchen, and lounge). An exceedance day was defined as any day on which the daily mean concentration exceeded the WHO threshold in at least one room. For each household and campaign, we then summed the number of exceedance days over the campaign

period.

3. Results

3.1. Elevated Indoor $PM_{2.5}$ Concentrations in Fragrance-use Homes

As shown in Fig. 3, homes using fragrance products consistently exhibited higher indoor $PM_{2.5}$ than in homes without fragrance use in both bedrooms and lounges in both seasons. In the cold season, daily mean $PM_{2.5}$ concentrations in fragrance-use homes reached 9.2 μg/m^3 in bedrooms and 12.3 μg/m^3 in lounges, approximately 51% and 19% higher, respectively, than those in non-use homes. In the warm season, the corresponding values were 6.4 μg/m^3 and 10.6 μg/m^3, which were about 31% and 49% higher, respectively, than those in homes without fragrance use. The larger standard deviations observed in fragrance-use homes indicate substantial household-level variability (Table S2), likely reflecting differences in room volume, ventilation conditions, and fragrance-use patterns.

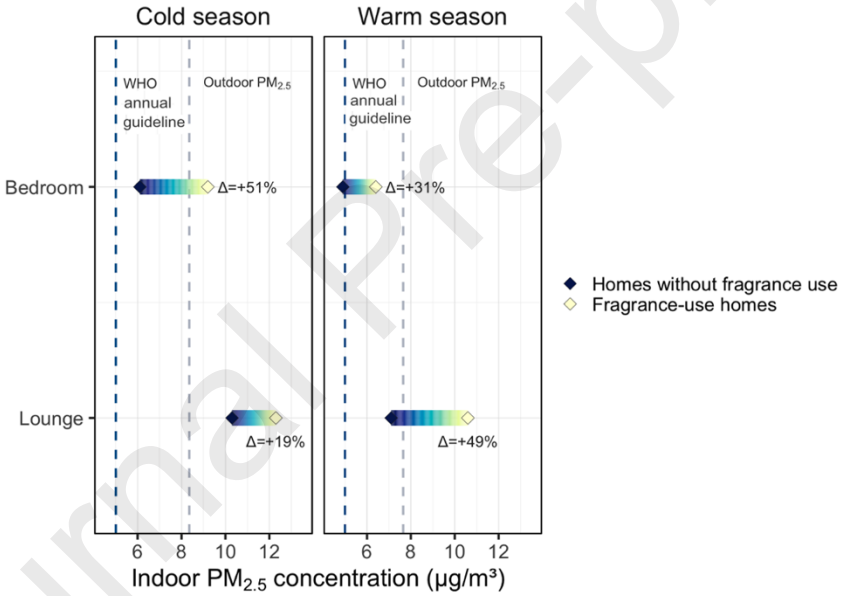


Fig. 3. Seasonal mean daily (24-h) $PM_{2.5}$ concentrations in homes with and without fragrance product use during the cold season (October–March) and warm season (April–September). Blue dashed line: WHO annual $PM_{2.5}$ guideline. Grey dashed line: Mean outdoor $PM_{2.5}$ concentrations during the sampling campaign.

Beyond these seasonal patterns, questionnaire data from 112 households showed that 82 reported fragrance use, including combustion-based types (candles and incense burners) and non-combustion types (air fresheners, reed diffusers, and oil diffusers). Additional results on fragrance product types and reported use frequency are presented in the Supplementary Results and Fig. S4. Analysis of per-minute $PM_{2.5}$ time series, excluding identified cooking periods, further showed that 28 homes exhibited unusually elevated $PM_{2.5}$ concentrations during non-cooking hours, attributable to candle burning,

incense burning or oil diffuser use. The remaining 54 fragrance-using households did not yield events that met all retention criteria. In total, 720 fragrance-source events were detected across these 28 homes, most frequently in bedrooms and lounges, consistent with household preferences reported in questionnaires. The diurnal patterns of hourly indoor $PM_{2.5}$ in homes reporting fragrance use showed strong temporal variability across the monitoring period (Fig. S5). Incense-use households exhibited the most pronounced evening peaks, with hourly concentrations frequently exceeding 40 $\mu g/m^3$. Candle-use households showed lower typical levels of around 12–15 $\mu g/m^3$, but 37% of identified burning events were associated with hourly peaks above 50 $\mu g/m^3$, with maxima up to 500 $\mu g/m^3$. Homes using oil diffusers generally had the lowest hourly $PM_{2.5}$ concentrations (about 8–10 $\mu g/m^3$), although a few households experienced sustained hourly concentrations above 400 $\mu g/m^3$ during periods of intense or prolonged use.

3.2. $PM_{2.5}$ Emissions and Sources Contribution from Fragrance Use

To contextualize the magnitude of fragrance-related emissions, we compared source-specific $PM_{2.5}$ emission rates from fragrance-related activities with kitchen emissions measured in the same households, utilizing the within-home kitchen median and 90th percentile (P90) as internal benchmarks (median = 454 μg/min; P90 = 891 μg/min) (Fig. 4a). Across the investigated fragrance categories, candle use exhibited the lowest $PM_{2.5}$ emissions, with median rates below 200 μg/min and distributions largely below 500 μg/min. Candle-event emission rates were typically below the within-home kitchen median benchmark, with only a small minority of events approaching the within-home kitchen P90 benchmark. This pattern is consistent with prior combustion studies, which indicate that stable burning generally yields lower particulate mass emissions, whereas brief periods of unstable burning can increase soot formation and elevate $PM_{2.5}$ emissions (Zai et al., 2006). Oil diffusers yielded median emission rates near 250 μg/min and intermittent episodes approached the kitchen P90 benchmark (924 μg/min). This indicated that while oil diffusers are non-combustive, they possess the potential for sporadic but appreciable $PM_{2.5}$ contributions. The observed variability in emission strength likely reflects the heterogeneous use inherent in real-world settings. Previous chamber tests have demonstrated that diffuser emissions are highly sensitive to operating intensity, oil formulation, and water composition. Specifically, the use of impure water has been shown to significantly elevate $PM_{2.5}$ concentrations, suggesting that household-level choices regarding device maintenance and refill quality act as critical determinants of exposure (Schwartz-Narbonne et al., 2021). Incense burning emerged as the most potent fragrance-related source, yielding the highest emission rates among all investigated fragrance products. With a median emission rate of (454 μg/min), incense use was found to be quantitatively comparable to kitchen activities, with peak events of 1293 μg/min frequently matching or exceeding major cooking episodes. This high emission intensity is intrinsically linked to the material composition of the incense, as reported in recent characterizations of incense biomass, emission factors are heavily dictated by the carbonaceous fraction of the woody substrate (Ofodile et al., 2024).

These emission rates were within the same order of magnitude as literature-reported values, with candle and incense emissions generally falling within reported ranges and

diffuser emissions more often aligning with the upper end of the literature (Andersen et al., 2021; Hu et al., 2023; Hu et al., 2012; Lee and Wang, 2004; Subramanian et al., 2025; Uhde and Schulz, 2015). Detailed source-by-source comparisons are provided in the Supplementary Results and Fig. S6. These results collectively indicate that while candles represent a relatively minor contribution to the indoor $PM_{2.5}$ emissions, oil diffusers can occasionally generate significant episodic peaks, and incense burning consistently poses the greatest exposure potential. In summary, this study demonstrated that all three fragrance sources had the capacity to generate $PM_{2.5}$ emissions at rates comparable to or exceeding those from cooking emissions, confirming them as important contributors to indoor $PM_{2.5}$ pollution in dwellings.

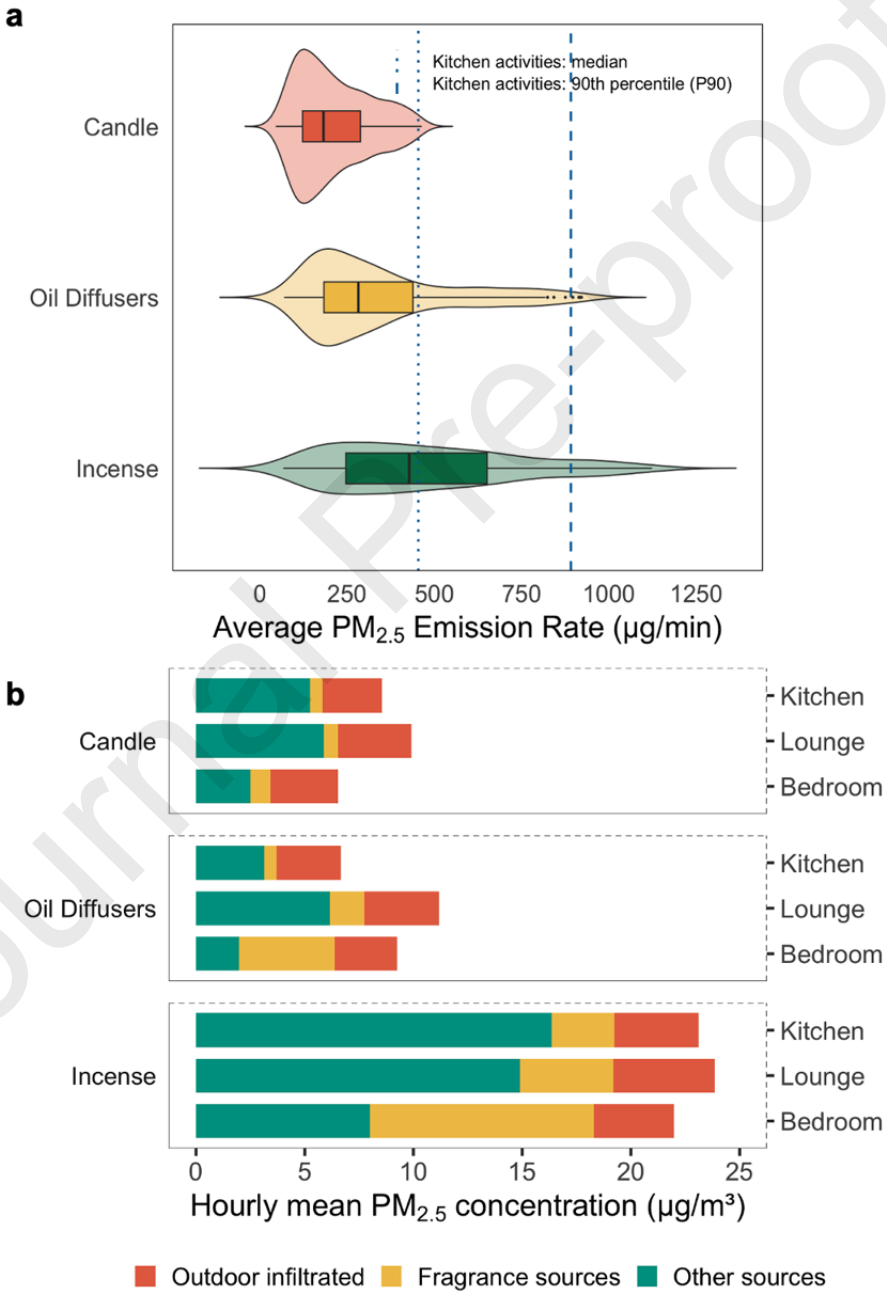


Fig. 4. Emission rates and indoor $PM_{2.5}$ contributions from domestic fragrance products. a, Average $PM_{2.5}$ emission rates from candles, oil diffusers and incense burners

compared with concurrent kitchen activities in the same homes. b, Source contributions to hourly mean indoor $PM_{2.5}$ concentrations in kitchens, lounges and bedrooms in homes using each fragrance product.

The contribution of outdoor-infiltrated $PM_{2.5}$ to indoor concentrations in bedrooms, lounges, and kitchens was examined for homes using fragrance products (Fig. S7). Although outdoor $PM_{2.5}$ occasionally exceeded 50 μg/m^3, indoor concentrations during fragrance-use episodes in some homes frequently reached 300 to 500 μg/m^3, with short-term peaks in bedrooms surpassing 1500 μg/m^3. These episodic extremes highlight the capacity for indoor sources to dominate $PM_{2.5}$ pollution over short timescales in fragrance-use households. To quantify source-specific contributions, we further estimated the relative contributions of outdoor infiltration, fragrance emissions, and other indoor sources on room-level hourly mean $PM_{2.5}$ concentrations, averaged over the monitoring period (Fig. 4b). In households using incense, mean indoor $PM_{2.5}$ averaged 22 to 25 μg/m^3 across rooms, nearly three times higher than outdoor $PM_{2.5}$ concentrations (8 μg/m^3). Incense emissions were the dominant contributors, accounting for approximately 47% of average $PM_{2.5}$ in bedrooms, 18% in lounges, and 13% in kitchens. Outdoor infiltration contributed only 17 to 20% of average indoor $PM_{2.5}$ across rooms, while the contribution from other indoor sources accounted for 36% of $PM_{2.5}$ in bedrooms and 70% in kitchens. The high residual contribution in kitchens is consistent with cooking as an important source, whereas the bedroom fraction may include both locally generated emissions and particles transported from other rooms, including kitchens; their relative contributions could not be quantified separately. These results indicate that incense combustion poses a substantial emission burden, especially in enclosed spaces such as bedrooms. Nevertheless, in homes using oil diffusers, average indoor $PM_{2.5}$ concentrations were lower, ranging from 10 to 15 μg/m^3. $PM_{2.5}$ from oil diffuser emissions contributed significantly to indoor exposure, accounting for 48% of $PM_{2.5}$ in bedrooms, 14% in lounges, and 8% in kitchens. Despite being non-combustion sources, the contribution was comparable to that of incense-use homes, likely to be a result of their continuous use. Outdoor infiltration ranged from 31 to 44% of $PM_{2.5}$, while other indoor sources contributed between 21 and 55%, depending on room type.

By contrast, candle use showed the lowest contribution from all fragrance products, with $PM_{2.5}$ concentrations attributable to candles typically in the range of 8–10 μg/m^3 during use episodes. The contribution of candle burning to indoor $PM_{2.5}$ ranged between 6 and 14% across rooms, whereas other indoor sources, primarily associated with kitchen activities, accounted for 38 to 61%. Outdoor infiltration contributed 32 to 48%, with the highest values found in bedrooms and lounges. Although candle burning can produce momentary peaks, the influence of these short-term and infrequent events is reduced when averaged across non-burning periods, resulting in relatively modest additional mean concentrations.

Overall, these findings demonstrated in this London-based residential study, indicate that incense use generates the highest fragrance-related contribution to indoor $PM_{2.5}$, followed by oil diffusers and candles. The results also reveal that indoor exposure levels depend not only on emission intensity but also behavioural factors such as product preference, usage frequency, and room selection, as well as on physical parameters such as room volume and dwelling type.

3.3. Short-term $PM_{2.5}$ Exposure Associated with Fragrance Product Use

We quantified short-term indoor $PM_{2.5}$ exposure using the exceedance frequency, defined as the percentage of monitored days on which the 24-h mean indoor $PM_{2.5}$ exceeded the WHO guideline (15 μg/m^3). Exceedances were common and showed clear contrasts by fragrance source (Fig. 5a). Incense was associated with the highest burden, with the distribution shifted toward substantially higher exceedance frequencies and several homes approaching near-daily exceedance. Candles also produced consistently elevated exceedance frequencies, with a median nearly 40% of days and multiple homes above 60%. Oil diffusers exhibited the widest range, from about 6% to 95% of days, indicating that exceedance risk is highly sensitive to household-specific factors. These source-specific patterns are consistent with the higher emission rates and longer particle residence times inferred for incense, the moderate but frequent emissions from candles, and the highly variable emission behaviour of oil diffusers.

Exceedance burdens also varied systematically with dwelling type (Fig. 5b). End-terrace houses showed the highest median exceedance frequency, close to 59% of monitored days, and maisonettes also exhibited elevated values around 37%. Flats had a lower median of about 22% but a broad spread, with the interquartile range extending from roughly 15% to 41%, consistent with diverse floor areas and dwelling configurations within this category. Mid-terrace houses had a much lower median, about 8%, although the upper quartile rose to nearly 38%, again indicating substantial household-level variability. Detached houses in this high-fragrance-use sample were close to zero additional exceedances. Across all dwelling categories, median frequencies were far above the approximately 1% exceedance of the WHO 24-hour $PM_{2.5}$ guideline definition, showing that exceedances in these homes were recurrent rather than rare. The pattern of results indicates that within short-term indoor $PM_{2.5}$ exceedances in fragrance-using households arise from systematic differences in source choice, usage patterns and dwelling characteristics, rather than from isolated extreme episodes.

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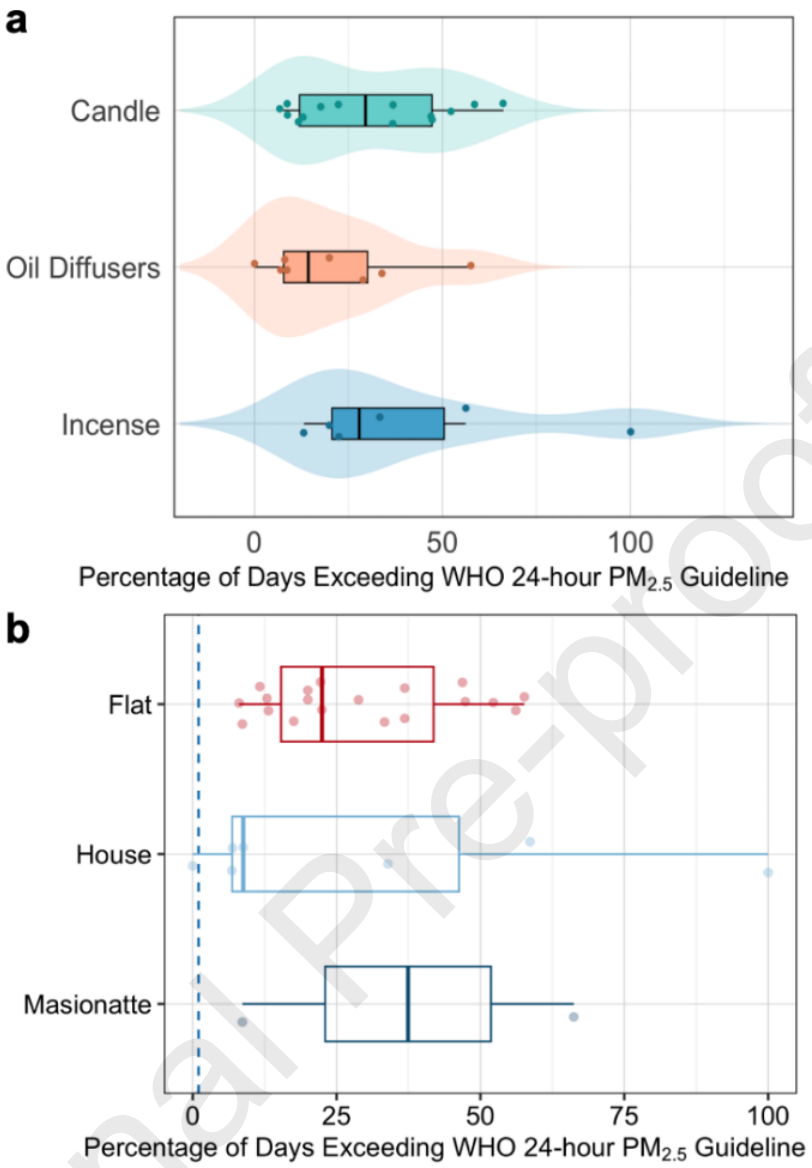


Fig. 5. Short-term indoor $PM_{2.5}$ exceedances associated with fragrance use. a, Percentage of monitored days on which 24-h mean indoor $PM_{2.5}$ exceeded the WHO guideline of 15 μg/m^3, stratified by primary fragrance source (candles, oil diffusers and incense). The shaded violins represent smoothed kernel density estimates and may extend beyond the range of the observed data; boxplots and points show the actual observed values. b, Median percentage of exceedance days by dwelling type. The horizontal dashed line marks the 1% exceedance frequency of the WHO 24-h $PM_{2.5}$ guideline (defined as the 99th percentile of daily means).

3.4. Dwelling-Level Drivers of Fragrance-related $PM_{2.5}$ Exposure

We further examined how housing characteristics mediate fragrance-related $PM_{2.5}$ exposure (Fig. 6 and Fig. S8), using dwelling type, total floor area and room floor area as structural indicators of dilution volume and use patterns. Flats showed the highest concentrations for candles and oil diffusers, whereas maisonettes and detached houses

were lowest; for incense, mid-terrace houses and maisonettes were highest and flats were lower. These contrasts suggest that dwelling type influences exposure, but not independently of floor area and the specific rooms where fragranced products are used.

Recognizing that dwelling type and total floor area are strongly interrelated, we further stratified the dataset by residence floor area to isolate the effect of total indoor volume on pollutant accumulation. When events were stratified by total residence floor area, clear volume effects emerged for incense and oil diffusers (Fig. 6a). For incense, average concentrations during the events in the smallest homes (≤ 50 m^2) exceeding 350 $\mu g/m^3$, compared with about 180 $\mu g/m^3$ in 51–99 m^2 homes and 150 $\mu g/m^3$ in homes ≥ 100 m^2. Diffuser-related concentrations showed a similar decline with increasing floor area, falling below 20 $\mu g/m^3$ in the largest homes (≥ 100 m^2), but remained high in small (160 $\mu g/m^3$) and medium-size (220 $\mu g/m^3$) dwellings. In contrast, candle-related concentrations were relatively insensitive to total floor area and remained close to 60 $\mu g/m^3$ across size bands, consistent with their lower emission rates and the more spatially distributed locations of candle use within homes.

Room floor area further modified exposure at the scale most relevant to personal inhalation (Fig. 6b). For candles and incense, concentrations decreased systematically with increasing room size, from roughly 70 and 240 $\mu g/m^3$ respectively in rooms ≤ 12 m^2 to around 30 and 60 $\mu g/m^3$ in rooms 17–40 m^2, consistent with stronger dilution in larger volumes. Oil diffusers departed from this simple pattern: concentrations peaked in mid-sized rooms (about 190 $\mu g/m^3$) and were lowest in the largest rooms (around 20 $\mu g/m^3$). This behaviour suggests that device placement and intensity of use can offset the expected benefits of larger volumes, for example when oil diffusers are operated for long periods in moderately sized bedrooms or lounges with limited ventilation. Together, these findings demonstrate that dwelling characteristics shape fragrance-related $PM_{2.5}$ exposure primarily through volume-dependent dilution, but that this structural control is strongly modulated by source type and occupant behaviour. Small dwellings and small rooms are particularly vulnerable to high concentrations during incense and diffuser events, which helps explain the pronounced short-term exceedances observed earlier and highlights the need for targeted guidance in compact, low-ventilation housing.

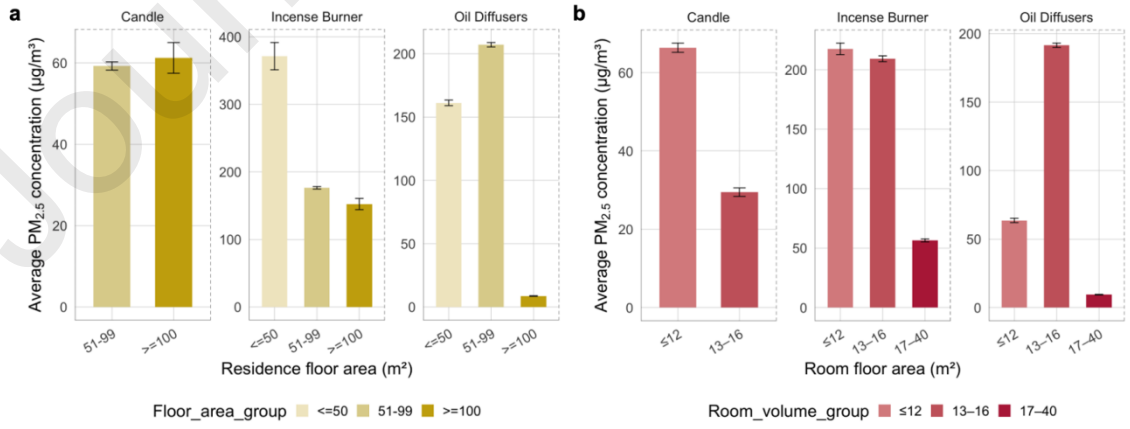


Fig. 6. Indoor $PM_{2.5}$ concentrations during fragrance source events by housing factors. a, Residence floor area (m^2), grouped using banded floor-area categories from the English Housing Survey. b, Room floor area (m^2). Bars represent mean $PM_{2.5}$

concentrations during fragrance-source events.

4. Discussion

This study demonstrates that fragrance products are a substantial yet underrecognized driver of indoor particulate pollution, with source-specific emission magnitudes comparable to those of cooking under real residential conditions (Chen and Zhao, 2024; Chen et al., 2018; Patel et al., 2020). Our findings show that routine fragrance practices can substantially reshape indoor exposures. In homes where fragrance products were used regularly, the dominant contributor to indoor $PM_{2.5}$ shifted from ambient infiltration to episodic, occupant-controlled indoor sources.

Incense use emerged as the dominant contributor to indoor particulate exposure, consistent with chamber experiments that report high emissions of carbonaceous fine aerosols with long indoor residence times than those from cooking (Tran et al., 2021). This behaviour explains the sustained evening peaks observed in incense-use households and aligns with residential observations from Copenhagen, where evening combustion activities rather than nighttime background infiltration dictated indoor particle concentrations (Bekö et al., 2013). Emissions from combustion sources are also sensitive to ventilation, indoor temperature, product formulation and subsequent physicochemical processing (Zai et al., 2006), which together provide a plausible explanation for the wide spread in emission strength and persistence that we observe across households. Oil diffusers generally exhibited lower hourly $PM_{2.5}$ levels, but occasional extreme episodes are consistent with chamber studies showing that oil diffusers can generate exceptionally high $PM_{2.5}$ concentrations under restricted ventilation, with emission rates spanning more than two orders of magnitude depending on oil composition and water quality (Schwartz-Narbonne et al., 2021).

Changes in the housing stock driven by the UK Net Zero target mean that the role of fragranced products in indoor air quality can no longer be treated as a secondary issue. As the country moves towards high-efficiency, airtight dwellings, structural retrofits and enhanced insulation are expected to mitigate the infiltration of outdoor $PM_{2.5}$ but also to exacerbate the accumulation of pollutants generated by domestic practices. Our study of London households reveals clear volume dependent differences in exposure, with occupants in smaller and more densely occupied dwellings experiencing substantially higher fragrance related $PM_{2.5}$ concentrations than those in larger homes. This pattern suggests that decarbonization measures may unintentionally widen health inequalities if they are not accompanied by indoor air quality strategies that address emissions from indoor sources, could disproportionately affect occupants of compact, densely occupied dwellings. For such dwellings, ventilation alone may be insufficient to control episodic indoor emissions without compromising energy efficiency, underscoring the need for complementary approaches such as filtration of recirculated indoor air. By resolving the frequency and duration of fragrance related episodes over multi week periods in occupied homes, this study provides empirical constraints for indoor air quality models that aim to simulate realistic exposure under evolving ventilation regimes. These data can be used to represent fragrance-related emissions in projections of future indoor air quality under low-carbon dwelling and ventilation scenarios and to explore how changes in building tightness or background ventilation alter the impact of indoor sources, helping to ensure that gains in energy

efficiency do not come at the expense of respiratory health. Whether the observed exposure disparities across dwelling types translate into measurable health inequalities requires further investigation linking dwelling characteristics to socio-economic and demographic factors.

Our study also clarifies how mitigation strategies should be designed. The high short term $PM_{2.5}$ peaks associated with fragrance use indicate that ventilation must address short-duration events rather than relying only on background air exchange. Even when daily or multi day mean concentrations are moderate, brief but intense episodes can dominate peak exposure. The high time-resolution monitoring deployed here captures variability in real household behaviour that is not accessible in short-term or chamber studies and provides a quantitative basis for targeted interventions. Effective mitigation needs to move beyond generic ventilation advice and offer specific guidance on how product type, duration of use and room volume combine to shape exposure. The disproportionately high burdens identified in confined spaces such as bedrooms point to the need for changes in practice, including reduced reliance on combustion-based products in small rooms and the use of compensatory ventilation during and after fragrance use. Where additional ventilation is limited by building airtightness or occupants' ventilation practices, portable in-room air cleaners with particle filtration may help reduce $PM_{2.5}$ concentrations during and after fragrance-use episodes. For non-combustion devices such as oil diffusers, this also highlights the importance of regular cleaning of the reservoir and atomizing components, together with the use of clean refill water, to reduce avoidable particle emissions. Embedding these real-home estimates in wider air quality assessment frameworks is essential for developing evidence based guidelines that protect occupants during the transition to a more energy efficient housing stock.

5. Limitations

The study sample comprised non-smoking households with at least one child with asthma, recruited from a single London borough, and was dominated by flats (78 of 112 homes, 70%). The findings are therefore most directly applicable to similar urban, non-smoking households in compact dwellings, and generalisability to other population groups, housing types, or regions requires further investigation. Uncertainty remains in identifying fragrance-source events because time-stamped participant activity diaries were unavailable. Attribution was based on questionnaire-reported fragrance use and the absence of other major indoor sources, with algorithms minimizing misclassification by excluding overlaps with kitchen activities and validating emission magnitudes against literature values. Nevertheless, without time-stamped activity records or chemical tracers, occasional misclassification of unrecorded non-fragrance activities cannot be excluded. For oil diffusers, the absence of device-type, chemical-speciation, and size-resolved measurements also prevented differentiation between primary aerosol emissions and secondary organic aerosol formation. As the majority of participating homes were flats within multi-unit residential buildings, a further source of uncertainty relates to pollutant transfer between dwellings. Because activities in adjacent, non-participating dwellings and shared building spaces were not monitored, $PM_{2.5}$ transfer through hallways or common ventilation pathways may have contributed to the measured indoor concentrations and therefore represents a potential source of confounding. Spatial concentration gradients during active fragrance use could not be

quantified because multi-point measurements were not conducted within participating homes. Consequently, event-specific emission-rate estimates may be biased by sensor–source distance, with closer placement tending to produce overestimates and greater separation tending to produce underestimates. However, because a consistent measurement protocol was used across all homes, relative source rankings and between-household comparisons are likely to be less affected. Future studies should record the locations of indoor sources relative to the sensors and establish standardised protocols for sensor placement to measure the representative exposure concentrations. The assumption of constant F values within 1-hour intervals may not fully capture sub-hourly ventilation dynamics, introducing some uncertainty in emission rate estimates during periods of rapidly changing air exchange.

A separate limitation concerns air filtration. Information on portable air-cleaner use was collected but was insufficiently detailed to quantify its effect on indoor $PM_{2.5}$ concentrations, and no data were available on building-integrated mechanical filtration systems. The role of air filtration in reducing fragrance-related $PM_{2.5}$ exposure therefore warrants future investigation. Despite remaining uncertainties, the findings redefine fragrance use as an important and underrecognized source of indoor particulate exposure, with implications for evidence-based emission regulation and equitable exposure reduction. Future research should combine improved source attribution (e.g., time-resolved activity diaries, direct product-use logging and device-operation measurements) with larger, nationally representative cohort studies across the UK to capture variation across housing types, retrofit status and socio-demographic groups, and to test how Net Zero-driven changes in airtightness and ventilation reshape indoor $PM_{2.5}$ exposures and related inequalities. Integrating such exposure data with individual-level health outcomes would further enable quantification of the health risks attributable to fragrance-derived $PM_{2.5}$.

Declaration of Competing Interest

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.

Supplementary Information

Supplementary material associated with this article can be found in the online version.

Fragrance product use patterns in study households; comparison of $PM_{2.5}$ emission rates from domestic fragrance products with literature-reported values; Fig. S1 showing the location of study households within Greater London; Fig. S2–S8 showing representative incense and candle cases used to illustrate event identification and multi-criteria cross-validation, fragrance product adoption and weekly usage frequency by ethnic group, diurnal patterns of hourly indoor $PM_{2.5}$ by fragrance type, comparisons of emission rates with literature-reported values, room-specific outdoor contributions to indoor $PM_{2.5}$ in fragrance-use homes, and indoor $PM_{2.5}$ concentrations during

694 fragrance-source events by dwelling type; Table S1 summarizing fragrance-related
695 questionnaire items and temporal coverage of the information collected; Table S2
696 summarizing $PM_{2.5}$ concentrations in homes with and without fragrance products.

697

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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.

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