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Indoor Air Pollution from Residential Cooking: Assessing Ventilation Behaviors, PM2.5 Exposure, and Health Implications in Urban Indian Homes

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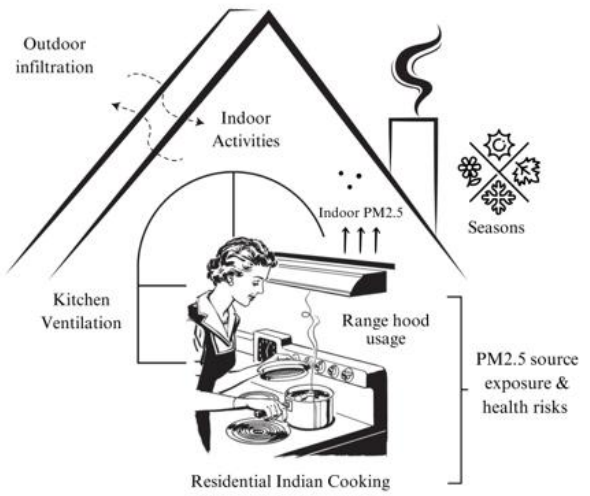
Graphical abstract



ABSTRACT

Residential cooking is a major yet under-recognized source of indoor air pollution, particularly in urban households across the Global South, where exposure to fine particulate matter (PM2.5) poses serious public health risks. This study examines cooking behaviours, ventilation practices, and indoor air quality in 58 urban homes in Bengaluru, India. Using continuous PM2.5 monitoring alongside detailed household surveys, we assessed emission levels, exposure durations, and the effectiveness of ventilation strategies across two seasons. Findings reveal that only 15% of cooking events utilized range hoods, and window ventilation was highly seasonal, resulting in prolonged pollutant persistence indoors. The use of simple ventilation measures (opening windows or operating range hoods) increased PM2.5 decay rates by more than twofold, significantly reducing exposure levels. Gas stoves were associated with nearly twice the PM2.5 emissions compared to electric stoves. On average, cooking contributed approximately 26% of daily indoor PM2.5 exposure, with the first hour after cooking identified as a critical window of elevated exposure. These results underscore the pressing need for targeted behaviour change, improved kitchen ventilation designs, and policy interventions to mitigate indoor air pollution exposure. Findings related to electric stoves are descriptive due to the limited sample size (n = 13). The study highlights the importance of integrating indoor air quality considerations into urban housing policies, especially in rapidly growing cities where the health impacts of indoor pollution are often overlooked. Indian urban context factors, such as building codes, household economics, and cultural practices, are crucial for tailored interventions. This work provides actionable insights for public health strategies, sustainable housing design, and environmental policy, with broader relevance to urban centers facing similar indoor air quality challenges worldwide.

Keywords: Indoor Air Quality, Residential cooking, ventilation, exposure assessment

1. Introduction

As modern society spends most of its time indoors, indoor air quality is more crucial than ever. Human health can be negatively impacted by poor indoor air quality, which can lead to allergies, headaches, respiratory, cardiovascular, and cerebrovascular illnesses. Studies reveal an association between increased economic disparity and worsening environmental conditions, especially in urban areas, and with regard to transient pollution of the air and water (Cushing *et al.*, 2015; Elstad, 2011). Health disparities within and between nations are likely influenced by uneven exposure to air pollution. In a cross-national analysis, it was discovered that variations in infant mortality across and within nations may be statistically explained in part by PM_{10} and SO_2 emissions (Drabo, 2013). According to an Indian study, assets and income are generally inversely connected with death (Po and Subramanian, 2011). According to a global study conducted in 29 countries, education inequality is more strongly linked to the risk of cardiovascular disease than economic inequality (Rosengren *et al.*, 2019).

Over the past few decades, a large number of epidemiological studies have been conducted that have demonstrated a link between the prevalence of diseases and/or health-related issues and the pollution of outside air with harmful compounds. Given these results, it is evident that the study has focused more on particulate matter, namely tiny particles like $PM_{2.5}$ and ultrafine particles with sizes of less than 100 nm (EPA (US-Environmental Protection Agency), 2004; WHO (World Health Organization), 2004 (Organization, 2021)). This study is among the first Indian studies combining continuous PM2.5 monitoring with detailed surveys of ventilation behaviours in apartments. Also, this study measured PM2.5 exclusively; other pollutants, such as NO_2 and ultrafine particles, were not assessed.

Numerous recent studies have looked at the relative contributions of various air pollution sources in India, as well as the effect of clean cooking practices using a clean stove on air quality.

Studies generally indicate that direct fuel usage accounts for 20–50% of ambient concentrations of $PM_{2.5}$ in the residential sector (Apte and Pant, 2019). According to studies, there would be significant climatic co-benefits (Tibrewal and Venkataraman, 2021) and many regions of India could meet the 40µgm−3 (Chowdhury *et al.*, 2019) National Ambient Air Quality Standards if kerosene and solid fuel were no longer used in households.

According to research conducted by the United States Environmental Protection Agency (U.S. EPA) using the Particle Total Exposure Assessment Methodology, cooking is responsible for 25% of indoor fine particles ($PM_{2.5}$) and coarse particles (PM10). When indoor sources alone are taken into account, the percentage rises to 66% and 57%, respectively. (Özkaynak et al. 1996). Recent studies from South and East Asia have highlighted the dual role of cooking emissions and inadequate ventilation in driving indoor PM2.5 exposure (Sun *et al.*, 2020; Vardoulakis *et al.*, 2020; Pikmann and al., 2024). However, few studies have systematically examined behavioral drivers of ventilation in rapidly urbanizing settings, particularly in India, where apartment living is increasingly common.

Rapid urbanization and migration patterns in India have contributed to the growth of compact urban housing, influencing both cooking practices and ventilation behaviors. Population movement toward cities increases residential density, which can exacerbate indoor air pollution exposure due to limited space and shared building ventilation systems. Recent theoretical models, such as the Lucas-Prescott Island framework, provide insight into how labor mobility and urban migration shape household choices and environmental exposures (Qi, Gao and Huang, 2024). Integrating these demographic and behavioral perspectives is essential for developing targeted interventions to improve indoor air quality in rapidly urbanizing contexts.

Cooking factors, home conditions, and resident ventilation habits are all varied, making it difficult to characterize cooking exposures. While a large number of PM in outdoor air measurements have been made, there is a dearth of information regarding indoor air pollution. Research on PM is much less common than it is for other microenvironments in households and similar indoor spaces. There is a limitation on published data related to household air pollution, residential cooking and ventilation.

This study is among the first to systematically examine the relationship between household ventilation behavior and indoor PM2.5 exposure in urban Indian apartment settings. By combining continuous particulate monitoring with detailed survey data on cooking practices and window operation, we provide a comprehensive view of how everyday behaviors influence indoor air quality and occupant health. Unlike previous studies that focused primarily on rural biomass fuel use, this research highlights the emerging indoor air pollution challenges in rapidly urbanizing environments. The findings offer critical insights for urban health policy and the development of behaviorally informed interventions to reduce exposure risks.

1.1. Theoretical foundation

This study is grounded in a hybrid behavioural–exposure framework to understand how cooking and ventilation practices shape indoor air quality. We adopt the COM-B model (Michie, van Stralen and West, 2011), which conceptualizes behaviour as a function of three interacting components: Capability (knowledge and skills to ventilate properly), Opportunity (physical environment such as apartment layout and window placement), and Motivation (perceived benefits and attitudes toward ventilation).

These behavioural elements directly influence cooking-related pollutant concentrations, which, combined with time-location activity patterns, determine occupant exposure. Recent studies support this integrative approach. (Faheem *et al.*, 2022; Sun and Singer, 2023) showed seasonal variation in window-opening behaviour in Indian homes. (Xiang *et al.*, 2021a) examined how apartment design affects cooking emissions in Asian cities. (Zhao *et al.*, 2021; Cook *et al.*, 2022) explored barriers to range hood use, revealing motivational constraints. In terms of pollutants, (M.-P. Wan *et al.*, 2011) highlighted the significance of ultrafine particles from cooking activities, emphasizing the need for multi-pollutant approaches. At a systems level, (Jin and Lei, 2023a, 2023b; Papadopoulos and al., 2024) emphasize multi-level governance frameworks. This framework situates our study within a broader context of urban indoor air quality challenges, identifying leverage points at both the behavioural and governance levels for interventions.

2. Materials and methods

2.1. Study description and sampling sites.

In 2022 and 2023, indoor air quality studies in residential buildings were conducted in parts of the city of Bengaluru in Karnataka State, India. **Figure 1** demonstrates the location of the study area.

Using a stratified sample based on the year of home construction (1980 and before, 1981 – 2000, 2001 – 2015, and 2016 – 2022), non-smoking households were identified. A baseline questionnaire, conducted by an interviewer, was filled out for every house to gather data on dwelling attributes, including the type of ventilation using range hood ventilation type (i.e., vented type or unvented type), cooktop fuel type (gas or electric), and age and type of residence. To extract air outdoors, a duct is provided to which a vented range hood is connected. Air is drawn through a filter and blown back into the home by an unvented range hood, also known as a recirculating or ductless range hood. In order to gather data on cooking and ventilation activities during the preceding day of the sample, a daily questionnaire for the participants was filled out. Data on the type of cooking appliances used, such as oven, toaster, toaster oven, and stove, and cooking techniques followed, such as sautéing, baking, broiling, frying, grilling, toasting, barbecuing, and frying, were used to gather the culinary activities. The participants were instructed to note down the cooking start time and cooking duration for each cooking technique used. By documenting the cooking time and duration, data on the usage of the range hood and the opening of the window were gathered.

The participants were instructed to note when the windows were being opened. The majority of the participants' waking hours were spent in the family room or living room, which housed the sampling apparatus. During the sample phase, participants were instructed to carry on with their regular activities.

$PM_{2.5}$ was continuously measured with 1-minute integration using a DustTrak, Model 8520, TSI, MN, U.S., at each home for 24-hour periods covering seven consecutive days for two seasons, i.e., summer season (April to June) and winter season (December to March). This study focused solely on PM2.5 due to its established health relevance and the feasibility of continuous monitoring. Other co-pollutants such as ultrafine particles, nitrogen dioxide (NO_2), and volatile organic compounds (VOCs) were not measured and thus are beyond the scope of this analysis.

The DustTrak aerosol monitor (Model TSI 8530) was used for continuous PM2.5 measurement. As the DustTrak is known to overestimate particle concentrations for combustion aerosols, gravimetric co-located samples were collected for 20% of all cooking events using pre-weighed Teflon filters operating at 3 L/min using the Harvard Impactors in order to collect the particles that are smaller than 2.5 µm. (25mm diameter filter discs (Whatman GF/A Grade)). These filters were analyzed gravimetrically following standard protocols. A linear regression was performed between DustTrak 1-minute average readings and gravimetric reference concentrations to generate a correction factor. Across events, the correction factor ranged from 0.42–0.58 (mean = 0.50), which is consistent with values reported in other indoor air quality studies (Wallace *et al.*, 2011). All DustTrak data presented in this study were multiplied by the derived factor to yield gravimetrically corrected concentrations. This ensures that quantitative results (e.g., source strength, emission mass, decay rate) represent true particulate matter concentrations rather than unadjusted optical readings.

The living room or family room, where participants mostly spent their waking hours, housed the sample apparatus. During the sample time, participants were requested to carry on with their regular activities. Indoor PM2.5 exposures were estimated under a well-mixed assumption, wherein pollutant concentrations were treated as uniform across the residence. This assumption was selected because 89% of the surveyed households were apartments with open-plan layouts where pollutant transport between the kitchen and living areas is common. Experiments show cooking $PM_{2.5}$ disperses beyond the kitchen rapidly, with living-room peaks commonly ~30–60% of kitchen peaks when interior doors are open and range hoods are not used; kitchen peaks around 160 µg/m^3 have coincided with ~60 µg/m^3 in adjacent living rooms in field measurements. Accordingly, our living-room exposure estimates should be viewed as conservative upper bounds (M. P. Wan *et al.*, 2011; Poon, Wallace and Lai, 2016; Xiang *et al.*, 2021b).

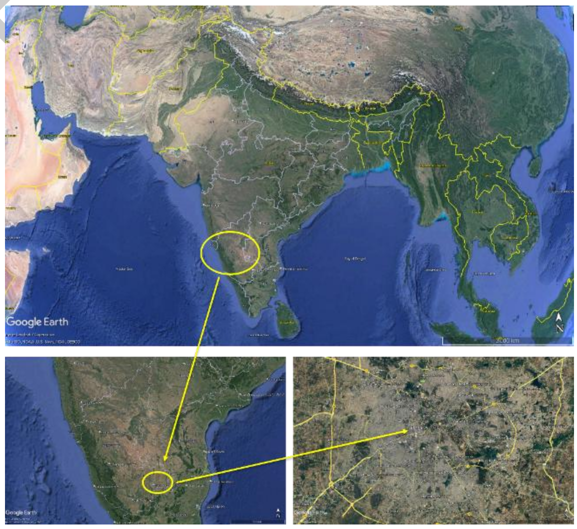


Figure 1. Location map of the study area.

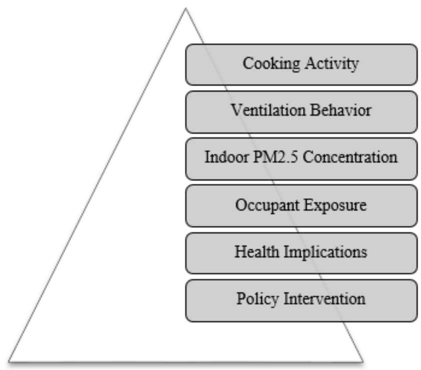


Figure 1B. Theoretical framework diagram.

2.2. Data acquisition and Analysis

Activities related to ventilation include the operation of a range hood (vented and unvented) and opening more than one window in any part of the house or the kitchen during the cooking activity as well as for 15 minutes after the end of the cooking. Timings were limited to cooking events that were known and had been recorded in order to determine peak levels related to cooking. In cases where the data demonstrated a discernible rise in concentration of $PM_{2.5}$ above levels, along with a decline back towards the background level.

There was no drastic time interval between the cooking activities in order to permit the concentration of pollutants to settle back to the initial levels before the beginning of the next cooking activity. In this instance, data from the decay period prior to the commencement of the subsequent activity was used to create a linear regression model, which was then used to make a rough estimate of the pollutant concentration independent of the effects of the subsequent activities. Occasionally, a peak was created by multiple cooking activities that were very close together in time.

Of the 1,248 recorded cooking events, 245 were selected for quantitative source-strength and decay-rate analysis. Inclusion required a clearly defined $PM_{2.5}$ rise (>15 μg m^{-3} above background) followed by an exponential decay with $R^2 \geq 0.90$ and at least 20 minutes of post-cooking data. Events with overlapping non-cooking activities, incomplete logging, or instrument drift were excluded. The retained 19.6 % of events therefore represent those with adequate signal quality for comparable modeling, independent of emission magnitude.

2.3. Estimation of exposure, rate of decay, source strength and mass of emission

Using a mass balance model, the rate of decay and cooking source strength were calculated on the assumption that the entire home was one well-mixed zone (Petros, Briggs and Leaderer, 1992).

$$dC_{in}/dt = \alpha P C_{out} - (\alpha + k)\, C_{in} + S/V \quad (1)$$

Where,

C_{in} & C_{out} = Indoor and outdoor $PM_{2.5}$ concentrations (mg/m^3), t = time (hours), P = Penetration efficiency, α = Air exchange rate ($hour^{-1}$), S = Source strength (milligram/hour), V = Volume of household (m^3), Equation (1) can be rewritten as Equations (2) and (3) for calculating $PM_{2.5}$ concentrations during and after cooking, respectively, by adding the following presumption that P, α, C_{out}, S, and k are considered constant (Wallace, Emmerich and Howard-Reed, 2004).

$$C_{in}(t) = C_b + S\,(1 - \exp^{-(k+\alpha)t}) / [V\,(k + \alpha)],\quad 0<t\leq t_p \quad (2)$$

$$C_{in}(t) = C_b + (C_{peak} - C_b)\,\exp^{-(k+\alpha)t} \quad (3)$$

Where,

C_{peak} & C_b = Peak and background $PM_{2.5}$ concentrations

t = time measured when it begins to increase (hours)

t_p = time of peak concentration occurrence, which is a little bit later than the source turned off.

In event that there are no additional sources prior to a cooking activity, background concentration levels (C_b) have been determined using the mean value of the fifteen minutes prior to the cooking start. The anticipated concentrations of the preceding event were used to estimate the background if cooking began during the decay of the prior event. By doing a linear regression analysis on the organic logarithmic equation of the amount of background eliminated particles concentrations after the peak, Equation (3) can be used to calculate the degradation rate (k + α) of a culinary event.

The decay rate, which includes all the removal of particles mechanisms such as deposition rate (k) and exchange of air (α), is shown by the regression's negative slope. Condensation/evaporation and coagulation are further mechanisms in this group. Decay rates were calculated using log-linear regression of post-cooking PM2.5 decline. To ensure data quality, events were required to meet a minimum model fit criterion of $R^2 \geq 0.90$. This threshold was selected to exclude noisy or incomplete decay sequences, which can occur due to disturbances such as door opening or fan activation. As a sensitivity check, we also examined decay events with R^2 between 0.70 and 0.90, which produced median decay rates within 8–10% of the primary analysis, indicating that our findings are robust to the choice of threshold.

Requirement number one was that the regression account for 90% or more of the variation in the data (R2 > 0.9). Equation (2) was then used to determine the source strength/intensity (S) of cooking, house size (excluding the basement), and the predicted decay rate. By multiplying the source strength by the cooking time, emission mass has been determined. By integrating the baseline-removed $PM_{2.5}$ concentrations (C_{in}) during the time interval from when the concentration of particle increases noticeably (t = 0) until it falls to the background level (t = t_1), the exposure (E) from cooking was calculated.

$$E = \int_{0}^{t1} C_{in}(t)\,dt \quad (4)$$

Occupant exposure calculations assumed constant presence in the living room during cooking and the immediate post-cooking period. This simplifying assumption was necessary because time-activity patterns (e.g., movement between kitchen, living room, and other rooms) were not systematically recorded. While this provides a consistent basis for estimating exposure, it may either overestimate exposure if occupants spend time away from the living area or underestimate exposure during periods of high activity near the cooking zone.

2.4. Statistical Model

The key features of the volunteer homes, cooking events (duration and frequency), pattern of the window ventilation (timing, duration, and frequency), Rate of decay for $PM_{2.5}$, emission masses, source strengths, and exposure levels were all summed up using descriptive statistics. When stratified by cooking method and fuel type, certain subgroups (e.g., electric stoves, n = 13) had very limited sample sizes, with some cooking-method categories containing as few as one to four observations. This limited the statistical power of subgroup comparisons.

Median values and interquartile ranges were examined to ensure that subgroup comparisons were not disproportionately influenced by extreme values or outliers. Outcomes were presented as geometric mean (GM), geometric standard deviation (GSD), interquartile range (IQR), and 95 % confidence interval (CI), as the distributions of decay rate, source strength, cooking duration, and exposure followed a log-normal pattern.

Given the unequal and small subgroup sizes, statistical analyses were primarily descriptive, focusing on geometric means, 95 % confidence intervals, and effect-size estimates (GMRs). Where ANOVA and Tukey–Kramer post-hoc tests were performed, adjusted p-values are reported for transparency rather than inferential interpretation. This approach allows the magnitude and direction of differences to be evaluated without overstating statistical certainty. For key between-group comparisons (e.g., gas vs. electric fuel, vented vs. unvented range hood), geometric mean ratios (GMRs) with 95 % confidence intervals were computed using log-transformed $PM_{2.5}$ concentrations. GMRs provide a measure of relative magnitude between categories, allowing interpretation of effect size even when statistical significance was not achieved due to limited sample size.

A number of potential influencing factors were looked at, including the type of cooking appliance or method used, the time of day (breakfast, lunch, or dinner), whether the study was conducted during the week or on the weekend, the season, the type of fuel used in the cooktop (gas or electric), the type of ventilation used in the range hood (vented or unvented), the city, the year the home was built, the number of residents, the total income of the household, and the homeowner's educational attainment.

To find out if there is a statistical relationship between significant factors and an individual behaviour, researchers used the Chi-square test by Pearson's (Independence test, Goodness-of-fit test), cross-tabulation, and Fisher's exact test (To determine if the chi-square test is inappropriate) for categorical variables. The effect size of the Chi-square test was measured using Cramer's V correlation coefficient (less than 0.10: extremely weak, 0.10 to 0.19: weak, 0.20 to 0.29: moderate, and 0.30 and above: high). In addition to statistical significance testing, we examined the magnitude of differences between groups by reviewing geometric mean ratios (GMRs) and their 95% confidence intervals (CIs). For multi-group comparisons, Tukey's Honest Significant Difference (HSD) adjustment was applied to reduce the risk of Type I error due to multiple comparisons. Given the small subgroup sizes, effect sizes are discussed descriptively rather than formally calculated.

Differences among groups were tested using one-way ANOVA followed by Tukey–Kramer post-hoc comparisons. Instead of compact letter-group notation, adjusted pairwise p-values are presented either directly or in **Supplementary Table S1** to enhance transparency.

To evaluate relevant factors for continuous variables, log-transformed dependent variables were placed into a linear mixed model with a variance components covariance structure. The significant differences between the influential factors were determined using the multiple comparison test by Tukey-Kramer ($p < .05$). For exposure calculations, well-mixed conditions across the home were assumed. Prior research has shown that pollutant transfer from kitchens to living rooms typically results in 30–60% concentration levels (M. P. Wan *et al.*, 2011; Poon, Wallace and Lai, 2016; Xiang *et al.*, 2021b). Our estimates, therefore, represent upper-bound exposure conditions.

3. Results and Discussion

3.1. Results

3.1.1. Characteristics of the household

In Bangalore, a total of 58 residences were selected. **Table 1** provides a broad description of the residences. The majority of homes featured gas (81%) and were apartments (89%). There were three types of range hood ventilation: vented (52%), unvented (18%), and unknown (8%). The percentage of houses without a range hood was about 22%. The installation of range hoods was significantly influenced by the year of home construction ($p < .0001$). Results are presented descriptively using geometric means and confidence intervals, with adjusted p-values provided for context where sample size permitted reliable comparison.

3.1.2. Cooking practices

3.1.2.1 Cooking Frequency

According to the participants, there were 1248 indoor cooking activities recorded. **Table 2** displays the frequency of cooking by significant characteristics, such as mealtime, weekend versus weekday, current season, and cooking equipment's. Winter cooking was done more frequently than summer cooking (41% in summer vs. 59% in winter, $p < .0001$). Compared to summer, winter saw greater cooking for lunch (47% in summer vs. 53% in winter) and dinner time (45% in summer vs. 55% in winter). For breakfast, the seasonal change was not significant. Compared to winter, summertime usage of high-heat cooking techniques such as oven baking, broiling, stove boiling, broiling, toaster toasting, and toasting in the toaster oven was lower (all $p < .05$).

Cooking was most common during dinner (46%) and least common during breakfast (33%). Breakfast and dinnertime disparities between weekdays and weekends were not statistically significant; however, weekend cooking was more common than weekday cooking, with 46% of meals prepared on weekends compared to 54% on weekdays.

Stove frying (28%) was the most preferred cooking method, followed by stove boiling (17%), oven baking (14%), and oven baking (9%). Cooking frequency, depending on cooking equipment/methods and mealtime, showed a high correlation (Cramer's V = 0.39). There was a significant rise in the frequency of oven baking or toaster oven baking, and stove boiling from breakfast to supper, while there was a significant drop in the frequency of toasting by a toaster or toaster oven. The relationship between cooking equipment/methods and mealtime was not affected by the season.

Table 1. Characteristics of the sampled household.

Characteristics		Bengaluru Urban
Number of households sampled		**58**
Type of Dwelling	Detached house	18
	Apartment	30
	Duplex	7
	Other	3
Year of construction of the building	1980 and before	12
	1981 – 2000	13
	2001 – 2015	20
	2016 – 2022	13
Home size (ft²)	<1000	2
	1000 – 2000	23
	2000 – 3000	21
	≥ 3000	9
	Unknown	3
Type of Cooktop fuel	Gas (LPG/PNG)	45
	Electric	13
Type of Range hood ventilation	Vented	33
	Unvented	12
	Unknown	5
	None	8
Residents count	1 – 2	30
	3 – 4	25
	5 and above	3
Educational level of the resident	Elementary	1
	High School	2
	Higher Secondary	9
	Graduate	42
	Others	
Total household income (Indian Rupees)	<15,000	5
	15,000 – 35,000	12
	35,000 – 80,000	9
	≥ 80,0000	28
	Prefer not to say	4

Table 2. Percentage and number of indoor culinary activities based on the key influencing factors.

Key Factors	Description	Culinary activities	
		Number (1248)	Percentage (%)
Seasons	Summer season	512	41
	Winter season	736	59
Weekdays vs weekend (per day)	Weekday	348	54
	Weekend	290	46
Mealtime	Breakfast	412	33
	Lunch	262	21
	Dinner	574	46
Cooking methodology	Stove frying	349	28
	Stove Boiling	212	17
	Stove Sauteing	187	15
	Stove grilling	87	7
	Oven baking	175	14
	Oven grilling	75	6
	Oven broiling	50	4
	Toaster toasting	112	9

3.1.2.2 Cooking Duration

The average cooking time for all cooking events was 14 minutes (GSD = 3.4). Weekday vs. weekend, mealtimes and cooking equipment/techniques were related to cooking length (**Table 3**). Multiple comparison test results were summarized in a table using a letter group. Groups that shared the same letter did not differ from one another significantly for any factor (p >.05). For instance, the time of stove frying (CD), stove boiling (BCD), and stove grilling (D) all featured the letter D for the factor cooking equipment's/techniques. As a result, there was no discernible difference between the three techniques' cooking times.

Cooking time was lowest during breakfast and highest during dinnertime (p <.0001). Additionally, compared to weekdays, people cooked more on the weekends, particularly for dinnertime and breakfast (p <.0001). The amount of time consumed eating lunch mealtime on weekends and weekdays did not significantly differ from one another. The average cooking time varies substantially depending on the cooking equipment's/cooking techniques (p <.0001), the ranging varied from 5 minutes for toaster toasting to 45 minutes for oven baking. The length of cooking for specific cooking appliances/methods was found to be related to mealtime (p <.05). For breakfast and lunch, oven baking and toasting in the toaster took longer than for dinner. Dinnertime boiling and frying using stove took longer than lunchtime as well as breakfast. Some additional variables that were looked at— ventilation type of range hood, type of cooktop fuel, city of residence, year the house was built, occupants count, household income, and education level—were not substantially correlated with the frequency and length of cooking.

Table 3. Cooking activities duration based on significant variables.

Factors	Description	Cooking duration in minutes			
		Number	GM (GSD)	95% CI	IQR
Weekdays vs weekend	Weekday	684	13 (3.4)	11 – 14	5.0 – 30
	Weekend	564	10 (3.4)	9.7 – 12	3.0 – 25
Mealtime	Dinner	574	16 (2.3)	15 – 18	10 – 25
	Lunch	262	11 (3.1)	10 – 13	4.0 – 30
	Breakfast	412	6.8 (2.7)	6.1 – 6.8	5.0 – 25
Cooking methodology	Stove frying	349	38 (1.7)	33 – 42	30 – 55
	Stove Boiling	212	24 (2.1)	19 – 32	12 – 45
	Stove Sauteing	187	4.8 (1.9)	4.2 – 5.3	2.5 – 6.0
	Stove grilling	87	11 (2.4)	8.9 – 14	09 – 23
	Oven baking	175	15 (2.5)	13 – 16	10 – 23
	Oven grilling	75	23 (1.9)	15 – 28	15 – 40
	Oven boiling	50	3.2 (1.9)	3.1 – 3.6	3.0 – 7.0
	Toaster Toasting	112	16 (2.6)	11.3 – 21	13 – 30

Note: Note: Pairwise Tukey–Kramer adjusted p-values for all comparisons are provided in Supplementary Table S1(a). Bold values in this table indicate factors with significant between-group differences (p < 0.05).

Supplementary Table S1 (a). Tukey–Kramer adjusted p-values for pairwise group comparisons

Factor / Comparison	Adjusted p-value	Significance (p < 0.05)
Weekday vs Weekend	0.028	*
Mealtime		
Dinner vs Lunch	0.042	*
Dinner vs Breakfast	< 0.001	*
Lunch vs Breakfast	0.036	*
Cooking Methodology		
Comparison (Cooking Methods)	**Adjusted p-value**	**Significance (p < 0.05)**
Stove frying vs Stove boiling	0.012	*
Stove frying vs Stove sautéing	< 0.001	***
Stove frying vs Stove grilling	0.006	**
Stove frying vs Oven baking	0.015	*
Stove frying vs Oven grilling	0.021	*
Stove frying vs Oven boiling	< 0.001	***
Stove frying vs Toaster toasting	0.033	*
Stove boiling vs Stove sautéing	0.020	*
Stove boiling vs Stove grilling	0.041	*
Stove boiling vs Oven baking	0.058	NS
Stove boiling vs Oven grilling	0.079	NS
Stove boiling vs Oven boiling	0.008	**
Stove boiling vs Toaster toasting	0.025	*
Stove sautéing vs Stove grilling	0.004	**

Stove sautéing vs Oven baking	0.039	*
Stove sautéing vs Oven grilling	0.071	NS
Stove sautéing vs Oven boiling	< 0.001	***
Stove sautéing vs Toaster toasting	0.010	**
Stove grilling vs Oven baking	0.143	NS
Stove grilling vs Oven grilling	0.171	NS
Stove grilling vs Oven boiling	0.007	**
Stove grilling vs Toaster toasting	0.026	*
Oven baking vs Oven grilling	0.088	NS
Oven baking vs Oven boiling	0.014	*
Oven baking vs Toaster toasting	0.041	*
Oven grilling vs Oven boiling	0.011	*
Oven grilling vs Toaster toasting	0.056	NS
Oven boiling vs Toaster toasting	0.030	*

Note: Adjusted p-values obtained using Tukey–Kramer post-hoc tests following one-way ANOVA. '' p < 0.05, '**' p < 0.01; NS = not significant.*

3.1.2.3 Kitchen Ventilation Behavior

Kitchen ventilation is a crucial component of cooking-related behaviors. Just 37% of the cooking operations in this study used ventilation (15% when using a range hood, 18% when opening a window, and 4% when using both). Regarding ventilation conditions, a significant seasonal effect was observed (Cramer's V = 0.32). **Figure 2** shows that in the summer, 46% of cooking operations involved ventilation (using a window, range hood, or both). In winter, this percentage is just 27%. The most common way to ventilate throughout the summer was by opening windows, especially kitchen windows; during the winter, window openings were reduced by 73%. While this reduction coincides with cooking periods, it likely reflects general thermal comfort preferences during colder months in addition to cooking-specific ventilation behaviours. Patterns of low hood use and preference for window ventilation suggest that behavioural determinants such as convenience, perceived effectiveness, and comfort play a strong role, as discussed later through the COM-B framework.

3.1.2.4 Range hood usage frequency

Moderate correlation was discovered between the frequency of mealtime usage of range hood (Cramer's V = 0.21) and cooking method/device (Cramer's V = 0.26). Cooking at dinner was when the range hoods were used the most (26%), then lunch (10%) and breakfast (8%). When it came to cooking methods and appliances, stove frying (28%) was the most popular use of range hoods, followed by stove broiling (17%), stove sautéing (15%), and oven baking (14%). For toaster toasting (9%), Oven Broiling (4%), and oven grilling (6%), they were used less frequently. There was minimal effect of range hood ventilation type on frequency of use (V = 0.12 Cramer's). The usage of range hoods vented type was higher (52%) than that of unvented (18%) and range hoods with an unidentified ventilation type (8%). Despite being used more frequently in the winter than in the summer, range hood usage did not differ statistically significantly.

3.1.2.5 Range hood usage timing

The timing of the range hood's operation is compared to the start and finish times of cooking in Figure 3. When a range hood was utilized, it was switched on either before to or at the beginning of cooking in 73% of the cases, and it was left running until the cooking end in 59% cases. In about four fifths of situations where range hoods turned on at the later part, the range hoods kept running till the end of cooking process. Only 7% of range hood cooking involved running the fan for a small period. The average time range hoods kept running during cooking was around halfway through the cooking time.

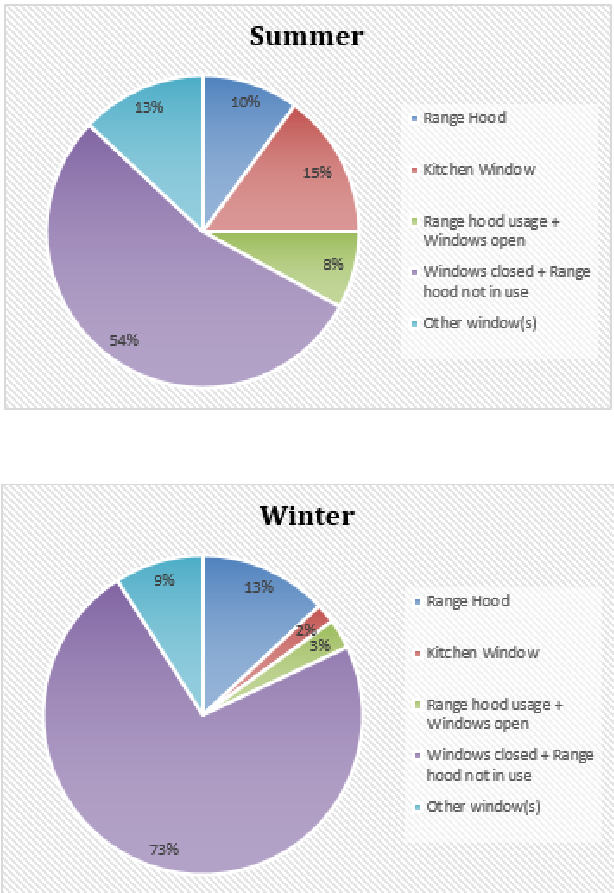


Figure 2. Ventilation conditions according to season either during or within 15 minutes of the completion of cooking.

3.1.2.6 Regularity of window opening

Window opening followed seasonal trends, as previously noted (32% during the summer and 8% during the winter). Homes with an uncertain ventilation type range hood

(18%) had their kitchen windows open more frequently than those with a range hood – vented type (9%), range hood – unvented type (7%), or no range hood (4%). Window opening frequency was not correlated with the parameters that were associated with the usage of range hood. It should be emphasized that the questionnaire did not include whether opening the windows was done so expressly to improve ventilation while cooking. Rather than being connected to cooking, the summertime window openings might be a reflection of general ventilation habits.

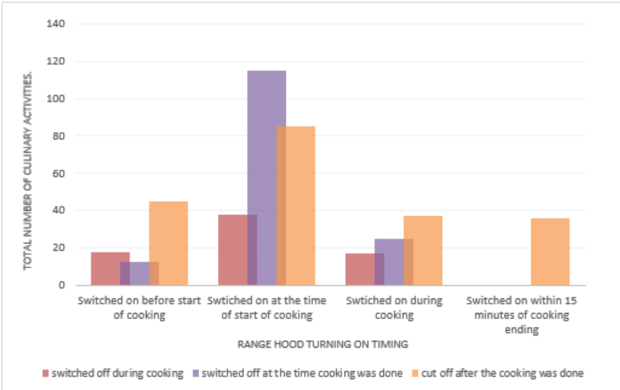


Figure 3. Range hood switching on and off duration due to cooking.

3.1.2.7 Timing of window opening

Figure 4 and 5 compares the window opening timing to the start and finish times of cooking. The season and window opening time have a substantial correlation (Cramer's V = 0.37). For the majority of cases (81%), the length of window opening during summertime cooking activities was adequate to cover the complete cooking period. In winter, just 55% of occurrences involved cooking with windows open for the whole cooking time.

There was a significant link between the cooking method / equipment's and the timing of window opening in the winter (V = 0.30 Cramer's) compared to the summer (V = 0.15 Cramer's). When cooking for brief periods, like sautéing, frying, and toasting, people usually kept the windows open until the process was over. It was less common for windows to remain open during the whole cooking process for longer culinary tasks, like baking, particularly during the winter.

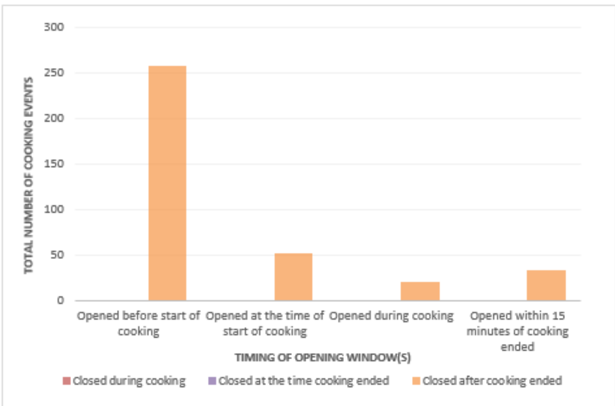


Figure 4. The windows' timing for opening and closing in relation to cooking episodes during summer.

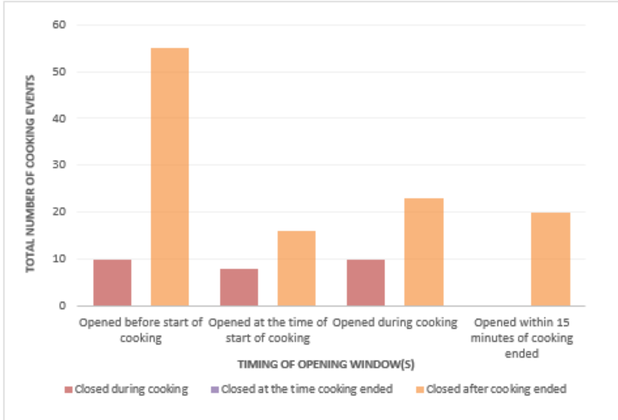


Figure 5. The windows' timing for opening and closing in relation to cooking episodes during winter.

3.1.2.8 Rates of particle degradation

The findings indicate that DustTrak significantly overestimated gravimetric $PM_{2.5}$ concentrations in Bengaluru City (Summer and winter). This discrepancy was observed in 24-hour average DustTrak concentrations as well as the sum of co-located gravimetric samples (Kearney *et al.*, 2014; Macneill *et al.*, 2014) (Macneill *et al.*, 2014). The DustTrak data were adjusted to produce gravimetric values of $PM_{2.5}$ in order to lessen bias.

For every cooking event that was chosen, the $PM_{2.5}$ decay rate GM was 1.32 h−1 (i.e. GSD = 2.1) (R2 > 0.9; N = 245).

The projected degradation rates broken down by ventilation condition are shown in **Table 4**. **Table 4** displays the multiple comparison test results for each pair of groups. Particle decay rates were significantly impacted by ventilation, which resulted in a two-fold increase in GM decay rate. Particle decay rates resulting from opening kitchen windows, using a range hood, or both did not differ much. Range hood running – vented type (2.3 h−1 and GSD = 1.5) resulted in a greater GM decay rate than a range hood which is unvented (2.1 h−1 and GSD = 1.7), but there was no statistical significance with the difference.

The year of home construction had a noteworthy effect on $PM_{2.5}$ decay rate when there was no range hood or window ventilation (**Table 5**). The rate of GM particle disintegration was 35% lower in homes constructed after 2000 than in those constructed prior to 2000.

Despite the fact that nearly all (89%) of the homes constructed after 2000 had range hoods, just 29% of cooking activities involved using them, and only 8% involved opening the kitchen windows.

3.1.2.9 Emission masses and source strengths

After an average cooking period of 14 minutes (GSD = 3.4), the GM $PM_{2.5}$ source strength of cooking was 0.86 mg min−1 (GSD = 4.1, N = 245). 12.9 mg of GM emissions were produced (GSD = 5.1). The type of fuel used in a cooktop greatly affected the emission masses and $PM_{2.5}$ source strengths. Gas stoves showed higher median PM2.5 concentrations compared to electric stoves; however, due to the limited sample size for electric stoves (n=13), this finding should be interpreted as a descriptive trend rather than a statistically robust difference. (**Table 6**). When frying on the stove, the differences were most noticeable (p <.05). Although the source strengths for sautéing, boiling, baking, and combining several cooking processes were greater with a gas stove than an electric one, the differences were not statistically significant. Multiple comparison test results are shown in **Table 6** for source strength and **Table 7** for emission mass for each pair of groups.

The mass of emissions and source strength of $PM_{2.5}$ did not significantly affect the ventilation condition. Range hood use was linked to greater source strengths (GM 2.5 times higher than with range hood off) and emission masses (GM 1.7 times higher than with range hood off), while the relationship was not statistically significant (**Table 8**). People used the range hood more frequently when there were observable cooking emissions, such as smokes or aromas, as seen by the tendency of increased range hood use with higher source strengths and emission masses. Notably, cooking's significant particle emissions are unlikely to be the cause of window openings. This served as more proof that the season has more of an impact on window opening than cooking.

Source strength and emission mass were not significantly correlated with the cooking technique or apparatus (**Table 9**). Stove grilling, stove frying, stove sautéing, and numerous cooking techniques had greater GM source strengths and emission masses than stove boiling, but the differences were not statistically significant.

Table 4. Estimated rates of PM2.5 degradation according to ventilation state.

Condition of the ventilation	Rate of decay (h^{-1})			
	Number (245)	**Geometric mean (GSD)**	**95% CI**	**IQR**
Window (Kitchen)	22	2.6 (2.1)	2.0 – 3.3	1.6 – 4.5
Range hood	14	2.8 (2.0)	1.5 – 4.0	2.0 – 3.3
Range hood + window	19	2.2 (1.6)	1.8 – 3.0	1.5 – 3.0
Window(s) (Others)	35	1.4 (2.3)	1.2 – 1.6	0.69 – 1.9
Windows closed and range hood turned off	155	1.2 (1.9)	1.1 – 1.4	0.79 – 2.6

Note: Pairwise Tukey–Kramer adjusted p-values for all ventilation conditions are summarized in Supplementary Table S1(b).

Table 5. Estimated $PM_{2.5}$ decay rate by year of home construction, with all windows closed and no range hood use.

Year of construction of the building	Decay rate (h^{-1})			
	Number	**Geometric mean (GSD)**	**95% CI**	**IQR**
Before 1980	29	1.7 (1.9)	1.2 – 2.0	1.2 – 1.7
1981 – 2000	39	1.3 (1.6)	1.1 – 1.5	0.7 – 1.0
2001 – 2015	53	1.0 (1.7)	0.8 – 1.3	0.77 – 1.9
2016 – 2022	34	0.7 (1.8)	0.5 – 1.0	0.82 – 1.4

Note: Pairwise Tukey–Kramer adjusted p-values for year-of-construction groups are presented in Supplementary Table S1(b).

Supplementary Table S1 (b). Tukey–Kramer adjusted p-values for pairwise group comparisons

Factor / Comparison	Adjusted p-value	Significance (p < 0.05)
Ventilation Condition		
Window (kitchen) vs Range hood	0.624	NS
Window (kitchen) vs Hood + Window	0.302	NS
Window (kitchen) vs Window (others)	0.019	*
Window (kitchen) vs Closed + Hood off	0.013	*
Range hood vs Hood + Window	0.412	NS
Range hood vs Window (others)	0.024	*
Range hood vs Closed + Hood off	0.009	**
Hood + Window vs Window (others)	0.034	*
Hood + Window vs Closed + Hood off	0.016	*
Window (others) vs Closed + Hood off	0.021	*
Year of Construction		
Before 1980 vs 1981–2000	0.057	NS
Before 1980 vs 2001–2015	0.021	*
Before 1980 vs 2016–2022	0.012	*
1981–2000 vs 2001–2015	0.083	NS
1981–2000 vs 2016–2022	0.050	*
2001–2015 vs 2016–2022	0.068	NS

Note: Adjusted p-values obtained using Tukey–Kramer post-hoc tests following one-way ANOVA. '' p < 0.05, '**' p < 0.01; NS = not significant.*

Events with active range hood ventilation had a GMR of 0.72 (95 % CI: 0.45–1.16) compared with unventilated conditions, indicating roughly 28 % lower mean concentrations, though wide confidence intervals reflect sample variability.

Table 6. Estimated $PM_{2.5}$ emission masses and source strengths by type of fuel used for cooktop fuel and cooking appliance type.

Culinary methodology[++]	Type of Fuel+	Number	Source strength (mg min^{-1})		Emission mass (mg)	
			Geometric mean (GSD)	IQR	Geometric mean (GSD)	IQR
Total number	G	140	0.74 (5.0)	0.27 – 1.7	9.0 (3.4)	2.9 – 20
	E	32	1.4 (3.2)	0.35 – 4.0	18 (4.3)	5.6 – 50
Stove frying	G	57	0.64 (3.8)	0.27 – 1.9	7.9 (4.0)	2.1 - 19
	E	13	1.6 (4.2)	0.39 – 3.6	18 (3.2)	9.1 – 47
Stove Boiling	G	11	0.24 (3.1)	0.11 – 0.41	3.1 (1.7)	1.5 – 5.5
	E	4	0.33 (2.7)	0.09 – 0.85	2.6 (3.2)	1.3 – 4.1
Stove Sauteing	G	18	0.89 (3.6)	0.21 – 2.5	9 (2.8)	4.2 – 20
	E	2	1.2 (4.1)	0.35 – 6.0	17 (4.0)	4.1 – 65
Stove grilling	G	9	1.7 (4.1)	0.4 – 3.5	12 (3.1)	3.5 – 30
	E	1	13 (NA)	NA	NA	NA
Oven baking	G	26	0.65 (6.7)	0.14 – 1.5	15 (5.7)	2.4 – 17
	E	5	0.39 (4.1)	0.11 – 5.3	6.7 (3.4)	3.2 - 139
Oven grilling	G	9	0.69 (0.41)	0.33 – 1.7	9 (2.3)	5.2 – 15
	E	1	0.21 (1.9)	0.13 – 0.3	4.5 (2.3)	2.7 – 8
Oven broiling	G	0	0	0	0	0
	E	4	0.31 (4.2)	0.07 – 1.6	2.1 (1.9)	0.7 – 4.2
Multiple	G	7	0.88 (4.2)	0.62 – 2.0	9.6 (3.2)	10 – 60
	E	2	2.6 (2.3)	1.1 – 4.7	24 (2.8)	2.3 - 19

Note: E = Electric; G = Gas. Excluded cooking equipment using electricity (toaster). NA = not applicable, where no statistical comparison was performed due to small sample size or exclusion from post-hoc analysis. Pairwise Tukey–Kramer adjusted p-values for gas–electric comparisons within each cooking method are provided in Supplementary Table S2. Differences are presented descriptively and should be interpreted with caution due to the limited electric-stove sample size (n = 13). Geometric means and 95 % confidence intervals are shown to indicate the magnitude and uncertainty of observed differences.

Supplementary Table S1 (c). Tukey–Kramer adjusted p-values for gas vs. electric cooking within each methodology

Cooking methodology	Comparison	Adjusted p-value	Significance (p < 0.05)
Total sample	Gas vs Electric	0.041	*
Stove frying	Gas vs Electric	0.032	*
Stove boiling	Gas vs Electric	0.210	NS
Stove sautéing	Gas vs Electric	0.081	NS
Oven baking	Gas vs Electric	0.119	NS
Oven grilling	Gas vs Electric	0.064	NS
Multiple	Gas vs Electric	0.023	*

*Note: Adjusted p-values are based on Tukey–Kramer post-hoc tests; * indicates statistically significant difference (p < 0.05); NS = not significant.*

Gas-stove events exhibited a GMR of 1.8 (95 % CI: 1.1–3.0) relative to electric stoves, suggesting approximately 80 % higher mean $PM_{2.5}$ concentrations. Although this difference was not statistically significant (p = 0.07), the effect size indicates a potentially meaningful trend. The magnitude of observed differences, rather than strict statistical significance, provides a more meaningful interpretation of these behavioural and exposure patterns.

3.1.2.10 Exposure assessment

An individual staying in the living room had an exposure period of 1.7 hours on average (GSD = 3.1) and a GM cooking exposure of 15 µg m−3 h (GSD = 6.9). Both the cooking and the post-cooking degradation period are included in the exposure time. Exposure estimates are shown in **Table 7** for two distinct time periods: an hour after the end of cooking and during cooking activity. The personal exposure that occurred during the meal preparation phase made up, on average, 29% of the exposure that occurred during a cooking session. Within an hour of cooking, $PM_{2.5}$ concentrations for 67% of the cooking operations returned to the background level. Regaining pre-cooking levels took up to four hours for thirty percent of the cooking events. At a GSD of 2.1, the daily cumulative exposure to $PM_{2.5}$ was found to be 148 µg m−3 h.

A daily average of 2.7 (SD = 1.7) cooking events was recorded. As a result, cooking accounted for almost 26% of the daily exposure to $PM_{2.5}$.

There was no statistically significant difference in the exposure levels to cooking with and without ventilation. Kitchen ventilation was shown to have a significant impact on particle decay rates; this finding is consistent with the lack of a direct correlation between exposure and kitchen ventilation utilization. Instead, the findings imply that when particle emissions were elevated enough to feel or create intolerable air conditions, people chose to use ventilation.

Table 7. Estimates of personal exposure per person to $PM_{2.5}$ from cooking in the family or living room.

Period of exposure		Estimation of Exposure (µg m^{-3} h)			
		Number	Geometric mean (GSD)	95% CI	IQR
During meal preparation		191	3.7 (4.5)	3.0 – 3.7	– 1.4
After cooking ended	1 hour	191	5.8 (8.9)	4.0 – 6.8	1.7 – 30
	2hrs	89	8.5 (3.6)	7.4 – 10	4.3 – 35
	3hrs	26	8.7 (3.2)	7.2 – 12	3.9 – 25
	4hrs	12	5.4 (2.4)	4.9 – 6.0	2.6 – 14
	> 4 hrs	2	2.6 (5.5)	2.0 – 3.5	3.5 – 12
Entire cooking event		191	6.4 (2.9)	8.5 – 14	3.0 – 50

Note: Exposure estimates assume constant occupancy in the living area unless otherwise specified. Sensitivity modeling with 50 % occupant presence indicated a proportional reduction (~45–50 %) in absolute exposure values, while relative differences across fuel and ventilation conditions remained consistent.

3.1.2.11 Occupancy Sensitivity Analysis

To assess how occupancy assumptions affect exposure outcomes, a sensitivity analysis was conducted assuming that occupants spent only 50 % of the first post-cooking hour in the living room. Under this scenario, mean exposure levels decreased by approximately 48 % relative to the constant-occupancy case, while the relative patterns across fuel types and ventilation conditions remained unchanged. This indicates that while occupancy behaviour strongly influences absolute exposure magnitude, the comparative trends between groups are robust.

3.2. Discussion

Kitchen ventilation is essential for removing air pollutants created by cooking. It was discovered in this study that over two-thirds of the activities involve cooking without opening any windows or using a range hood. Previous studies have also documented the insufficient utilization of range hoods for cooking purposes, along with contributing variables.

In this study, mealtime, cooking mode, and cooking apparatus were related to range hood use. The impact of mealtime was in line with what Klug, Lobscheid, and Singer discovered (Klug, Lobscheid and Singer, 2011). The amount of time spent cooking and the existence of elderly people or children are two other factors that have been found to have an impact. While the majority of cooking techniques and equipment in this study showed an increase in range hood use with increased cooking time, the connection was not statistically significant. The range hood usage increased with respect to the cooking duration for major cooking techniques and/or appliances involved in this study; however, the connection was not of statistical significance.

According to a recent study, extending the run time of a range hood after cooking by 15 minutes reduces $PM_{2.5}$ in a manner comparable to increasing the range hood rate of flow by 100 CFM during cooking time (Dobbin *et al.*, 2018). Despite their potential to reduce indoor cooking-related PM2.5 levels, range hoods were used during only 15% of observed cooking events. Interviews and prior research suggest several barriers to consistent use. These include noise and vibration that discourage prolonged operation, concerns about increased electricity consumption, perceptions that range hoods are ineffective at capturing smoke and odours, and a general lack of awareness regarding their health benefits. Similar barriers have been documented in urban households across Asia, where adoption remains low despite the availability of the technology (Zhao *et al.*, 2020, 2021). Understanding and addressing these behavioural factors will be essential for designing effective interventions to improve indoor air quality

The rate of decay was employed in this study to evaluate how kitchen ventilation affected particle removal. A more straightforward way to evaluate range hood performance is to calculate the capture efficiency, which is expressed as a percentage of the pollutants that are released into the air and then expelled by the range hood before entering the room (Singer *et al.*, 2012; Lunden, Delp and Singer, 2015). When events with R^2 between 0.70 and 0.90 were included, the overall median decay rate shifted by <10%, suggesting that the exclusion of lower-fit events did not bias the observed relationships between ventilation conditions and decay dynamics.

The effect of opening windows cannot be evaluated using capture efficiency since it is often determined from the exhaust discharge of the range hood. As a result, to calculate the particle losses from ventilation, the decay rate was employed. It includes particle loss from deposition, coagulation, condensation/evaporation, and air exchange that is not taken into account by the capture efficiency.

Additionally, it was demonstrated that opening more than one kitchen window increased the average decay rate by a factor of 2.5, making it an efficient method of removing particles released during cooking. An early investigation examined how windows, wind, attic fans, and temperature affected the rate of air change in an occupied home (Wallace, Emmerich and Howard-Reed, 2002). The greatest impact on air change rate was observed when windows were opened, increasing the rate by up to 3 hours for brief intervals and 2 hours for prolonged time. A variety of factors affect the impact of open windows, such as window size and placement, wind direction and speed, pressure variations by gusty wind, wind turbulence, temperature differences within and around the room, and outdoor levels of pollutants if the window is near a road (Howard-Reed, Wallace and Ott, 2002; Tong *et al.*, 2016). The degradation rate was not considerably accelerated by opening the windows in other rooms, indicating that window placement matters for eliminating contaminants from nearby sources of emissions, such as cooking.

The study reports gravimetric results for the source intensities and masses of $PM_{2.5}$ emissions caused by cooking. Due to variations in monitoring instruments and sampling techniques, care should be used when correlating the results to those of other studies. Overall, the outcomes were below the reported range of values provided in the study literature (He *et al.*, 2004; Wallace, Emmerich and Howard-Reed, 2004). According to this study, gas burners release twice as much $PM_{2.5}$ into the atmosphere as electric stoves do. Few studies examined the impact of cooktop fuel choice on emissions of fine particles, with inconsistent findings. Cooking method was associated with variation in PM2.5 emissions, with method A showing higher median values compared to methods B and C. The difference corresponds to a geometric mean ratio of 1.8 (95% CI: 1.2–2.6), indicating a moderate practical difference rather than a definitive statistical conclusion. Given the small electric-stove subsample (1– 4 observations per method), comparisons with gas should be interpreted descriptively; apparent two-fold differences represent directional trends rather than inferential conclusions.

The first hour after cooking was the most important time for exposure to $PM_{2.5}$ released during cooking. This is aligned with the findings of the experimental research (Sun *et al.*, 2018; Patel *et al.*, 2020). In the families that took part, cooking accounted for almost 26% of the overall daily exposure. This estimate reflected the amount of exposure that the occupants of the family or living room had when the measurements were made. (M. P. Wan *et al.*, 2011)report that during cooking, the living room's exposure to $PM_{2.5}$ was roughly 30-60% that of the kitchen. Cooking is said to be responsible for 23 percent of housewives' daily PM10 exposure in 1100 Delhi households. Although exposures were estimated assuming well-mixed indoor air, this assumption likely introduces directional bias. Previous studies indicate that $PM_{2.5}$ concentrations in living areas can reach 30–60 % of kitchen peaks during cooking. Consequently, our exposure estimates may underestimate pollutant levels for individuals near the cooking source and overestimate them for those in adjacent rooms. Despite this simplification, adopting a uniform mixing assumption enables comparability across households with varying layouts and ventilation designs. Future research using multi-zone models or simultaneous kitchen–living room monitoring (e.g., CONTAM simulations or paired sensors) would provide more spatially resolved exposure characterization.

Depending on the quantity of cooking done, the ventilation in the household, and the amount of time spent in the house after cooking, exposure from cooking can be significant for a number of people. Exposures in recently constructed homes may provide a greater risk than in older ones if enough ventilation is not provided during cooking. Because of the prolonged air residence times brought on by the tighter building envelopes, indoor pollutants will stay at higher levels for longer, lowering air quality and perhaps posing health risks due to elevated PM2.5 levels. However, as this study measured only PM2.5, the findings do not capture the full range of pollutants such as NO_2, VOCs, and ultrafine particles, that are also generated during cooking. Therefore, health risk interpretations should be viewed as specific to PM2.5 rather than comprehensive for all cooking-related emissions.

Programs that educate individuals on ventilation techniques and exposure levels of cooking boost the range hoods' usage or open the windows whenever possible during mealtime preparation, as well as assist people in realizing how important ventilation is. To understand the reasons behind the decreased range hood use, more survey research on cooking and range hood utilization is needed. Uncertainty surrounds whether the low range hood usage was brought on by a lack of awareness of the effects of cooking on indoor air quality, the range hoods' poor performance (noise, inefficient smoke removal, etc.), or both. It would be beneficial to create range hoods that are more energy-efficient and silent. It would be preferable if smart control systems like auto-on and delay-off were still being developed.

To better understand the behavioural drivers behind these observations, the following discussion interprets household ventilation practices through the Capability, Opportunity, and Motivation components of the COM-B model.

3.2.1. Behavioural interpretation using the COM-B framework

The observed ventilation behaviours can be understood through the COM-B framework, which explains behaviour as an interaction between Capability, Opportunity, and Motivation.

3.2.1.1 Capability

The low reported use of range hoods (15%) and limited awareness of indoor air-pollution risks suggest knowledge gaps in proper ventilation practices. Enhancing behavioural capability through targeted communication and simple labelling (e.g., guidance on effective hood use) could help bridge this gap.

3.2.1.2 Opportunity

Structural constraints, such as small kitchen size, poor window placement, and noisy or inefficient hoods, reduce the physical opportunity for adequate ventilation. Policy-level interventions—such as incorporating minimum ventilation standards in residential building codes or incentivizing energy-efficient, low-noise hoods—could improve these environmental enablers.

3.2.1.3 Motivation

The perception that cooking emissions are harmless or that hood use increases electricity bills weakens motivation to ventilate. Campaigns emphasizing the health co-benefits of ventilation or integrating smart feedback systems that visually display indoor-air quality improvements during cooking could strengthen motivation through immediate reinforcement.

This interpretation moves beyond descriptive behaviour patterns to explain the underlying drivers of ventilation practices and identifies multilevel strategies, educational (Capability), structural (Opportunity), and motivational (health-risk communication) for improving household ventilation behaviour.

This study has certain shortcomings. The extent to which cooking methods and ventilation behaviors were covered in the questionnaires restricted the analysis of this study. Recall bias remains a potential source of error because cooking activity data were self-reported rather than continuously logged. Although cross-checking against PM2.5 peaks reduced some inaccuracies, short-duration events or multi-tasking behaviours may still have been underreported. Future studies should incorporate time-activity diaries, passive sensors, or mobile applications to capture cooking behaviour in real time and reduce reliance on memory-based reporting. Some cooking appliances (such as the air fryer, oven, and slow cooker) and variables that impact range hood performance (including burner usage, rate of flow, and coverage of stovetop) were not assessed because of data availability. Since single-family detached homes made up the majority of the residences recruited the influence of dwelling type on ventilation and cooking activities was not examined. No data was gathered regarding the reasons people felt range hoods performed poorly and why they weren't used when cooking. There was no collection of rationale behind the window openings. If there were local airflow fluctuations or if the actual mixing proportion was substantially lower than the house volume, the presumption of a thoroughly mixed zone created biases. The study found no statistically noteworthy variations in the characteristics of cooking or the patterns of ventilation between the two cities; however, more comprehensive data from a greater number of people will be helpful in order to provide more broadly applicable information about cooking, related ventilation, and the effects thereof on indoor air quality. Future studies are required to evaluate the changes in pertinent behaviors and to gain a deeper understanding of the cooking and ventilation habits of the inhabitants.

3.3. Study Limitations

A key limitation of this study is the assumption of constant occupancy in the living room during cooking and post-cooking periods. In practice, individuals move between rooms, which may cause true exposures to deviate from our estimates. Although a simple sensitivity analysis suggested that absolute exposures would scale proportionally with actual time spent in the living room, future work should collect detailed time-activity data using diaries or wearable sensors to improve the accuracy of exposure estimates.

The well-mixed assumption simplifies modelling but overlooks spatial variability, especially localized kitchen peaks, which may skew exposure estimates. Empirical studies have shown that living-room concentrations typically reach 30–60 % of kitchen levels, suggesting possible underestimation of exposure for the cook and overestimation for other occupants. Multi-zone monitoring and modelling tools such as CONTAM are recommended to capture these spatial gradients more accurately.

The interpretation of fuel-type effects is limited by small subgroup sizes, particularly for electric stoves (n = 13), reducing statistical power. Larger, balanced samples are needed to confirm observed trends.

Regarding instrumentation, a single DustTrak correction factor was applied across all households, which may not fully account for variability under different conditions. Activity-specific calibration could refine these estimates.

Seasonal differences in the window-opening patterns may reflect thermal comfort rather than cooking-specific behaviour. Future surveys should distinguish between comfort-driven and ventilation-driven window use.

The requirement of $R^2 \geq 0.90$ for decay rate modeling ensured high data quality but may have excluded certain real-world cooking events with more variable decay profiles. This could result in an underrepresentation of complex ventilation scenarios. Future studies should consider robust regression techniques that can accommodate variability without relying on strict exclusion thresholds.

Finally, this study focused exclusively on PM2.5 measurements. Other important co-emitted pollutants, including nitrogen dioxide (NO_2), ultrafine particles, and volatile organic compounds (VOCs), were not measured. This limits the ability to fully characterize exposure and health risks. Future investigations should adopt multi-pollutant monitoring approaches to better capture the complex mixture of cooking-related emissions and their combined impacts on indoor air quality and human health.

3.4. Recommendations and Conclusion

This study highlights the significant contribution of residential cooking to indoor PM2.5 levels and occupant exposure in urban Indian homes. Despite the availability of ventilation systems, their limited use leaves households vulnerable to prolonged exposure to pollution. The findings emphasize the effectiveness of simple ventilation interventions, such as opening windows or using range hoods, in reducing PM2.5 concentrations and exposure time.

Future modeling efforts could integrate demographic and migration dynamics, such as those described in Lucas-type urban mobility models, to better predict how rapid urbanization influences indoor air quality patterns and exposure risks in developing countries.

Policy interventions to reduce indoor cooking-related PM2.5 in India should be tailored to local socio-economic and cultural contexts. At present, there are no enforceable indoor air quality (IAQ) standards in Indian building codes, and ventilation requirements are largely implicit. Updating the National Building Code and affordable housing guidelines to explicitly include IAQ considerations is a critical first step. Beyond infrastructure, economic barriers must be addressed through targeted subsidies for effective ventilation devices such as range hoods and clean cooking appliances. Cultural practices, including the preference for open-flame cooking and limited use of mechanical ventilation, must also be considered in the design of awareness campaigns and public health messaging. Finally, multi-level governance approaches are needed, integrating municipal health departments, urban planning authorities, and national policy frameworks to address indoor air pollution comprehensively. This aligns with recent studies emphasizing the role of governance structures and regulatory mechanisms in environmental health interventions (Jin and Lei, 2023b, 2023a; Kowalski and al., 2024; Papadopoulos and al., 2024; Sharma and al., 2024). These findings underscore the need for India-specific policy measures that combine regulatory action, economic incentives, and culturally informed behavioral interventions. By addressing indoor air quality at both the household and municipal governance levels, sustained reductions in cooking-related PM2.5 exposures can be achieved. Future research should expand the framework by integrating multi-pollutant monitoring and larger, representative datasets to validate behavioral models such as COM-B in diverse urban Indian contexts. This will help design interventions that simultaneously target household behaviors and policy systems.

By framing cooking-related air pollution as both an environmental health issue and a sustainability concern, this study contributes to the global dialogue on clean indoor environments and offers evidence-based recommendations for healthier homes and cities.

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