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Characterization of particulate matter in a multizonal residential apartment: transport, exposure, and mitigation†

Alok Kumar Thakur [a] and Sameer Patel *[bcd]

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Due to rapid urbanization and lifestyle changes, people in developing countries like India spend most of their time indoors, just like those in developed countries. Indoor air pollution (IAP) studies in urban built environments in India are yet to gain momentum. Studies conducted so far are restricted to reporting pollutant concentration, providing limited insights into pollutants' source, transport, and fate. Comprehensive studies are critical to assessing IAP severity and developing and deploying effective mitigation strategies in built environments. The present study includes spatio-temporal monitoring of particulate matter (PM) in a multizonal residential apartment using a network of low-cost air quality monitors and research-grade instruments to characterize emission sources, assess transport metrics, estimate spatial exposure, calculate *I*/*O* ratios, and assess efficacies of different mitigation measures. Sub-micron particles dominated number size distribution for cooking and incense. Operation of air conditioners (AC) led to faster transport of pollutants from the kitchen to the bedrooms. PM exposure in all zones relative to the kitchen had comparable (∼0.8–0.9) exposure during cooking. The average *I*/*O* ratios during cooking were elevated throughout the apartment, with the kitchen (10.1 ± 8.9) and bedrooms (7.2 ± 5.7 & 7.4 ± 5.9) being the highest and lowest, respectively. Natural ventilation through balcony doors led to an average exposure reduction of 74–86% in different zones. AC operation reduced cumulative exposure, which was further reduced upon affixing a filter sheet on the AC pre-filter. Among the mitigation measures assessed, the highest cumulative loss rate (2.3 ± 0.1 h^{-1}) was observed for the portable air cleaner with the default HEPA filter.

Environmental significance

Studies in urban indoor environments in emerging economies, such as India, are mostly restricted to reporting pollutant concentration, which restricts our understanding of the fate and transport of pollutants. Comprehensive studies, particularly in multizonal indoor environments, are required to understand the inter-zonal transport of pollutants and spatio-temporal exposure for implementing mitigation measures. The present study includes spatio-temporal particulate matter monitoring in a multizonal apartment. Exposure to cooking emissions in all zones was comparable to the kitchen, with average *I*/*O* ratios of ∼7–10. Adding filter sheets on pre-existing air conditioners reduced exposure and lowered airflow, which might compromise thermal comfort. Key insights from the study have implications for similar urban built environments in India.

1 Introduction

Indoor air pollution (IAP) accounts for around 3 million annual deaths globally due to solid fuels, primarily used in rural settings.[1] Similar health impact or mortality burden data is limited for urban settings with cleaner fuels being used, particularly in developing nations. Most IAP studies in India related to measurement and health impacts are restricted to rural areas, focusing on cooking fuels or types of cookstoves.[2–6] In urban India, most studies focus on ambient or outdoor air pollution.[7,8] While people in developed nations spend around 80–90% of their time indoors,[9] data on such activity patterns is unavailable for India. However, it is reasonable to state that a similar activity pattern in India is emerging due to urbanization and changes in lifestyle. These recent changes in activity patterns, the adaptation of cleaner fuels, and the rural–urban transition call for more studies in urban built environments.[10]

[a]Department of Earth Sciences, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat 382355, India

[b]Department of Civil Engineering, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat 382355, India. E-mail: sameer.patel@iitgn.ac.in

[c]Department of Chemical Engineering, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat 382355, India

[d]Kiran C. Patel Centre for Sustainable Development, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat 382355, India

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Though limited Indian studies have focused on various built environments like schools,[11] universities,[12] hospitals,[13] and commercial offices,[14] comprehensive IAP studies for residential apartments, where the majority spend more than half of their time, are still lacking. In developed nations, several comprehensive IAP studies in residences have been conducted to understand emission sources, characteristics, transport, transformation, and fate.[15–20] However, the conclusions derived from such studies cannot be directly applicable to India due to variations in lifestyle, occupants' behaviors, house layout and design, the absence of centralized HVAC systems, a wide range of indoor emission sources, and a significantly higher contribution of infiltration of particles from ambient.

Exposure characterization and its spatial–temporal variation to understand the transport of pollutants and exposure occurring in multizonal indoor spaces is critical to devise and implement any mitigation strategy. Single-point measurements limit the ability to understand the overall indoor dynamics of pollutants in multizone buildings like residential apartments where the well-mixed assumption does not hold. However, fine-resolution spatio-temporal monitoring using research-grade instruments is usually cost-prohibitive. Low-cost air quality monitors (LCAQM) for PM are widely researched alternatives enabling high-resolution spatio-temporal measurements. While the accuracy of the absolute measurements by LCAQM depends on the calibration, LCAQM measurements have demonstrated high linearity against research-grade instruments.[21–25] Tryner *et al.* collocated nine units of LCAQM against tapered element oscillating microbalance for one week in a home kitchen and reported $r = 0.96–0.97$.[26]

Spatio-temporal studies in developed countries have focused on several aspects of IAP, including estimation of the true extent of exposure in different zones,[27] the evolution of concentration,[28] analysis of the transport of pollutants,[29] devise mitigation strategies,[30] source apportionment.[31] However, only a few studies have focused on spatio-temporal variation in indoor spaces in India. Sahu and Gurjar studied the spatio-temporal variation of PM and VOCs across all floors in a university's library.[12] They reported the highest PM concentrations on the first floor and the highest TVOC and CO_2 concentrations on the ground floor.[12] Dhiman *et al.* measured PM concentration at different heights in two zones in an institutional dining hall and reported higher concentrations at the upper level.[32] However, these multizonal studies provide a limited understanding of the inter-zonal transport of pollutants and the corresponding exposure occurring due to it. The limitation also hampers further studies on modeling and mitigation.

Further, IAP studies in India focused primarily on reporting cumulative PM levels ($PM_{2.5}$ and PM_{10}),[14,33,34] and a handful of studies have reported PM size distribution.[34,35] Moreover, the inter-zonal transport of pollutants in multizonal indoor spaces in India is yet to be studied. Interzonal transport of pollutants from the source zone governs the exposure occurring in different zones. Therefore, exposure estimated using single-point measurement might not represent cumulative exposure occurring in multizonal settings. Therefore, spatio-temporal measurements are critical for more accurate exposure assessment. Knowledge of spatio-temporal PM levels is also required to devise and deploy efficient and effective mitigation measures to reduce personal cumulative exposure.

This work deploys a network of in-house developed LCAQMs (with PMS5003 sensors) for spatio-temporal measurements of PM in a three-bedroom residential while performing uncontrolled and controlled emission activities to (i) characterize various emissions sources (cooking, dusting, and incense sticks), (ii) understand the inter-zonal transport of emissions from the source zone to other zones of the apartment, (iii) exposure occurred under different scenarios in different zones, (iv) estimates indoor–outdoor ratios under different conditions at different instances of the day, and (v) characterize and assess the efficacy of the common mitigation strategies like the portable air cleaner, air conditioner, filters, and natural ventilation.

2 Material and methodology

2.1 Study site

The study was conducted in a 146 m^2 three-room residential apartment at the IIT Gandhinagar campus in May 2023. In May, ambient temperatures varied between 27 °C to 44 °C. The apartment, occupied by non-smoking residents, was on the middle floor of a three-story building with three identical apartments per floor. The apartment had two bedrooms, a study room, a living room, one kitchen, and two balconies on either side of the living room (Fig. 1).

The apartment did not have a centralized cooling system. Three independently operating air conditioners (AC) were installed (one each in the two bedrooms and the living room) to maintain thermal comfort (Fig. 1). All ACs were split types, *i.e.*, comprising two units, air cooling units installed inside and the compressors installed outside. Split-type air conditioning units did not take any fresh air as they are designed to operate with 100% recirculation air. Multiple independently operating ACs are common in Indian residences, allowing for partial space cooling and saving energy. All ACs can also be operated in blower mode at different flow rates without cooling. Pictures of indoor AC units are in Section S1 (Fig. S1a–c†) of the ESI.†

A ∼120 USD portable air cleaner (PAC) with a clean air delivery rate (CADR) of 360 $m^3 h^{-1}$ was used for exposure mitigation experiments (Fig. S1d†). The PAC with HEPA filter had three fan speed operating modes, and all experiments were performed at the highest setting. Commercially available filter sheets (∼2 USD each), advertised to capture dust, pollens, and allergens that can be affixed to the existing pre-filters of the ACs (Fig. S1e†), were also tested. A cooking stove with three burners was used with piped natural gas for cooking (Fig. S2†). Mustard cooking oil was used for most cooking, with a few instances of refined rice bran oil.

2.2 Experimental design

The experiments can be broadly classified into two categories: (1) non-intervention cooking by the resident and (2) controlled experiments with specific sources and ventilation settings. The

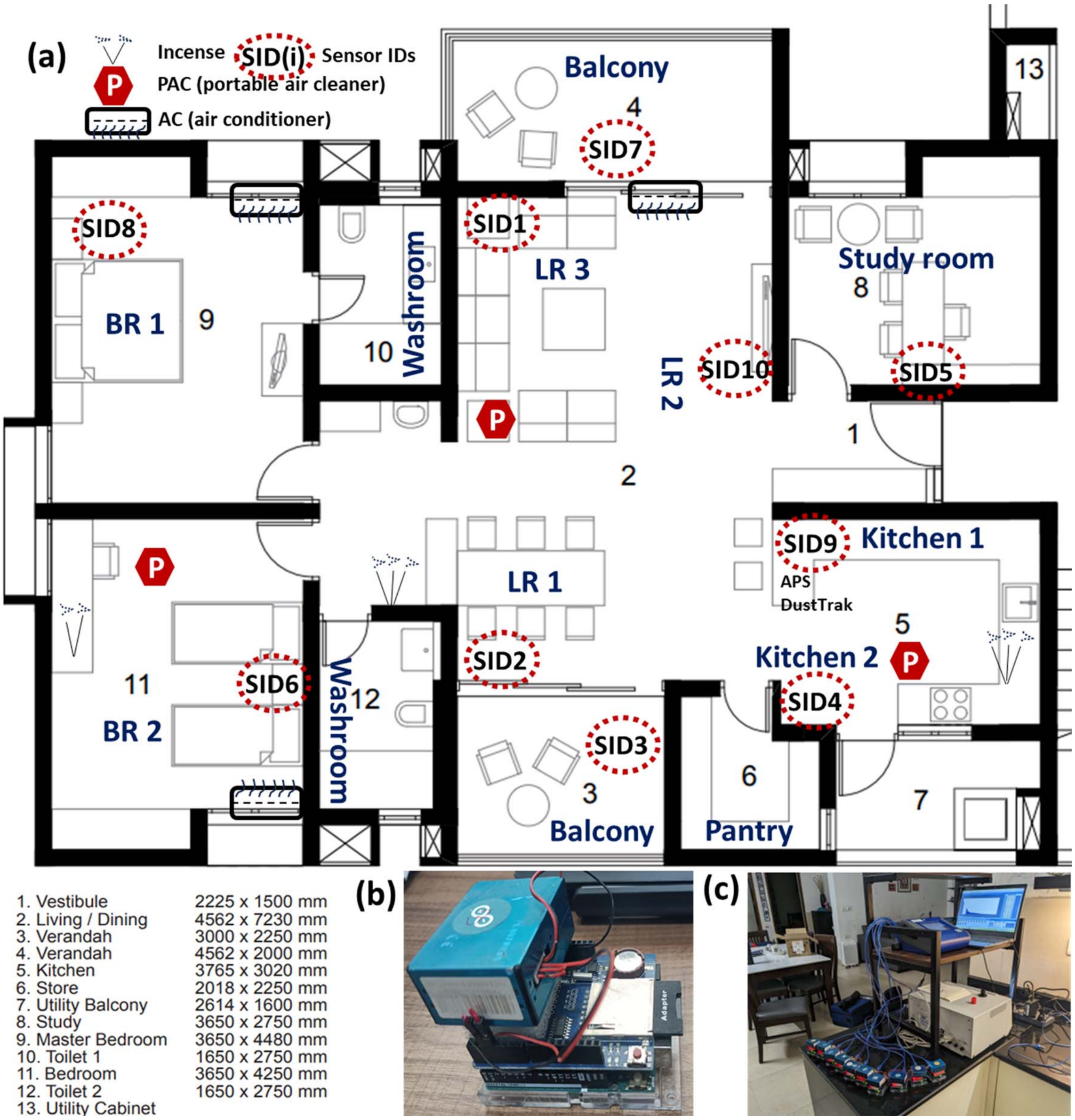

Fig. 1 (a) Layout of the apartment showing the locations of ten low-cost air quality monitors (LCAQMs), air conditioners (ACs), portable air purifier (PAC), and emission sources, (b) Plantower PMS5003-based LCAQMs; and (c) the collocation of all the LCAQMs along with the APS and DustTrak. Floor plan layout adapted from the campus plan document (https://campus.iitgn.ac.in/pdf/Design-of-Housing.pdf).

non-intervention cooking included preparing Indian meals under different indoor environmental and ventilation conditions, as documented by the resident. The cooking methodology included shallow and deep frying, baking on an iron pan, and boiling (Table S1†). There were no cooking-related instructions provided to the resident except to maintain an activity log that included information such as the type of food being cooked, the number of stoves used, the start and end time of cooking, and ventilation-related information (timings of opening and closing balcony doors).

Two types of controlled experiments were performed during the campaign. For controlled experiments – type 1, the emission source was kept either in the kitchen or the worship place, with all internal doors opened (except the washrooms and pantry). Three incense sticks from the same production batch were used as a relatively consistent emission source to estimate (i) the relative exposures under different scenarios, (ii) the interzonal transport of pollutants from the source to other apartment sections, and (iii) the efficacy of various mitigation measures. The balcony doors were kept open and closed according to the need for specific experiments. Further details about all the different experiments conducted during controlled type I are mentioned in Table 1.

All controlled experiments – type 2 were performed in BR 2, housing the emission source (incense sticks) with its door closed to isolate it from the rest of the apartment. Experiments in this category were performed to characterize and compare different mitigation strategies. Two incense sticks were used as

Table 1 Two types (type 1 and type 2) of controlled experiments conducted during the experimental campaign[a]

Controlled experiments – type 1				Controlled experiments – type 2		
Emission source location	Balcony doors	ACs	PAC	Emission source location	AC	PAC
Kitchen	Closed	NA	NA	BR 2	NA	NA
Kitchen	Opened	NA	NA	BR 2	ON	NA
Kitchen	Closed	All ON, without filter sheet	NA	BR 2	ON, with filter sheet	NA
Kitchen	Closed	All ON, with filter sheet	NA	BR 2	NA	ON, with HEPA filter
Kitchen	Closed	NA	In kitchen	BR 2	NA	ON, without HEPA filter, with filter sheet
Kitchen	Closed	NA	In living room	BR 2	NA	ON, with HEPA filter, with filter sheet
Kitchen	Closed	NA	In BR 2			
Worship place	Closed	NA	NA			
Worship place	Closed	All ON, without filter sheet	NA			
Worship place	Closed	All ON, with filter sheet	NA			

[a] All experiments were performed using LCAQM.

the emission source during these experiments. The PM mitigation efficacy was characterized for (a) AC, (b) AC with filter sheet, (c) PAC with HEPA filter, (d) PAC with filter sheet, and (e) PAC with HEPA filter and filter sheet, as outlined in Table 1. The stand-alone mitigation technologies (AC and PAC) were switched on after the incense sticks were extinguished, and all the experiments were done in triplicates. The deposition rate and clean air delivery rate (CADR) were calculated to assess the performance of the applied stand-alone technologies.

2.3 Instrumentation and sampling scheme

In-house developed LCAQM using Plantower PMS5003 sensors (Fig. 1b) was used for high-resolution spatio-temporal monitoring. These sensors work on the light scattering principle where a photodiode collects the light scattered by the particles at an angle of 90° to the incident light, which has a wavelength of around 650 nm. The sensor provides mass concentration in three fractions: PM_1, $PM_{2.5}$, and PM_{10}, and number concentration in six size channels (>0.3 μm, >0.5 μm, >1.0 μm, >2.5 μm, >5.0 μm and >10.0 μm). The data shield logger was used with a microSD card slot to record the data at a specified interval of one-second resolution. The total cost of the sensor assembly, including the microcontroller board, logger, microSD card, and sensor, was ∼60 USD. Ten LCAQM were produced and collocated for multiple sources before spatial deployment. Collocation (Fig. 1c) was done before and after the experimental campaign for three types of aerosols, *i.e.*, cooking, incense, and background (ambient). After the initial collocation, the LCAQMs were deployed at different locations in the house at ground heights ranging from ∼1–1.5 meters, with two LCAQMs kept in the balconies to record outdoor concentrations (Fig. 1a and Table S2†).

An Aerodynamic Particle Sizer (APS 3321, TSI Inc., Shoreview, MN) measured size distribution (542 nm–∼20 μm) at one-minute resolution. DustTrak (DustTrak 8533, TSI Inc., Shoreview, MN) measured mass concentrations (PM_1, $PM_{2.5}$, PM_{res}, PM_{10}, and PM_{tot}) at 10 seconds resolution. APS and DustTrak were located in the kitchen (Fig. 1c). A time activity diary was maintained to perform the uncontrolled and controlled experiments in the apartment. The time activity diary contained information about (i) types of meals cooked, (ii) cookstove on and off time, (iii) the opening and closing time of various doors, (iv) the time of switching on/off air conditioning and portable air cleaner, and (v) timing of incense stick lightening. Continuous measurements were recorded throughout the entire campaign except for short durations when the instruments were offline for downloading data and any required maintenance. The data were downloaded every five days. A hotwire anemometer was used to measure the inlet and outlet air velocity of ACs and the outlet velocity of the PAC. Emporia Vue energy monitor was used to monitor the energy consumption of each air conditioner separately in real-time at a one-minute resolution.

2.4 Data analysis

LCAQMs measurements at 1 Hz frequency were averaged every 60 seconds for further analysis. Collocation of the LCAQMs was done for three types of aerosols: (i) incense, (ii) cooking aerosols, and (iii) background aerosols. Data obtained from all nine monitors (SID1–SID9) were linearly correlated against the remaining monitor (SID10) during the post-emission decay periods. All the LCAQMs were corrected by applying the calibration factor from the collocation experiments for further analysis. Data from collocation experiments, analysis, and calibration factors are presented in Section S2 and Fig. S3–S5.†

The analysis was divided into four broad categories: (a) source characterization, (b) assessing the transport of pollutants from the source to different parts of the apartment, (c) estimating the exposure at different locations under different scenarios, and (d) comparative evaluation of mitigation strategies. For source characterization, PNSD (particle number size distribution) ($dN/d\log d_p$) from APS was plotted for each major activity (cooking, incense, dusting) along with the background-size distribution, averaged over 30 minutes from the onset of the activity. Mass distribution ($dM/d\log d_p$) was also calculated for the current study, assuming spherical particles of unit density. The maximum and average $PM_{2.5}$ concentration (averaged over cookstove ON and OFF time duration) during the different non-intervention cooking were also calculated to predict the exposure corresponding to different cooking styles.

The $PM_{2.5}$ transport time from the place of origin (kitchen and worship place) to reach three extreme sections of the apartment (BR 1, BR 2, and SR) is calculated. The transport time of $PM_{2.5}$ is estimated using the time it took for the concentration in the respective section of the house to become 2×, 3×, and 4× of the background concentration and reach the peak concentration. The transport time was calculated for three scenarios: (i) control (without AC), (ii) all three ACs (LR, BR 1, BR 2) on, and (iii) all three ACs on with filter sheets.

The integrated exposure (E) over the time interval t_1 and t_2 is calculated using eqn (1).[36] Exposure was calculated for the following scenarios: (i) the cooking period (60 minutes from the onset of cooking; $t_2 - t_1 = 60$ min), (ii) the whole day ($t_2 - t_1 =$ 24 hours), and (iii) background (12 AM–6 AM; $t_2 - t_1 = 6$ hours). Further, exposure was also calculated for the scenario where ACs (with and without filter sheet) were tested as a control measure (120 minutes from the onset of incense lightening, $t_2 - t_1 = 120$ min). Exposures were calculated relative to the kitchen to briefly compare the personal exposure occurring in different zones of the house using eqn (2). Additionally, the $PM_{2.5}$ I/O ratio was calculated to determine the dominant contribution (particles of indoor or outdoor origin) in the cumulative indoor exposure using eqn (3). All the experiments were done in triplicates.

$$E = \int_{t_1}^{t_2} C(t)\mathrm{d}t \tag{1}$$

$$\text{Relative exposure}_{\text{zone}} = \frac{E_{\text{zone}}}{E_{\text{kitchen}}} \tag{2}$$

$$I/O = \frac{PM_{2.5}(\text{zone})}{PM_{2.5}(\text{ambient})} \tag{3}$$

Lastly, different mitigation techniques were compared under various scenarios, as mentioned in Table 1 under controlled experiments – type 2. The combined loss rate $(\vartheta + \frac{\eta Q}{V})$ was calculated using eqn (4) by assuming the well-mixed zone for BR 2 using the mass balance box model for controlled experiments – type 2. Experiments were done in triplicate, and the mean and standard deviation were reported. The CADR value is further calculated to assess the performance of the employed techniques using eqn (5). The room volume (V_{chamber}) of BR 2 is 44.52 m^3 (3.65 m × 4.25 m × 2.87 m).

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -\left(\vartheta + \frac{\eta Q}{V}\right)C \tag{4}$$

$$\text{CADR} = \left(\left(\vartheta + \frac{\eta Q}{V}\right)_i - \left(\vartheta + \frac{\eta Q}{V}\right)_{\text{control}}\right) \times V \tag{5}$$

Here, C is the indoor concentration, t is the time interval, V is the volume of BR 2, ϑ is the deposition rate, η is the filtration efficiency, Q is the flow rate, and i is the different tested mitigation measures.

3 Results and discussion

3.1 Source/activities characterization

Fig. 2 shows the particle size distribution obtained using APS for three primary sources: incense, cooking, and cleaning. For incense (Fig. 2a), sub-micron particles dominated the number concentration. While APS does not measure sub-500 nm particles, the experimental data appears to be consistent with those reported by previous studies. Ji *et al.* reported a peak diameter of 136 nm for incense emissions.[37] Chang *et al.* reported count median diameter (CMD) in the range of 90 to 177 nm for four types of incense sticks.[38] Sub-500 nm size distribution could not be measured due to instrumental limitations, and therefore, the median diameter is not discussed in this study. Particle mass size distribution (PMSD) for incense (Fig. 2b) shows no considerable difference between incense and background for super-micron particles.

The PNSD corresponding to one of the cooking activities (shallow frying flatbread, Fig. 2c) demonstrates a considerable difference between the cooking and background concentration for sub-micron particles. Fig. 2d shows the corresponding PMSD, where, unlike incense, elevated concentrations relative to the background are observed for both super and sub-micron particles. Similar trends for PNSD and PMSD can also be seen for other cooking activities (deep frying flatbread and frying chips) in Fig. S6.† The elevated number concentration in the sub-micron is attributed to the nature of particles emitted during cooking, which are primarily sub-500 nm, as reported by earlier studies.[17,39] Patel *et al.* measured mass concentrations during various cooking activities and reported that the average $PM_{0.5}/PM_{20}$ ratio varied between 27.5–88%,[17] showing a significant mass contribution from the sub-500 nm particles. Sub-500 nm particles fall beyond the APS measurement range, leading to underestimating concentration during cooking activities, which is discussed later in the section. The elevated concentration in the super-micron range in Fig. 2d was entirely due to the cooking-generated aerosols. It was not due to the dust resettlement that occurred due to occupant movements, as was verified by comparing the size distribution data from the 'cooking preparation' and 'actual cooking' phases. Earlier studies have also reported the emissions in the super-micron range from cooking activities.[40,41]

A domestic helper came every day to sweep and mop the floors. Surfaces such as dining tables and shelves were cleaned weekly using a wet cloth. Fig. 2e shows the PNSD measured during one such dusting activity, along with the corresponding mass distribution in Fig. 2f. PNSD and PMSD corresponding to the cleaning activity followed the same trend as background in the super-micron range, with slight variation noticed in the sub-micron range for PNSD plot. The results differ from one of the earlier studies focused on cleaning and dusting, where dominance was noticed in the super-micron range due to the

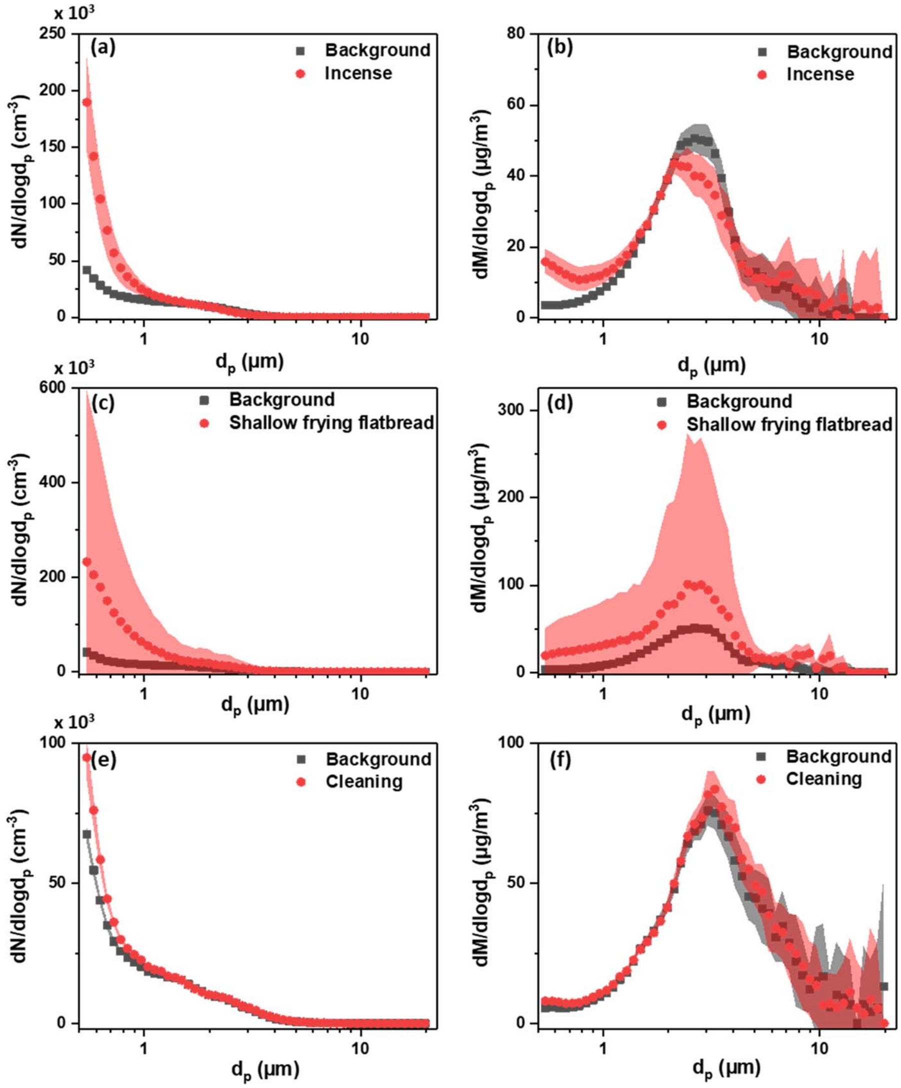

Fig. 2 The left panel shows the particle number size distribution (PNSD), and the right panel shows the particle mass size distribution (PMSD) corresponding to three sources: (a and b) incense, (c and d) cooking, and (e and f) cleaning.

resuspension of 1–10 μm particles after broom sweeping.[42] The differences observed in the current work may be due to the use of wet cloth in cleaning activities, which might have prevented dust resuspension.

Apart from the particle size distribution obtained using APS, average PM mass concentrations (PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{tot}) recorded by a DustTrak for different cooking activities are tabulated in Table S3.† Table S3† also contains the average PM_1, $PM_{2.5}$, and PM_{10} reported by LCAQM to allow a relative comparison. The PM concentrations reported by LCAQM were underreported compared to the ones reported by DustTrak. It should be noted that the DustTrak and LCAQM are calibrated for aerosols whose properties are most likely different from cooking. As per DustTrak, the average concentration was the highest for deep-fried flatbread and stir-fried vegetables, with $PM_{2.5}$ concentrations of 1033.9 μg m^{-3} and 806.6 μg m^{-3}, respectively. The concentrations were the lowest for peanut roasting and vegetable pancakes, with average $PM_{2.5}$ of 91.1 μg m^{-3} and 96.3 μg m^{-3}, respectively. In contrast, the LCAQM reported the highest $PM_{2.5}$ for shallow-fried flatbread in a flat pan (322.2 μg m^{-3}) and deep-fried flatbread (307.8 μg m^{-3}). LCAQM reported the lowest $PM_{2.5}$ for roasting peanuts, similar to the DustTrak.

3.2 Transport of pollutants within the apartment

Metrics like exposure, emission/deposition rate, and air-exchange rate are usually estimated using an indoor air mass balance model assuming well-mixed volume, which is rarely the case in IAQ studies conducted in multizone indoor environments.[43] Therefore, studying inter-zonal pollutant transport is crucial to understanding indoor dynamics for more accurate estimation of metrics such as exposure and transport characteristics. Sankhyan *et al.* used the time difference between observing the highest concentration in two different zones of an apartment as a proxy for inter-zonal transport time.[30] However, it might not be the best metric as emission profiles from various sources, such as cooking and incense, are dynamic with multiple peaks. Thus, selecting a single absolute peak might lead to inconsistencies in the estimation of transport time. Therefore, the current work has also included the time taken for concentration in a zone to become 2×, 3×, and 4× of the background as an additional proxy for estimating pollutant transport time from the source zone, *i.e.*, kitchen.

The $PM_{2.5}$ recorded by the LCAQMs in the two bedrooms and study room was used to characterize the transport of pollutants from the kitchen. In Fig. 3, the top three plots show the time it took (from the ignition) for the PM concentration to become two (2×), three (3×), and four (4×) times the background concentration in the respective zones (BR 1, BR 2, and SR) of the house. The bottom plot (Fig. 3d) reports the time corresponding to the peak concentrations. The time metrics were estimated under three conditions: (a) control (without AC), (b) AC blower fans switched on at the highest speed (with AC on), and (c) AC switched on with a filter sheet inside it (with AC on + filter sheet). All the experiments were performed independently in triplicates.

On average, it took 10.6 ± 1.9, 14.0 ± 0.8, and 10.3 ± 1.7 minutes for the concentrations in the SR, BR 2, and BR 1 to reach twice the background levels under the 'without AC' condition. When the ACs were switched on, the average time decreased to 6.0 ± 0.8 minutes and 4.6 ± 0.5 minutes for BR 2 and BR 1, respectively, indicating enhanced internal mixing due to the AC operation in BR 1, BR 2, and LR. However, the time to reach 2× concentration remained relatively the same (9.0 ± 1.6) for the SR, even with the AC operation in the bedrooms and living room. This could be attributed to the absence of AC in the SR. Similar trends were observed for the time it took for 3×, 4×, and peak concentrations in BR 1, BR 2, and SR. The two-tailed *p*-test with a significance value set at $p = 0.05$ was performed to assess the statistical significance difference between the three categories (without AC, with AC on, with AC on + filter sheet). For the study room, the time differences estimated for all three conditions (without AC, with AC, and with AC + filter sheet) did not demonstrate any significant difference. However, a statistically significant difference ($p < 0.05$) was observed between the 'without AC' and 'with AC on' scenarios for BR 2, as shown by the asterisk symbol in Fig. 3.

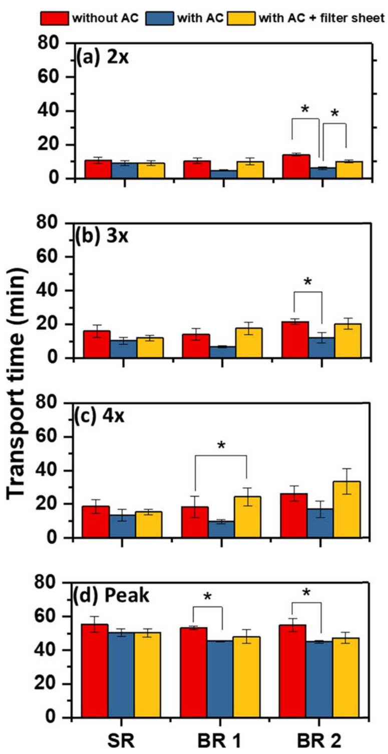

Fig. 3 Time for the concentrations in the study room (SR), bedroom 1 (BR 1), and bedroom 2 (BR 2) to reach (a) 2×, (b) 3×, (c) 4×, and (d) peak relative to the background concentration under three scenarios: without AC, with AC on, and with AC on + filter sheet, * with bracket shows the compared categories and presence of significance difference.

The time metrics reported in this section depend on internal AC settings and vary with the apartment's layout. Therefore, the reported numbers cannot be directly compared with other such studies. However, such metrics provide an idea about the homogeneity, interzonal transport, and exposure in different parts of the houses. Certain insights from the studies might be applicable to similar residential settings. For example, exposure in different locations in the house might be comparable irrespective of distance from the emission source. Further, the deployment of mitigation near the emission source location (PAC in our study) will be more effective than restricting it to bedrooms. Moreover, the transport of pollutants in the case can be further validated using CFD or theoretical modeling, which is beyond the scope of the current study.

While the incense sticks were placed in the kitchen for all experiments discussed in this section, one experiment was performed where the incense sticks were placed at the worship place, shown as an incense symbol near 'LR 1' in Fig. 1. The results and a brief discussion is available in the ESI (Fig. S7).†

3.3 Multizonal exposure assessment under different scenarios

The previous sections demonstrate that emissions from the kitchen travel to other zones, creating spatial concentration gradients. Therefore, cumulative exposure of occupants will depend on their location and time spent there. This section discusses exposure in different zones of the apartment relative to the kitchen. Relative exposure (RE) instead of absolute exposure is being discussed because (1) emission and, therefore, concentrations from each activity are different and (2) the LCAQMs were not calibrated for the measured PM, making discussion on absolute exposure less ideal. Fig. 4 illustrates the $PM_{2.5}$ exposure occurring in different zones relative to the kitchen over (a) the cooking period (60 minutes from the start of cooking activity), (b) the entire day (24 hours), and (c) during the night (12 AM–6 AM). While all external doors were closed during cooking (Fig. 4a), those doors were kept open during nighttime (Fig. 4c). Potential hotspots can be identified by studying exposure variation in different zones throughout the day. A comparison with the ambient condition has been made in each case to assess the simultaneous exposure taking place in the designated zone and outdoors.

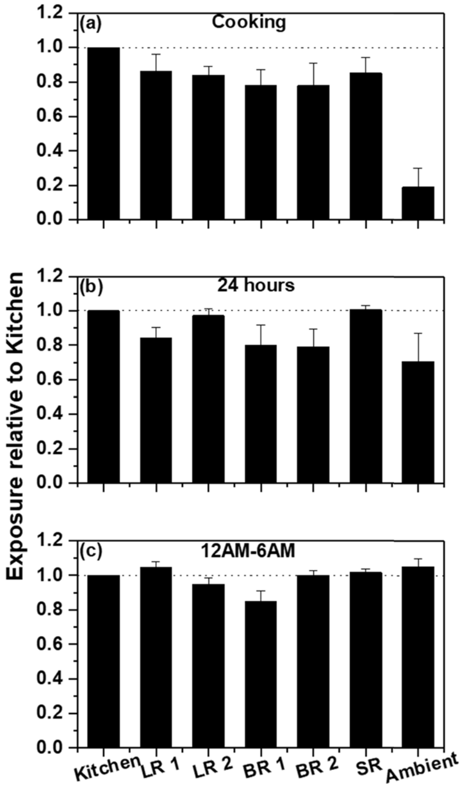

Fig. 4 Exposure relative to kitchen occurred during (a) cooking period, (b) 24 hours, and (c) 12 AM–6 AM at two locations in the living room (LR 1 and LR 2), bedroom 1 (BR 1), bedroom 2 (BR 2), study room (SR), and ambient.

For cooking (Fig. 4a), the highest average RE was observed in the kitchen, followed by the comparable REs in the living room (LR 1: 0.8 ± 0.1 and LR 2: 0.8 ± 0.0), SR (0.8 ± 0.1), and bedrooms (BR 1: 0.8 ± 0.1 and BR 2: 0.8 ± 0.1). The lower REs in other zones can be attributed to the distance of the respective zones from the source zone, as PM is diluted and lost *via* deposition during transport from the kitchen to different zones. RE in all zones was approximately ∼0.8–0.9, suggesting that the other occupants away from the kitchen have comparable exposure to the person cooking. The average RE calculated for the ambient condition during the same period of cooking activity is 0.2 ± 0.1, *i.e.*, five times more exposure in the kitchen compared to outdoors. In such cases, opening the external doors and windows could be an effective mitigation strategy, but extreme weather outside deterred it. RE was also estimated for incense as a source (Fig. S8†); a brief discussion is included in Section S3.

For 24 hours duration (Fig. 4b), the SR had the highest average RE (1.0 ± 0.0). While the AC and ceiling fans were operated in both bedrooms and living room at some time over the 24 hours, the study room was not used at all. The operation of AC enhances PM deposition rates, as discussed in the later section, which explains higher RE in the study room. Moreover, it was observed that the cooking smell lingered for much longer in the study room, indicating that it had a relatively more stagnant environment. The relatively less exposure in BR 1 (0.8 ± 0.1) and BR 2 (0.8 ± 0.1) can be attributed to the use of air conditioners in both bedrooms while resting and working. RE in all apartment zones is equal to or greater than ambient, signifying the dominance of indoor activities in overall IAP exposure.

The nighttime (12 AM–6 AM) RE was the highest for ambient, indicating outdoor PM infiltration *via* open balcony doors was a major indoor PM source (Fig. 4c). Lower REs in all zones compared to ambient are due to surface deposition. While BR 1 and BR 2 were similar in location and size, RE for BR 1 (0.8 ± 0.1) is considerably lower than BR 2 (1.0 ± 0.0). BR 1 door was closed to isolate it from the rest of the apartment during AC operation while the occupant slept there. Closing the door restricted the outdoor pollutant transport to BR 1, and the continuous operation of the AC acted as a PM sink, explaining the lowest RE observed for BR 1. Observations from cooking and nighttime REs highlight that while opening external doors could reduce exposure during high-emission indoor activities, outdoor pollutants can dominate personal exposure during periods of no indoor emissions.

Fig. 5 demonstrates the evolution of absolute exposure in different zones of the apartment, *i.e.*, kitchen, bedrooms (BR 1 and BR 2), living room (LR 2, the central sampling point of LR), and study room (SR), over 60 minutes since the start of one cooking activity. Exposure in the kitchen starts rising at the onset of cooking and continues to increase during the cooking period. After the cookstove is turned off, exposure in the kitchen decays due to PM surface deposition and dispersion into other zones. A similar trend was noticed in the living room adjacent to the kitchen. Exposure in the extreme zones (BR 1, BR 2, and SR) also demonstrated an upward trend that continued to rise even after cooking ends, accounting for the time pollutants take to reach these zones, as discussed in Section 3.2. Soon after the cooking ended, exposure in these zones exceeded that in the kitchen till the end of the evaluation period. Over 60 minutes, the cumulative exposure in BR 1, BR 2, and SR were 91.1%, 96.6%, and 88.1% of that in the kitchen, respectively, indicating the exposure of the cook is comparable to exposure of other occupants who did not participate in cooking.

3.4 *I*/*O* ratios for background, cooking period, and entire day

The indoor–outdoor (*I*/*O*) ratio indicates the relationship between indoor and corresponding outdoor PM concentrations. The $PM_{2.5}$ *I*/*O* ratio was calculated to identify the dominant origin of particles (indoor or outdoor) contributing to cumulative personal exposure discussed in the previous section. Fig. 6 demonstrates the $PM_{2.5}$ *I*/*O* ratio calculated for (a) the cooking period (60 minutes from the start of cooking), (b) 12 AM–6 AM duration with the balcony closed, (c) 12 AM–6 AM duration with the balcony open, and (d) the entire day (24 hours).

Fig. 6a shows the average *I*/*O* ratios calculated during the cooking period. The *I*/*O* ratios for cooking were considerably elevated throughout the apartment, with the kitchen (10.1 ± 8.9) and BR 2 (7.2 ± 5.7) being the highest and lowest, respectively. The relatively large standard deviations can be attributed to the different types of cooking activities. Comparable *I*/*O*

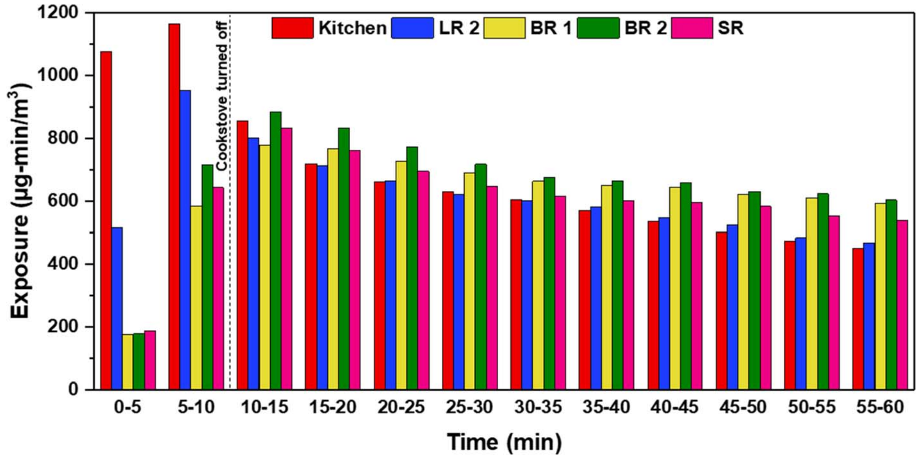

Fig. 5 Exposure evolution in kitchen, living room (LR 2), bedroom 1 (BR 1), bedroom 2 (BR 2), and study room (SR) over 60 minutes from the start of cooking.

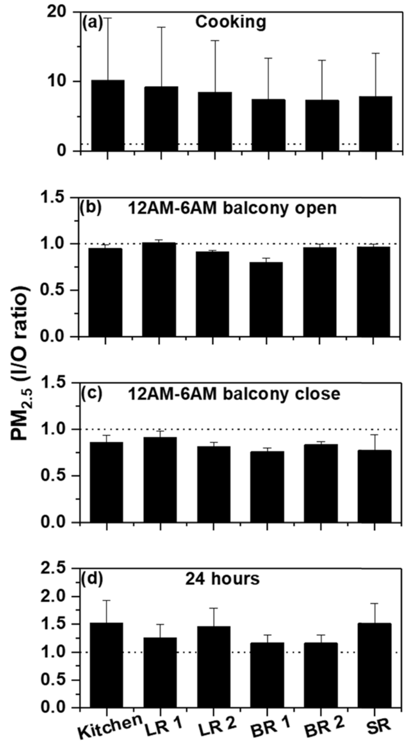

Fig. 6 $PM_{2.5}$ indoor to outdoor (I/O) ratio calculated for different zones of the apartment during (a) cooking, (b) 12 AM–6 AM with open balconies, (c) 12 AM–6 AM with closed balconies, and (d) over entire 24 hours (midnight–midnight).

ratios were noticed throughout the apartment for the cooking period.

I/O ratios, calculated overnight (12 AM to 6 AM) with balcony doors opened (Fig. 6b), was near unity for all zones barring BR 1 (0.8 ± 0.0). The lower I/O ratio in BR 1 is due to the occupant closing the door at night while sleeping, preventing the particles of outdoor origin from infiltrating the BR 1. Additionally, the continuous operation of AC in BR 1 might increase the deposition rates, as discussed in the previous section. The I/O ratio trend for the same duration is consistent with the relative exposure trend for the same scenario in Fig. 4c. The I/O ratio decreased during the same period when the balconies were closed (Fig. 6c), with an average reduction of 21% in SR, 10% in LR 1, 11% in LR 2, and 13% in BR 2. Only a 4% reduction in BR 1 was observed, as the room was isolated in both cases during the nighttime.

Fig. 6d illustrates the estimated I/O ratio for 24 hours periods, which is less than the cooking period for all the zones but greater than the I/O ratio observed during the night. This observation suggests that particles of indoor origin dominate cumulative personal exposure. Kulshreshta and Khare, 2011 calculated the $PM_{2.5}$ I/O ratio for middle-income (1.80 ± 1.34) and high-income (0.83 ± 0.33) flats in the IIT Delhi campus.[44] The ratios were approximately similar to the average 24 hours I/O ratio of 1.3 ± 0.1 measured in this study. One of the studies in Iran showed the capability of housing to reduce exposure to outdoor PM where the I/O ratio for $PM_{2.5}$ was estimated to be 0.71,[45] which can also be seen in the current study during nighttime (balcony closed scenario) when there is no active indoor emission source.

3.5 Assessment of different mitigation strategies

Previous sections demonstrated high PM concentrations throughout the apartment during indoor emission activities. This section discusses the mitigation strategies assessed in the study. IAP mitigation strategies can be broadly classified as source control, ventilation, and removal. In a typical household, source control is usually impractical for day-to-day activities like cooking, dusting, and incense/mosquito coil lighting. On the other hand, the efficacy of ventilation depends on air exchange rates and outdoor concentrations relative to that indoors. Removal mechanisms include in-duct filters in an HVAC system[46–48] and air purifiers in different indoor settings like residential households, office rooms, and classrooms, reducing indoor PM exposure.[49–55] The following sections discuss the exposure mitigation efficacy of (i) natural ventilation, *i.e.*, opening balcony doors, (ii) a PAC at different locations (kitchen, LR, BR 2), and (iii) ACs operating in blower mode with and without filter sheet. A separate set of experiments was performed in a closed room (BR 2) to quantify the filtration performance of the AC (with and without filter sheet) and PAC.

3.5.1 Natural ventilation. Fig. 7 shows the indoor exposure, over 60 minutes from the start of the cooking, at different locations (kitchen, LR 1, LR 2, BR 1, BR 2, and SR) relative to the ambient environment for two scenarios: (i) closed and (ii) opened balcony doors. The large error bars are due to the wide range of cooking styles, representing the variability in emissions. Natural ventilation due to open balcony doors led to an average exposure reduction of 74–86% in different zones. The relative exposure in BR 1 (1.3) and BR 2 (1.2) is closer to one, whereas it is considerably higher in the kitchen (2.3) and SR (2.1). These differences in relative exposure can be attributed to the location of these zones relative to the living room with balcony doors on its two sides (Fig. 1), potentially making the living room the zone most affected by natural ventilation. The kitchen and SR were on one side of the LR, and the bedrooms (BR 1 and BR 2) were on the other. The emissions from the kitchen reached SR without going through LR. However, kitchen emissions must go through LR during transport to the bedrooms, where emissions appear to be exfiltered *via* natural ventilation. Such observations highlight the importance of airflow field patterns inside built environments in spatio-temporal exposures, as also discussed in studies performing computational fluid dynamics simulations.[56–58] Diaz-Calderon suggested using air age as a performance parameter instead of ACH to evaluate the efficacy of natural ventilation.[58] Subhashini and Thirumaran suggested that an optimum percentage of openings at a particular orientation can enhance the efficacy of natural ventilation in buildings.[57] Though natural ventilation decreased personal exposure considerably, the challenges with natural ventilation include (i) lesser control over flow field and air exchange rates relative to mechanical ventilation as placement of windows, doors, and balconies are permanent, (ii) lesser efficacy in cases where ambient concentrations are high or infiltration of pollutants of outdoor origin, and (iii) compromised indoor thermal comfort in case of extreme outdoor conditions. On the other hand, mechanical ventilation can be engineered to address these shortcomings, where in-duct filters can capture outdoor pollutants, and air conditioning can be done at the inlet. To summarize, natural ventilation can be one of the effective strategies to curb the IAP and reduce exposure in particular seasons of summer and post-monsoon, when ambient concentrations are generally lower[59,60] while keeping in mind the thermal comfort for occupants.

3.5.2 Portable air cleaner (PAC). As discussed in the previous section, the natural ventilation mechanism for IAP mitigation is favorable if the ambient PM concentrations are lower than indoor levels. However, most cities in developing countries have high ambient concentrations,[61] which, if infiltrated, could dominate the cumulative indoor exposure. Under such scenarios, other strategies like PACs offer an alternative. Previous studies have focused on PACs from different aspects like reducing PM and VOC concentration,[62] efficiency for different-sized PM and ions,[63] the effectiveness of photocatalytic oxidation-based air purifiers,[64] and reducing bioaerosols.[65]

The efficacy of the PAC was assessed by operating it in three different locations in the order of increasing distance from the kitchen, (i) kitchen, (ii) living room, and (iii) BR 2, while three incense sticks were burned in the kitchen. Fig. 8 shows the exposure, over 120 minutes from lighting the incense, occurred at different locations relative to the kitchen. Without the PAC, the exposure in all the zones was higher than in the kitchen, demonstrating that cumulative exposure in indoor environments is not necessarily higher in the source zone (kitchen in this case). This observation can be attributed to the lower but prolonged elevated PM concentrations in other zones relative to the kitchen, as shown in Fig. S9.† PAC operation reduced relative exposure in all the zones irrespective of PAC's location. Similar trends in relative exposure were observed for the PAC operating in the kitchen and LR. However, when operated in BR 2, PAC considerably reduced relative exposure in BR 2, demonstrating that using PAC can benefit the occupant whose activity is confined to a single zone. However, placing PAC in

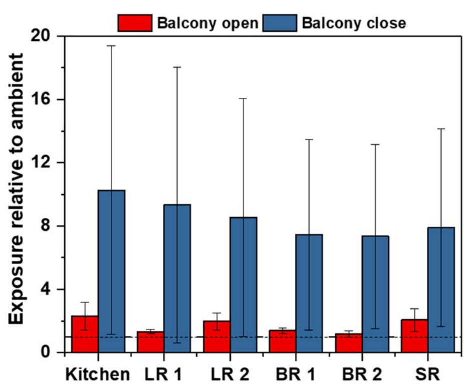

Fig. 7 Exposure in different zones (kitchen, living room 1: LR 1, living room 2: LR 2, bedroom 1: BR 1, bedroom 2: BR 2, and study room: SR) relative to the ambient environment for closed and open balcony conditions.

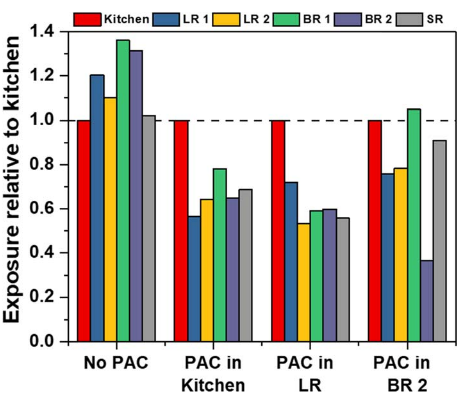

Fig. 8 Exposure in different zones (kitchen, living room 1: LR 1, living room 2: LR 2, bedroom 1: BR 1, bedroom 2: BR 2, and study room: SR) relative to the kitchen without PAC and with PAC operating at three locations – kitchen, LR, and BR 2.

a common space like LR or kitchen might be preferred if occupants are simultaneously present in different zones. Cooper *et al.* reported an average 45% reduction in $PM_{2.5}$ in the bedroom while using PAC for 90 minutes,[66] which is comparable to the current study, where an average of 41% and 59% reduction (compared to without PAC) in relative exposure was seen in BR 1 and BR 2, respectively, for different PAC locations. Dubey *et al.* used PACs for two types of aerosols, *i.e.*, indoor air without any source and incense/candle, in a room chamber and reported a PM level reduction of 29–68% and 12–64%, respectively.[63] Küpper *et al.* reported that positioning PAC beneath the desk in the room resulted in 50% lower CADR compared to other locations within the same room, indicating the impact of PAC location on its overall efficacy.[49] Sankhyan *et al.* reported that PAC operated in the kitchen or bedroom reduced the average exposure by 30–90% compared to the no PAC case.[30] Similar results were noticed in the current study, where relative exposure decreased by 30–59% in the apartment during PAC operating in different locations compared to no PAC case.

3.5.3 AC (with and without filter sheet). While PACs can considerably reduce personal exposure, as discussed in the previous section, the mass adoption of PACs in developing countries is yet to happen. PACs were used only by 10% of Chinese families in 2015.[67] On the other hand, the penetration of air conditioning systems in developing countries is higher, and the same is expected to grow faster than PACs as weather extremes become more frequent and severe.[68] Davis *et al.* predicted that 50% of Indian households will be equipped with air conditioning units by 2050.[69] With worsening air quality and growing consciousness among the public, new ACs in the market are getting equipped with PM filters. For older AC units, commercially available filter sheets can be affixed to the pre-filters of the ACs. Therefore, this study also evaluated the performance of ACs with and without filter sheets as a PM sink.

Fig. 9a shows the indoor exposure, over 120 minutes from the start of the incense lighting, at different locations (LR 1, LR 2, BR 1, BR 2, and SR) relative to the kitchen for three scenarios: (i) control, *i.e.*, no ACs operating, (ii) with ACs of BR 1, BR 2, and LR switched on, and (iii) with ACs of BR 1, BR 2, and LR switched on equipped with filter sheet. Fig. S10† demonstrates the AC with filter sheets affixed on the AV pre-filters. The control experiment, *i.e.*, without AC case, demonstrates higher relative exposure in all the zones than the cases when ACs were operational. Compared to the control case, the operation of ACs, even without filter sheets, led to a reduction in relative exposures at all locations – (LR 1: 26%, LR 2: 24%, BR 1: 35%, BR 2: 28%, and SR: 19%). The reduction in PM concentration is likely due to the combined effect of the pre-filter mesh and surface deposition of particles during their passage through the heat exchanger, which is designed to provide a high contact surface area with air. While no experiments were performed to bifurcate the contribution of pre-filter mesh and surface deposition in total PM capture, loss *via* surface deposition might be greater than *via* pre-filter because the coarse mesh size of the pre-filter is unsuitable for capturing fine PM.

Under the third scenario, all ACs equipped with filter sheets were turned on, leading to further reductions in relative exposures (LR 1: 38%, LR 2: 30%, BR 1: 52%, BR 2: 46%, and SR: 27%). BR 1 and BR 2 showed a significant ($p < 0.05$) reduction when ACs were equipped with filter sheets compared to ACs without filter sheets, demonstrating the efficacy of the sheets in reducing relative personal exposure. Mak *et al.* also reported that while using filters with window AC, the exponential decay index of off-mode, normal filter, and additional filter was 0.2–0.5, 0.5–1.7, and 1.2–2.8 h^{-1} (ref. 70) – a trend similar to the observed in the current study in terms of relative exposure.

Parameters like flow rate variability, power consumption, and thermal comfort should also be considered before using AC as a filtration device.[71] ACs are not manufactured to handle the additional pressure drop introduced due to the addition of a filter sheet. The additional pressure drop through the filter sheets reduced the flow rate through the AC. The average outlet air velocity of the AC in BR 2 reduced from 2.9 ± 0.7 m s^{-1} to 1.2 ± 0.6 m s^{-1} after affixing the filter sheets. A similar reduction in the average outlet air velocity from 4.4 ± 0.3 to 3.2 ± 0.5 was observed for the living room AC due to the filter sheets. This decrease in flow rate could affect AC's cooling performance. Also, the filtration efficiency could be even higher if ACs

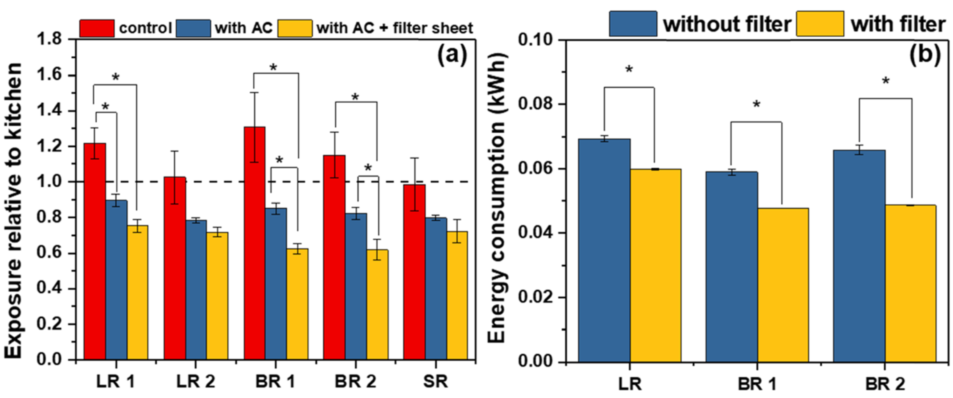

Fig. 9 (a) Exposure in different zones (living room 1: LR 1, living room 2: LR 2, bedroom 1: BR 1, bedroom 2: BR 2, and study room: SR) relative to the kitchen under three scenarios: (i) control (*i.e.*, without AC), (ii) with AC on, and (iii) with AC equipped with filter sheet on. (b) Power consumption by AC without filter and with filter sheets.

operated at the same flow rate, even with the filter sheets. Fig. 9b demonstrates energy consumed by ACs without and with filter sheets, where a significant decrease is noticed when ACs were equipped with a filter sheet. This is due to the reduced flow rate of ACs equipped with filter sheets compared to those without filter sheet cases. This highlights that the non-OEM filter sheets are not optimized for any particular AC and can affect AC performance.

3.5.4 Comparison of different mitigation strategies. A set of experiments was performed in a closed room (BR 2) to characterize the PM capture efficacy of PAC and AC (with and without filter sheets). The cumulative loss rate (CLR) and CADR are calculated as comparative metrics. Fig. 10 demonstrates the efficacies of different tested strategies: AC, AC + filter sheet, PAC + HEPA filter, PAC + filter sheet, and PAC + HEPA filter + filter sheet. PAC + HEPA filter is the default arrangement as purchased. In the case of the PAC + filter sheet, the HEPA filter was removed, and a filter sheet was affixed at the outlet of the PAC (Fig. S11†). In the PAC + HEPA filter + filter sheet case, the filter sheet was affixed at the PAC outlet while keeping the default HEPA filter. The CLR was lowest (0.12 ± 0.01 h^{-1}) for the control scenario with only surface deposition as the major PM sink. The average CLR of the mitigation measures followed the order – AC (0.4 ± 0.1 h^{-1}) < PAC + filter sheet (0.6 ± 0.1 h^{-1}) < AC + filter sheet (0.8 ± 0.2 h^{-1}) < PAC + HEPA filter + filter sheet (1.9 ± 0.2 h^{-1}) < PAC + HEPA filter (2.3 ± 0.1 h^{-1}). These CLR trends further validate the reduction in exposure due to AC operation, as discussed in the previous section. Even without the filter sheet, the CLR of AC was more than 3× of control. Adding the filter sheets doubled the CLR compared to that without filter sheets, even though filter sheets reduced air flow rates from 2.9 ± 0.7 m s^{-1} to 1.2 ± 0.6 m s^{-1}, as discussed in the previous section. Since the CLR is proportional to both the flow rate and filtration efficiency, the reduction in flow rates appears to have been compensated by the increased efficiency in this case.

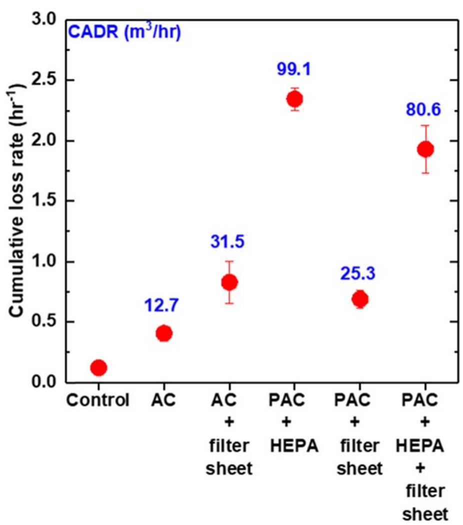

Fig. 10 Cumulative loss rate (CLR) of different mitigation techniques: (i) AC (without filter sheet), (ii) AC + filter sheet, (iii) PAC + HEPA, (iv) PAC + filter sheet, and (v) PAC + HEPA filter + filter sheet; CADR (m^3 h^{-1}) is written on top of each compared technique.

The PAC operated with the default HEPA filter (PAC + HEPA filter) had the highest CLR value, but when used with a non-compatible filter sheet (PAC + filter sheet), its CLR value was reduced by more than three times. This reduction in CLR can be attributed to the changes in filtration efficiency and airflow rates. Velocity was measured at the outlet of the PAC as a proxy for the flow rate. The outlet velocity for the PAC + filter sheet scenario was 2.5 + 0.5 m s^{-1}, which is more or comparable to the PAC + HEPA filter (2.2 ± 0.4 m s^{-1}). Therefore, the decrease in CLR value is due to the lower efficiency of the filter sheet compared to the HEPA filter. For the PAC + HEPA filter + filter sheet case, the PAC outlet velocity was 1.5 ± 0.3 m s^{-1}, which is less than the PAC + HEPA filter case (2.2 ± 0.4 m s^{-1}). Therefore, even if the efficiency of the PAC + HEPA filter + filter sheet setup is higher, the decrease in outlet velocity has decreased its CLR value. Though PAC combinations performed on par or better than AC combinations, unlike AC, they will not serve the purpose of maintaining thermal comfort.

4 Conclusion

A network of ten LCAQMs was deployed in multizonal residential apartments to measure indoor spatio-temporal PM concentrations from different sources, transport, and assess various PM mitigation strategies. Measurements included both non-intervention cooking activities and controlled experiments using incense sticks as the source. A wide range of food was cooked during the campaign, with average $PM_{2.5}$ concentrations ranging from 91.1 to 1033.9 μg m^{-3}. Sub-micron particles dominated the PNSD for incense and cooking, whereas super-micron particles dominated the PMSD only for cooking. Transport time metrics evaluation demonstrated that pollutants took less time to reach BR 2 (6.0 ± 0.8 minutes) and BR 1 (4.6 ± 0.5 minutes) during AC operation than under the ‘without AC’ condition (BR 2: 14.0 ± 0.8 minutes, and BR 1: 10.3 ± 1.7 minutes), which is attributed to the enhanced mixing. However, the time to reach SR, under both conditions, was approximately similar due to the absence of AC. Exposure estimated during cooking demonstrated that RE in all zones was approximately ∼0.8–0.9 times that of the kitchen, suggesting that the occupants away from the kitchen and in the kitchen might have comparable exposure.

I/*O* ratio analysis demonstrated a multifold increase in the indoor–outdoor ratio during the cooking period, with kitchen (10.1 ± 8.9) and BR 2 (7.2 ± 5.7) being the highest and the lowest. Moreover, a ratio of more than one was observed during the entire day, indicating the dominance of indoor PM in cumulative indoor exposure. The *I*/*O* ratio dropped below one during the nighttime since the balcony was closed, showing that the apartment acted as a protective blanket against ambient PM. Subsequently, the study evaluated the efficacies of natural ventilation, PAC, and ACs to mitigate IAP. Natural ventilation due to open balcony doors led to an average exposure reduction of 74–86% in different zones, with slight variation b/w zones on either side of LR directly connected to both balconies. PAC operations at different locations of the house reduced relative exposure compared to the case with no PAC. Evaluation of ACs as filtration devices demonstrated that the use of AC decreases cumulative exposure, which, when equipped with filter sheets, further lowers it. Lastly, a comparison of PAC and AC, with and without filter sheets, was made, restricted to a single zone, where PAC + HEPA filter tends to have the highest CLR (2.3 ± 0.1 h^{-1}) among all the compared mitigation techniques. The variation in CLR of compared mitigation strategies was attributed to the changes in filtration efficiency and airflow rates. The lower PAC outlet velocity for the PAC + HEPA filter + filter sheet case (1.5 ± 0.3 m s^{-1}), than the PAC + HEPA filter case (2.2 ± 0.4 m s^{-1}) negated the increase in combined efficiency of the former setup. The current work will have implications for similar multizonal urban built environments. Multizonal exposure assessment showed that exposure in different zones is comparable to that in the source zone. Insights from the study demonstrate the need for appropriate mitigation strategies for such multizonal settings. Commercially available solutions, such as filter sheets for existing ACs, might decrease the cumulative exposure but at the expense of cooling performance. Therefore, further research is needed to enhance the compatibility of these filter sheets with air conditioning units.

The current study is limited to the data obtained from a single apartment with a non-smoker occupant in a second-floor apartment located in an area away from vehicular and industrial emissions in the summer season, where low ambient PM concentration was observed. Therefore, specific results like *I*/*O* ratios reported here might vary owing to the apartment's location, weather conditions, and occupant behavior. Future cross-sectional studies with more apartments of varying sizes and layouts will provide further insights into the impacts of these variations on the transport and deposition of particles, affecting the exposure. Using low-cost sensors (PMS5003) limits the discussion on absolute values of concentration and exposure. Future studies with research-grade instruments can provide further insights into the type of aerosols being measured in the current study.

Data availability

Raw data and relevant calibration factors are available upon reasonable request made to the corresponding author.

Author contributions

AKT: conceptualization, data curation, formal analysis, writing – original draft. SP: conceptualization, supervision, funding acquisition, writing – review and editing.

Conflicts of interest

The authors declare no conflicts of interest.

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