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Indoor air quality among Mumbai's resettled populations: Comparing Dharavi slum to nearby rehabilitation sites

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0. Abstract

This study presents results from an experimental investigation of the severity and sources of household air pollution across two low-income housing archetypes in Mumbai. Experimentation was carried out in Dharavi—one of the world's largest slums—and two nearby communities representing Mumbai's current slum resettlement scheme. Household surveys were conducted to understand aspects of occupant behavior that impact indoor air quality. Multi-pollutant logging sensors were installed inside units and in nearby outdoor locations to measure concentrations of particulate matter ($PM_{2.5}$,) and CO_2. While rehabilitation architecture and gas cookstoves are often assumed to provide higher indoor air quality than in traditional slums, field monitoring and occupant behaviour surveys demonstrated that indoor pollution levels were consistent across the two typologies even after infrastructure enhancements and ubiquitous gas cookstove usage. Indoor $PM_{2.5}$ measurements ranged between 150-300 $\mu g/m^3$, substantially higher than World Health Organization (WHO) guidelines. $PM_{2.5}$ indoor/outdoor (I/O) ratios spiked during cooking periods but were otherwise less than 1.0 in over half of logged instances in rehabilitation units, highlighting the role of particle deposition phenomena and ambient-sourced $PM_{2.5}$ in indoor environments. To minimize the impact of both indoor and outdoor pollutant sources while respecting culturally-normative occupant behavior, this study points to the need for architectural design guidelines and enhanced indoor air quality interventions.

Keywords: Slum; rehabilitation housing; indoor air quality; household air pollution; cookstoves; measurement

1. Introduction

Household air pollution (HAP) has been described as the most significant environmental cause of death globally, accounting for an estimated 3.8-4.3 million premature deaths each year over the past decade, with an estimated 1.5 million deaths occurring in India alone (World Health Organization, 2016, 2018). In total, it is believed that HAP accounts for around 4.8% of all disability adjusted life years, or DALYs (Bardhan et al., 2018; Debnath et al., 2016; Smith et al., 2014). The trend of urbanization has caused people to spend up to 90% of their time indoors in major cities around the world (Habre et al., 2014; Yuan et al., 2018). Therefore, indoor air quality becomes integrally crucial to address health and well-being of the occupants. Indoor pollution is of special concern since it is an estimated 1,000 times more likely to infiltrate the lungs than pollution released outdoors (Zhang & Smith, 2003). HAP, other than being affected by high ambient pollution is also derived from indoor emissions from burning fuels for cooking, heating, or lighting. The issue is especially prevalent for women and children under the age of five, who account for an estimated 60% of HAP-related premature deaths due to a larger percentage of time spent indoors (Smith, 2000; World Health Organization, 2016).

HAP sourced from indoor cooking with solid fuels accounts for 12% of global fine particulate matter emissions, defined as $PM_{2.5}$, where particles are 2.5 microns or less in diameter (Chafe et al., 2014). Exposure to HAP and $PM_{2.5}$ is a major health concern, as $PM_{2.5}$ particles have sufficiently small diameters to penetrate pulmonary alveoli and damage airway cells (Numno R. Martins & Graça, 2018). Short-term effects include suffocation, burning eyes, and headaches. Long-term effects include chronic disease and premature death, of which an estimated 34% comes from stroke, 26% from ischemic heart disease, 22% from chronic obstructive pulmonary disease (COPD), 12% from pneumonia, and 6% from lung cancer (Maharana et al., 2018).

No threshold of $PM_{2.5}$ exposure has been shown to provide total protection from adverse health effects. Nevertheless, the World Health Organization (WHO) provides Air Quality Guidelines (AQG) with 24-hour and annual $PM_{2.5}$ exposure limits based on the perceived minimization of health risks. In India, over 50% of the population lives in areas with average ambient $PM_{2.5}$ concentrations exceeding the Indian National Ambient Air Quality Standard (NAAQS) of 40 $\mu g/m^3$. Less than 0.01% of the population lives in areas with ambient air that meets the World Health Organization's $PM_{2.5}$ exposure guideline of 10 $\mu g/m^3$ (Pant, Guttikunda, & Peltier, 2016).

Current literature recognizes a strong association between United Nations Sustainable Development Goal (SDG) 11, which fosters the concept of "sustainable urban habitats" and SDG 3, which targets good health, well-being and quality of life among global populations (United Nations, 2016). An important control measure to alleviate indoor air pollution is indoor ventilation effectiveness. However, ventilation-effective habitat design and the impact of the built environment on occupant health and well-being remains an elusive concept. Fast urbanization coupled with population growth has contributed to public health degradation and distressed quality of life for many urban dwellers (Neirotti et al., 2014). (Bardhan et al., 2015; Marans, 2015). This investigation becomes exigent for the low-income settlements where space constraints couples with economic and socio-cultural restraints.

The recent trend of rapid urban migration in Mumbai and other metro-cities of India leads to a shortage of affordable housing, driving many low-income urbanites to reside in informal settlements, or "slums." The megacities have therefore been portrayed as residential zones with overcrowded and poorly designed dwelling units, intrinsically delivering the inhabitants an inferior quality of urban life. Currently, around 52.5% of Mumbai's population resides in less than 9 percent of Mumbai's land area, especially in zones classified as slums (P.K. Das & Associates, 2011). The shortage of affordable permanent housing in Mumbai is a major hindrance in the pathway of social evolution through urbanization. In response, government housing authorities seek to resettle the slum populations to permanent hyper-dense, multi-story towers with provision of individual tenement units built in accordance with the Slum Rehabilitation Development Control Regulations (DCR) (Bardhan et al., 2015).

Existing slum rehabilitation housing, particularly in Mumbai, is characterized by inefficient airflow paths in living zones and thus poor IAQ, high temperatures, heat-trapped zones, inadequate daylight, increased pollutant concentrations apart from lack of infrastructure services (Bardhan & Debnath, 2016; Debnath et al., 2019; Nutkiewicz et al., 2018). Overcrowding and insufficient ventilation within these tenement units often increase the moisture level thus leading to the proliferation of mold and respiratory viruses (Williamson et al., 1997). These low-income units of hyper-dense housing, often with no cross-ventilation strategies employed, fail to attain ventilation thresholds, thus leading to reduced removal rates of smoke generated during cooking, burning of incense sticks and insect repellents, etc. (Bardhan et al., 2018a). The poor environmental quality of these compact high rises has led to the moniker "vertical slums" (Bardhan et al., 2018b). Despite the extreme density and inadequate IAQ in Mumbai's current resettlement projects, new regulations only threaten to increase occupancy density further. Following India's initiative for "Housing for All" by 2022, Mumbai's "Development Plan 2034" was implemented in 2018 and targets the construction of 1,000,000 affordable housing units (Kumar and Babar 2018).

The novelty of this study lies in addressing the unique IAQ challenges for slum resettlement buildings in an urban Indian context, where project resources are often constrained in terms of budget, energy availability, and cultural factors. These challenges require immediate study as a significant proportion of Mumbai's population represents a low-income class that faces possible resettlement in the near future. There is an established standard that the households which spend more than 10% of disposable income on electricity and cooking fuel are considered income-energy-poor. Approximately 52.5% of current Mumbai residents can thus be classified as energy-poor, and nearly 20% are extreme-energy poor (spending more than 20% of income on energy) (Möller et al., 2015). Furthermore, the lack of environmentally-conscious and ventilation-effective habitat design guidelines represents a major knowledge gap in the urban planning process for cities such as Mumbai. Through quantifying IAQ patterns in Mumbai's low-income housing archetypes, the major factors contributing to HAP can contribute to energy- and environment-sensitive habitat design policies.

To date, there have been very few comparative studies on the effect of slum resettlement on household pollution. Burgos et al. (2013) measured IAQ for families in slums and nearby resettlement sites in Santiago, Chile, determining that both indoor and outdoor pollution were higher for slum dwellers. To the author's best knowledge, no similar large-scale studies have yet been carried out for the urban Indian context. By gathering empirical data in existing Mumbai dwellings, the influence of architecture on IAQ can be identified, ultimately eading optimized ventilation strategies indoor spaces in a highly polluted city. This study thus intends to aid planning and design authorities in enacting sustainable urban renewal initiatives.

2. Literature review

Context-specific slum development guidelines focusing on the built environment remain an under-researched area. Though India's affordable housing policies have offered optimistic outcomes regarding housing delivery, their efficacy in the long run remains a planning challenge. There is a dearth of consistent methodology for efficacy studies, quantifiable measures or specific determinants of a good housing and habitat design. This, in turn, leads to degraded health condition with increased occurrence of diseases related to environmental pollution, sick building syndrome, and poor quality of life (Bardhan et al., 2018a). Thus, despite the Government of India's continuous attempt to develop "slum-free cities," local initiatives to create sustainable urban habitats remain inadequate due to technical and policy-based challenges.

This study builds upon the existing literature involving household pollution data logging inside Indian homes over the past four decades. Among the earliest are Smith & Aggarwal (1983), Patel et al. (1984), Menon (1988), and Ramakrishna (1990); each of these studies examined the effect of geographical, climatic, and socioeconomic factors on HAP levels, and each determined that particulate matter and carbon monoxide can reach dangerous levels in rural Indian kitchens. Among other examples include Saksena et al. (1992) who measured total suspended particulates in Delhi households to be as high as 20,000 $\mu g/m^3$ near cook-stoves—much higher than other spaces in the home. Massey et al. (2012) studied seasonal variations in $PM_{2.5}$ I/O concentration ratio for 10 houses in the Agra region of India, finding ratios to fluctuate between 0.6-1.4 with highest values occurring during winter months. Mukhopadhyay et al. (2012) conducted 24- and 48-hour logs in 10 households using traditional cookstoves in rural houses in Haryana, India, with median concentrations near the cookstove around 500 $\mu g/m^3$. Phuleria et al. (2018) installed $PM_{2.5}$ loggers in 20 Mumbai slum households, concluding that mean $PM_{2.5}$ concentrations were 39 ± 17 $\mu g/m^3$ indoors and 23 ± 4 $\mu g/m^3$ outdoors, with average $PM_{2.5}$ I/O ratio ranging from 0.9 to 3.7 and proving to be higher than in non-slum homes.

IAQ improvement mechanisms are relatively straightforward and intuitive in cities with ambient pollution less severe than Mumbai. For most places in the United States, for instance, improved IAQ can be achieved through three primary principles: limiting indoor pollution sources, maximizing outdoor airflow, and employing HEPA filtration of outdoor air if necessary (U.S. Environmental Protection Agency, 2018). These strategies are also effective in rural Indian contexts, where many past studies have focused. However, all three strategies face challenges in the Mumbai context. In such megacities, we observed through household surveys that almost all households use low-emitting LPG cookstoves and electric lighting, suggesting indoor $PM_{2.5}$ sources are already kept to a minimum. Ambient air in Mumbai far exceeds recommended $PM_{2.5}$ exposure levels, hampering the effectiveness of natural ventilation as an air purification mechanism. And lastly, slum resettlement projects in Mumbai are often financially constrained; developers seek fast, low-cost designs that generally don't employ central ventilation systems or HEPA filtration. Meanwhile, inhabitants of slum resettlement dwelling dwellings face significant financial constraints and are unable to afford air purification devices typically seen in middle- and high-income households. This work addresses these unique challenges for IAQ improvement in Mumbai tenement housing.

3. Methodology

3.1. Selection of housing communities

Fieldwork was conducted in three communities in the central region of the Mumbai peninsula and targeted a combination of slum and resettlement neighborhoods. For a representative slum housing configuration, a neighborhood in Dharavi's Matunga Labour Camp was selected, a mixed-use community with informal structures spanning one to three levels. Two representative resettlement configurations, Natwar Parekh and Lallubhai Compound, were selected as sites housing project-affected persons (PAPs) relocated by major infrastructure projects and slum redevelopment campaigns. In total, 72 occupied dwellings were surveyed across the three sites, identified in Figure 1.

Dharavi
Slum typology
18 households surveyed

Natwar Parekh
Resettlement project
34 households surveyed
+ 1 controlled test unit

Lallubhai Compound
Resettlement project
20 households surveyed

Figure 1. Spatial context of the three housing communities selected for fieldwork. Source: Google Earth.

Natwar Parekh and Lallubhai Compound represent two typical SRA typologies, with floorplans included in Figure 2. Natwar Parekh was constructed in 2008 and contains 4,800 dwellings across 50 tenements. Here, apartments are accessed via single-loaded corridors around the building perimeters, with bathing rooms and water closets abutting a central natural ventilation shaft. Lallubhai Compound was constructed in 2003, containing 9,300 dwellings across 65 tenements with units accessed via internal double-loaded corridors approximately 2 m wide, whose kitchens and water closets are located against the outermost walls. The floor-to-ceiling height of these dwellings was measured between 2.6-2.7 m.

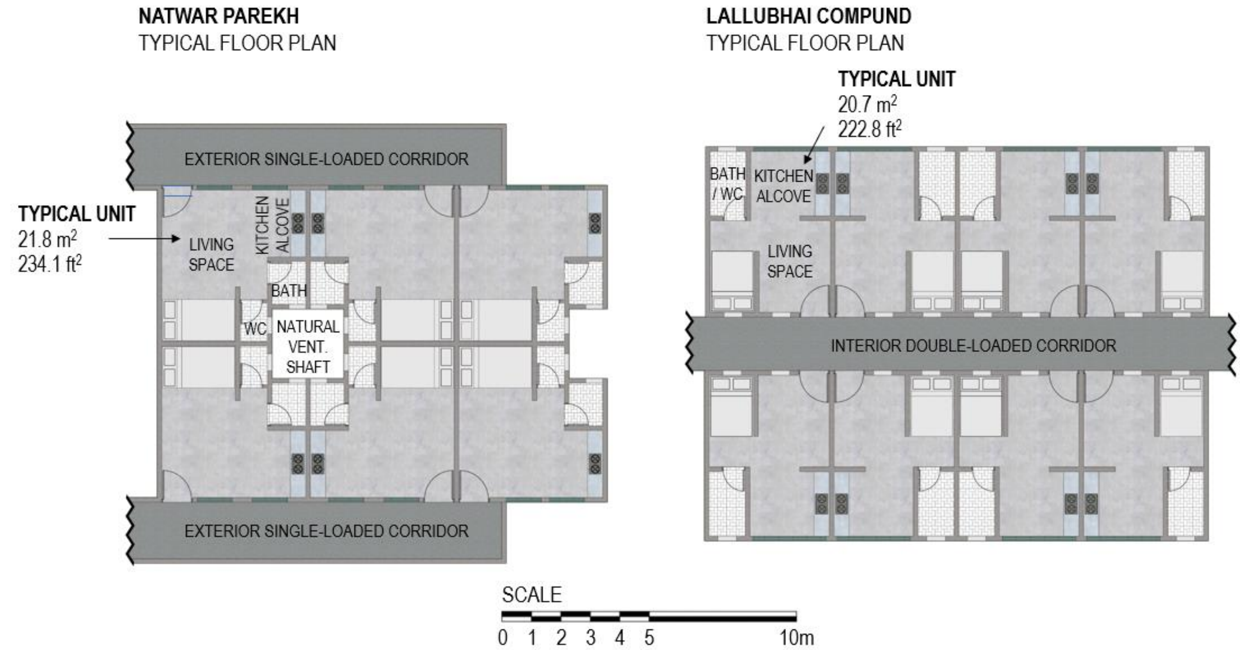


Figure 2. Typical floor plans of two resettlement typologies: Single-loaded corridor arrangement at Natwar Parekh (left) and double-loaded corridor arrangement at Lallubhai Compound (right). Dimensions based on author's measurements.

3.2. Household surveys

Oral questionnaires were conducted in offline mode with one adult member of each household during weekday late mornings and early afternoons. Interviews were typically administered to middle-aged female members of the households and were conducted in the subjects' native languages by a female research partner introduced to the residents of the household by a community member already familiar with the family. Information related to the family structure, daily schedule regarding pollution-creating activities, cooking behaviour, fuel choices and monthly expenditures were inquired. Information was also gathered on the extent to which occupants perceive HAP to be a problem, and what efforts are taken for HAP remediation, if any. Apart from the household questionnaire, interior architectural features, including floor plans, sectional characteristics, envelope features, and ventilation components were additionally recorded, with the consent of the occupants.

3.3. Field monitoring Phase I- HAP measurement in occupied dwellings

One-time HAP point-measurements and data logging were employed simultaneously to gain insight on pollution trends within slum and resettlement households. Here, point-measurements refers to one-time instantaneous sensor readings. A Kestrel 5400 multi-sensor was used to gather point-measurements for temperature, humidity, and airspeed inside the units, near ceiling fans (if any), and at any open windows. A DustTrak 8532 handheld particulate matter sensor affixed with a $PM_{2.5}$ impactor was used to gather between 30-50 $PM_{2.5}$ point measurements throughout three areas of each household—generally the foyer area near the door, the kitchen area, and the sleeping area. This accounted for all major zones of the single multipurpose room based dwellings except for attached water closets, bathing rooms, and lavatories, which were generally not measured at the occupants' reservations. All sensors were within certified calibration periods and a zero-calibration cycle was performed on the DustTrak prior to each use.

To supplement point measurement data and alleviate the potential for data to be skewed by temporary indoor source phenomena or diurnal ambient pollution cycles, pollution loggers were installed for periods of two to four days in several households. Data was logged at either 5- or 10-second intervals. Two fleets of custom-built HAP sensors were deployed (see Figure 3). The first set contained Alphasense OPC-N2 optical particle counters to measure PM as well as sensors for temperature and humidity. The second set contained Plantower PMSA003I sensors to measure PM as well as Figaro CDM7160-C00 CO_2 sensors and sensors for temperature and humidity. For each household, one HAP sensor assembly was installed 0.5-1.5 m above the primary cookstove used in each household, while another was installed at an outdoor location to record ambient conditions—either affixed outside a window or at a nearby rooftop location. All logging sensors were within certified calibration periods, and the custom-built assemblies were co-located in an environmental test chamber against laboratory-grade $PM_{2.5}$ and CO_2 sensors, with the data post-processed with a linear or second-order calibration factor accordingly.

Figure 3. Examples of pollution logging sensor installations (encircled in red) for indoor and ambient air readings. Top left and right: custom assemblies incorporating Alphasense OPC-N2 optical particle counters (logged measurements). Bottom left: custom assemblies incorporating Plantower PMSA003I $PM_{2.5}$ sensors (logged measurements). Bottom right: iButton DS1922L temperature sensors to track stove usage patterns.

To assess the relationship between cookstove use and HAP levels (and to provide accurate indoor source inputs for subsequent simulations), compact iButton DS1922L temperature sensors were affixed discreetly to the back side of the primary household cookstoves, measuring temperature trends to indicate cooking times.

For an indication of city-wide ambient $PM_{2.5}$ concentration, $PM_{2.5}$ data was supplemented with readings gathered from the United States Consulate General rooftop pollution monitoring station (U.S. Department of State, 2019), approximately 3.5 km from the Dharavi housing site and 6 km from the resettlement communities.

3.4. Field monitoring Phase II- HAP measurements in controlled dwelling

Data from the HAP loggers in occupied dwellings was further validated with data from full-scale experiementation and controlled testing conducted in a vacant Natwar Parekh unit over a three-day period. This process alleviated some of the uncertainty regarding the impact of occupant behavior on HAP levels, including window operation, use of ceiling fans or kitchen exhaust fans, or the amount of deposition surface area near the cookstove at a given time. Within the test unit, $PM_{2.5}$ sources were introduced including a LPG double-burner cookstove similar to those observed across resettlement communities and a common combustible mosquito coil. To measure the air exchange rate, CO_2 was introduced as a tracer gas, emitted from a tank to drive interior concentrations above 2,000 ppm. In-situ environmental sensors measuring operative temperature, humidity, particulate matter, and CO_2 were deployed at three locations within the unit and two locations outside, away from windows where indoor sources might interfere. Additionally, a Kestrel 5400 climate sensor was placed directly outside the windows within the single-loaded corridor to measure temperature, humidity, and airspeed. Prior to the measurements commencing, while CO_2 and $PM_{2.5}$ were being emitted, a floor-mounted box fan and two ceiling fans were activated to ensure effective air mixing. Once the levels stabilized to a sufficiently high concentration across all three interior sensors, the box fan was deactivated, and the ceiling fans were either kept active or deactivated based on the specific test. Windows were left closed or opened entirely depending on the test criteria. The approximate locations of each component within the test unit are displayed in Figure 4.

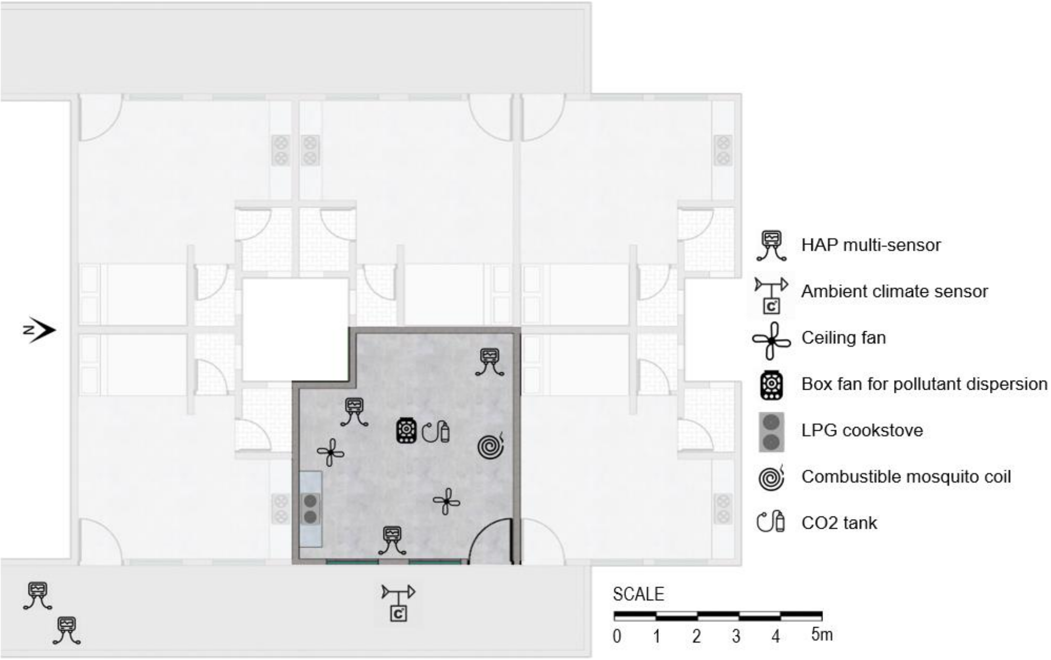


Figure 4. Experimental setup of vacant test unit at Natwar Parekh in context of other dwellings, including controlled $PM_{2.5}$ and CO_2 sources and HAP sensors. Dimensions based on author's measurements.

4. Results

4.1. Architectural observations

A notable observation among the 52 occupied resettlement units was the frequent obstruction of natural ventilation paths. A number of residents reported privacy concerns—particularly those in units on lower levels—while others mentioned the need for additional storage, and had installed permanent window coverings as a result. These obstructions had noticable effects on natural airflow and natural daylight reaching the living spaces. Other occupants had chosen to embellish the permanent floor plans with additional low-cost temporary partition walls, citing privacy conerns or the desire to create separate areas for sleeping, lounging, and preparing meals. Figure 5 includes examples of window obstructions and partition arrangements observed in occupied resettlement dwellings.

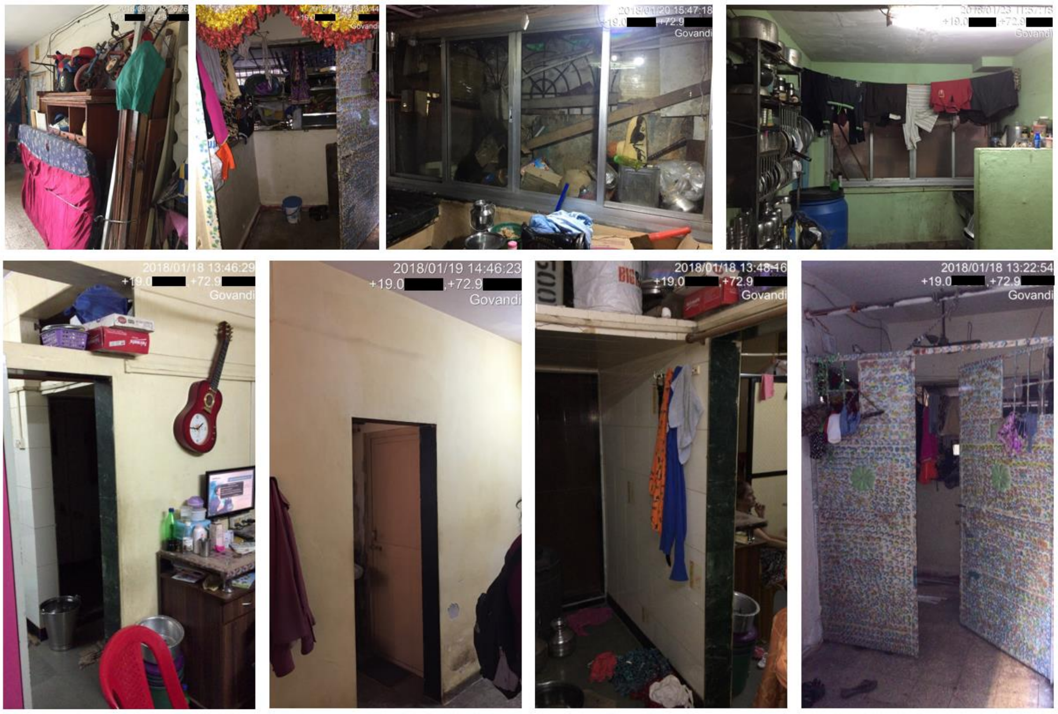


Figure 5. Top row: permanent window obstructions observed in resettlement dwellings inhibiting ventilation paths and natural light. Bottom row: Units retrofitted with low-cost partition walls by occupants.

4.2. Observations from household questionnaires

It was observed that LPG was by far the most common cooking fuel used in both the slum and resettlement typologies, due in part to a widespread distribution network for LPG tanks and subsidized costs (See Figure A1 in Appendix). A few households reported using kerosene stoves, either as a sole cooking fuel or in conjunction with LPG. The trends for cooking fuel choices were similar between slum and resettlement households with no apparent relationship to a household's socioeconomic status. This closely resembled the trends reported in the 2011 India National Census for urban Mumbai households as displayed in (Government of India, 2011).

Occupant surveys included questions on typical monthly expenditures for household electricity consumption, with the results implicating the feasibility of installing electric air purifiers or other appliances intended to clean personal environments. Among resettlement households, residents reported spending an average of 9.0% of the household monthly incomes on electricity bills, with a peak expenditure of 25.0%. Among Dharavi households, the average was 7.4% with a peak of 12.5%.

In order to populate future simulations with accurate boundary conditions and occupant exposure locations, questionnaires also addressed cooking habits and daily schedules. Questionnaires conducted in January and August 2018, combined with results of fieldwork conducted by Sunikka-blank et al. (2019) in Mumbai SRA buildings, indicate that housewives in typical resettlement dwellings use a cookstove around three times a day for a total of 3-5 hours, and spend approximately 2.5 hours outside each day, while the rest of their time is spend inside dwellings. This equates to around 89.6% of the day spent indoors—a value in close agreement with values reported for global demographics in major cities. These include the 90% figure reported by Yuan et al. (2018) for occupants of Chinese megacities and 80-90% figure reported by Habre et al. (2014) for occupants of New York City. Furthermore, the observations are in agreement with Maharana et al. (2018) who reported that housewives in major Indian cities typically spend between 3-7 hours/day near cookstoves.

Household surveys indicated two primary sources of indoor $PM_{2.5}$—the use of cookstoves followed by incense sticks. A majority of households reported that no members smoke cigarettes indoors. Furthermore, stove temperature data collected from the iButton data loggers generally showed 4-5 cooking events per day in accordance with the questionnaire responses. Stoves were typically first operated between 6-8am and were used sporadically throughout the day thereafter for periods of approximately 30 minutes to two hours. Cookstove usage times-of-day and durations appeared consistent between slum and resettlement dwellings.

Of all surveyed households, around 33% were observed to have working exhaust fans in the vicinity of the cooking areas. However, these were rarely observed to be active during cooking times. It was observed that, for areas such as Natwar Parekh with single-loaded corridors around the building exteriors, exhausted household pollution would stagnate in the corridor areas and would possibly re-infiltrate the same household or a neighboring household.

4.3. Ambient pollution results

Ambient $PM_{2.5}$ data collected from the U.S. Consulate General pollution monitoring station in Mumbai for the period 2015-2019 indicates noticeable yearly and daily trends (see **Error! Reference source not found.** in the attached Appendix). Peak levels are typically observed during the winter months of December and January, while levels are lowest during the summer and monsoon months of June through August. Daily and yearly trends suggest some predictability for peak ambient $PM_{2.5}$ levels, and thus, suggest the potential to inform times when outdoor airflow to occupied indoor spaces should be limited or subject to enhanced filtration. For example, during the month of January, $PM_{2.5}$ is observed to be at its highest between the morning hours of 02:00 and 09:00, with averages far exceeding recommended daily thresholds. The planetary boundary layer, being a subject of both wind speed, the thickness of air and eventually temperature, becomes low during colder periods. Additionally, less wet deposition in winter also leads to higher aerosol pollution and smog formation over urban locations in South-west India (K.B et al., 2012). Hence, dry weather conditions during winter lead to the formation of further smog and air quality issues. In addition to acquiring data from a centralized urban weather station, the research team gathered ambient $PM_{2.5}$ data at three housing sites with the data summarized in Table 1.

Table 1. Comparison of $PM_{2.5}$ measured at 3 housing sites in January and August 2018 with simultaneous data from pollution monitoring station at U.S. Consulate in Mumbai.

			Measured Site $PM_{2.5}$ [μg/m^3]		Simultaneous U.S. Consulate $PM_{2.5}$ [μg/m^3]	
Site	Context	Date	Average	Maximum	Average	Maximum
Dharavi	Slum	Jan. 2018	121	505	113	192
Dharavi	Slum	Aug. 2018	56	3,570	49	112
Natwar Parekh	Resettlement	Jan. 2018	129	1,390	97	165
Natwar Parekh	Resettlement	Aug. 2018	47	1741	*Not available*	*Not available*
Lallubhai	Resettlement	Jan. 2018	179	1,661	117	199

The comparison reveals that data published by the U.S. Consulate pollution monitoring station (in the Bandra neighbourhood approximately 9.4 km away from the resettlement housing sites) consistently show lower concentrations than those measured at the three sites while failing to capture the short-term particulate spikes that commonly afflict the air surrounding residential communities. With the sensors used in the site deployments being co-located and against laboratory-grade instruments (and the sensor data adjusted accordingly), the comparison suggests that the pollution monitoring station may be in a location of the city (or installed at an altitude) with less-polluted air than the air surrounding these three housing sites. Such findings encourage a more in-depth examination of ambient $PM_{2.5}$ levels specific to the microenvironments surrounding housing sites, especially as pollution values are used to inform environmental and health policy and predict occupant exposures.

4.4. HAP trends in slum and resettlement typologies

Before logging sensors were installed for multi-day periods, $PM_{2.5}$ point measurements were gathered within each dwelling. 30 or more point measurements were taken at varying heights and distances to fenestration in three select zones—foyer areas, kitchen areas, and sleeping areas. For slum units, the small size of the dwellings did not allow for room demarcation; each household was thus treated as a single zone. Pollution transport simulations often assume pollutants are well mixed in rooms, where rooms can then be designated as single zones (Dols et al., 2015). To assess the feasibility of this assumption for future $PM_{2.5}$ simulation work in rehabilitation housing, the spatial $PM_{2.5}$ measurements were gathered in different zones within dwellings.

For the foyer, kitchen, and sleeping areas, point measurements indicated that Natwar Parekh households had average $PM_{2.5}$ levels of 305, 326, and 192 $\mu g/m^3$ respectively, while the same zone types in Lallubhai Compound had levels of 226, 223, and 413 $\mu g/m^3$. These values exceed the average $PM_{2.5}$ point measurements of 118 $\mu g/m^3$ measured in slum dwellings at Dharavi. Furthermore, the rehabilitation dwellings experienced far greater variation in concentrations within zones, as portrayed in the large interquartile ranges in Figure . Other notable observations include the disparate zonal trends in Natwar Parekh and Lallubhai Compound; in the former, foyer areas generally had the highest point measurements, while in Lallubhai Compound, sleeping areas had the highest. In neither complex did cooking areas have the highest average point measurements. Ultimately, the median point measurements across dwellings in any given rehabilitation complex did not vary greatly across zones, as indicated by the relatively small values for ΔC_{median} in Figure .

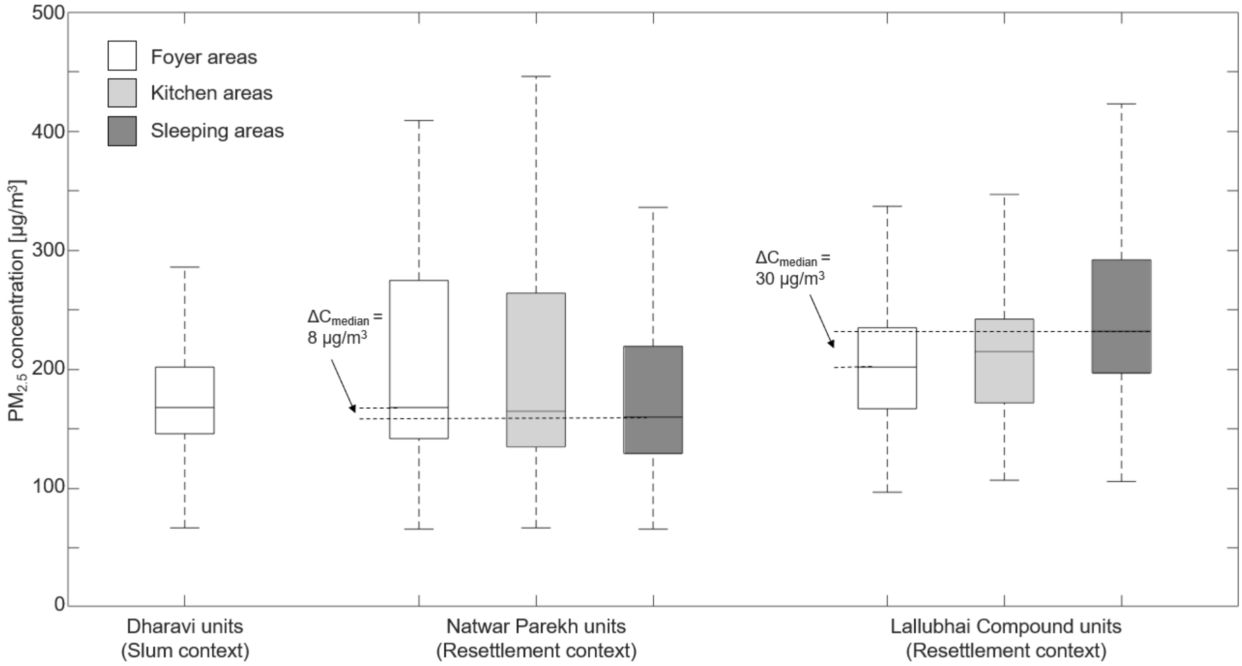


Figure 6. Spatial variations for $PM_{2.5}$ point measurements taken in slum and resettlement households. Boxes include median values and interquartile ranges (25th and 75th percentiles).

For $PM_{2.5}$ data logged over a period of days, this study emphasizes a metric of $PM_{2.5}$ indoor/outdoor (I/O) ratio as the best indicator of the built environment's influence on IAQ. I/O ratios that consistently exceed a value of 1.0 indicate that indoor sources are the leading contributor to household air pollution, whereas values below 1.0 suggest the significance of ambient pollution infiltrating indoor spaces. Through January and August 2018 measurement campaigns, high fluctuations of outdoor $PM_{2.5}$ were filtered by removing outliers (defined as values that exceed three median absolute deviations of each data collection) and smoothed with a one-hour moving average function. For sensor deployments at Dharavi, Natwar Parekh, and Lallubhai Compound, the percentages of time where the I/O ratios fell between designated bands are displayed in Figure .

While Dharavi and Natwar Parekh tenements demonstrated $PM_{2.5}$ I/O > 1.0 in 45.7% and 44.7% of cases, respectively, data from Lallubhai tenements trended more significantly toward values below 1.0, with only 20.5% of data exceeding this threshold. These trends were observed despite residents of all three housing archetypes relying on predominantly low-emitting LPG cookstoves in roughly similar proportions as indicated in **Error! Reference source not found.**. Furthermore, the generally lower I/O ratios measured in LC rehabilitation dwellings correlated with higher indoor point measurements—suggesting that even while indoor sources were less impactful at this particular site, outdoor sources were still sufficient enough to contribute to higher HAP concentrations. Outdoor particulate emissions at these sites can be unpredictable and challenging to alleviate, and thus, indoor retrofits and design optimization remains the most feasible alternative to alleviate HAP.

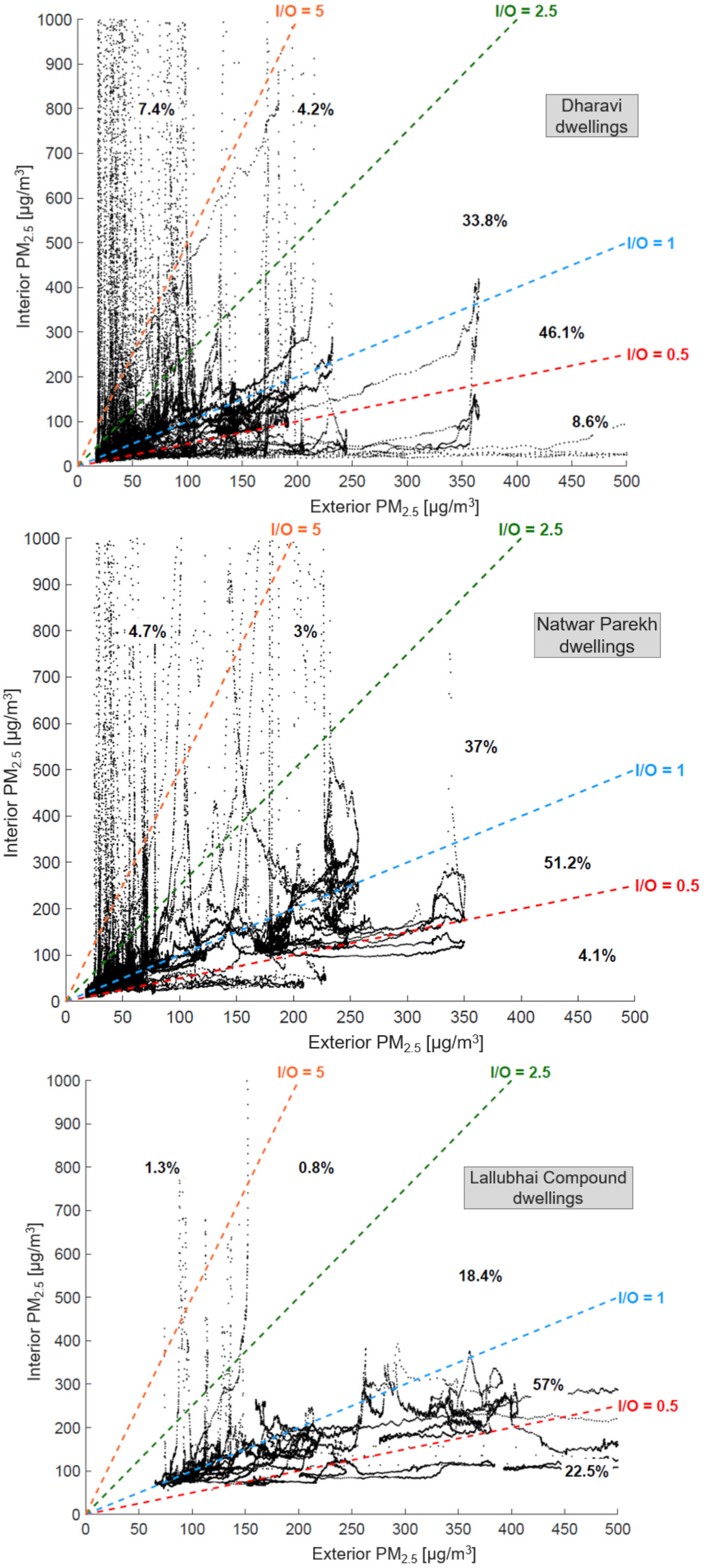
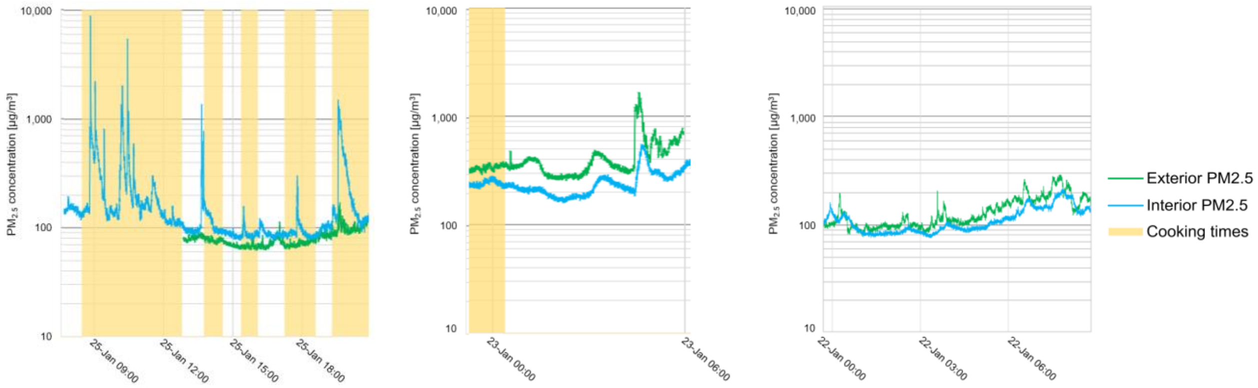


Figure 7. Scatter plot showing $PM_{2.5}$ I/O ratio trends at Dharavi (top), Natwar Parekh (middle), and Lallubhai Compound (bottom) regions representing I/O ratio bands. Colored dotted lines delineate regions of I/O ratio bewteen values of 0.5, 1, 2.5, and 5.

4.5. HAP source and sink apportionment

In order to comprehensively assess the contribution of cooking activities on HAP, the cooking-induced indoor pollution was investigated for all the archetypes. To assess likely source and sink mechanisms, indoor $PM_{2.5}$ concentrations were further compared against outdoor pollution spikes and cookstove activities. By plotting these data sets against one another, it was observed that despite the near-ubiquitous use of clean LPG fuel in slum and resettlement dwellings alike, cookstove events are generally accompanied by large $PM_{2.5}$ spikes. Outside of cooking times, indoor and outdoor levels appear to be closely coupled, with outdoor spikes leading to indoor spikes with very little time delay. Furthermore, after cooking-induced particulate spikes, indoor levels gradually fall below outdoor levels, indicating the role of surface deposition as an appreciable indoor pollution sink. These trends are highlighted with selected examples below in Figure . Another phenomenon contributing to this trend might be the socially constrained occupant behaviour of the rehabilitation residents regarding the operation of openings. It was observed that 80% of the surveyed households tend to keep their openings closed during cooking in favour of maintaining privacy, strengthening the evidence of higher indoor cooking induced $PM_{2.5}$ levels from Figure (a). Whereas, Figure (b) andFigure (c) elucidate that during non-cooking times, indoor levels are not only impacted by changes in outdoor concentration with a short lag time but also sharply falls to $PM_{2.5}$ concentration less than outdoor levels. This can be attributed to larger ventilation rates which might be because of the opening of the window during post-cooking hours.



(a) (b) (c)

Figure 8. Observable trends in data logs of indoor $PM_{2.5}$, ambient $PM_{2.5}$, and cookstove events. (a) LPG cookstove activity consistently leads to major spikes in indoor $PM_{2.5}$ concentration. (b) During non-cooking times, indoor levels are largely impacted by changes in outdoor concentration with a short lag time. (c) During non-cooking times, indoor $PM_{2.5}$ gradually falls to concentrations less than outdoor levels, demonstrating the role of surface deposition phenomena as a significant pollutant sink mechanism.

4.6. Air exchange analysis

The relationship between built-environment, occupant behaviour and air exchange phenomena can play a critical role in providing designers with the information needed to construct healthy indoor spaces. As a comparison of the relative ventilation performance of slum and resettlement housing units, the air exchange rate (AER, or λ) was calculated according to the SHEDS-PM single-compartment steady-state mass balance model for tracer gas decay (Deshpande et al., 2009). Large CO_2 spikes were frequently observed in the dwellings—majorly sourced from cooking-induced combustion activities, thus making CO_2 an ideal tracer gas for air exchange analysis. Furthermore, it also avoids the need to introduce more invasive tracer gases in occupied dwellings. The model indicates that CO_2 can be estimated as in Equation 1:

$$C_{\mathrm{in}} = \frac{P\lambda}{\lambda + k} C_{\mathrm{out}} + \frac{Q}{(\lambda + k)V} \tag{1}$$

where: C_{in} = Indoor tracer gas concentration [ppm]
P = Penetration factor of tracer gas [unitless]

λ = Air exchange rate [hr^{-1}]
k = Deposition rate of tracer [hr^{-1}]
C_{out} = Outdoor tracer [ppm]
Q = Indoor tracer emission rate [m^3/hr]
V = Room volume [m^3]

Here, we assume a non-reactive tracer gas such as CO_2 will have no surface deposition ($k = 0$) and perfect penetration ($P = 1$), indicating no absorption of the gas by facade materials during infiltration. To assess the potential impact of respiration of room occupants on the mass balance model, we assume conservatively a small room volume of 13 m^2 (representative of typical floor areas observed in Dharavi units of 4.8 m^2 with ceiling heights of 2.8 m). We also assume high individual respiration levels of 0.13 m^3/hr CO_2, corresponding to the upper range of a normal working activity level from literature sources (Engineering ToolBox, 2004). For a typical Dharavi outdoor CO_2 concentration of 450 ppm (as measured during sensor deployments), an assumption of three occupants contributing to indoor CO_2 generation (also a conservatively high assumption given the small floor plan), and assumed air exchange rate of 5 hr^{-1} were considered. The first term of Equation 1 (representing CO_2 transport through outdoor air exchange) was compared with the second term (representing CO_2 emissions from people). The effect of outdoor air infiltration on CO_2 concentration is calculated using Equation 2:

$$\frac{P\lambda}{\lambda + k} C_{\text{out}} = \frac{1 \times (5\ \text{hr}^{-1})}{(5\ \text{hr}^{-1}) + 0\ \text{hr}^{-1}} (450\ \text{ppm}) = 450\ [unitless] \qquad (2)$$

Meanwhile, the effect of human respiration effect on CO_2 concentration is calculated using Equation 3:

$$\frac{Q}{(\lambda + k)V} = \frac{0.13\ \frac{\text{m}^3}{\text{hr}}}{(5\ \text{hr}^{-1} +\ 0\ \text{hr}^{-1}) \times 13\ \text{m}^3} = 0.002\ [unitless] \qquad (3)$$

Thus, even with an assumption of a small compartment and very high indoor respiration, the indoor CO_2 source term is several orders of magnitude smaller than the outdoor source/sink term. The occupants were therefore neglected as an appreciable CO_2 source, and cookstove combustion was assumed to be the major source of CO_2 apart from other minor sources like incense sticks, mosquito repellent coils etc.

To calculate AER, instances of CO_2 decay were located that agree closely with Equation 4 (ASTM, 2017):

$$\ln\left(\frac{C_{\text{in,t}} - \overline{C_{\text{out}}}}{C_{\text{in,t=0}} - \overline{C_{\text{out}}}}\right) = -\lambda t \qquad (4)$$

where $C_{\text{out,ave}}$ is the three-hour moving-mean outdoor CO_2 concentration straddling the timestamp in question. A computational script was developed to identify CO_2 spikes and subsequent decays for periods with initial indoor CO_2 values of 1,000 ppm, durations between 10 and 60 minutes, and reasonably good agreement ($R^2 > 0.95$) with the logarithmic (left-hand) term of Equation 4. For such events, a linear regression was performed to solve for the air-exchange term (λ). The resulting air exchange rates calculated for two slum dwellings and three resettlement dwellings are shown in Figure . The variations in AER in different units of resettlement colonies may be attributed to the differences in floor levels and uncertainty in occupant behaviour related to windows, which was not recorded during the measurement period.

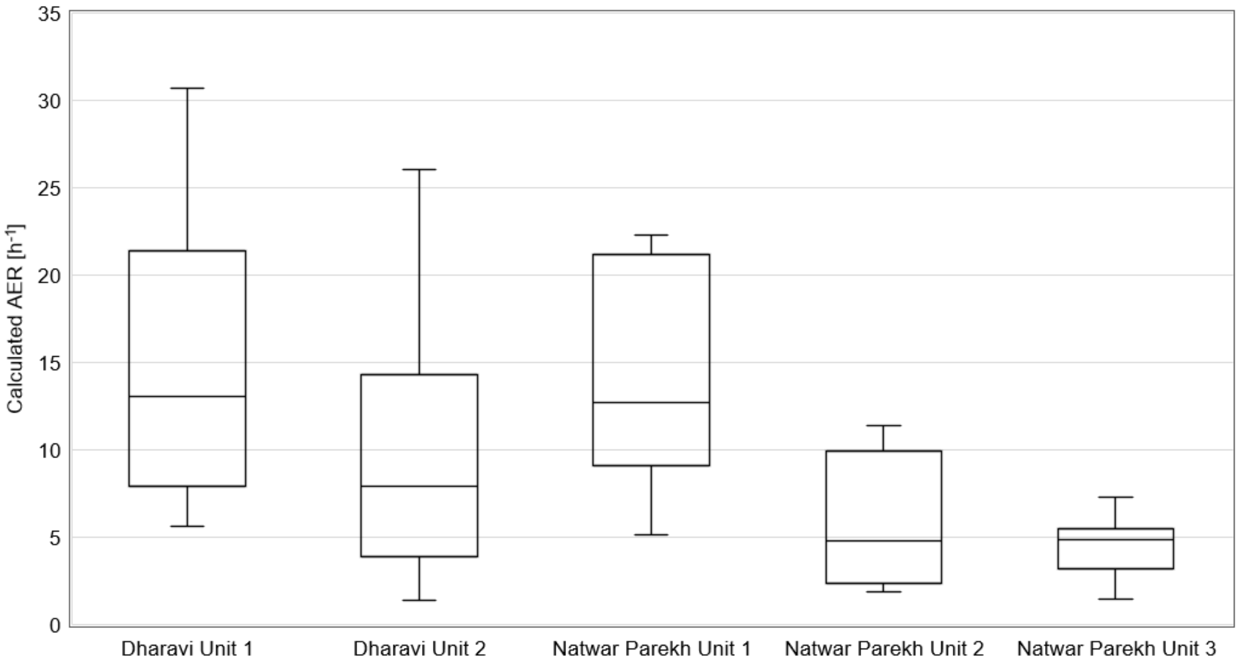


Figure 9. Comparison of AER calculations between designated slum and resettlement units using CO_2 generated from LPG cookstoves as an indicator of air exchange.

With the air exchange term determined, we expand the examination from non-reactive CO_2 to a different pollutant, $PM_{2.5}$, which has reactive properties with surfaces. For $PM_{2.5}$ decay, we assume that mass balance phenomena fit Equation 5. Here we only consider $PM_{2.5}$ decay in the absence of indoor sources (for the periods immediately following a cookstove being turned off):

$$\frac{dC_{\mathrm{in}}}{dt} = P\lambda C_{\mathrm{out}} - (\lambda + k)C \tag{5}$$

where: C_{in} = Indoor $PM_{2.5}$ concentration [μg/m^3]
C_{out} = Ambient $PM_{2.5}$ concentration [μg/m^3]
P = $PM_{2.5}$ penetration factor [unitless]
k = $PM_{2.5}$ deposition rate [hr^{-1}]

In order to simultaneously solve for P and k, we perform a non-linear regression to the analytical solution of Equation 5, employing similar methods from previous pollutant decay analyses for other surface-reactive indoor pollutants, such as ozone (Stephens et al., 2012; Zhao & Stephens, 2016).

$$C_{\mathrm{in,t}} = C_{\mathrm{in,t=0}} e^{-(\lambda+k)t} + \frac{P\lambda C_{\mathrm{out}}}{\lambda + k}\left(1 - e^{-(\lambda+k)t}\right) \tag{6}$$

To assess the behaviour of CO_2 and $PM_{2.5}$ pollutants in resettlement dwellings in a more controlled experimental setting, similar regression techniques were employed for 12 tests measuring CO_2 and $PM_{2.5}$ concentration decay in the vacant apartment at Natwar Parekh. The experimental setup is depicted in Figure . In this case, the room was intentionally filled with $PM_{2.5}$ derived from cooking activities and a mosquito coil, as well as CO_2 emitted from a tank. CO_2 and $PM_{2.5}$ decay were measured under 12 different scenarios. Two ceiling fans were activated and deactivated, windows were either fully open or fully closed, and vertical surface area was either left as bare walls or increased with the hanging of approximately 4.8 m^2 of blanket surface area. The tests were carried out until a predicted minimum of 1.0 full air exchange had been achieved, using real-time CO_2 regression calculation during the course of the tests. This follows the recommended test duration from the referenced guidelines (ASTM, 2017). The results of these tests are summarized in Table 2. It should be noted that $PM_{2.5}$ was only emitted for Tests 5 through 12, so k and P parameters are not calculated for Tests 1 through 4. The AER was found to be nearly four times lower when windows were closed and ceiling fans were functioning (Test 5), in comparison to the scenario when just windows were kept opened and ceiling fans switched off (Test 2). This emphasizes the argument that a ceiling fan simply serves as an air circulation device and does not aid in improving ventilation quality, whereas fenestration can be a more effective design parameters.

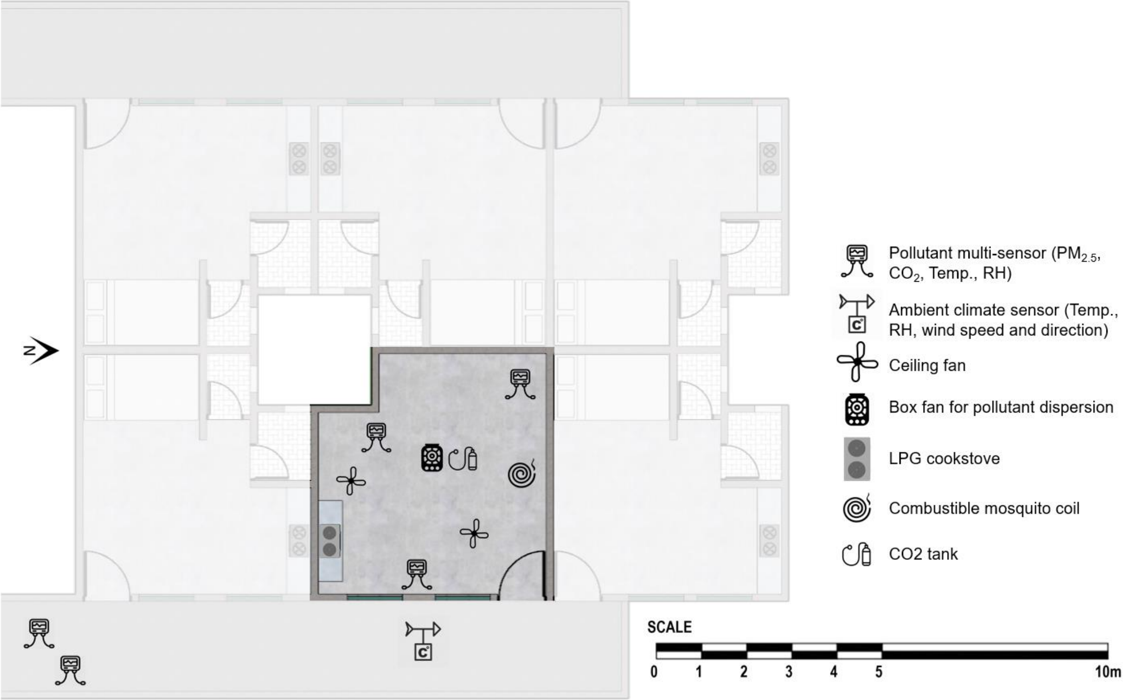


Figure 10. Experimental setup in controlled dwelling at Natwar Parekh (approximate locations of components shown).

Table 2. Summary of regression calculations for AER and *k* across 12 decay tests in vacant test apartment at Natwar Parekh.

Test ID	Test length [minutes]	Window position	Ceiling fan status	Surface area adjustment	λ [hr^{-1}]	k [hr^{-1}]	P
1	133	Closed	Off	None	0.42	N/A	N/A
2	27	Open	On	None	7.19	N/A	N/A
3	45	Open	Off	None	3.64	N/A	N/A
4	39	Closed	On	None	0.33	N/A	N/A
5	119	Closed	On	None	0.53	0.78	1.00
6	15	Open	On	None	9.40	0.00	0.24
7	30	Open	Off	None	2.58	0.81	1.00
8	25	Open	On	Blankets hung	8.73	0.51	0.11
9	15	Open	Off	Blankets hung	5.55	0.29	0.00
10	96	Closed	On	Blankets hung	0.62	0.96	1.00
11	123	Closed	Off	Blankets hung	0.52	0.08	0.00
12	155	Closed	Off	None	0.37	0.02	0.00

5. Discussion

The data logging campaign indicates that both the surveyed slum and resettlement typologies contain indoor environments that far exceed World Health Organization (WHO) guidelines for particulate matter exposure. The guidelines recommend $PM_{2.5}$ exposure not exceeding 25 µg/m^3 mean 24-hour exposure and 10 µg/m^3 mean annual exposure (World Health Organization, 2005). Indoor $PM_{2.5}$ point measurements indicated an interquartile range (between 25th and 75th percentile of gathered data) consistently between 150-300 μg/m^3. Logged data demonstrated indoor levels frequently in excess of 300 μg/m^3, with daily spikes exceeding 1,000 μg/m^3.

These high readings occurred despite nearly ubiquitous use of LPG cookstoves in slum and resettlement households alike. Such LPG stoves have been demonstrated to output far lower $PM_{2.5}$ emissions per useful thermal output than kerosene stoves (between 500-1,500x less) or charcoal stoves (between 3,000-7,000x less) (Shen et al., 2018). Despite the reductions in emissions associated with LPG cooking fuel, none of the surveyed households was shown to have pollution levels that meet exposure guidelines, indicating that pollution derived from either indoor or outdoor sources continue to present hazard to occupants. This explains that even with the provision of clean cooking fuel and improved built-environment related infrastructure in resettlement colonies, the household air pollution remains deteriorated. This can be attributed to the socio-culturally restrained occupant behaviour and ventilation-path-related interior design faults. These conclusions match those of a past survey of households in North-Central India which suggested that the mean indoor $PM_{2.5}$ rates were actually higher in the living rooms of homes using LPG as a cooking fuel than those using solid fuels (David et al., 2012). These results point to other sources of HAP independent of fuel choices, such as the charring of food (a phenomenon that occurs in LPG and solid fuel stoves alike) or other occupant-induced indoor emissions.

In slum and resettlement households alike, $PM_{2.5}$ I/O ratio was less than 1.0 for over half of logged instances, a result of outdoor levels exceeding those for indoors. In slum households, 54.7% of measurements yielded I/O ratios larger than 1.0, while in Natwar Parekh and Lallubhai resettlement sites, 55.3% and 79.5% of measurements were less than 1.0, respectively. These data suggest particle deposition phenomena that serve to reduce indoor levels. The results also indicate the predominant role of ambient-sourced $PM_{2.5}$ in household air pollution in Mumbai households, despite the large spikes observed during cooking events. These conclusions should inform architects of rehabilitation projects that the infiltration of ambient pollution must be central to their design of building envelopes and ventilation systems. HAP interventions that succeed in regions with low ambient pollution—for example, clean cookstove initiatives or distribution of exhaust fans to promote air exchange—will not be effective to create clean indoor environments. In fact, the frequent I/O values below 1.0 suggest a potential adverse effect of enhanced air exchange. I/O values below 1.0 indicate higher ambient pollution; hence enhanced air exchange rates introduce polluted ambient air with a potentially adverse effect on IAQ.

The point measurements displayed in Figure indicate that room spatial variations are generally small. Median $PM_{2.5}$ readings in different dwelling zones were within 5% of one another at Natwar Parekh, with highest readings occurring in the foyer areas, on average. At Lallubhai, readings were within 15% of one another, with highest readings generally occurring in the sleeping areas. At neither site were the measurements consistently highest near the kitchens. This indicates the need for interior design interventions where partition walls, furniture placement, cookstove position with respect to fenestration, and sleeping areas can improve IAQ in multipurpose tenement units.

Next, the analysis of air exchange rates using CO_2 as a tracer gas demonstrated significant variance between units—even those within the same building. Air exchange rates are influenced by numerous factors including wind pressure on the building exterior, occupants' use of fans, and interior-exterior temperature gradient. The results demonstrate that opening windows has the largest effect on air exchange rate, increasing the rate by a factor of 15 or more. Ceiling fans also have a significant impact for open-windows tests, increasing AER by more than a factor of 2, but only contributed to a slight increase for the closed-windows tests. This phenomenon indicates the requirement of openings at optimized locations for enabling effective cross-ventilation. The tests also demonstrate the difficulty and unpredictability of measuring the parameters k and P for such an experimental setup. With k confined to a minimum of 0, Test 6 results showed a best-fit k value of 0. With P confined between 0 and 1, a number of test results showed best-fit P values at exactly 0 or 1, precisely at the boundaries. To investigate these results in greater detail, future experimentation will involve additional tests or allow tests to run for longer periods. While the precise mechanisms for air exchange variance cannot be determined for the decay events measured here, the data indicated that slum households can have similar—and in some cases significantly larger—air exchange rates than resettlement households. Dharavi Unit 2, for example, was shown to have median air exchange rates nearly 3x higher than those in Natwar Parekh Unit: 3, though with much greater variance in rates. Broadly, these results challenge the notion that movement from dense slum typologies to high rise clusters leads to improved natural ventilation by default.

Lastly, the relatively large percentage of monthly incomes that occupants reported spending on electricity bills reduces the potential for energy-consuming personal air purification devices as a solution for HAP mitigation in low-income Mumbai households. In resettlement communities, residents reported spending an average of 9.0% of monthly income on electricity, with a maximum of 25% in one household. By comparison, a 2016 report indicated that low-income residents of multi-family buildings in the U.S. spent an average of 5.0% of monthly income on electrical bills, against a national average of 3.5% (Drehobl et al., 2016).

Future efforts will attempt to alleviate uncertainty related to occupant behavior. The research team is engaging with an NGO stationed at the Natwar Parekh site to commence an "adopt an apartment" arrangement where additional sensors are installed to definitively track HAP-related activities such as fan operation or window adjustments. Additional outdoor sensors may also be installed, perhaps at higher altitudes or on rooftops, to alleviate the potential for indoor environments interfering with outdoor readings.

6. Conclusion

This measurement campaign concluded that low-income housing typologies in Mumbai experience household air pollution that far exceeds recommended limits. This is true in both slum and rehabilitation communities, despite the use of clean-burning cooking fuels in 75-85% of the households. While HAP levels varied significantly between units, resettlement dwellings frequently yielded higher HAP levels than slum households and experienced more limited air exchange. Ambient pollution was indicated as a major factor contributing to this phenomenon. Mean household $PM_{2.5}$ indoor/outdoor ratios were found to vary significantly between rehabilitation sites, and in some cases closely match the values measured in a slum context. In all archetypes, I/O ratios were most often less than 1.0, indicating cleaner indoor environments than out, on average. Pollutant decay tests indicated window openings as the primary architectural parameter to improve IAQ and impact air exchange rates. Future efforts to optimize low-income housing design must address infiltration of ambient air as a major contributor to household pollution. Special focus should be given to interior level design parameters like cross-ventilation paths, opening location, partition wall and space separators, furniture layout, and cookstove location. The cost-effective solution of natural ventilation must be combined with mechanisms to treat outdoor air before it is delivered to indoor environments using passive or low-energy solutions to the greatest possible extent to provide feasible housing solutions for Mumbai's low-income population.

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Appendix

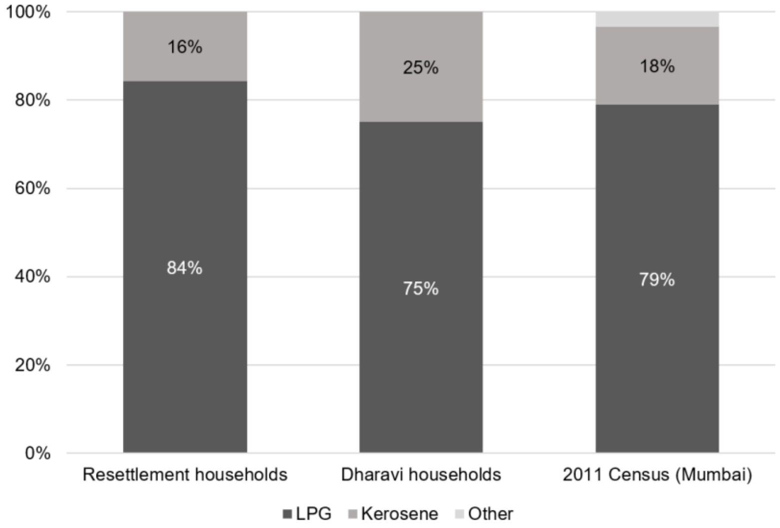

Figure A1. Survey results for household fuel choices in slum and resettlement contexts, in comparison to results reported in the 2011 Census of India for Mumbai urban households.

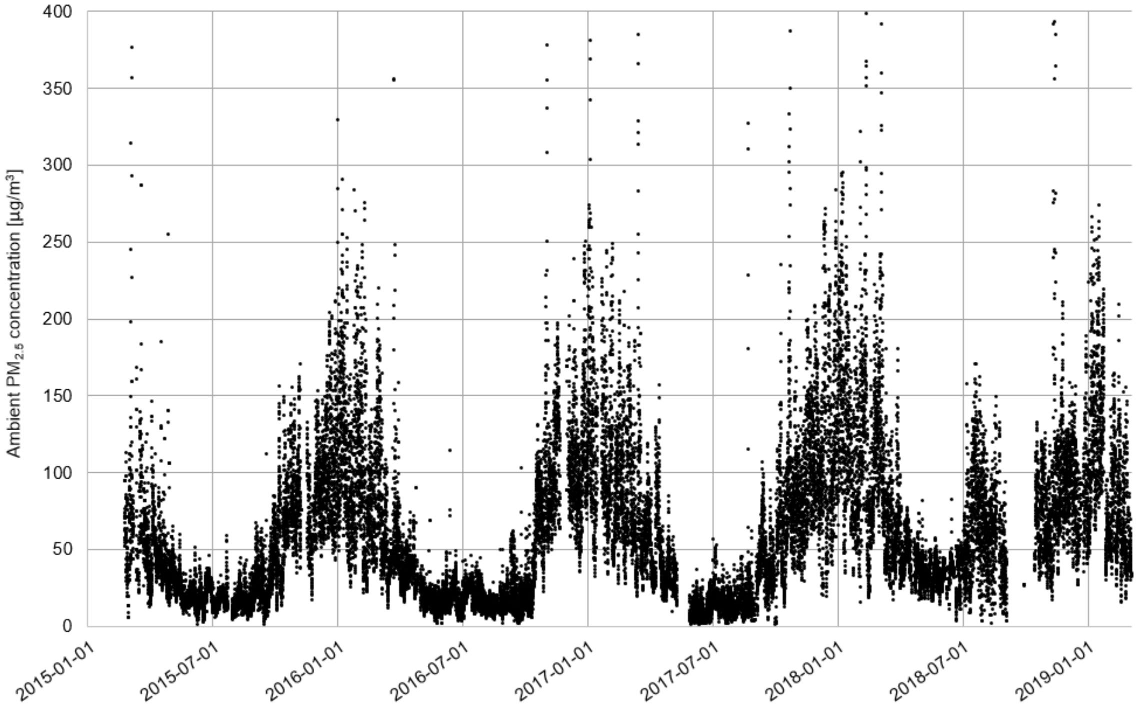

Figure A2. Ambient Mumbai PM$_{2.5}$ data 2015-2019. Data from U.S. Consulate General pollution monitoring station (U.S. Department of State, 2019).