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Impact of Occupant Behavior on Indoor Thermal Comfort and Ventilation Patterns in Social Housing of Mumbai, India: Observation from Experiments and Household Surveys

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Abstract

Investigating socio-cultural induced occupant behavior and its impact on indoor thermal comfort is essential in low-income tenements in India, owing to financial and space restraints. This study utilized household surveys followed by sensor-based field measurements to explore the occupant behavior-driven indoor temperature trends within slum rehabilitation housing in Mumbai.

The findings underscore the use of ceiling fans and windows as primary strategies for adaptive comfort. Regression analysis validated an association between air temperature, fan, and cooking. However, fans dominate natural ventilation, as privacy concerns and architectural design limit window utilization. The study offers valuable insights for enhancing thermal comfort, in the context of energy-efficient design.

Introduction

People spend 80-90% of their total time indoors (Klepeis et al., 2001). Indoor environmental conditions thus considerably affect occupant's health, well-being, productivity and quality of life (Verma et al., 2023). Indoor environmental quality (IEQ) is strongly affected by interactions between factors like local climate, dwelling characteristics, heating, ventilation, and air conditioning (HVAC) system, as well as occupancy patterns. Occupant activities (temporal and spatial characteristics), lifestyle choices, and building operation schedules significantly impact indoor environment. For instance, movement of people or objects, opening and closing of doors and windows, fan operation, cooking, and use of materials affect indoor microclimate metrics including air temperature (AT), relative humidity, wind speed, contaminant concentration etc. (Silva et al., 2017), ultimately affecting thermal performance of buildings and occupant comfort (Gupta & Deb, 2022).

With imminent threats from climate change and energy crises, there has been a growing interest in natural ventilation techniques for enhancing thermal comfort in buildings, particularly in hot climates (Liping & Wong, 2007). Natural ventilation, reporting 30%–40% less energy consumption compared to mechanical ventilation, can minimize greenhouse gas emissions (Sarkar & Bardhan, 2020b; Schulze & Eicker, 2013). Moreover, passive cooling through adequate natural ventilation (NV) provides an attractive alternative to overcome challenges associated with operation costs, and indoor air quality (IAQ) in mechanically cooled buildings.

The thermal performance in a naturally ventilated building depends on local climate, and design features like window-to-wall ratio, opening type, design, and their subsequent controls. Individuals demonstrate an inherent tendency to adjust to changing environmental conditions by the use of controls (Nicol & Humphreys, 2002). They often use environmental controls like closing/ opening windows, blinds, doors, and fans to modify their thermal environment to enhance comfort (Indraganti, 2010). Accordingly, the use of controls varies with time, occupant activity patterns, and climate and is determined by the psychological and cultural traits of occupants, establishing a systematic relationship between outdoor climate and indoor temperature (Ferrari & Zanotto, 2012).

In India, an estimated 50% of the energy consumed in residential buildings is used for ventilation and cooling (fans – 34%; Air coolers – 7%; A/C – 7%) (BEE, 2017). A 5°C reduction in temperature at which AC is switched on is possible using open windows and fans (Nakaya et al., 2008). The occupant behavior and their use of controls driven by socio-economic characteristics thus play a critical role in enhancing indoor comfort and reducing energy consumed, and consequent environmental impacts.

However, achieving thermal comfort, a critical IEQ parameter, turns challenging in low-income settlements due to extreme space constraints leading to hyper-density and high occupancy levels coupled with financial restraints compelling them to restrict use of energy-exhaustive mechanical cooling devices (Frontczak & Wargocki, 2011). While extensive literature revolves around establishing built-environment- occupant behavior-thermal comfort-energy interlinkages across residential and commercial sectors, the differences in thermal comfort related behavior within disadvantaged population attributed to economic restraints leading to energy cost and space constraints, deteriorated housing quality, occupant density, weather extremities vulnerability, and lastly, socio-cultural norms and practices remain under-ventured.

The research has a multi-fold novelty; first, it attempts to capture the complex interplay of socio-culture and financial restraint-driven unique occupant behavioural patterns that modify the adaptive thermal comfort controls within hyper-dense low-income apartments. Secondly, it investigates the indoor thermal comfort levels on a normal day with limited use of mechanical cooling devices.

While using cooling devices to attain comfort is common in tropical hot and humid climate (Indraganti, 2010), the urban poor often adapt and compromise their well-being by limiting energy use. Recent research conducted in affordable mass housing is either experiment-based with a focus on household air pollution (HAP) (Lueker et al., 2020) or employs sensor-data-driven computational simulations to analyse the impact of dwelling design on indoor natural ventilation (Sarkar & Bardhan, 2020b, 2020a). Recently, field survey-based data-driven econometric modelling to understand the impact of household characteristics and appliance ownership on environmental satisfaction has also been looked into (Sarkar & Jana, 2023). Nevertheless, a transverse method integrating both experimental data and survey-based field data is essential for capturing the holistic image regarding occupant behavior-driven thermal comfort perceptions. Financial restraints and space constraints, and contrastingly, the constant aspiration to rise the social ladder, alter the occupant behavior within these communities.

The uniqueness of the study also lies in investigating the distinct socio-cultural practices that affect occupant's use of comfort controls on a normal day and, consequently, the indoor temperature levels. Understanding the comfort and well-being of the already energy-deficit urban poor communities is crucial for the sustainable development of emerging nations, where 50% of city dwellers belong to low-income groups. The findings of this study would pave way towards formulating inclusive, environmentally sustainable, and energy-efficient low-income housing development policies and design guidelines, particularly for developing nations in the future.

Background

In tropical regions like India, the ability to modify thermal conditions via the use of passive controls remains limited due to high outdoor AT and relative humidity (Feriadi & Wong, 2004). However, due to limited ownership of cooling devices like air-conditioners, particularly amongst the low-income groups, individuals have adapted to the local conditions. As a part of behavioral adaptation, the occupants use low-energy controls like fans and windows to aid air movement and enable acceptance of warmer conditions (Feriadi & Wong, 2004; Indraganti et al., 2013).

Most of the existing research examines the use of controls in office environments with a growing focus on residential dwellings (Indraganti, 2010; Omrani et al., 2017). However, the pattern of use of controls and their effect on thermal comfort in low-income apartments, particularly slum rehabilitation housing (SRH) is unique, failing to which leads to occupant discomfort and distress. Further, the majority of the micro-climate properties (affecting IEQ), depend on gradients of AT, and ventilation in a building (Szczurek et al., 2018). In this regard, this study discusses a thermal comfort field study that was conducted in a typical SRH unit in Mumbai to understand the behavioral adaptations of dwellers and their effect on indoor AT.

In response to rapid urban migration and consequent slum proliferation in megacities of Mumbai, the housing authorities have initiated resettlement of the slum dwellers to permanent overcrowded, high-rise towers with infrastructural amenities and individual tenement units, less than 250sq.ft, unsegregated kitchen and tenement-level toilet and bath facilities, conforming to the Slum Rehabilitation Development Control Regulations (DCR, 1995). However, the current occupied units exhibit poor livability attributed to energy-inefficiency, extreme temperatures leading to thermal discomfort and distress, household air pollution (Lueker et al., 2020). Occupant activities, majorly cooking, further aggravate discomfort level due to increased indoor heat (Sarkar & Bardhan, 2020b). Furthermore, due to financial constraints, the only "cooling" appliance available to the residents is a ceiling fan; whereas doors and windows serve as the only passive controls. Nevertheless, it is important to note that the mere availability of a control does not indicate its use or enhancement of comfort (Nicol & Humphreys, 2002).

The increasing population density and escalating temperatures present a significant challenge to both energy security and the overall well-being of individuals, especially those who are constrained by socio-economic factors. Consequently, it is critical to understand the importance and effect of passive controls on their indoor thermal comfort. Thus, an investigation into the possible linkages between the occupant behavior characterized by the availability and use of windows and fans and its effects on indoor AT of SRH in Mumbai was performed. Additionally, as the effectiveness of natural ventilation in hot and humid climates remains uncertain, the analysis provides vital insight into the indoor design for this climate.

Methods

A mixed-mode approach was adopted in this study integrating household surveys of 412 SRH units followed by a campaign of sensor-based field measurements in one typical SRH unit. While the household surveys aided in determining the generalized occupant behavior and energy-time use patterns across the low-income socio-demographic sector, including the availability and usage of different cooling/ ventilation appliances; the detailed field experiment helped in comprehensively investigating the occupant behavior and indoor thermal comfort levels and their diurnal variations owing to indoor anthropogenic activities.

Study area

A transverse methodology was adopted, where on-field observation coupled with detailed questionnaire survey followed by narrative interviews were conducted across four low-income mass housing communities of Mumbai megacity. The recent SRH in Mumbai is characterized by densely spaced towering structures, 5-30 floors high with multi-purpose apartment units of less than 250sq.ft area as shown in Figure 1. Four representative resettlement configurations, Kohinoor Colony, Lallubhai Compound, Kanjurmarg and Sangharshnagar SRH were selected as sites housing project affected persons (PAP) relocated by major infrastructure projects and slum redevelopment campaigns. Kohinoor SRH colony, constructed in 2008, containing around 32 13-floored huge building blocks and accommodating 16,000 households across 53 acres (0.213 km2) has a housing density of 932 DU/Ha. Here, the apartments are accessed by double-loaded corridors further accessed by a number of central staircases and lift, with bathing rooms and water closets abutting external wall. Lallubhai Compound was constructed in 2003, containing 9300 apartments across 65 building blocks with units accessed via 2 metres wide double-loaded corridors, whose kitchens are located against the external wall. The third neighbourhood, Kanjur Marg SRH, near Kanjur Marg railway station, comprises of 12 eight-storied buildings accommodating 2232 households. Each block with 24 apartments on each floor is accessed by a double-loaded corridor. Sangharshnagar SRH, consisting of 18,362 households, each eight floored building contains 6 dwelling units per floor accessed by central staircase and lift, with kitchen abutting external wall.

Figure 1: Photographs of selected slum rehabilitation housing communities

Household survey

Computer Aided Personal Interviews (CAPI) involving face-to-face interviews were conducted during December 2022-January 2023 using a pre-coded questionnaire form. Both the surveys were conducted in Marathi/Hindi/English language for convenience of the respondents. Respondents above 18 years who were either housewives or spend maximum time indoors were selected for the surveys. The households owning the tenements were included, whereas rented houses were excluded.

The surveys spanned across 500 households, of which, 412 valid samples were finally selected for this study post data cleaning. The survey questionnaire comprising of sections involving basic household information, built-environment details and occupant behavior characteristics was administered through face-to-face interviews. A more profound understanding of behavioural patterns was obtained by enquiring about the related socio-cultural, environmental, or economic limitations. Figure 2 shows the survey design and explanatory variables used in the study. Measures of built-environment characteristics included building-to-apartment-level information like floor-level, corridor archetype, apartment design and size, kitchen location, and window details with information on their operating schedule were also determined.

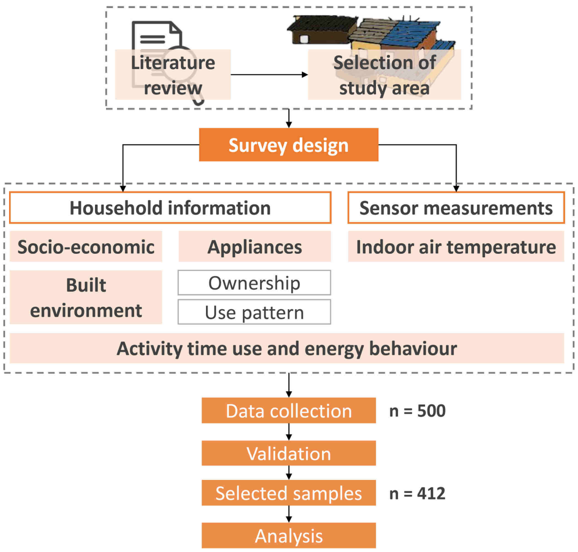

Figure 2: Survey design process adopted in the study

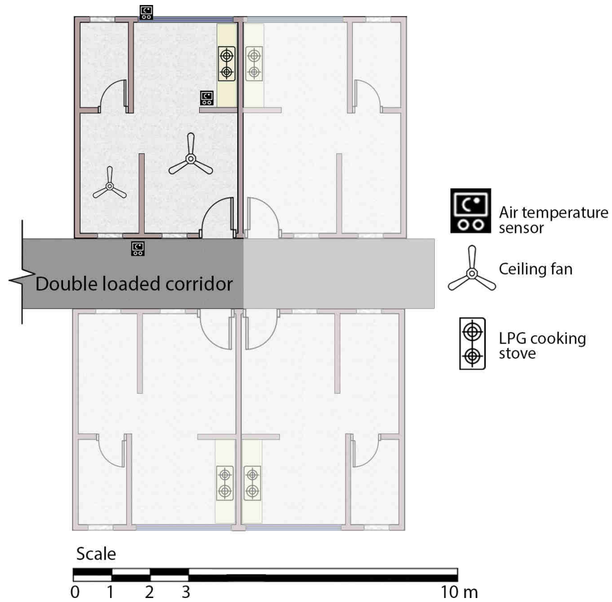

Figure 3: Experimental setup of air temperature sensors in a typical SRH unit. Dimensions based on author's measurements.

Further information was reckoned on the frequency of operation of active cooling devices like air conditioner, ceiling fans, exhaust and stand fans and other energy-exhaustive appliances. Occupant behavior information concerning in-home activities, etc. was also collected.

Field measurements

Data logging was employed for a day in July 2023 in a typical SRH dwelling unit to gain insights on indoor air temperature. While Testo 480® temperature sensors were installed in the living/central area of the SRH unit, other sensors were installed in the corridor and outdoor to investigate the impact of indoor anthropogenic activities and occupant behavior in modifying the indoor temperature levels as illustrated in Figure 3. Since the aim of the field experiment was to understand the impact of occupant behavior on indoor thermal comfort, the measurement campaign was later analyzed based on the pre-classified occupancy level and occupant behavior patterns. All sensors were within certified calibration periods.

Results and Discussion

Observations from household surveys

As per the existing status of appliance ownership as illustrated in Figure 4, ceiling fan is the only cooling appliance available in all households in SRH. While almost 25% households have exhaust fans (24.27%), AC ownership remains lowest due to higher associated energy consumption. Studies reveal that though the use of AC has been found to have positive impacts on occupants' satisfaction, its availability and use remains limited due to economic constraints (Sarkar & Jana, 2023).

Due to common external walls in the case of slums, exhaust fans remain the only alternative to ensure air movement. However, as the occupants move to SRH, the availability of windows and ventilator reduces the reliance on exhaust fans. The reconnaissance survey revealed that exhaust fans, despite being installed in maximum units either remain unrepaired or are rarely used during cooking hours (Lueker et al., 2020).

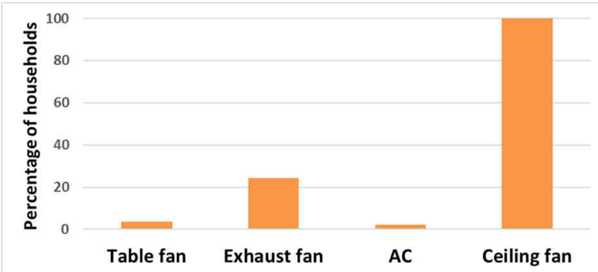

Figure 4: Ownership of cooling appliances (n=412)

Figure 5 illustrates the different factors for keeping windows open at night. More than 80% of households reported keeping windows open at night to allow ventilation, followed by night-time cooling and removal of odors (60%). Increase in night-time ventilation through open windows not only ensure cooling during summers but also improves IAQ; thereby reducing the reliance on electro-mechanical systems for space cooling and total energy consumed by the household (Feriadi & Wong, 2004; Tavakoli et al., 2022). Windows thus play a critical role in promoting occupant satisfaction (Sarkar & Jana, 2023).

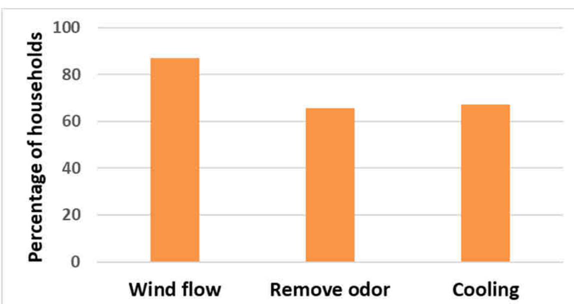

Figure 5: Purpose of keeping windows open (n=412)

It can therefore be inferred that the use of ceiling fans and window controls are the major adaptive comfort practices in SRH for achieving desired indoor thermal comfort. There is negligible reliance on energy-intensive appliances for thermal comfort.

Observations from reconnaissance survey

Figure 6 shows the daily time use profile of anthropogenic activities carried out in most of the SRH units in the surveyed households, derived majorly from reconnaissance surveys and informal discussions. The naturally occurring daily occupant behavior was categorized into seven-time phases (referred to as cases) based on the variations in occupant patterns. Emphasis was on cooking activity, period of occupancy and use of fans and windows as adaptive controls for thermal comfort.

Case ID	Duration	Activity profile	Occupancy	Windows | Fans
Case 1	07:00:00 to 07:25:10	Cooking	All	Open | On
Case 2	07:25:15 to 08:22:55	Household chores	Adult female	Open | Off
Case 3	08:23:00 to 12:24:30	Flexible time for household work/ rest/ income generating work	Intermittent movement	Closed | Off
Case 4	12:41:10 to 13:21:00	Cooking	Adult female	Open | Off
Case 5	13:45:15 to 14:43:00	Household work and childcare	Adult female and kids	Open | On
Case 6	15:10:15 to 17:08:05	Lunch/ household work/ rest/ income generating work	Adult female and kids	Closed | On
Case 7	17:25:05 to 19:02:15	Cooking	Male and female/ kids	Closed | On

Figure 6: Activity time use and occupancy pattern of a typical SRH unit for a day

The female household member allocates a significant portion of their time within indoor environment, particularly in SRHs. The reconnaissance survey-based observation revealed that even females who are involved in economic activities prefer working remotely to fulfil their childcare responsibilities. Particularly during daytime, in absence of male workforce and children, female members often prefer to spend time together in adjacent corridors to foster social bonds, engage in activities, household level businesses and social interactions on one hand, while benefiting natural ventilation and daylight from communal spaces, ultimately, contributing to lower energy use.

The time use pattern as illustrated in Figure 6 reveals that females restrict the use of fans and other active ventilation modes when alone at home. This complex phenomenon is rooted to the socio-cultural norms, gender roles, gender-based traditional expectations and economic factors, including preferred utilization of amenities by male workforce of the household, preventing financial burden owing to increased energy bills. Hence, this study executed the field measurement campaigns based on the context-specific observations, that are unique to the socio-cultural and socio-economic context of the low-income population.

Observations from in-situ measurements

Figure 7 presents the summary of temporal variation in AT data- indoor, corridor and outdoor. The field measurements report higher indoor AT inside the SRH unit, followed by temperatures in corridor and outdoors.

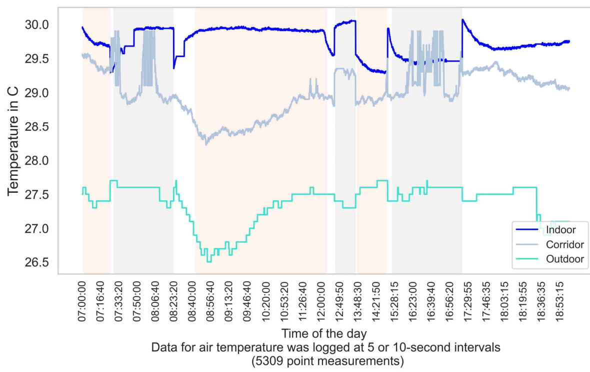

Figure 7: Trends observed in data logs of AT- indoor, corridor and outdoor. The vertical-colored bars represent different cases based on daily occupant activities. Total 5309 data points were recorded.

Indoor heat gain from occupant activities like door and window controls, appliance usage, cooking in unsegregated kitchen, use of heat generating objects like candles, incense sticks, mosquito coils and kerosene lamps and fluctuation in occupancy levels might lead to higher indoor AT (Szczurek et al., 2018). A comparatively lower AT in corridor implies the positive effect of the single loaded corridor that enables natural ventilation via open alleys and windows. However, the observed intermittent peaks can be attributed to resident movements and other occupant activities such as drying of clothes, storage of household items or old furniture in corridor spaces often resulting in airflow obstruction, and temperature rise (Szczurek et al., 2017).

Figure 7 illustrates that outdoor and corridor AT reduce by around 1℃ between 08:20 to 09:30. However, the indoor temperature remains constant due to non-operational ceiling fans, and closed windows to maintain privacy. Lack of privacy, and safety prevents residents from keeping windows and doors open for the most part of the day, particularly those in units on lower floor levels- "we keep windows/ door close while doing household chores to maintain privacy…. we also draw curtains while sleeping as we do not feel comfortable"

Further, it is observed that in an attempt to reduce expenditure on energy usage, female members refrain from using appliances like fan in absence of male members and kids for their comfort and spend time in corridors performing household activities- "We run fans and light in evening after kids and male members of the family are at home…. I do not need fan or light during daytime… There is enough light and air flow in the corridor…. I can sit in corridor...It also helps to reduce electricity costs"

This pattern is evident from activity time use map, case 2, 3 and 4 as illustrated in Figure 6. Cooking in unsegregated kitchen also compel the female members to turn off their fans to avoid spread of cooking-induced smoke and heat in the living space as seen in case 4.

Research suggests that lower outdoor temperature coupled with use of fans can aid air circulation and encourage cooling of thermal mass, resulting in lower indoor temperatures during evening time (Gupta & Deb, 2023; Sunikka-Blank et al., 2019). However, the act of window closing behavior owing to privacy, safety and preventing mosquitoes, especially during late evening hours is a common practice in SRH (Lueker et al., 2020). This is evident from Figure 7 and Figure 8- case 6 and case 7 (after 17:30). This blocks the ingress of cool external air, hindering the cooling of indoor environment via convection (Rijal et al., 2008). The utilization of fans as the sole intervention results in a decrease in the average indoor AT from 29.9℃ in case 3 to 29.5℃ in case 6.

"We keep openings covered in evening as everyone is home…we want privacy"

However, it does not lead to any additional reduction (possible via open windows) as reported in case 5.

The least temperatures are observed for case 1 and case 5 (Figure 8). The parallel use of fans and window openings during early evening hours might considerably reduce indoor AT. A higher indoor AT in case 1, compared to case 5 can be attributed to the east orientation of the unit. The direct solar gain during morning, coupled with heat gains from occupants and cooking activity result in higher indoor AT (Al-Yasiri & Szabó, 2023). For case 5, the effect of enhanced ventilation in the absence of solar radiation is effective in improving thermal comfort (Indraganti, 2010).

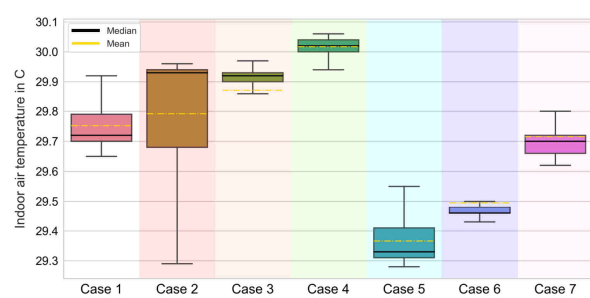

Figure 8: Indoor AT- variations based on occupancy patterns and activities.

The periods of peak indoor AT values are around 07:00, followed by 13:00 to 13:30 in noon and 17:30 in the evening (case 1, 4 and 7). The sudden spikes can be attributed to cooking induced heat traverses in living areas (Figure 7). Within the cooking hours (case 1, and

4), indoor and corridor temperature appear to be closely related due to air exchange via open windows (Lueker et al., 2020).

"My exhaust fan is not working… it needs repair…I switch on the fan and keep windows/ doors open while cooking as there are small kids… other members also have problem with smell and smoke… However, we keep all openings covered at night to maintain privacy"

However, the indoor heat gain from cooking exceeds the effect of natural ventilation as visible in case 4. The mean AT rises from 29.89℃ to 30℃ from case 3 to case 4 (Figure 8). Higher cross ventilation during peak summer hours can add to temperature and discomfort (Indraganti, 2010).

Similar observations can be made from case 6 and case 7. Under identical conditions, case 7 exhibits elevated interior AT, primarily attributed to the thermal gains from cooking and usage patterns of additional occupants in relation to equipment.

Regression analysis: Indoor air temperature and occupant behavior

To quantify the effect of occupant behavior in terms of window/ fan controls and cooking activity on indoor AT, a regression model was constructed for the seven cases. The descriptives are shown in Table 1. The status of ceiling fan/ window is coded as 1 if it is switched on/ open and 0 if it is switched off/ close (on=1, off=0). Similarly, for cooking, 1 denotes ongoing activity and 0 represents the absence of cooking. The mean indoor AT is 29.73℃, around 2℃ higher than outdoor AT. The results from the regression model are summarized in Table 2.

Table 1: Mean and standard deviation of the predictors used in the regression model

	Mean	Std. Deviation	Min.	Max.
Indoor AT	29.731	0.203	29.34	30.035
Outdoor AT	27.387	0.288	26.667	27.9
Ceiling fan	0.545	0.506	0	1
Window	0.333	0.479	0	1
Cooking	0.333	0.479	0	1

Table 2: Summary of regression calculations for impact of occupant activity on indoor AT (R^2= 0.793)

Model	β	S.E.	p- value
Outdoor AT	-0.060	0.075	0.431
Ceiling fan (1)	-0.364***	0.045	< .001
Window (1)	-0.058	0.040	0.157
Cooking (1)	0.223***	0.042	< .001
Constant	31.522	2.048	< .001

*Note: * Significant at 90% CI, ** Significant at 95% CI and *** Significant at 99% CI.*

The estimates demonstrate that the use of ceiling fans and cooking activity has a significant relationship with indoor AT. The two factors account for around 80% of the variation in indoor AT. The positive coefficient for cooking indicates that indoor AT increases during cooking activity. The experimental study by Chen at al. 2023, report similar findings for a naturally ventilated kitchen in China (Chen et al., 2023). In absence of appropriate ventilation, authors report high indoor AT during cooking period. However, for SRH units, the effect of natural ventilation via windows is dominated by the use of fans. A negative coefficient suggests that use of fans reduces indoor AT in SRH.

The indoor air temperature decreases by approximately 0.36℃, holding all other factors constant, when the ceiling fan is running. Conversely, it increases by approximately 0.22℃, when cooking is being carried out. The model further reveals that the estimated indoor air temperature when none of these factors are in effect is 31.52℃.

The ceiling fans not only serve as an air circulation device, but also aid in improving thermal comfort by reducing the indoor AT. Thus, it can be inferred that fenestration in SRH is not effective in lowering indoor AT. Since the measurement campaign was performed predominantly during the day, the window opening behavior did not yield statistically significant results. Research has shown that open windows during the night can effectively improve ventilation and facilitate the cooling of indoor spaces. It not only improves indoor air quality, but it also diminishes the dependence on mechanical cooling systems as a result of decreased interior AT (Sarkar & Jana, 2023).

Another potential factor could be the environment-insensitive layout design of the SRH units, which hinders cross ventilation due to the positioning of windows in the common corridor rather than on the exterior wall, narrow window openings, and the use of sliding windows. This issue is exacerbated by the tendency of occupants to keep windows closed owing to privacy and other concerns (Sunikka-Blank et al., 2019).

Conclusion

This study utilized a mixed-mode approach combining household surveys followed by sensor-based field measurements in space-constrained low-income tenements to comprehensively study the occupant behavior and examine its effect on indoor thermal comfort. While the household surveys revealed energy-time use patterns across the dwellings, including the availability and usage of different cooling/ ventilation appliances; the field measurements helped in investigating the effect of occupant behavior in terms of environmental controls- ceiling fan and windows on diurnal variations in indoor air temperature.

The household surveys highlighted the use of ceiling fans and window controls as the major adaptive comfort practices in SRH. A significant majority of homes opt to keep their windows open during the nighttime to enable indoor natural ventilation and promote passive cooling, thereby reducing energy consumed by electro-mechanical systems. A unique socio-cultural practice induced behavior was noticed among the female members of the households, who tend to turn off fans, open windows and spend time in communal spaces such as corridors, especially during daytime as thermal and economic-related adaptive adjustments. The social norm-driven act of predominantly utilizing ceiling fans during evening hours in presence of male workforce and children highlights the aspiration of the SRH dwellers to step up the social stratum through appliance ownership, while limiting their usage to reduce economic burden. Therefore, high energy costs and socio-economic constraints often force women to compromise their thermal comfort.

In-situ temperature measurements showcased that occupant behaviors such as door and window controls, appliance usage, cooking, and changes in the number of occupants impact indoor temperature levels. The significant positive association between indoor temperature and cooking activities highlighted the non-utilization of exhaust fans and absence of adequate cross-ventilation and airflow distribution within the tenements leading to peaking of temperature levels due to cooking-induced heat.

While privacy-related concerns and socially insensitive housing design prompted the closure of windows, hindering natural cooling via convection; the ceiling fans were observed to be the only control available to SRH residents for improving their thermal comfort.

The study also highlighted the role of solar gains, and orientation, in affecting indoor AT, with east-oriented units experiencing higher morning temperatures. A more environmentally sensitive design in neighborhood and building level in terms of orientation and integrated open spaces, and provision of operable windows, its location, design, type and placement at tenement level should be recommended for better indoor airflow distribution.

Additionally, as appropriate openings are crucial for improving thermal comfort and IAQ, clerestory windows or ventilators can be used for daylight and effective removal of stack air while maintaining privacy, thereby reducing energy consumption.

The results underscore the complex interaction between occupant behavior, environmental variables, and housing design characteristics would pave way towards shaping indoor thermal comfort, while providing useful perspectives for the development of energy-efficient cooling design approaches in the future. The interlinkages provide architects, housing policy makers, and urban planners with valuable insights for the design and implementation of future affordable mass housing in developing nations context.

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