Field study on measuring Indoor Air quality in certified Green-rated urban Indian residences

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Abstract

India has the second largest registered green building footprint in the world, however, there is growing recognition that green building rating and certification systems do not always ensure better indoor air quality (IAQ) over conventional buildings. Moreover, residents spend a substantial fraction of their lives indoors, yet IAQ in homes has been studied far less than air quality outdoors, especially in urban India. To verify the actual IAQ performance of green-rated buildings built to sustainability standards, this study uses a socio-technical building performance evaluation (BPE) approach to empirically assess daily trends and variations in IAQ parameters measured across a sample of twelve green-rated urban Indian residences (high-income group) co-located in an apartment complex in Delhi. Using internet-enabled Airveda devices, time-series monitoring data at 30' intervals were gathered for indoor temperature, relative humidity, CO2, PM2.5 and PM10 for 7 days during the summer season when air conditioning was prevalent. Contextual data about the physical and social aspects of residences were gathered using household surveys. Results were compared against the recommended ISHRAE and WHO standards to observe any deviations. Given the paucity of empirical data, an online interactive dashboard (RIAQ) for visualising IAQ in green-rated homes was developed to enable further research.

Keywords - Indoor air quality, post-occupancy evaluation, green-rated residences, visualization

1. Introduction

The building sector in India is experiencing unprecedented growth, which is responsible for 47% of total energy consumption in India [1]. Catering to sustainable development, the Indian Green Building Council (IGBC) has launched 30 different IGBC GREEN building rating systems [2] to suit different types of buildings (residential, commercial, industrial, educational, etc.). To date, IGBC has over 10,698 registered projects with a footprint of over 10.26 billion square feet (as of March 2023), making India 2nd in the world in terms of green footprint [3]. Although many emerging smart technologies and building performance assessment systems have been developed to save energy and improve occupant-perceived comfort, many buildings do not perform as planned [4]. There is growing recognition that green building rating and certification systems do not always ensure better indoor air quality (IAQ) over conventional buildings. There is an unbalanced building evaluation development between the design and operation stages.

Building performance evaluation (BPE) in the green buildings sector is an emerging area of research in India, especially in the residential building field [5-7]. To address these concerns, Gupta, Gregg, Manu, et al., based on their experience in BPE work and the feedback from the expert survey, have developed one of the first BPE frameworks in India, namely the I-BPE framework (Building performance evaluation in an Indian context), to evaluate green building performance in the Indian context [8]. In the same year, Gupta, Gregg, & Joshi [9] and Gupta, Gregg, & Panchal [10] applied the I-BPE approach to a sample of 29 Platinum-certified green residential units located in the warm-humid climate and a green-certified office building in the hot-dry climate, respectively, to assess buildings' performance in actual energy consumption and indoor environmental conditions. These studies evidenced the applicability of the I-BPE framework and benchmarking data for green-rated buildings in India.

To better understand the green buildings' in-use performance, some studies have been conducted to develop an India-specific BPE method for green buildings in India, from both technical and occupants' perspectives. Table 1 summarises BPE-related studies in the Indian context related to

energy consumption, indoor environment, and thermal comfort. These studies cover residential and non-residential buildings, such as office buildings, educational buildings, etc., as shown in Table 1. The table also indicates that there has been limited focus on monitoring the indoor environment as compared to energy consumption.

Table 1: BPE- related studies of green-rated buildings in India

Building type	Source	Energy	Indoor environment	Occupant Questionnaire
Domestic Building	Gupta, Gregg, & Joshi (2019) [9]	✓	✓	✓
	Verma et al. (2019) [11]			
	Basu et al. (2020) [5]	✓	×	✓
	IFC (2018) [12]	×	×	✓
	Batra et al. (2013)[13]	✓	✓	×
Non-Domestic Building	Gupta, Gregg, & Panchal (2019) [10]	✓	✓	✓
	Sonar & Nalawade (2019) [4]			
	Gupta, Gregg, Manu, et al. (2019) [8]			
	Sabapathy et al. (2010) [14]	✓	×	✓

Very limited resources and studies are available on building performance assessment of green-rated buildings in the Indian context [4]. Against this context, this study empirically investigates IAQ parameters' daily trends across a sample of twelve green-rated urban Indian residences located in Delhi, representing the composite climate. Contextual data about the physical and social aspects of residences were gathered using face-to-face household surveys. The results were compared against the recommended ISHRAE to observe any deviations. An online and interactive dashboard (RIAQ-Green Homes) for visualizing IAQ was developed for academics, policymakers and industry to enable further research.

2. Methods

2.1 Monitoring and survey data collection

The field study was carried out in a sample of twelve green-rated urban Indian residences located in Delhi during the summer season. The IAQ parameters of temperature, RH, CO2, PM2.5 and PM10 were monitored at 30' intervals by using the internet-enabled Airveda devices for 7 days (25th-31st May 2023) when air conditioning was prevalent. Airveda monitoring devices were installed in the most occupied space - the living room of the case study residences. Outdoor environmental data were gathered from the Central Pollution Control Board (CPCB) online portal [15]. A series of face-to-face interview-based surveys were conducted to collect data on dwelling and household characteristics of residences, such as the dwelling size, built-up area, the number of residents, annual income groups, the number and usage habits of different household appliances, as well as their received thermal comfort feedback information.

2.2 Overview of case study residences

The twelve sample residences are co-located in a 31-storey luxurious apartment complex in Delhi, which is certified as an 'IGBC Green Homes Pre-Certification' and was built 3-5 years ago. All sample residences were from the high-income group (HIG, income more than INR 18 lac per annum), with at least 6AC equipped in each home. Modern amenities, such as electric geysers, washing machines, TVs, music systems, computers, etc., are commonly equipped in every home, as detailed in Table 2. Except for DG-020 and DG-047, all the other residences are self-owned. Most of the sample residences were constantly occupied, except for dwelling DG-010, all others have 2 or more residents living in, with DG-012 having the highest number of occupants with 7. Across the overall sample, all residences owned 6 or more AC units, with DG-018 having the most, 9 AC.

Table 2: Residences' characteristics

Dwelling ID	Home tenure	Floor area (m^2)	Dwelling size	No. of residents	No. of AC	No. of computer	No. of Electric geyser	AC usage
DG-008	Self-owned	277	3BHK	4	6AC	2	4	7-9 hours per day
DG-010	Self-owned	277	3BHK	1	6AC	2	2	7-9 hours per day
DG-012	Self-owned	337	4BHK	7	7AC	3	More than 5	4-6 hours per day
DG-017	Self-owned	277	3BHK	4	6AC	2	3	7-9 hours per day
DG-018	Self-owned	337	4BHK	6	9AC	2	More than 5	7-9 hours per day
DG-020	Rented	277	3BHK	3	7AC	1	4	10-12 hours per day
DG-024	Self-owned	277	3BHK	2	7AC	1	4	7-9 hours per day
DG-028	Self-owned	337	4BHK	3	7AC	1	3	7-9 hours per day
DG-032	Self-owned	337	4BHK	2	7AC	1	5	7-9 hours per day
DG-033	Self-owned	337	4BHK	3	6AC	2	5	10-12 hours per day
DG-040	Self-owned	277	3BHK	4	6AC	2	4	7-9 hours per day
DG-047	Rented	277	3BHK	3	6AC	2	4	7-9 hours per day

Statistical analysis was carried out to derive the descriptive statistics and perform significance tests for the IAQ data from measurements and household characteristics survey data. The daily mean IAQ values were compared against classification limits specified by the Indoor Environmental Quality Standard, ISHRAE Standard - 10001:2016 [16], which attributes three specific threshold levels for individual IEQ parameters under Class A (Aspirational), Class B (Acceptable) and Class C (Marginally acceptable). In this study, the maximum values (Class C) for indoor PM2.5 at 25µg/m3, PM10 at 100µg/m^3, CO2 at 1100ppm, RH at 70% and temperature at 27°C, have been adopted.

3. Results

3.1 Temperature and Relative Humidity

Descriptive statistics were conducted to identify the variations between IAQ elements in each of the case study dwellings. During the monitoring period, external temperatures ranged from 10°C to 49°C, indoor temperature varied across 12 residences (with air conditioning), with daily mean temperatures ranging from 28.5°C in DG-008 to 33.4°C in DG-010, while the outdoor mean temperature was 26.4°C. The mean RH ranged from 37.7% in DG010 to 67.2% in DG-047, these values remained within the acceptable comfortable RH band of 30%-70% prescribed by the ISHRAE standard.

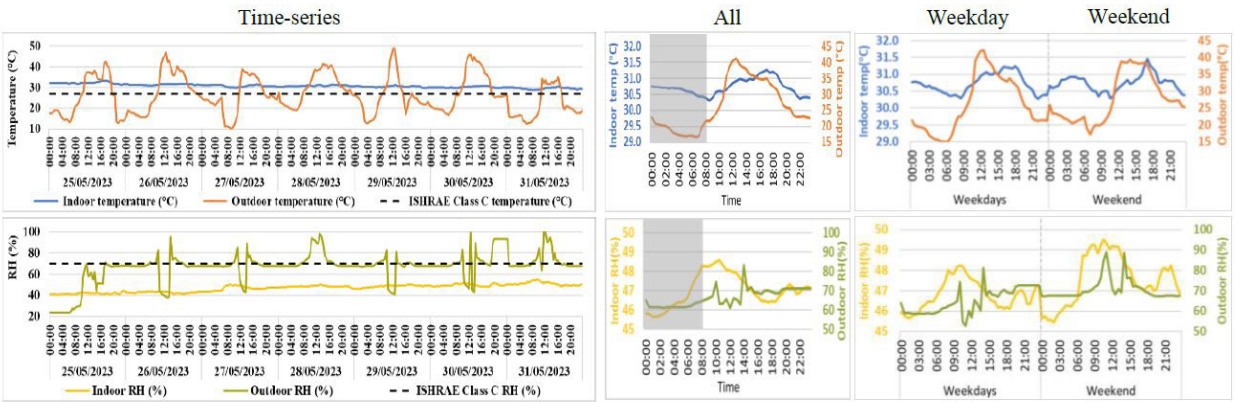

Figure 1: Line graphs of indoor and outdoor temperature & RH across the weekday and weekend

The daily profiles across all days, weekdays and weekends of indoor temperature and RH are given in Fig.1. The mean temperature of each case study dwelling during the monitoring period exceeded ISHRAE's recommended limit of 27°C for indoor temperature. At the sample level, the mean indoor temperature was 30.7°C, which is 3.7°C warmer than the recommended acceptable temperature prescribed by ISHRAE. More specifically, at the individual dwelling level, the temperature difference between the mean temperature of each dwelling and the maximum specified by the ISHRAE threshold varied from 1.5°C to 6.4°C, where DG-010 had the biggest temperature difference from the ISHRAE threshold, which was 6.4°C, and DG-008's mean temperature was 1.5°C higher than the ISHRAE threshold.

Profiles for weekdays and weekends in Fig.1 show that the mean indoor temperature on weekends was lower than on weekdays, but the relative humidity was slightly higher than on weekdays. The mean RH levels varied from 37.7% - 67.2%, with a sample mean of 47%, these RH values correspond with the ISHRAE required range of 30%–70%. Over the course of sleeping hours (00:00-08:00, the shaded area in figures), mean relative humidity levels were respectively consistent when compared to the waking hours. Indoor RH showed a weak correlation with external RH with Pearson correlation r= 0.195, but a moderate negative correlation with indoor temperature with Pearson correlation r= -0.435, both significant at the 0.01 level. Observe when the outdoor temp is high at which indoor RH drops. This indicates the use of a space-cooling appliance. In addition, the indoor temperature is also influenced by the occupancy pattern and appliance usage. Residence DG-010 which was occupied by one person experienced the lowest mean indoor humidity and highest mean indoor temperature, which might be because of the lower frequency of cooling appliances (ACs, fans) usage.

3.2 CO2 level

Indoor CO2 levels indicate the level of ventilation in buildings. It is also used as a proxy for IAQ [17]. Throughout the monitoring period, the mean CO2 levels varied from 451ppm in DG-024 to 714ppm in DG-012, much below the ISHRAE standard's maximum threshold of 1100ppm. In line with the window opening frequency leading to higher ventilation rates, all residences experienced low CO2 concentrations in rooms. The mean CO2 concentrations on weekdays and weekends was 548ppm and 615ppm, respectively. There were some significant variations of CO2 levels during waking hours observed in the daily mean CO2 profiles for all residences. Weekday daily profile of CO2 showed a similar trend with the overall CO2 profile - with CO2 concentrations increasing around 07:00 at 510ppm and peaking at 600ppm at 21:30. On weekends, CO2 levels started increasing at 09:00 (560ppm) and peaking at 21:30 (695ppm). Daily profiles of CO2 showed a direct relationship to room occupancy rates and household activities like cooking, children playing, watching TV, etc. In addition, weekend effects were also obvious, in which CO2 levels were higher on weekends and during the evening time when more residents were at home most of the time. Residence DG-012 which experienced the highest CO2 levels was occupied by seven residents majority of the time (Table 2). A moderate correlation between indoor CO2 levels and number of residents was found, with a Pearson correlation value of 0.456, significant at the 0.01 level.

3.3 Particulate matter (PM2.5 and PM10)

India has been ranked the 8th most polluted country in 2022, with PM2.5 levels 10 times the WHO limit. Exposure to PM2.5 can impair cognitive and immune functions and could cause cardiovascular, respiratory disease and cancers [18]. Indoor PM sources include indoor origins and outdoor infiltration [21]. The level of indoor air pollution in the majority of Indian households is far worse than ambient air pollution [19]. More specifically, sources of PMs are indoor activities like smoking, cooking, cleaning, burning candles or incense, and air fresheners usage, etc. In addition, high PM concentrations are caused by outdoor infiltration sources including industrial and vehicular emissions, dust from construction activities, emissions from local power plants and biomass burning from the surrounding rural areas [20]. Other factors like the design of the building, air exchange efficiency in the room and occupancy pattern rate also have an impact on indoor PM concentrations [21].

In this study, at the sample level, the mean concentrations of PM2.5 and PM10 were observed to be 35.5µg/m3 and 57.8µg/m3, respectively. PM2.5 levels in all residences were both double

both double over the 24-hour recommended WHO limit of 15ug/m3 [22] and the recommended ISHRAE limit of 25ug/m3. Throughout the monitoring period, the daily mean PM2.5 levels in DG-010 was recorded with the lowest value at 25µg/m³, while DG-033 had the highest value at 48.3µg/m³. Overall, the daily profiles of PM2.5 varied significantly throughout the daytime with high concentrations between 08:00 and 12:00, the influence of traffic and house cleaning activities were noticeable here. The weekday profile of PM2.5 concentrations showed a similar trend with the overall profile but with generally higher concentrations. Weekend trend was lower than weekday trend throughout the daytime, unexpectedly, higher and variable concentrations of PM2.5 were observed during the sleep hours on weekends than on weekdays, which were mainly attributed to human activities.

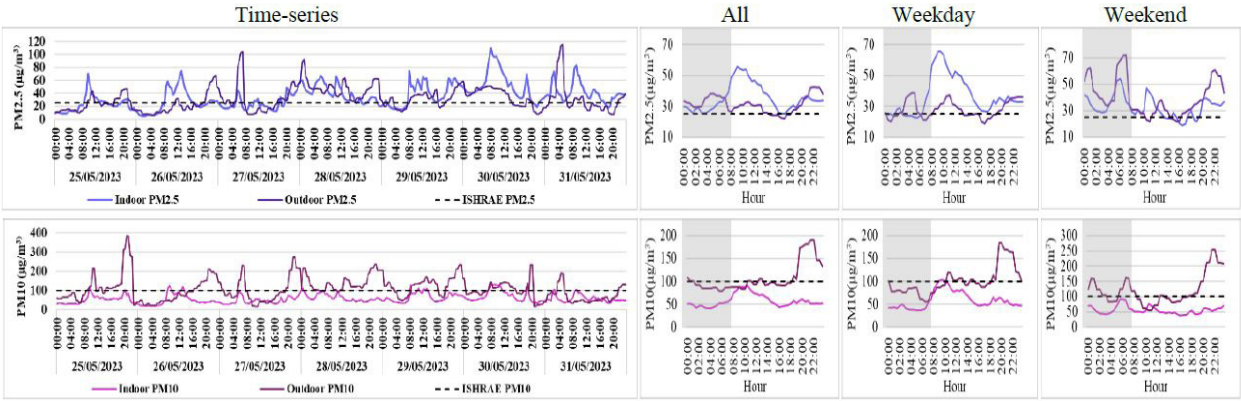

Figure 2: Line graphs of indoor and outdoor PM2.5 & PM10 across the weekday and weekend

At an individual residence level, the daily mean level of PM10 ranged from 42.2µg/m³ in DG-047 to 75µg/m³ in DG-033 and varied significantly throughout the daytime. Except for DG-047, the PM10 levels at the other 11 residences exceeded the 24-hour recommended WHO limit of 45µg/m³ but remained much below the ISHRAE limit of 100µg/m³ during a 24-hour period. Overall, PM10 had obvious diurnal variations with high concentrations between 08:00 to 10:00 but the lowest hourly concentrations often occurred around 03:00 and 16:00. The weekday profile of PM10 concentrations showed a similar trend with the overall profile. The weekend trend was higher than the weekday trend between 21:00 and 07:00. This might be associated with changes in the outdoor ambient PM10 concentrations, it can be seen from the daily profile in Fig. 2, that the outdoor PM10 concentrations at the weekend were higher than weekdays around the above-mentioned time frame. Higher concentrations of PM10 were observed between 08:00 to 16:00 on weekdays than on weekends, which might be associated with the traffic on weekdays. As evidenced by other studies, the average daily concentration of PM10 decreases as traffic flows decrease during late-night hours, and vice versa [23].

PM levels were related to household activities, with the highest PM concentrations observed between 20:00 to 22:00 wherein cooking and eating activities would have taken place. Cooking fuels are the main contributor to high PM concentrations in Indian households. In this study, all 12 households use gas as their primary cooking fuel, and 25% do not have exhaust fans in their homes, which explains why PM peaks occurred during cooking time in this study. Suggestions to reduce indoor PM levels include ensuring there is adequate ventilation, especially when doing activities that may generate PM.

3.4 Cross relating IAQ parameters and household characteristics

The strength of the relationship between indoor and outdoor parameters across dwellings has been calculated using Pearson's Correlation and presented in Table 3. Indoor CO2 levels were found to be weakly correlated with outdoor temperature and PM10, with the Pearson correlation value at 0.229 and 0.232, respectively. Weak negative correlation was found between indoor temperature and outdoor RH, with a Pearson correlation r= -0.201. Indoor and outdoor PM was weakly associated where Pearson correlation r=0.227 for PM2.5 and r=0.155 for PM10.

Table 3: Pearson's Correlation Coefficient between indoor and outdoor air quality parameters at the sample level.

	Outdoor Temp	Outdoor RH	Outdoor $PM_{2.5}$	Outdoor PM_{10}	Indoor Temp	Indoor RH	Indoor CO_2	Indoor $PM_{2.5}$	Indoor PM_{10}
Indoor Temp	.156**	**-.201****	-.078**	.065**	1	**-.435****	-.080**	-.174**	-.064**
Indoor RH	-0.012	.195**	.100**	-0.021	**-.435****	1	-0.024	.160**	.080**
Indoor CO_2	**.229****	.063**	.183**	**.232****	-.080**	-0.024	1	.150**	.106**
Indoor $PM_{2.5}$	.127**	.072**	**.227****	.113**	-.174**	.160**	.150**	1	**.928****
Indoor PM_{10}	.167**	0.020	**.203****	.155**	-.064**	.080**	.106**	**.928****	1

Unsurprisingly, a strong positive correlation was observed between PM2.5 and PM10, which had a correlation coefficient of 0.928. Moderate negative correlation with a Pearson correlation value of –0.435 was observed between indoor temperature and RH. Generally, as air temperature increases, air can hold more water molecules, and its relative humidity decreases. When temperatures drop, relative humidity increases, and vice versa. Weak correlation was observed between indoor PMs and CO2, implying that CO2 concentration on its own may not be an appropriate proxy for measuring IAQ in Indian residences since most of the PMs are generated due to household activities like cooking and cleaning. The relationship between CO2 and PMs is still under researched.

Using statistical analysis, the relationship between IAQ elements and household characteristics, such as the number of residents, and the number of appliances in terms of AC units, computers, and electric geysers, has been investigated. Indoor CO2 levels had a moderate correlation with number of residents, with a correlation coefficient value of 0.550, while weak negative correlation was observed between indoor CO2 and number of ACs, with a correlation coefficient value of -0.254. Interestingly indoor CO2 levels were observed to have a weak correlation with the number of exhaust fans with a correlation coefficient value of 0.358, showing that the exhaust fans were not used enough, while weak negative correlation has been found between indoor temperature and the number of electric geysers (correlation coefficient value = -0.184), both significant at the 0.01 level.

3.5 IAQ dashboard for green homes

To provide an overview of IAQ in green homes, a visualisation dashboard called RIAQ (RESIDE Indoor Air Quality Dashboard-Green Homes) has been developed. This is an online interactive platform that can be used to rapidly analyse and visualize the technical monitoring IAQ data along with the social data on physical dwelling properties and household characteristics. RIAQ dashboard consists of five main tabs, i.e. Characterising, Profiling, Distribution, Correlation, and Benchmarking. The outputs of each tab are varied by the selection of input variables, which can be filtered by different levels in terms of the Overall level (all residences), Typology level (by Home tenure, Occupation, Dwelling size and No. of AC units), and dwelling ID.

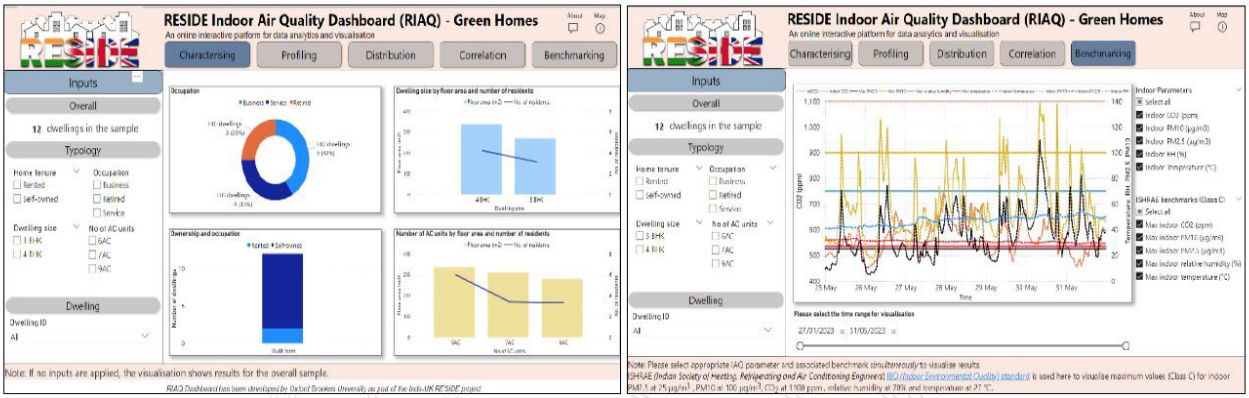

Figure 3: RIAQ green homes dashboard profile examples: Characterising (left) and Benchmarking (right)

The association between physical building properties and household characteristics can be reviewed on the Characterising page (Fig. 3. left). The Profiling page visualizes the indoor and outdoor ambient air quality monitoring data. Grouped by the number of AC units, the Distribution page presents the distributions of IAQ through the box plots by home tenure, occupation, dwelling size and the number of AC units. Grouped by dwelling size, the Correlation tab demonstrates the correlations between IAQ parameters data, the correlation strength between paired variables can be seen by positive and negative linear trend lines in each scatter plot. The Benchmarking tab (Fig. 3. right) presents the comparison between the IAQ data and the recommended acceptable range prescribed by the ISHRAE IEQ standard Class C [16], which attributes three specific threshold levels for individual IEQ parameters.

To our knowledge, there is no available interactive online dashboard that has been developed for green-rated urban Indian residences yet. It is free to access and easy to use for the public. The RIAQ dashboard developed in this study empowers users like academics, industry or building standards legislation authorities, to understand the changes happening in the indoor environment quality of green-rated homes in India, and also provides insights into the green building further development as well as the demand on IAQ legislation progress in India.

4. Discussion

A socio-technical BPE assessment of IAQ in a small sample of twelve certified green-rated urban Indian residences over seven days revealed IAQ conditions that exceeded recommended thresholds, particularly with regard to indoor temperatures and PM2.5. Indoor temperatures were found to vary across the 12 residences with daily mean temperatures ranging from 28.5°C to 33.4°C, all dwellings failed to meet the ISHRAE IEQ standard recommended minimum mean indoor temperature of 27°C, with an overall average of 3.7°C higher temperature than the ISHRAE threshold, where dwelling DG-010 having a 6.4°C higher temperature than the ISHRAE threshold, and DG-008's mean temperature was 1.5°C higher than the ISHRAE threshold. Mean indoor RH levels ranged from 37.7% to 67.2% and remained within the acceptable comfort range of 30%-70% prescribed by the ISHRAE standard. Despite all case study residences having 6 or more air conditioning units, indoor temperature and RH were found to have a moderate negative correlation.

All twelve residences experienced low levels of CO2 concentration ranging from 451ppm to 714ppm, much below the maximum benchmark of 1100ppm prescribed by ISHRAE. The mean CO2 concentrations on weekdays increased around 07:00 at 510ppm and peaked at 600ppm at 21:30. On weekends, the rise in CO2 levels started 2 hours later than on weekdays – with CO2 levels increasing from 09:00 at 560ppm and peaking at 695ppm at 21:30. Residents usually have a later start of the day during weekends. Weekend effects were also obvious, in which CO2 levels were higher on weekends and during the evening time when more residents were at home most of the time.
Although daily mean PM10 concentration ranged from 42μg/m^3 to 75μg/m^3, much below the ISHRAE prescribed upper limit of 100μg/m^3, daily mean PM2.5 levels (arising from cooking and cleaning activities) had a range of 25μg/m^3-48μg/m^3, much above the upper limit of 25μg/m^3 set by ISHRAE. PM levels were related to occupant activities, with high PM levels observed between 08:00 to 12:00, the influence of traffic and house cleaning activities was noticeable here. Weekend trend was lower than weekday trend throughout the daytime, unexpectedly, higher and variable concentrations of PM2.5 were observed during the sleep hours (00:00-08:00) on weekends than on weekdays, which were mainly attributed to human activities.

The RIAQ dashboard, an online interactive platform developed for the first time in this study, can be used to rapidly analyse and visualize the technical monitoring IAQ data along with the social data on physical dwelling properties and household characteristics. This allows academics, researchers, policymakers and building practitioners to better understand how IAQ varies daily in Indian residences with different numbers of residents. This can potentially enable further research related to improving IAQ in residences.

5. Conclusion

To verify the actual IAQ performance of green-rated buildings built to sustainability standards, this study used a socio-technical BPE approach to empirically assess the daily trends and variations in IAQ elements measured across a sample of twelve green-rated urban Indian residences co-located in an apartment complex in Delhi. The findings revealed that the green-rated homes had good levels of IAQ in terms of RH, CO2 levels and PM10 levels that remained within the acceptable thresholds prescribed by the ISHRAE standard. However exposure to PM2.5 levels was found to be high. Due to the lack of a comprehensive protocol for monitoring indoor PM2.5 levels in residences, such exposures go unnoticed.

Since the research presented is based on a small sample, there are limitations in drawing general conclusions on the link between IAQ and household characteristics in green-rated urban residences. Nevertheless, the proposed socio-technical POE method and valuable findings presented here can be rolled out more widely to provide more comprehensive coverage of green-rated urban Indian residences. The findings also reveal the urgent need for developing large-scale monitoring campaigns to measure different IAQ parameters in Indian residences and how these relate to occupant activities and behaviours. Starting this effort in green homes may have a rapid uptake.
The RIAQ dashboard, an online interactive platform developed for the first time in this study, can be used to rapidly analyse and visualize the technical monitoring IAQ data along with the social data on physical dwelling properties and household characteristics. This allows academics, researchers, policymakers and building practitioners to better understand how IAQ varies daily in Indian residences with different numbers of residents. This can potentially enable further research related to improving IAQ in residences.

6. Acknowledgement

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