Field study on measuring indoor air quality in certified green-rated urban Indian residences

Highlights

- One of the first field study that uses a socio-technical post-occupancy evaluation (POE) approach to assess IAQ and household characteristics in green-rated urban Indian residences.
- Daily mean indoor temperatures were slightly warmer than the operative temperature prescribed by ISHRAE by up to 3.7°C.
- An online interactive dashboard (RIAQ) for visualising IAQ in green-rated homes was developed for academics, policymakers and industry to enable further research.

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, people spend a substantial fraction of their lives indoors in India, yet IAQ in homes has been studied far less than air quality outdoors, especially in urban India, where outdoor air pollution frequently exceeds recommended levels. To verify the actual IAQ performance of green-rated buildings built to sustainability standards, this study uses a socio-technical post-occupancy evaluation (POE) approach to empirically assess the daily trends and variation in IAQ parameters measured across a sample of 12 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, CO_2, $PM_{2.5}$ and PM_{10} for 7 days during the summer season when air conditioning was prevalent. Contextual data about the physical and social aspects of the 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-GH) 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. As a critical economic development pillar of a country, the building sector is also responsible for 47% of total energy consumption in India (The World Bank, 2023). To cater for sustainable development, green concepts and techniques have been introduced into this sector to provide a user-centric, environment-friendly, and energy-efficient building to reduce the overall impact of the built environment on the natural environment and human health (Gou et al., 2013). Against this context, the Indian Green Building Council (IGBC) has launched 30 different IGBC GREEN building rating systems (Ukey et al., 2022) to suit different types of buildings, e.g. 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), out of which 3,321 Green Building projects are certified and fully functional in India, making India 2nd in the world in terms of green footprint (IGBC, 2023).

Despite the fact that 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, still, there are significant performance gaps between the design intent and actual building performance in the aspects of energy consumption, indoor environmental performance, occupant satisfaction, etc (Sonar & Nalawade, 2019). There is an unbalanced building evaluation development between the design stage and operation stage. As Grover (2019) pointed out in his research to re-validate the effectiveness of green strategies implemented in the green building industry, it is necessary to conduct a post-occupancy evaluation (POE) during the operation phase of buildings, and the results from the POE of buildings during operation phase is evidentiary.

POE in the building sector is an emerging area of research in India, especially in the residential building field (Basu et al., 2020; Kumar & Khan, 2022). POE studies for green-rated residential buildings are even rare, which further increases the gap between estimated design intents and actual performance (Sharmin & Khalid, 2022). There is a need to develop a holistic India-specific post-occupancy performance framework for green 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. According to the review of existing green buildings POE studies in India, the studies not only covered residential buildings but also spread into the non-domestic buildings field, such as office buildings, educational buildings, etc., as listed in Table 1. In terms of the coverage of BPE elements, this table also indicates that there is less focus on indoor air quality monitoring when compared to the energy consumption subject.

summarises some BPE-related studies in the Indian context in aspects of three main assessment fields, i.e. energy consumption, indoor environment quality, and occupant thermal comfort.

The International Finance Corporation (IFC) (2018) led a POE study under the Eco-Cities India Program that interviewed over a thousand residents from both green-rated and conventional buildings to understand their awareness of green building concepts and the benefits of living in green homes. Results showed that less than half of green home residents were aware of the green homes concepts, and most conventional home residents were unaware of the concepts and the benefits that they provided. The weak public awareness about the usefulness and benefits of BPE and the lack of trained professionals for teaching BPE have become the key challenges for POE development in Inda (Gupta, Gregg, Manu, et al., 2019).

Verma et al. (2019) conducted a study to assess the existing UK-BPE methodology through a 'IGBC Green Homes Platinum' rated residential building located in a hot-dry climate zone of India, to evaluate its applicability and relevance for green-rated residential buildings in India. This study came to the conclusion that because of the different types of metrics used in Indian rating systems, a customized appropriate India-specific BPE framework is required for the prevalent metrics used in India.

Based on the authors' experience in BPE work and the feedback from the expert survey, Gupta, Gregg, Manu, et al. (Gupta, Gregg, Manu, et al., 2019) developed an I-BPE framework (Building performance evaluation in an Indian context) to evaluate green building performance in the Indian context. As one of the first green building performance assessment frameworks in India, the I-BPE approach was tested in a green building in a university to gain insights for improving the I-BPE method and implementation process for further BPE studies in India. In the same year, Gupta, Gregg, & Joshi (2019) and Gupta, Gregg, & Panchal (2019) 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 environmental conditions. These studies evidenced the applicability of the I-BPE framework and benchmarking data for green-rated buildings in India.

Basu et al. (2020) implemented a POE assessment for an 'IGBC Green Homes Gold Certified' eight-storied multifamily residential building with a focus on evaluating the energy performance gap between Green buildings base-case, as-constructed, and as-occupied case. Interestingly, a positive 'performance gap' has been observed in this study, i.e. the as-occupied building performs better than anticipated, which might be caused by the low occupancy rates during the study period.

According to the review of existing green buildings POE studies in India, the studies not only covered residential buildings but also spread into the non-domestic buildings field, such as office buildings, educational buildings, etc., as listed in Table 1. In terms of the coverage of BPE elements, this table also indicates that there is less focus on indoor air quality monitoring when compared to the energy consumption subject.

Table 1 Summary review of POE studies of green-rated buildings in India

Building type	Source	Energy	IEQ	Occupant Questionnaire /Interview
Domestic Building	Gupta, Gregg, & Joshi (2019)	✓	✓	✓
	Verma et al. (2019)			
	Basu et al. (2020)	✓	×	✓
	IFC (2018)	×	×	✓
	Batra et al. (2013)	✓	✓	×
Non-Domestic building	Gupta, Gregg, & Panchal (2019)	✓	✓	✓
	Sonar & Nalawade (2019)			
	Gupta, Gregg, Manu, et al. (2019)			
	Sabapathy et al. (2010)	✓	×	✓

Very limited resources and studies are available on building performance evaluation (BPE) of green-rated buildings using POE in the Indian context (Sonar & Nalawade, 2019). Against this context, this study empirically investigates daily trends and variations in indoor temperature, relative humidity (RH), CO_2, and Particulate Matter ($PM_{2.5}$ and PM_{10}) across a sample of 12 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) for visualizing IAQ was developed for academics, policymakers and industry to enable further research.

3 Methods

3.1 Monitoring and survey data collection

The field study was carried out in a sample of 12 green-rated urban Indian residences (high-income group) co-located in an apartment complex in Delhi during the summer season. The indoor air quality parameters of temperature, RH, CO_2 and Particulate Mater ($PM_{2.5}$ and PM_{10}) were monitored at 30' intervals by using the internet-enabled Airveda devices for 7 days (25^{th}-31^{st} May 2023) when air conditioning was prevalent. AirVeda monitoring devices were installed in the most occupied space - the living room of each case study residence. The monitoring data is available in the Airveda server platform along with Indian AQI (Air Quality Index), day, week, and month history as well as outdoor data in different parts of the city. Table 2 presents the technical specifications of AirVeda devices.

Table 2 Technical specifications of Airveda devices

Parameter	Unit	Range	Accuracy	Resolution
Temperature	°C	10 - 60	±1	1
Relative Humidity	%	0 – 90	±3	1
CO_2	ppm	0 - 5000	±50 ±3%	--
$PM_{2.5}$	$\mu g/m^3$	0 - 999	±10%	< 0.3
PM_{10}	$\mu g/m^3$	0 - 1999	±10%	< 0.3

To better explain the reasons behind IAQ conditions, the outdoor environmental data in terms of temperature, RH, CO, $PM_{2.5}$ and PM_{10}, were gathered from the Central Pollution Control Board (CPCB) online portal run by the Ministry of Environment, Forest and Climate Change, Government of India (Bedi & Bhattacharya, 2021). The selected sample residences are located in Delhi, during the monitoring period, the recorded outdoor temperature ranged from10°C to 49°C, with an average of 26.4°C; RH had a range of 24%-100% with a mean value at 66.5%; $PM_{2.5}$ concentration ranged from 6μg/m³ to 115μg/m³, with a daily mean value at 31.5μg/m³. The outdoor PM_{10} had a mean value of 107μg/m³, ranged from 16μg/m³ to 384 μg/m³.

Data on household characteristics were collected through a series of face-to-face interview-based surveys with an adult resident in each residence, including the building's physical data in terms of size, built-up area and construction materials, etc., household data about the number and age groups of residents, occupation, annual income groups, etc., the number and usage habits of different household appliances, as well as their received thermal comfort feedback information, and so on. Examples of survey questions are given in Figure 1.

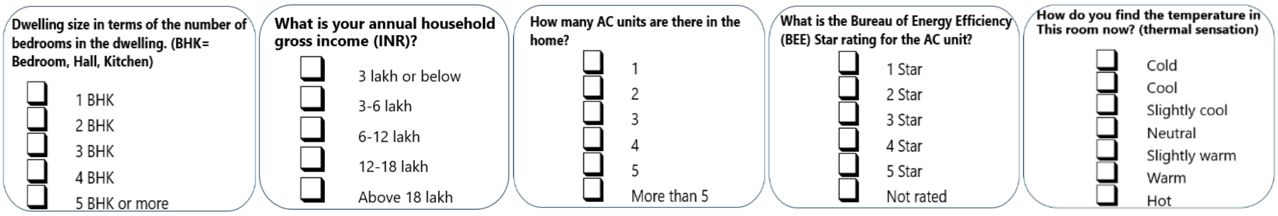

Figure 1 Examples of face-to-face surveys questions

3.2 Overview of case study residences

The case study residences are co-located in an 'IGBC Green Homes Pre-Certification' certified luxurious apartment complex present in Gurugram, Delhi. It was built 3-5 years ago and is 31 storeys high. These representative forms along with the exterior and interior of dwellings in this study are shown in Figure 2.

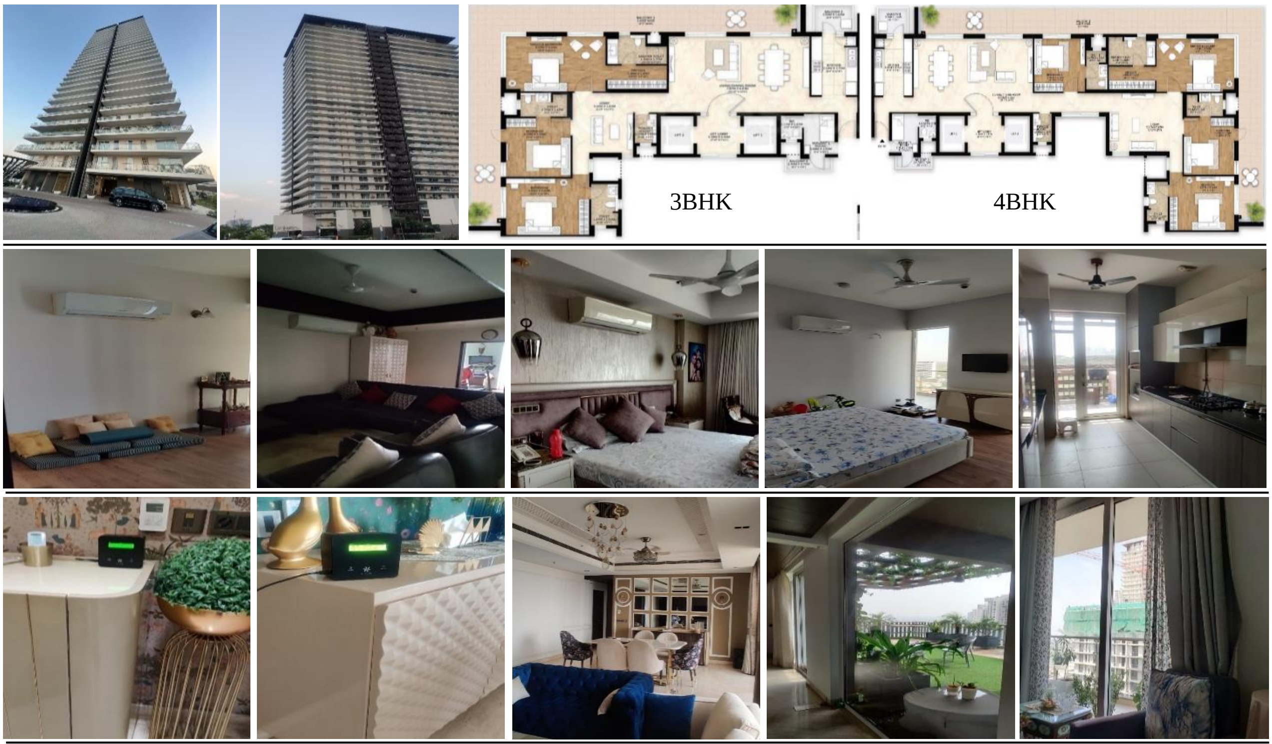

Figure 2 External dwelling image and representative floor plan (top), Internal dwelling image (bottom)

The twelve sample residences were all from the high-income group (HIG, income more than INR 18 lac per annum), with at least 6 AC equipped in each home. Modern amenities, such as electric geysers, washing machines, TV, music system, computers, etc., are commonly equipped in every home, as detailed in Table 3. Except for residences of DG-020 and DG-047, all the other residences are self-owned. Most of the case study 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. All dwellings used gas as their primary cooking fuel, 3 out of 12 used the LPG (gas cylinder), and the rest of 9 dwellings had a natural gas pipe connection.

Table 3 Residences characteristics

Dwelling ID	***Home tenure***	***Floor area (m^2)***	***Dwelling size***	***No. of residents***	***No. of AC***	***No. of TV***	***No. of computer***	***No. of Exhaust fan***	***No. of Electric geyser***	***Frequency of AC usage***
DG-008	Self-owned	277	3BHK	4	6AC	3	2	1	4	7-9 hours per day
DG-010	Self-owned	277	3BHK	**1**	6AC	1	2	0	2	7-9 hours per day
DG-012	Self-owned	337	4BHK	**7**	7AC	3	3	More than 5	More than 5	4-6 hours per day
DG-017	Self-owned	277	3BHK	4	6AC	3	2	1	3	7-9 hours per day
DG-018	Self-owned	337	4BHK	6	**9AC**	3	2	More than 5	More than 5	7-9 hours per day
DG-020	**Rented**	277	3BHK	3	7AC	1	1	1	4	10-12 hours per day
DG-024	Self-owned	277	3BHK	2	7AC	2	1	1	4	7-9 hours per day
DG-028	Self-owned	337	4BHK	3	7AC	2	1	0	3	7-9 hours per day
DG-032	Self-owned	337	4BHK	2	7AC	4	1	1	5	7-9 hours per day
DG-033	Self-owned	337	4BHK	3	6AC	2	2	More than 5	5	10-12 hours per day
DG-040	Self-owned	277	3BHK	4	6AC	2	2	0	4	7-9 hours per day
DG-047	**Rented**	277	3BHK	3	6AC	1	2	3	4	7-9 hours per day

Statistical analysis was carried out using IBM SPSS Statistics software to derive the descriptive statistics and perform significance tests for the IAQ data from measurements (temperature, RH, CO_2, $PM_{2.5}$ and PM_{10}) and household characteristics survey data, such as built-up area, dwelling size, the number of residents and variety of appliances, etc.

The daily mean IAQ values were compared against classification limits specified by the Indoor Environmental Quality Standard, ISHRAE Standard - 10001:2016 (ISHRAE, 2016), 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 $PM_{2.5}$ at 25µg/m^3, PM_{10} at 100µg/m^3, CO_2 at 1100ppm, RH at 70% and temperature at 27°C, have been adopted.

4 Results

4.1 Temperature and Relative Humidity

As presented in Table 4, descriptive statistics were conducted to identify the variation between the 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 the 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. In this study the mean RH ranged from 37.7% in DG-010 to 67.2% in DG-047, these values remained within the acceptable comfortable RH band of 30%-70% prescribed by the ISHRAE standard.

Table 4 Descriptive statistics for indoor Temperature, RH, CO_2, $PM_{2.5}$ and PM_{10}

Indoor temperature (°C)												
Dwelling ID	**DG-008**	**DG-010**	**DG-012**	**DG-017**	**DG-018**	**DG-020**	**DG-024**	**DG-028**	**DG-032**	**DG-033**	**DG-040**	**DG-047**
Mean	**28.5**	**33.4**	29.4	32.6	32.4	29.4	28.9	31.0	30.9	31.6	29.9	30.6
Minimum	25.0	31.0	26.0	29.0	29.0	25.0	27.0	29.0	29.0	27.0	27.0	27.0
Maximum	31.0	38.0	32.0	35.0	34.0	33.0	31.0	33.0	34.0	33.0	33.0	33.0
Indoor RH (%)												
Dwelling ID	**DG-008**	**DG-010**	**DG-012**	**DG-017**	**DG-018**	**DG-020**	**DG-024**	**DG-028**	**DG-032**	**DG-033**	**DG-040**	**DG-047**
Mean	49.6	**37.7**	42.3	42.7	40.0	46.7	50.6	42.5	56.9	43.7	44.3	**67.2**
Minimum	40.0	29.0	33.0	34.0	34.0	36.0	46.0	34.0	50.0	37.0	35.0	61.0
Maximum	59.0	46.0	51.0	53.0	51.0	58.0	56.0	51.0	63.0	53.0	54.0	74.0
Indoor PM2.5 (µg/m3)												
Dwelling ID	**DG-008**	**DG-010**	**DG-012**	**DG-017**	**DG-018**	**DG-020**	**DG-024**	**DG-028**	**DG-032**	**DG-033**	**DG-040**	**DG-047**
Mean	47.8	**25.0**	30.5	36.7	29.3	26.5	47.9	31.7	37.5	**48.3**	35.5	28.8
Minimum	5.0	6.0	7.0	3.0	4.0	6.0	6.0	6.0	4.0	6.0	3.0	3.0
Maximum	310.0	64.0	114.0	312.0	273.0	188.0	399.0	234.0	176.0	419.0	234.0	107.0
Indoor PM10 (µg/m3)												
Dwelling ID	**DG-008**	**DG-010**	**DG-012**	**DG-017**	**DG-018**	**DG-020**	**DG-024**	**DG-028**	**DG-032**	**DG-033**	**DG-040**	**DG-047**
Mean	64.8	52.8	52.7	60.7	50.9	52.5	71.9	49.1	65.7	**75.0**	55.4	**42.2**
Minimum	14.0	16.0	17.0	18.0	15.0	17.0	15.0	21.0	19.0	18.0	15.0	10.0
Maximum	331.0	205.0	192.0	364.0	339.0	328.0	586.0	260.0	260.0	551.0	273.0	159.0
Indoor CO_2 (ppm)												
Dwelling ID	**DG-008**	**DG-010**	**DG-012**	**DG-017**	**DG-018**	**DG-020**	**DG-024**	**DG-028**	**DG-032**	**DG-033**	**DG-040**	**DG-047**
Mean	613.3	479.2	**713.6**	657.4	581.6	580.3	**451.0**	466.3	457.9	603.4	585.8	616.5
Minimum	418.0	437.0	496.0	431.0	401.0	407.0	394.0	404.0	397.0	422.0	421.0	436.0
Maximum	1275.0	562.0	1211.0	1063.0	1425.0	1532.0	555.0	632.0	784.0	1286.0	1023.0	966.0

The time-series data of indoor temperature and RH are given in Figure 3, as well as their daily profiles across by all days, weekdays and weekend, respectively. 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 to 6.4, 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.

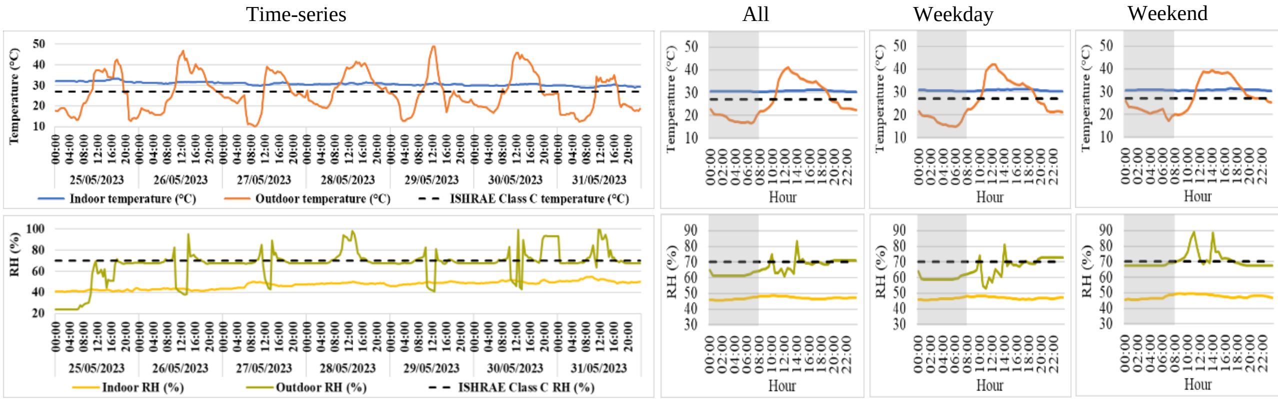

Figure 3 Line graphs of indoor and outdoor temperature & RH across the week and weekend

The distinction between weekday and weekend is more apparent in Figure 3 where profiles of indoor RH showed less daily variation during the weekend. 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 less frequency of cooling appliances (AC, fans) usage.

4.2 CO_2 level

Indoor carbon dioxide is usually used as a surrogate ventilation index to indicate the ventilation efficiency in air-conditioned buildings, it is an indicator of IAQ (Kim et al., 2020). Over the course of the 7 days monitoring period in this study, the mean CO_2 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 case study residences experienced low CO_2 concentrations in rooms. The mean CO_2 concentrations on weekday and weekend was 548ppm and 615ppm, respectively. As shown in Figure 4, there were some significant variations of CO_2 levels during the waking hours were observed in the daily mean CO_2 profiles for all residences. Weekday daily profile of CO_2 showed a similar trend with the overall CO_2 profile - with CO_2 concentrations increasing around 07:00 at 510ppm and peaking to 600ppm at 21:30. On weekend daily profile, CO_2 levels started increasing at 09:00 at 560ppm and peaking to 695ppm at 21:30. Daily profiles of CO_2 showed a direct relationship to room occupancy rates and household activities like cooking, children playing, and watching TV, etc. In addition, weekend effects were also obvious, which CO_2 concentrations were higher on weekend and during the evening time when more people were at home most of the time.

Residence DG-012 being the only residence with the highest CO_2 levels also showed the highest number of occupancies in the residence with 7 people occupying the residence most of the time (Table 3). The correlation between indoor CO_2 concentration levels and the number of people was moderately strong with the Pearson correlation value at 0.456, significant at the 0.01 level. The excessive CO_2 level can indicate inadequate ventilation levels in homes, with possible accumulation of other indoor pollutants, while elevated levels are suggestive of potential air quality problems.

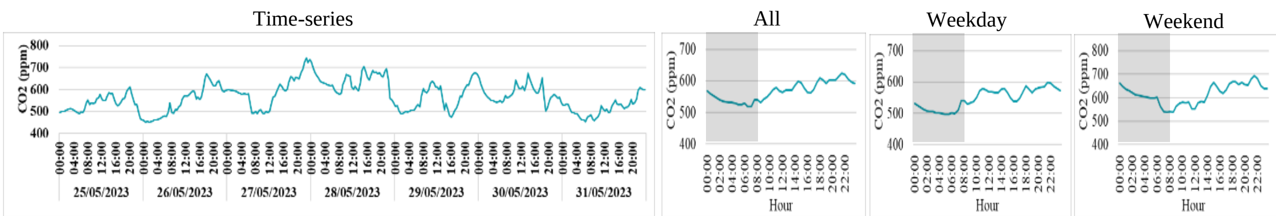

Figure 4 Line graphs of indoor and outdoor CO_2 across the week and the weekend

4.3 Particulate matter ($PM_{2.5}$ and PM_{10})

Particulate Matter (PM) is a mixture of solid and liquid particles that are suspended in the air, which is used to indicate pollutant levels both outdoors and indoors. According to the annual 2022 World Air Quality Report released by IQAir (2020), India was ranked the 8th most polluted country in 2022, with $PM_{2.5}$ levels 10 times the WHO limit. Indoor PM sources include indoor origins and outdoor infiltration (Zhang et al., 2021). The level of indoor air pollution in the majority of Indian households is far worse than the ambient air pollution one (Kankaria et al., 2014). As the most dangerous pollutant, $PM_{2.5}$ has health impacts even at very low concentrations. Exposure to $PM_{2.5}$ can impair cognitive and immune functions and could cause cardiovascular, respiratory disease and cancers (Mannan & Al-Ghamdi, 2021; Rohra & Taneja, 2016).

More specifically, primary indoor origins are from indoor activities like smoking, cooking, cleaning, burning candles or incense, and air fresheners usage, etc. In addition, high PM concentrations 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, and so on (Assimakopoulos et al., 2018; Kaur & Pandey, 2021). 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 (Zhang et al., 2021).

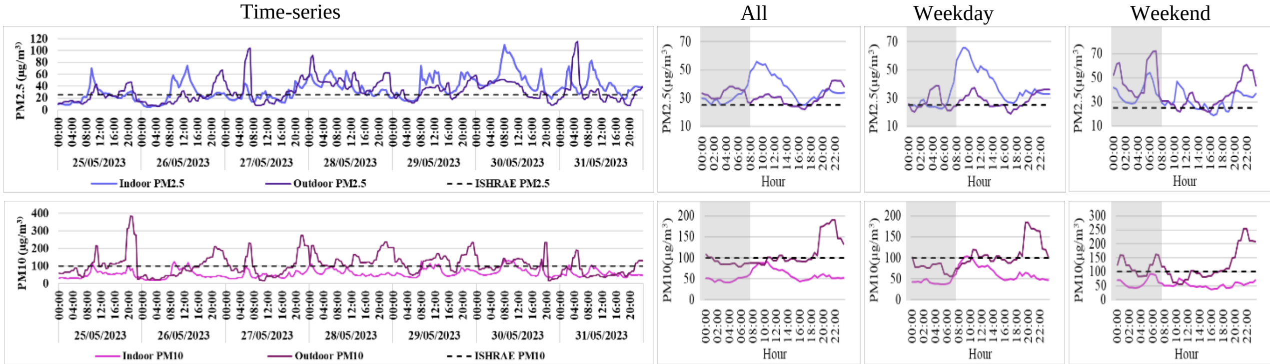

Figure 5 Line graphs of indoor and outdoor $PM_{2.5}$ & PM_{10} across the week and the weekend

In this study, at the sample level, the mean concentrations of $PM_{2.5}$ and PM_{10} were 35.5µg/m^3 and 57.8µg/m^3, respectively. $PM_{2.5}$ levels in all residences were both double over the 24-hour recommended WHO limit of 15ug/m^3 (WHO, 2021) and the recommended ISHRAE limit of 25ug/m^3 (ISHRAE, 2016). Throughout the monitoring period, as shown in Table 4, the daily mean $PM_{2.5}$ level in DG-010 was recorded with the lowest value at 25µg/m^3, while DG-033 had the highest value at 48.3µg/m^3. Overall, the daily profiles of $PM_{2.5}$ varied significantly throughout the daytime with high concentrations between 08:00 to 12:00, the influence of traffic and house cleaning activities were noticeable here. The weekday profile of $PM_{2.5}$ 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 $PM_{2.5}$ were observed during the sleep hours (00:00-08:00) on weekends than on weekdays, which were mainly attributed to human activities.

At an individual level, the daily mean level of PM_{10} ranged from 42.2µg/m³ in DG-047 to 75µg/m³ in DG-033, and varied significantly throughout daytime. Except for DG-047, the PM_{10} levels at the other 11 residences exceeded the 24-hour recommended WHO limit of 45ug/m^3 (WHO, 2021), but remained much below the ISHRAE limit of 100ug/m^3 during a 24-hours period (ISHRAE, 2016). Overall, PM_{10} 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 PM_{10} concentrations showed a similar trend with the overall profile. Weekend trend was higher than weekday trend between 21:00 – 07:00. This might be associated with changes in the outdoor ambient PM10 concentrations, it can be seen from the daily profile in Figure 5, the outdoor PM10 concentrations at the weekend were higher than the 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 PM_{10} decreases as traffic flows decrease during late-night hours, vise versa (Gietl & Klemm, 2009; Goudarzi et al., 2020).

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 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.

4.4 Cross relating IAQ parameters and household characteristics

The association strength between indoor and outdoor parameters across dwellings has been calculated using Pearson's Correlation and presented in Table 5. Indoor CO_2 concentration was weakly correlated with the outdoor temperature and PM_{10}, with the Pearson correlation value at 0.229 and 0.232, respectively. But a weak negative correlation has been found between indoor temperature and outdoor RH, where the Pearson correlation r= -0.201. Indoor and outdoor PM was weakly associated with the Pearson correlation r =0.227 for $PM_{2.5}$ and r =0.155 for PM_{10}.

Table 5 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 $PM_{2.5}$ and PM_{10}, which had a correlation coefficient of 0.928. Interestingly, a moderate negative correlation with a Pearson correlation value of –0.435 was observed betweeen 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. There was a very weak correlation observed between indoor PMs and CO_2, implying that CO_2 is not suitable to be used as a proxy for IAQ in Indian residences since most of the PMs are generated due to household activities like cooking and cleaning. The relationship between CO_2 and PMs is still under researched.

By statistical analysis, the relationship between IAQ elements and household characteristics, such as floor area, number of residents, and the number of appliances in terms of AC units, computers/Laptops, exhaust fans, electric geysers, etc., has been investigated as well and presented in Table 6.

Table 6 Correlations between IAQ and physical residences characteristics

	No. of AC	***No. of Residents***	***No. of Computer***	***No. of TV***	***Floor area (m2)***	***No. of Exhaust fan***	***No. of Electric geyser***
Indoor Temp	.053**	-.147**	.105**	-.051**	.152**	.077**	**-.228****
Indoor RH	-.191**	-.113**	**-.214****	-.043**	-.186**	-.075**	.088**
Indoor $PM_{2.5}$	-.063**	-.038*	-0.028	.087**	0.000	0.010	.035*
Indoor PM_{10}	-.040*	-.072**	-.041**	.080**	0.016	0.009	0.027
Indoor CO_2	-.086**	**.456****	**.457****	.067**	-0.016	**.317****	**.226****

Indoor CO_2 concentrations are usually higher, due to the CO_2 exhaled by occupants. Unsurprisingly, indoor CO_2 was observed to have a moderate correlation with the number of residences (r= 0.456, significant at the 0.01 level). Evidently, the humankind is the main contributor to indoor CO_2 concentration. Interestingly, a moderate positive correlation was observed between the level of indoor CO_2 and the number of computers/laptops, with a Pearson correlation value of 0.457. Given this study presented was based on a small sample, more data will be needed for further study on the correlation of personal computers on perceived air quality. Indoor CO_2 was also observed to have a weak correlation with the number of exhaust fans (r= 0.317), but a weak negative correlation has been found between indoor temperature and the number of electric geysers (r= -0.226), both significant at the 0.01 level.

4.5 Green homes visualisation dashboard

To provide an overview of the indoor air quality presented in green homes, a visualisation dashboard called RIAQ-GH (RESIDE Indoor Air Quality Dashboard-Green Homes) has been developed, which 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-GH dashboard consists of 5 main tabs, i.e. *Characterising, Profiling, Distribution, Correlation,* and *Benchmarking*. The outputs of each tab are varied by the selection of inputs 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), as well as assigned dwelling ID. The outputs of the *Profiling* and *Benchmarking* tabs can also be filtered by the input selection of IAQ parameters and selected time period.

The association between the physical building properties and household characteristics can be reviewed on the Characterising page through a series of line graphs and bar charts, which can be filtered based on the data Input of the Typology and the Dwelling. The users can explore the relationship between the floor area and number of dwellings based on dwelling size (3BHK and 4BHK), home tenure status and the number of dwellings, as well as floor area and number of AC units (Figure 6, top-left). The default visualisation displays results at the sample level.

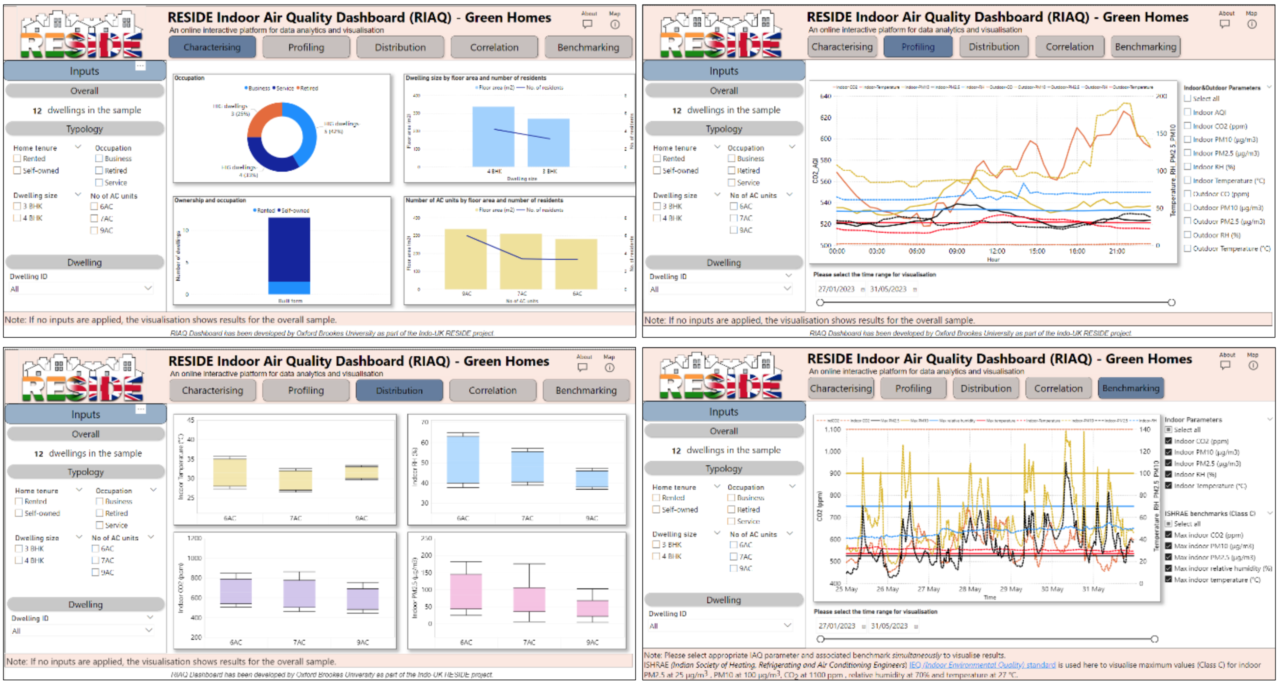

Figure 6 RIAQ dashboard profile examples: Characterising (top-left), Profiling (top-right), Distribution (bottom-left) and Benchmarking (bottom-right)

The *Profiling* page visualizes the indoor and outdoor ambient air quality data including temperature, relative humidity, PM and CO_2. The outputs can be filtered by typology, individual dwellings, IAQ parameters as well as the selected time period (Figure 6, top-right). 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 (Figure 6, bottom-left). Grouped by dwelling size, the *Correlation* tab demonstrates the correlations between IAQ parameters data through scatter plots, i.e. RH and temperature, CO_2 and temperature, CO_2 and RH, as well as CO_2 and $PM_{2.5}$. The correlation strength between paired variables can be seen by positive and negative linear trend lines in each scatter plot.

The *Benchmarking* tab presents the comparison between the monitoring IAQ data and the recommended acceptable range prescribed by the ISHRAE IEQ standard (ISHRAE, 2016), which attributes three specific threshold levels for individual IEQ parameters under Class A (Aspirational), Class B (Acceptable) and Class C (Marginally acceptable). In *Benchmarking* tab (Figure 6, bottom-right), Class C with indoor $PM_{2.5}$ at 25μg/m^3, PM_{10} at 100μg/m^3, CO_2 at 1100ppm, RH at 70% and temperature at 27°C, have been adopted.

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-GH 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 in the building sector as well as the demand on IAQ legislation progress in India.

5 Discussion

A socio-technical POE assessment of IAQ in a small sample of 12 certified green-rated urban Indian residences over 7 days revealed overall unpleased IAQ conditions, particularly with regard to indoor temperatures and $PM_{2.5}$, which has potential health implications for residents. Indoor temperatures were found to vary across the 12 residences (with air conditioning), 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% - 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 (AC) units, indoor temperature and RH were found to have moderate negative correlation (r=0.4).

The case study residences experienced low levels of CO_2 concentration ranging from 451ppm to 714ppm, much below the maximum benchmark of 1100ppm prescribed by ISHRAE standard. The mean CO_2 concentrations on weekdays increased around 07:00 at 510ppm and peaked to 600ppm at 21:30. On weekends, the rise in CO_2 levels started 2 hours later than on weekdays – with CO_2 levels increasing from 09:00 at 560ppm and peaking to 695ppm at 21:30. People usually have later start of the day during the weekend. In addition, weekend effects were also obvious, in which CO_2 concentrations were higher on weekend and during the evening time when more people were at home most of the time.

Although daily mean PM_{10} concentration ranged from 42μg/m^3-75μg/m^3, much below the ISHRAE prescribed upper limit of 100μg/m^3, daily mean PM2.5 levels (arising from cooking and cleaning activities) ranged from 25μg/m^3-48μg/m^3, much above the upper limit of 25μg/m^3 set by ISHRAE. PM levels were related with occupant activities, with high PM levels observed around 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 $PM_{2.5}$ were observed during the sleep hours (00:00-08:00) on weekends than on weekdays, which were mainly attributed to human activities.

The online interactive platform, RIAQ-GH dashboard, was first time developed in this research to help users understand how indoor air quality varies daily in Indian residences having different built forms and occupied by different income groups. Insights from this study can help policymakers understand the trends of residential IAQ and support the development of regulations, with the ultimate aim of improving IAQ in Indian homes.

The RIAQ-GH dashboard, an online interactive platform developed for the first time in this study, which 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 Conclusion

To verify the actual IAQ performance of green-rated buildings built to sustainability standards, this study used a socio-technical post-occupancy evaluation (POE) approach to empirically assess the daily trends and variation in IAQ elements measured across a sample of twelve green-rated urban Indian residences (high-income group) co-located in an apartment complex in Delhi. The findings revealed that the green-rated homes had a better IAQ performance in the aspects of indoor RH, CO_2 connections and PM_{10} levels, both of them remained within the acceptable comfortable thresholds prescribed by the ISHRAE standard. Evidence gathered in this study suggests that the ISHRAE IEQ standard has underpredicted the thermal adaptivity of Indian occupants in both green-rated and conventional homes, also, exposure to $PM_{2.5}$ levels was high. Due to the lack of a comprehensive protocol for monitoring indoor $PM_{2.5}$ 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 Indian 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.

Acknowledgement

This study is part of the Indo-UK RESIDE project, which has received funding from the Engineering and Physical Sciences Research Council (EPSRC), UK grant no: EP/R008434/1.

References

Assimakopoulos, V. D., Bekiari, T., Pateraki, S., Maggos, T., Stamatis, P., Nicolopoulou, P., & Assimakopoulos, M. N. (2018). Assessing personal exposure to PM using data from an integrated indoor-outdoor experiment in Athens-Greece. *Science of the Total Environment*, *636*, 1303–1320.

Basu, C., Paul, V. K., Syal, M. G. M., & Dandia, G. (2020). Post Occupancy Evaluation to Assess Multifamily Residential Building Energy Performance in India. *OIDA International Journal of Sustainable Development*, *13*(03), 25–44. www.oidaijsd.comalsoavailableathttp://www.ssrn.com/link/OIDA-Intl-Journal-Sustainable-Dev.htmlElectroniccopyavailableat:https://ssrn.com/abstract=4064125

Batra, N., Gulati, M., Singh, A., & Srivastava, M. B. (2013). It's different: Insights into home energy consumption in India. *BuildSys 2013 - Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings*, *August*.

Bedi, T. K., & Bhattacharya, S. P. (2021). An Investigative Study on Perceived Indoor Air Quality During COVID-19 Lockdown in India. *Journal of The Institution of Engineers (India): Series A*, *102*(4), 885–900.

Gietl, J. K., & Klemm, O. (2009). Analysis of traffic and meteorology on airborne particulate matter in Münster, Northwest Germany. *Journal of the Air and Waste Management Association*, *59*(7), 809–818.

Gou, Z., Prasad, D., & Siu-Yu Lau, S. (2013). Are green buildings more satisfactory and comfortable? *Habitat International*, *39*, 156–161.

Goudarzi, G., Sorooshian, A., & Maleki, H. (2020). Local and Long-Range Transport Dust Storms Over the City of Ahvaz: A Survey Based on Spatiotemporal and Geometrical Properties. *Pure and Applied Geophysics*, *177*(8), 3979–3997.

Grover, A. C. (2019). Understanding the role of Occupants in green building energy performance. *Proceedings of the International Conference of Architectural Science Association*, 547–556.

Gupta, R., Gregg, M., & Joshi, S. (2019). Performance evaluation of a certified green-rated housing development in the warm humid climate of India. *IOP Conference Series: Earth and Environmental Science*, *294*(1), 012085.

Gupta, R., Gregg, M., Manu, S., Vaidya, P., & Dixit, M. (2019). Customized performance evaluation approach for Indian green buildings. *Building Research and Information*, *47*(1), 56–74.

Gupta, R., Gregg, M., & Panchal, R. (2019). Energy and Environmental performance of a green certified office building in the hot dry climate of India. *IOP Conference Series: Earth and Environmental Science*, *329*(1), 012028.

IFC. (2018). *Post Occupancy Evaluation of Green Homes: Consumer Insight Eco-cities India program*.

IGBC. (2023). *Green Building Movement in India*. IGBC. https://igbc.in/igbc/redirectHtml.htm?redVal=showAboutusnosign

ISHRAE. (2016). *Indoor Environmental Quality Standard ISHRAE Standard - 10001:2016*.

Kankaria, A., Nongkynrih, B., & Gupta, S. (2014). Indoor air pollution in India: Implications on health and its control. *Indian Journal of Community Medicine*, *39*(4), 203.

Kaur, R., & Pandey, P. (2021). Air Pollution, Climate Change, and Human Health in Indian Cities: A Brief Review. *Frontiers in Sustainable Cities*, *3*(August).

Kim, J., Hong, T., Kong, M., & Jeong, K. (2020). Building occupants' psycho-physiological response to indoor climate and CO2 concentration changes in office buildings. *Building and Environment*, *169*(October 2019), 106596.

Kumar, M., & Khan, S. H. (2022). Using post-occupancy evaluation as a methodological approach to assess residential hostels in CFTI. *International Jouranl of Architectural Research: Archnet-IJAR*.

Mannan, M., & Al-Ghamdi, S. G. (2021). Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structure. *International Journal of Environmental Research and Public Health*, *18*(6), 3276.

Rohra, H., & Taneja, A. (2016). Indoor air quality scenario in India-An outline of household fuel combustion. *Atmospheric Environment*, *129*(2), 243–255.

Sabapathy, A., Ragavan, S. K. V., Vijendra, M., & Nataraja, A. G. (2010). Energy efficiency benchmarks and the performance of LEED rated buildings for Information Technology facilities in Bangalore, India. *Energy and Buildings*, *42*(11), 2206–2212.

Sharmin, T., & Khalid, R. (2022). Post occupancy and participatory design evaluation of a marginalized low-income settlement in Ahmedabad, India. *Building Research & Information*, *50*(5), 574–594.

Sonar, S. G., & Nalawade, R. V. (2019). Performance Assessment of Green Rated Built Environment using Post Occupancy Evaluation. *International Journal of Recent Technology and Engineering (IJRTE)*, *8*(4), 1449–1454.

The World Bank. (2023). Improving Building-Level Thermal Comfort and Indoor Air Quality in South Asia: Energy-Efficient and Cost-Effective Interventions for a Changing Climate. In *The World Bank*.

Ukey, N., Gawande, A., Kankate, A., Kulte, A., Bankar, C., & Kamble, P. S. (2022). EVOLUTION OF GREEN BUILDING CONCEPT IN INDIA. *International Research Journal of Modernisation in Engineering Technology and Science*, *04*(04), 2313–2318.

Verma, S., Manu, S., & Dixit, M. (2019). Evaluating the UK-Building performance evaluation (UK-BPE) methodology for a residential green building in India. *Proceedings of the International Conference of Architectural Science Association*, *2019-Novem*, 313–322.

WHO. (2021). WHO global air quality guidelines. In *Coastal And Estuarine Processes*.

Zhang, L., Ou, C., Magana-Arachchi, D., Vithanage, M., Vanka, K. S., Palanisami, T., Masakorala, K., Wijesekara, H., Yan, Y., Bolan, N., & Kirkham, M. B. (2021). Indoor particulate matter in urban households: Sources, pathways, characteristics, health effects, and exposure mitigation. *International Journal of Environmental Research and Public Health*, *18*(21).