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Empirical Examination of Trends in Indoor Air Quality in a Sample of Urban Indian Residences

Rajat Gupta
Oxford Brookes University, Oxford, UK
(Corresponding Author: rgupta@brookes.ac.uk)

Yuanhong Zhao
Oxford Brookes University, Oxford, UK

Vishal Garg
Plaksha University, Mohali, India

Jyotirmay Mathur
Malaviya National Institute of Technology, Jaipur, India

Highlights

- Pioneering empirical study that combines time-series data on IAQ with contextual data on household characteristics.
- Middle-income group residences were found to experience better IAQ than those with high and low incomes.
- Daily mean indoor temperature was 4.8°C warmer than the recommended acceptable temperature prescribed by ISHRAE (Class C).
- An online interactive dashboard (RIAQ) for visualising IAQ was developed for academics, policymakers, and industry to enable further research.

Abstract

Indoor air quality (IAQ) in residences is a complex phenomenon determined by many factors. IAQ in homes has been studied far less than air quality outdoors, especially in urban India, where outdoor air pollution frequently exceeds recommended levels. This paper empirically examines daily trends and variations in IAQ parameters measured across a sample of eight urban Indian residences located in three cities, representing the warm-humid and composite climates. 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 10 days during the monsoon season when air conditioning was prevalent. Contextual data about the physical and household characteristics of residences were gathered using household surveys. The 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 was developed for academics, policymakers, and industry to enable further research.

Keywords: Indoor air quality, particulate matter, residences, monitoring, visualization

Introduction

Over the past two decades, there has been a rapid increase in urbanization in many cities in India [1], resulting in a significant increase in the number of residences, together with an increase in household activities (such as cooking, heating, cooling) and associated indoor air pollutants such as particulate matter. About 10 of the world's top 15 most polluted cities are located in India [2]. The number of deaths due to air pollution was 1.67 million, of which 0.61 million deaths were attributable to household air pollution (HAP). This has resulted in an economic loss of $36.8 billion, accounting for 1.36% of India's gross domestic product (GDP) [3]. In contrast to the attention paid to ambient air quality, indoor air quality (IAQ) research has recently received attention from Government authorities and researchers due to the COVID pandemic and the adverse health impacts of poor IAQ related to Sick Building Syndrome.

Several studies have indicated the need for having appropriate thresholds for IAQ and a standardized measurement approach for producing reliable results [4-8]. Rawal et al. proposed an India Model for Adaptive Comfort-Residential (IMAC-R) based on year-long thermal comfort field surveys across the five climatic zones of India and showed that existing models (like the PMV model) and standards (ASHRAE) had under-predicted thermal adaptive capacity of Indian occupants in both mixed-mode and naturally-ventilated residential buildings [8]. To address these concerns, IAQ standards have been recently published for the Indian context. The Indoor Environmental Quality Standard ISHRAE Standard-10001: 2016 as India's first Indoor Environmental Quality (IEQ) standard, defines recommended threshold values, methods of measurement, and technical specifications of the measuring instruments for IAQ, thermal, lighting, and acoustic comfort [9]. It is hoped that the ISHARE standard will help to increase the number of empirical studies on indoor air quality for different types of building typologies (residential, public, commercial, institutional) in India.

Most studies have focused on office buildings [4] and institutions like schools [10]. The number of studies on measuring IAQ in residential buildings is scarce [11-13]. A recent study by Greenstone et al. [14] used low-cost indoor air quality monitors to measure indoor $PM_{2.5}$ concentrations across thousands of homes in Delhi and found that average indoor $PM_{2.5}$ concentration levels were 23 and 39 times higher than the WHO [15] recommended limit of 10 μg/m³ respectively. Garg & Ghosh measured the conventional air pollutants of $PM_{2.5}$, SPM, NO_2, and SO_2 across diverse socio-economic zones and revealed better IAQ in middle-income group households in comparison to the high- and low-income groups [16]. The study pointed out that ventilation (air exchange) plays a critical role in improving IAQ, which was substantiated by the calculation of indoor/outdoor (I/O) ratios.

Despite these recent studies, IAQ in residences has received limited attention from policymakers and researchers due to the limited use of established protocols for long-term measurement of IAQ to pick up seasonal differences [17-18] and lack of awareness of the link between poor IAQ and health [14,17,19]. This has resulted in a lack of accessible data on the variation in IAQ in residences (with different income groups, locations, and construction) across India [18]. In addition, national guidelines on IAQ monitoring and management in residences may need to be varied given the outdoor pollution levels in cities across India that influence indoor-outdoor air exchange.

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 eight urban Indian residences located in three cities, representing the warm, humid and composite climates of India. 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 standards to observe any deviations. An online and interactive dashboard (RIAQ) for visualizing IAQ was developed for academics, policymakers, and industry to enable further research.

Methods

The study adopted a mixed methods approach combining IAQ monitoring with household surveys across a sample of eight urban Indian residences located in three cities, representing the warm, humid, and composite climates. Using internet-enabled Airveda devices, time-series monitoring data at 30’ intervals were gathered for indoor temperature, RH, CO_2, $PM_{2.5}$, and PM_{10} for 10 days (6th-15th August 2022) during the monsoon season when air conditioning was prevalent. The IAQ conditions were monitored in the most occupied space - the living room of the case study residences. The technical specifications of Airveda devices are detailed in Table 1 below. To investigate the relationship between indoor and outdoor air quality, outdoor air quality data (temperature, RH, CO, $PM_{2.5}$, and PM_{10}) of studied cities were obtained from the Central Pollution Control Board (CPCB) online portal run by the Ministry of Environment, Forest and Climate Change, Government of India [11].

Table 1: Specifications for Airveda devices

	Parameter	Range	Accuracy	Resolution
	Temperature (°C)	10 – 60	±1	1
	RH (%)	0 – 90	±3	1
	CO_2 (ppm)	0 – 5000	±50 ±3%	--
	$PM_{2.5}$ (μg/m^3)	0 - 999	±10%	< 0.3
Device Model: PM2510CTH	PM_{10} (μg/m^3)	0 - 1999	±10%	< 0.3

Contextual data about dwelling and household characteristics of the residences were gathered using face-to-face interview-based surveys with householders. The survey questionnaires were implemented using online Google Forms and included details about the building (size, orientation), household (number of occupants, occupancy pattern, activities), cooling systems (set point temperature), appliance ownership and usage, and thermal comfort.

Table 2: Residence characteristics

Cities	Dwelling ID	Dwelling type	No. of AC units	Floor area (m²)	No. of occupants	Income group	Weekly occupancy
Pune	P01	Row house	0AC	135	2	MIG	Evenings and Weekends
	P03	Apartment (<4 story high)	3AC	125	5	HIG	All the time (24/7)
		Apartment (<4 story high)	2AC	125	8	HIG	All the time (24/7)
Pondi cherry	PD2	Stand-alone house	2AC	112	4	MIG	Most of the time
	PD5	Stand-alone house	0AC	121	7	LIG	All the time (24/7)
Patna	PT7	Stand-alone house	0AC	102	3	LIG	All the time (24/7)
	PT8	Row house	0AC	65	5	LIG	All the time (24/7)
	PT10	Apartment (<4 story high)	2AC	139	2	HIG	NA

Overview of case study residences

The eight sample residences were categorized as three low-income group (LIG, income up to INR 6 lac per annum), two middle-income group (MIG, income between INR 6 lac to INR 12 lac per annum), and three high-income group (HIG, income more than INR 12 lac per annum). The residences were grouped as three apartments, two-row houses, and three stand-alone houses. They were located in the following cities - Pune (P01, P03, P04), Pondicherry (PD2, PD5), and Patna (PT7, PT8, PT10), representing the warm-humid and composite climates, as shown in Table 2. The residences varied in size from 65m^2 to 139m^2. The majority of case study residences were constantly occupied and had more than two occupants, with P04 having eight occupants (highest). AC ownership varied across the sample - as 50% were MIG, there was no ownership of AC across LIG residences, and all the HIG residences owned two or more AC units. Throughout the monitoring period, the frequency of AC usage was about 7-9 hours per day among the four AC-equipped residences.

To better explain the reasons behind IAQ trends, outdoor air quality data were examined. During the monitoring period, Pondicherry experienced the highest mean outdoor temperature of 31.8°C, with the lowest mean values of outdoor $PM_{2.5}$ and RH at 13.8µg/m³ and 67.6%, respectively. Pune experienced the lowest mean values in temperature (24.5°C) and PM_{10} (29.6µg/m³). Patna experienced the highest mean values for RH, $PM_{2.5}$, and PM_{10} at 74.3%, 30µg/m³, and 61.5µg/m³.

Results

Temperature and Relative Humidity

Table 3 summarises, by each residence, the measured mean, maximum, and minimum concentrations of IAQ parameters during the monitoring period of 10 days in August 2022. Indoor temperature was found to vary across the residences, with daily mean temperature ranging from 28.3°C in P01 to 35.2°C in PT10.

Table 3: Descriptive statistics for indoor Temperature, RH, CO_2, $PM_{2.5}$ and PM_{10}

	Cities	**Pondicherry**		**Pune**			**Patna**		
	Dwelling	**PD2**	**PD5**	**P01**	**P03**	**P04**	**PT7**	**PT8**	**PT10**
Date Range:6-15 August	**Temperature (°C)**								
	Mean	32.1	33.4	28.3	30.7	30.2	30.1	34.2	35.2
	Min	28	31	26	29	29	29	32	32
	Max	34	35	30	33	33	32	38	38
	Humidity (%)								
	Mean	48.3	53.2	64.0	60.9	63.4	58.0	50.8	56.1
	Min	28	43	56	49	55	51	40	49
	Max	62	65	71	68	68	67	60	67
	CO_2 (ppm)								
	Mean	577.2	586.6	420.1	551.8	1119.3	502.7	461.4	421.9
	Min	392	440	384	398	526	406	391	382
	Max	1112	891	554	1090	2000	724	632	554
	$PM_{2.5}$ ((µg/m^3)								
	Mean	30.6	44.9	10.6	7.0	14.5	29.1	67.8	26.5
	Min	7	7	0	0	0	3	7	7
	Max	476	786	214	88	133	229	994	80
	PM_{10} ((µg/m^3)								
	Mean	59.6	98.5	33.5	34.4	45.5	55.0	97.6	59.2
	Min	19	24	1	2	6	12	14	14
	Max	671	1091	369	176	307	414	1590	338

The boxplot of temperature in Figure 1 shows the monitored mean indoor temperature for each residence compared against the upper limits of indoor operative temperature prescribed by ISHRAE, which is 27°C (Class C). At the sample level, the mean indoor temperature was 31.8°C, which was 4.8°C warmer than the acceptable temperature recommended by ISHRAE. More specifically, at the individual dwelling level, the temperature difference between the mean indoor temperature of each dwelling and the maximum specified by the ISHRAE threshold varied from 1.3°C to 8.2°C. Residence PT10 had the largest temperature variation from the ISHRAE threshold at 8.2°C, while P01's mean temperature was 1.3°C higher than the ISHRAE threshold.

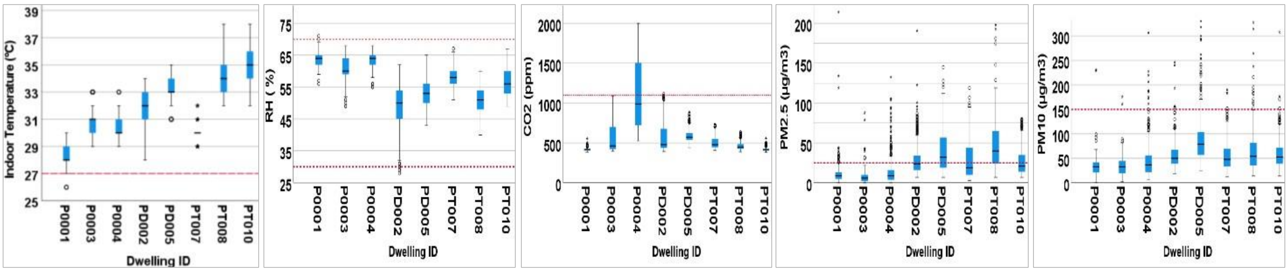
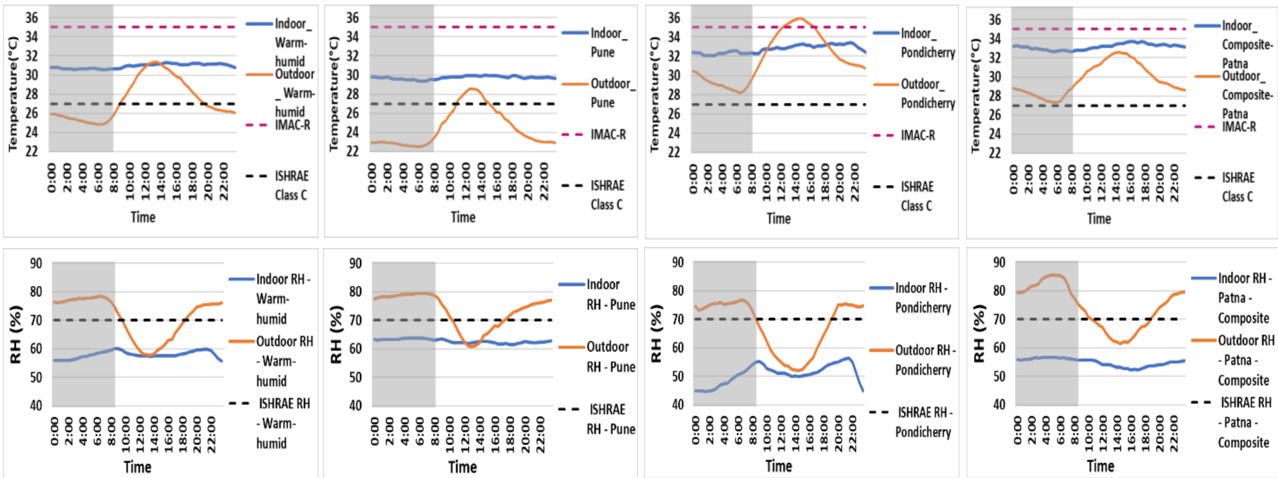


Figure 1: Boxplots showing the distribution of (left to right) indoor temperature, RH, CO_2, $PM_{2.5}$ and PM_{10} of each individual residence compared against ISHRAE standard

Figure 2 shows the indoor and outdoor temperature profiles during the sleeping (00:00-08:00) and awake hours (08:0024:00) by different dwelling cities and climates. In this case, the monitored indoor temperature was compared against the Class C indoor operative temperature (27°C) prescribed by ISHRAE IEQ standard [9] and the upper limit of the neutral temperature range prescribed by IMAC-R [8]. According to the IMAC-R model, more than 80% of the Indian residents experienced a neutral thermal sensation in the indoor operative range of 16.3°C–35°C. Overall, the mean indoor temperature measured in this study was in line with the operative temperature range prescribed by the IMAC-R model.

In general, Patna, in the composite clime, had higher outdoor and indoor temperatures than cities in the warm-humid climate. Even though Pune and Pondicherry have a warm-humid climate, the daily indoor temperature profiles show a difference of 3°C between them. While the correlation between indoor-outdoor temperature for residences in the composite climate was found to be weak (Pearson correlation r =0.164, R^2 = 0.027), a moderate correlation was observed in residences located in the warm-humid climate (Pearson correlation r = 0.58, R^2 = 0.338), both statistically significant at 0.01 level. Moreover, indoor temperature is also influenced by local environmental conditions, which is why a higher indoor temperature was found in residences with 2 AC units than those without AC units.



(a) Warm-humid climate (b) Pune (c) Pondicherry (d) Composite climate-Patna

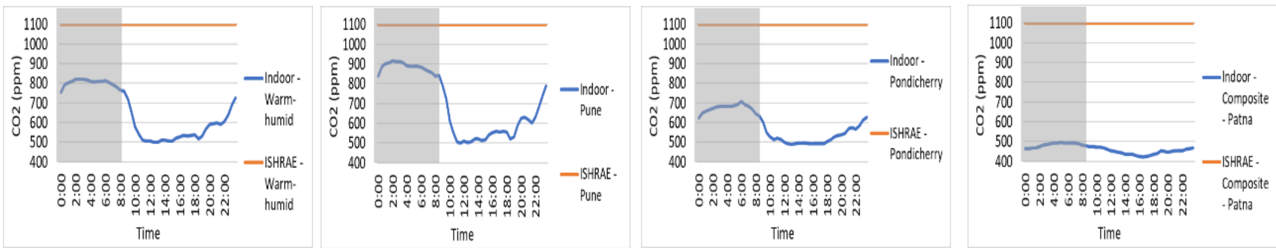
Figure 2: Indoor and outdoor temperature (top) and RH (bottom) profiles averaged over 10 days by Warm-humid and Composite climatic zones. The shaded area represents sleeping hours.

Profiles of indoor RH showed less daily variation over the course of the monitored period. Although daily mean RH ranged from 48% in PD2 to 64% in P01 (Table 1), they were in line with ISHRAE's recommended acceptable range of 30-70%. Indoor RH showed a weak correlation with external RH with Pearson correlation r = 0.288 and 0.314 for the composite and warm-humid climates, respectively, both significant at the 0.01 level.

CO_2 levels

Since indoor CO_2 is mainly emitted by building occupants, CO_2 levels can be a useful indicator of occupancy patterns. Excessive CO_2 indoor concentrations can indicate inadequate ventilation levels in homes, with possible accumulation of other indoor pollutants [20]. Throughout the monitoring period, CO_2 concentrations varied across case study residences due to diversity in residents' window opening behaviours and the number of occupants. The ISHRAE recommended maximum value for CO_2 is 1100ppm [9]. Except for residence P04, all other residences experienced lower CO_2 levels ranging from 400ppm to 700ppm, as shown in Figure 3. Low CO_2 concentration levels could be due to the frequency of window openings by the residents to remove smells due to cooking activities. Residence P04 experienced the highest CO_2 level at 1119ppm due to a high number of occupants – eight residents occupying the residence constantly (Table 2).

The correlation between indoor CO_2 concentration levels and the number of residents was moderately strong, with the Pearson correlation value at 0.6 and significant at the 0.01 level.



(a) Warm-humid climate (b) Pune (c) Pondicherry (d) Composite climate -Patna

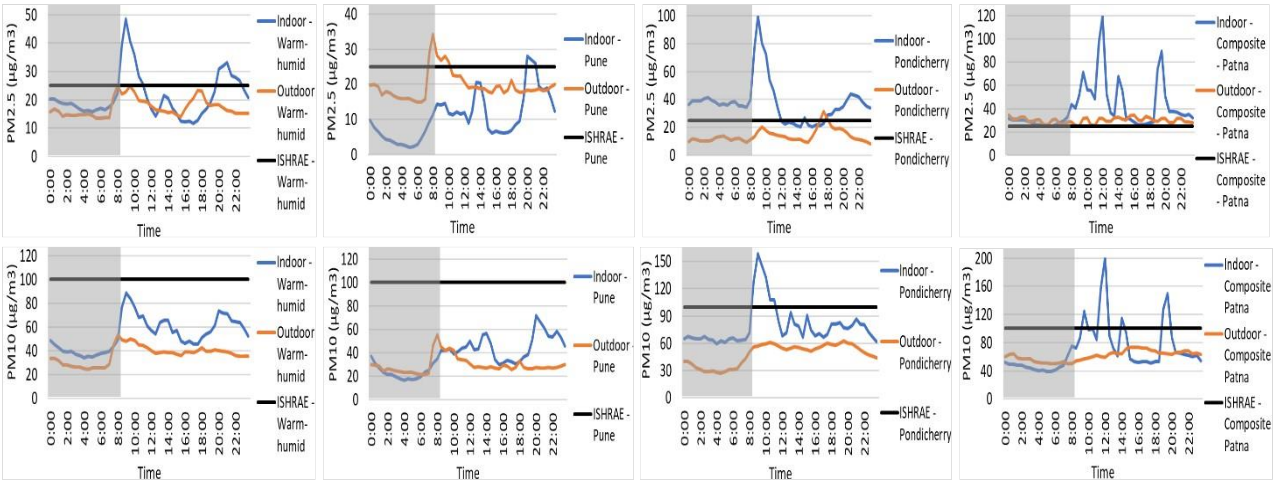
Figure 3: Indoor CO_2 daily profile averaged over 10 days by climate. The shaded area represents sleeping hours.

CO_2 levels varied during the sleeping hours and waking-up hours, as observed in the daily CO_2 profiles. The peak CO_2 concentration occurred during sleeping time. While in residences located in composite climatic zones, CO_2 concentration was stable between 400 to 500ppm, the CO_2 profile in the residences of warm-humid climate varied significantly during the daytime and between sleeping and waking up hours (Figure 3, left figure). This is likely to be due to the difference in the window opening behaviours of residents.

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

Particulate matter (PM) consists of tiny solid or liquid particles found in the air. Pollutants from combustion processes, such as $PM_{2.5}$ and $PM_{10,}$ are generated from outdoor sources, such as traffic and industrial processes, as well as indoor sources, such as cooking and cleaning. The indoor levels of $PM_{2.5}$ and PM_{10}, in the presence of indoor sources of PM, are usually higher than the outdoor PM levels [21]. Exposure to $PM_{2.5}$ is known to induce oxidative stress and is the leading cause of cardiovascular mortality [13, 22]. High $PM_{2.5}$ levels could lead to death in the worst-case scenarios.

The concentrations of particulate matter $PM_{2.5}$ and PM_{10} were found to vary significantly across the residences throughout the monitored period. As shown in Table 3, mean concentrations of $PM_{2.5}$ in residences P01, P03, and P04 were found to be below the ISHRAE recommended limits of 25µg/m^3 ($PM_{2.5}$), while residence PT8 experienced the highest mean $PM_{2.5}$ levels at 68µg/m^3. Mean PM_{10} levels varied between 34µg/m^3 in residences P01 and P03, 45µg/m^3 in P04, 55µg/m^3 in PT7, 59µg/m^3 in PT10, 60µg/m^3 in PD2, 98µg/m^3 in PT8 and PD5. Across all case study residences, PM_{10} levels were found to be below the ISHRAE's recommended limit of 100µg/m^3 for PM_{10} [9].



(a) Warm-humid climate (b) Pune (c) Pondicherry (d) Composite climate -Patna

Figure 4: Indoor and outdoor particulate matters ($PM_{2.5}$ (top) and PM_{10} (bottom)) profiles averaged over 10 days by climate: Warm-humid, Composite. The shaded area represents sleeping hours.

The daily profiles of $PM_{2.5}$ in residences of warm-humid and composite climates varied significantly throughout the daytime because of the relationship with occupant activities. Spikes in $PM_{2.5}$ levels were observed around the cooking time in the evening, as shown in Figure 4. As other studies have shown, cooking fuels are the biggest contributor to high PM concentration levels in Indian households, which explains why PM peaks occurred during the cooking time in this study. While in the warm-humid climate residences, more than 70% of the monitored $PM_{2.5}$ concentrations were below the ISHRAE recommended range, this proportion was 50% in the residences located in composite climate.

Interestingly, non-AC residence PT8, with the smallest internal floor area of 65m^{2,} was constantly occupied by five residents (Table 2) and experienced higher PM levels. In contrast, residence P03, with three AC units and a bigger floor area of 125m², experienced the lowest PM levels. As shown in Table 1, residence PT8 experienced the maximum range of mean $PM_{2.5}$ and PM_{10} compared with the rest of the sample residences.

Cross relating IAQ parameters

The strength of the relationship between indoor and outdoor IAQ parameters across different cities, climates, and dwellings was determined using Pearson's Correlation. As shown in Table 4, at the sample level, the correlation between outdoor and indoor temperature was moderate (Pearson correlation r=0.556), and the correlation between outdoor and indoor RH was weak with a Pearson correlation value of 0.254; both sets of correlations were statistically significant at 0.01 level. The Pearson correlation values of $PM_{2.5}$ and PM_{10} were both less than 0.2, indicating a weak correlation between indoor and outdoor PM. Indoor temperature was found to have a moderate correlation (r=0.43) with outdoor PM_{10}, which was statistically significant at 0.01 level. The household survey revealed that most residents chose to keep windows closed because of dust and high outdoor temperatures. Dust is one of the main contributors to PM_{10} [13, 22], which might explain the moderate correlation.

Table 4: 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	.556	-.099	.172	.430	1	-.589	-.224	.185	.149
Indoor RH	-.553	.254	.067	-.320	-.589	1	.227	-.145	-.096
Indoor CO_2	-.374	.161	-.118	-.240	-.224	.227	1	-.069	-.057
Indoor $PM_{2.5}$	.243	-.028	.138	.200	.185	-.145	-.069	1	.964
Indoor PM_{10}	.205	-.109	.082	.171	.149	-.096	-.057	.964	1

Interestingly, indoor temperature and indoor humidity had a moderate negative correlation with a correlation coefficient of around –0.6. 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. Levels of CO_2 and indoor humidity showed a positive weak correlation with the Pearson Correlation value of 0.227. In addition, indoor CO_2 and indoor temperature had a weak negative correlation of -0.224. There was no correlation observed between indoor PM ($PM_{2.5}$, PM_{10}) and CO_2, implying that measuring CO_2 alone may not be a suitable proxy for assessing IAQ in Indian residences. Occupant activity affects indoor PMs as the value increases significantly during waking hours. Most of the PMs were generated due to household activities such as smoking, cooking, cleaning, and use of air fresheners. The relationship between CO_2 and PMs is still under researched.

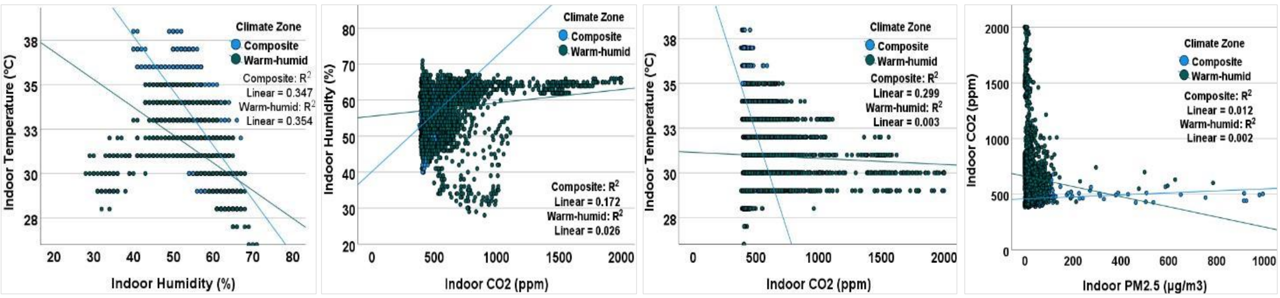


Figure 5: Scatter plots showing a relationship between IAQ parameters across two climates

IAQ parameters and household characteristics

The monitored IAQ variables were analysed based on dwelling and household characteristics that included built form, income group, number of AC units, and number of residents. At the building typology level, the apartment residences showed higher indoor temperature, RH, and CO_2 levels than the house residences but with better air quality in PMs levels. The row houses (with two sides covered) had the lowest indoor temperature.

As seen in Figure 6, daily profiles of IAQ parameters varied by number of AC units. Evidently, the residents experienced lower levels of $PM_{2.5}$ and PM_{10} as the number of AC units increased. Residences with three AC units were found to have the lowest indoor temperature, $PM_{2.5}$, and PM_{10} levels while also having the highest indoor RH during the monitoring period. Residences with two AC units experienced fluctuations in daily mean indoor RH and had the highest indoor temperature and CO_2 levels. Residences without AC performed well in terms of indoor RH and CO_2 concentrations in homes, but had the highest levels of $PM_{2.5}$ and PM_{10} levels during the monitoring period. The mean concentrations of $PM_{2.5}$ were up to four times more than the ISHRAE $PM_{2.5}$ safe limit of 25µg/m³.

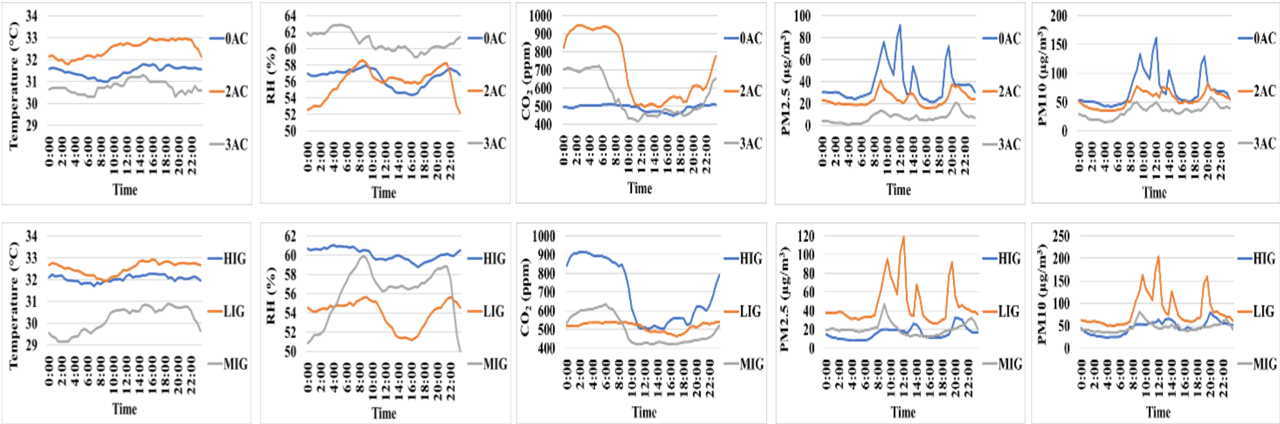


Figure 6: Distribution of daily IAQ parameters across different physical household characteristics: Number. of AC (top), income groups (bottom)

The study also found that daily indoor temperature and $PM_{2.5}$ and PM_{10} levels were found to be high during the monitoring period. As presented in Figure 6 (bottom), non-AC LIG residences were observed to have the lowest indoor RH, while the monitored daily average temperature, $PM_{2.5}$ and PM_{10}, were highest during the study period. The MIG residences were observed to have the lowest indoor temperature, as well as lower levels of CO_2 during waking hours. In contrast, high levels of CO_2 concentration and indoor RH were observed in HIG residences. This may be due to inadequate ventilation, possibly driven by closing windows during the use of air-conditioning, as indicated in the household survey with HIG residences, wherein residents preferred to use AC or fans instead of opening windows. No major differences were observed between the MIG and HIG residences in terms of the concentrations of $PM_{2.5}$ and PM_{10}. The indoor $PM_{2.5}$ had a weak negative correlation with the floor area of residences (Pearson Correlation $r = -0.228$, significant at the 0.01 level). Higher indoor CO_2 levels were observed in residences with a high number of occupants. The peak CO_2 concentration occurred during sleeping time (00:00-08:00) when there were more people in homes. This is why a moderate correlation was observed between indoor CO_2 levels and the number of residents, with a Pearson correlation value of around 0.6.

Data analytics and visualisation dashboard

To provide access to the empirical data gathered and raise awareness about exposure to poor IAQ in homes, IAQ data gathered in the study has been made available to the academic, policy, and business communities through an online data analytics and visualisation dashboard called RIAQ (RESIDE Indoor Air Quality Dashboard). RIAQ dashboard is designed to be an online interactive platform that has the capability to rapidly analyse and visualise IAQ parameters for individuals or a combination of case study urban Indian residences. RIAQ can also generate IAQ profiles and cross-relations between different IAQ parameters for any time scale in the monitoring period and relate them to key building and household characteristics.

The RIAQ dashboard presents the outputs in the form of a bar graph, line graph, box plot, and scatter plot, while allowing users to filter the outcome data based on the typology, time period, dwelling ID, and IAQ parameters. It brings together technical monitoring data on IAQ performance and contextual data on building attributes, household characteristics, and appliances ownership and visualises data at different levels, including the *sample level* (all residences), *typology level* (by climatic zone, built form, dwelling size, income group and the number of AC units), and the *individual residence* level.

The RIAQ dashboard includes five elements (tabs) - *Characterising, Profiling, Distribution, Correlation,* and *Benchmarking*. Characterising presents information on the contextual characteristics of the residences through a series of line graphs and bar charts, including built form, dwelling size, income group, and appliance ownership. These can be filtered by typology and by individual residences. The daily trends and variations in IAQ parameters across the sample are visualised on the Profiling page as presented in Figure 7 (left figure), which can be filtered based on by typology and by individual residences, as well as the IAQ parameters and time period. The default visualisation displays results at the sample level.

The distribution of IAQ parameters can be explored through the box plots presented in the *Distribution* section of the EIAQ dashboard. The IAQ parameters are characterised by the number of residents, built form, income group, and the number of AC units. The strength of the relationship between IAQ parameters data and contextual characteristics of the residences can be explored in the *Correlation* section four scatter plots, as shown in Figure 7 (right). Grouped by AC and non-AC residences, the relationship between indoor humidity and indoor temperature, indoor CO_2 and temperature, indoor CO_2 and humidity, and indoor CO_2 and $PM_{2.5}$ are shown in this section. Users of RIAQ can identify the strength of the relationship through positive and negative linear trend lines in each scatter plot.

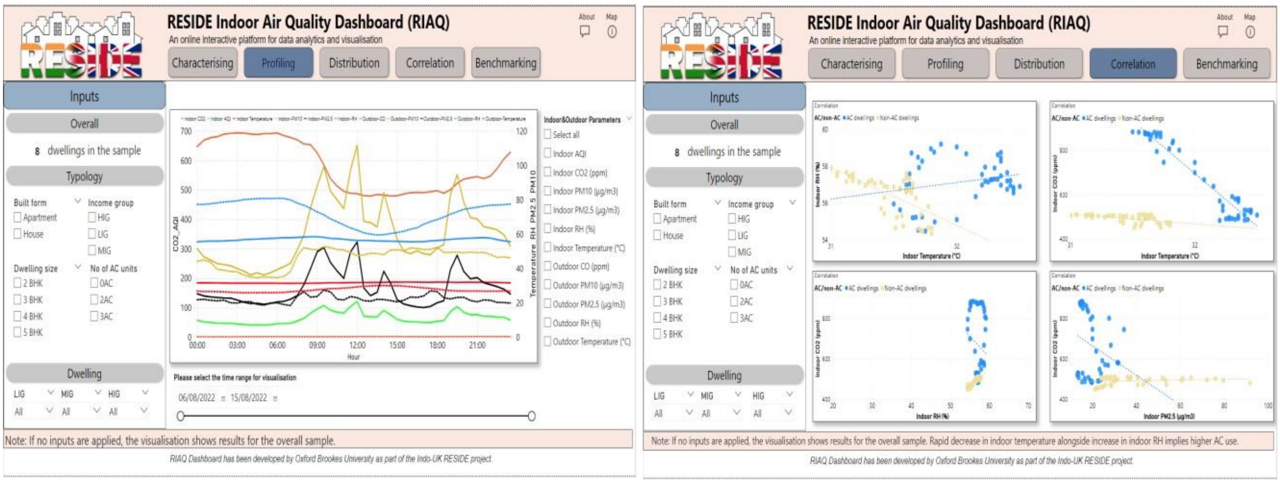


Figure 7: RIAQ dashboard profile examples: Profiling page (left) and Correlation page (right)

In the *Benchmarking* section, IAQ parameters are compared against the corresponding recommended levels by standards to observe any deviations. The ISHRAE IEQ standard [9] is used to visualise maximum values (Class C) for the indoor temperature at 27°C, RH at 40% -70% range, CO_2 at 1100ppm, $PM_{2.5}$ at 25µg/m^3 and PM_{10} at 100µg/m^3. Users can select appropriate IAQ parameters and associated benchmarks simultaneously to visualise results.

To our knowledge, there is no freely-available online and interactive dashboard that has the capability to rapidly analyse and visualise IAQ in urban Indian residences. The RIAQ dashboard developed in this study can generate user-determined IAQ profiles, show cross-relations between different IAQ parameters for any time scale in the monitoring period, and relate them to key building 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.

Discussion

This study has discovered interesting findings through an empirical approach combining monitoring (indoor IAQ) with household surveys (context) for eight urban Indian residences located in three cities covering two climatic zones. Despite the small sample, variation in the levels of IAQ parameters was observed during the monitoring period (6th-15th August 2022). Daily mean temperatures ranged from 28.3°C to 35.2°C, which were slightly warmer than the operative temperature prescribed by ISHRAE. Mean indoor RH levels varied from 48%-64%, which remained within the acceptable range of the ISHRAE standard. Apart from one residence (P04), all other residences experienced lower levels of CO_2 ranging from 400ppm to 700ppm, much below the upper benchmark of 1100ppm prescribed by the ISHRAE standard. Residences in apartments experienced higher indoor temperature and CO_2 levels than stand-alone houses since apartments are likely to have smaller areas for windows (for ventilation) in relation to floor area.

The measurements of $PM_{2.5}$ and PM_{10} showed interesting trends. While $PM_{2.5}$ and PM_{10} levels remained low, under 50µg/m^3 and under 80µg/m^{3,} respectively, during sleeping hours, they varied significantly throughout the daytime. Monitored $PM_{2.5}$ levels (arising from combustion and cooking) varied across the study sample, with mean $PM_{2.5}$ levels ranging from 11µg/m^3-68µg/m^3, with half of the residences experiencing $PM_{2.5}$ levels above the upper threshold value of 25µg/m^3 set by ISHRAE. Mean PM_{10} concentration ranged from 34µg/m^3-98µg/m^3, which was below the ISHRAE prescribed upper threshold value of 100µg/m^3. Overall, PM levels were related to occupant activities such as cooking.

Indoor air quality is also influenced by outdoor pollution through air exchange. This is why indoor $PM_{2.5}$ and CO_2 levels correlated with corresponding outdoor levels. A moderate correlation was observed between indoor temperature and outdoor PM_{10}. The fact that no correlation was observed with CO_2 levels, $PM_{2.5}$, and PM_{10} implies that simply monitoring CO_2 levels in residences may not be a suitable proxy for assessing IAQ in Indian residences. Monitoring of PMs also needs to be encouraged to get a true picture. Even though high-income households have more modern amenities, they experienced poor levels of IAQ, followed by the low-income group, while residents in the middle-income group experienced better levels of IAQ. This finding is similar to the study by Garg & Ghosh [16], wherein they used the calculation of indoor/outdoor (I/O) ratios to compare the IAQ across the three income groups.

Given the paucity of empirical data, this research developed an online interactive platform, i.e., the RIAQ dashboard, to help users understand how indoor air quality varies daily in Indian residences that have different built forms and are 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.

Conclusion

Indoor air quality is a global issue being associated with health, economic, and sustainable development goals, yet there is limited research on measuring IAQ in Indian residences. This study has adopted a field study-based approach to empirically examine the trends and concentrations of IAQ in a sample of urban Indian residences and explore the relationship between contextual characteristics and IAQ. Empirical evidence gathered in the study suggests that even for a small sample of eight residences, there was wide variation observed in indoor temperature, relative humidity, and PM_{10} levels, possibly due to occupancy patterns and personal activities of occupants. Interestingly, although the high-income group living in apartments are equipped with more AC units, their overall indoor air quality was found to be poorer, followed by the low-income group, while the middle-income households were found to have better IAQ.

To raise awareness about the exposure to poor IAQ in homes, IAQ data gathered in the study has been made available to the academic and policy communities, as well as industry, through the online RIAQ Dashboard. This interactive dashboard has the capability to rapidly visualise IAQ parameters for individuals or a combination of case study residences. RIAQ can also generate IAQ profiles and cross-relations between different IAQ parameters for any time scale in the monitoring period and relate them to key building and household characteristics.

Since the research presented is based on a small sample, there are limitations in drawing generalisations on the relationship between IAQ and household characteristics in urban Indian residences. Nevertheless, the methodological approach adopted in the study can be rolled out nationally to provide a more comprehensive coverage of urban Indian residences across different types and locations.

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