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Evaluation of Indoor Environmental Quality in an Academic Building in the Temperate Climate of South Bengaluru

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Abstract

The quality of indoor environments in academic buildings significantly influences occupant comfort, learning efficiency, and overall well-being. This study aimed to evaluate the indoor environmental quality of a contemporary academic building in South Bengaluru through objective environmental measurements and occupant perception surveys, and to assess its impact on user comfort and satisfaction. Field measurements and occupant surveys were conducted during three different time slots: 9:30–10:30 am, 1:00–2:00 pm, and 3:00–4:00 pm. Environmental parameters, such as air temperature, relative humidity, air speed, lux levels, and noise levels were recorded both indoors and outdoors. Simultaneously, questionnaires were distributed to 89 students and faculty members to understand subjective comfort responses related to thermal comfort, daylight, glare, air movement, noise, and seating comfort. Post-occupancy evaluation revealed an overall comfort satisfaction rate of only 34.8%. The primary cause of discomfort appeared to be temperature, with high dissatisfaction related to temperature (57.3%), air freshness (52.8%), and air movement (50.6%) against background environmental ranges of 31.3–32.9°C and relative humidity of 49–60%. However, for visual comfort, higher acceptance came about due to artificial lighting (58.4%), while daylight availability scored a value of 52.8%, spanning from 81 to 969 lux. Background noise strongly varied from 48 to 77 dB(A) and was deeply suppressed on lower floors. The results of the study support the design of climate-responsive educational facilities through consideration of shade, natural ventilation, and daylighting to positively impact the comfort of users, their ability to learn, and the overall quality of the indoor environment.

Keywords: Academic building, Daylighting, Perception survey, Temperate climate, Thermal comfort

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Introduction

The impact of the built environment's performance on the occupants depends on the indoor environmental quality (IEQ) model, which is a multidimensional classification that includes thermal comfort, indoor air quality (IAQ), visual performance, and acoustic comfort. An estimated 90% of human life is spent indoors in urban environments, and thus, the physical and psychological well-being of the occupants of buildings by default depends on how well the indoor microclimates function.[1] The dependence of occupants on indoor microclimates is further exacerbated in institutional and post-secondary educational facilities where there are high densities of people, different levels of metabolic activity, and long duration of stays.[2] Historically, empirical investigations in building physics have focused on maximizing building energy efficiency and achieving aggressive levels of building envelope insulation to minimize mechanical utility expenses. Several recent studies indicate that by attempting to optimize the macro-energy characteristics of buildings, without considering the human factors of building occupants, design approaches to buildings have created a growing performance gap manifested in the prevalence of sick building syndrome, greater fatigue of individuals, and marked declines in the cognitive capabilities of individuals.[3] In temperate climates, buildings are typically designed to use passive, natural ventilation. However, such buildings face substantial vulnerabilities related to the IEQ of buildings when subjected to changing exterior environmental conditions, such as weather patterns, variations in solar azimuth, and building operations.[4]

There are many existing studies showing that systemic obstacles to achieving acceptable IEQ exist both globally and regionally. The level of evidence for these claims has been demonstrated through a wealth of credible statistical data. According to the United Nations Environment Programme and the framework published by UN-Habitat, global buildings account for approximately 36% of all energy consumed and generate nearly 40% of all direct and indirect carbon emissions,[5] and this is primarily due to the large operation requirements for mechanical ventilation systems.[6] In addition, from an economic and corporate performance standpoint the combination of several Global research synthesis studies published by McKinsey and Company show that suboptimal indoor microclimates can act covertly as a drag on macroeconomic output, indicating that poor distribution of air within an indoor environment and extreme swings in indoor temperature could result in reductions in both direct cognitive performance of the individual as well as reductions in productivity of operational workers by as much as 15%.[7] Klynveld peat marwick goerdeler (KPMG) India's localized market intelligence reports also indicate that India is experiencing an exponential increase in institutional construction projects, yet heating, ventilation, and air conditioning (HVAC) and artificial lighting arrays account for up to 73% of total commercial/institutional energy footprint due solely to correcting for baseline comfort issues.[8] Despite these high operational outlays, architectural reviews demonstrate that across developing tropical and subtropical regions, school and university

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classrooms routinely underperform, frequently displaying internal noise thresholds that exceed 65 dB(A), extreme seasonal glare anomalies, and persistent thermal dissatisfaction rates ranging from 25% to 72% among student cohorts.[9]

An urgent call for targeted field studies on the rapidly urbanizing and temperate sub-regions of Indian metropolitan cities can be made by reviewing these systemic failures. Existing academic literature includes extensive foundations for IEQ and adaptive comfort for composite, hot-dry, and warm-humid climates; yet, the temperate urban centers that house the greatest number of people, for example, South Bengaluru, are still under-studied.[10] This gap in research leads to a lack of verification for what is assumed by local building designers that moderate outdoor weather would lead to comfortable indoors without active climate-responsive measures. Therefore, a necessary challenge to this assumption is to develop a detailed and granular mapping of multi-spatial and multi-temporal, real-time building performance. Theoretical contributions of this new research include expanding existing theories on adaptive thermal and visual comfort by studying micro-environmental variations (e.g., distinct floors, interior depth, and/or directional orientation) shared by occupants of naturally cross-ventilated educational buildings.[11] From a practical standpoint, this research offers immediate value to local architects, institution administrators, and engineering stakeholders; by providing cross-verified, empirical data alongside occupant feedback, this study delivers actionable insights to optimize spatial layouts, implement low-energy retrofits, reduce unnecessary HVAC usage, and create healthier, more productive learning spaces.

Literature Review

Recent research into IEQ has indicated that there is an increasing emphasis on the disparity between how buildings were designed and what the actual comfort is like for occupants in real life. As an example, major changes to how buildings are constructed in developing countries, such as India, have increased demand for the use of all-glass buildings rather than buildings that use local and natural materials that respond to their surrounding environment (microclimatic) to provide comfort and maintain thermal balance. Research has shown that by using modern construction materials (e.g., glass), daylight is allowed into the building; however, advanced building materials have also created conditions for thermal traps (e.g., an area that receives high levels of daylight but is still uncomfortably warm) and serious acoustic issues (e.g., very loud sound levels). Research conducted by Kapoor *et al*.[9] supports the finding that IEQ factors in classrooms in Indian schools are very poor due to insufficient ventilation strategies (air movement) and inadequate solar protection strategies (sunlight), thereby creating thermal pockets or areas of warmth that exceed target comfort levels in relation to current comfort expectations. In a similar way, studies that examine the IEQ of Indian residential and public buildings have shown that regional weather patterns at full-scale do not match anticipated weather patterns when assessed at the building scale, and that buildings built with a lot of structural mass (weight) and a lot of windows (glazed surfaces) trap heat inside of buildings due to how buildings absorb solar radiation.[8,12,13] Studies conducted worldwide (but especially in the context of higher education) have proven the potential of these underlying IEQ factors to negatively influence the productivity and health of building occupants. Long-term assessments of postsecondary institutions indicated that it is inherently challenging to achieve consistent IAQ and thermal thresholds in high-density university environments, as metabolic heat loads are permanently skewing the environmental parameters within these types of facilities when measured over long periods of time.[14,15] In addition, climate change is further complicating this challenge has given that building adaptation frameworks are not able to manage the escalating frequency of extreme localized microclimatic thermal shocks.[6] Much like the above-noted issues with non-ventilation or manual-natural-ventilation versus occupant satisfaction in non-ventilated Mediterranean climates, the authors discovered that optimally using only manual-natural-ventilation to achieve acceptable levels of air quality in university facilities will often require the introduction of massive thermal penalties and generation of drafts during the peak-use periods. While modern green building rating systems, such as leadership in energy and environmental design, green rating for integrated habitat assessment, and Indian green building council incentivize energy-conscious design, proving unsuccessful in creating measurable reductions in the carbon footprint of the facilities, Abinaya and Suseelan[11] found that these types of formal rating systems are primarily focused on the property of the asset rather than the user's sensory experience. Recent research on alternative methods of mitigating exposure inside buildings has included studies like those of Budaniya *et al*.,[1] which analyzed how integrating biophilic elements (e.g., plants, trees) into Indian open floor plans can have a positive impact on the psychological well-being of individuals, and on how they perceive temperature, though they do not have much effect on specific environmental characteristics found in a room as measured by physical attributes; that is, they have little effect in terms of changing air temperature. Thus, holistic performance of all building systems requires that all systems can be controlled in multiple ways. As demonstrated by Dai *et al*. 2025[3] and Kaczmarczyk *et al*. 2025,[16] elements of IEQ are highly related to human responses and experiences. If the performance and interaction between visual, sound (i.e., philic) pathways, and heat is not addressed holistically, a cascading effect of discomfort and energy consumption (i.e., high HVAC use) will occur. Altering structural design elements for local climate conditions (e.g., the development of parametric building roof designs responsive to environmental conditions as researched by Gopalakrishnan *et al*., 2026[10] is also an effective tool for combating climate loads from localized outdoor temperatures that may otherwise penetrate the interior spaces of educational facilities. Adaptive comfort literature is primarily based on climate templates from a macro-regional perspective and has thus neglected urban microclimates. In addition, standard post-occupancy evaluations do not assess thermal comfort in conjunction with other variables, such as acoustic comfort and visual comfort, as they commonly separate objective (instrumentation) from occupant subjective satisfaction measurement.

To reduce this discrepancy, the study introduces two innovations that help fill the knowledge gaps: (1) Development of multi-level horizontal floor-depth and vertical structural-level environmental mapping, and (2) implementation of simultaneous and multi-axis evaluations coupling high-fidelity physical measures of the above with occupant surveys. Specifically, the proposed research addresses three main research questions: RQ1: What is the spatial variability of the major IEQ parameters of a naturally ventilated building along the horizontal depth and vertical structural levels? RQ2: What is the relationship between objective microclimatic measures and occupants' degree of satisfaction as measured by using multiple senses? RQ3: How does the orientation of a building and site limitations dictate the performance trade-offs between natural ventilation, daylighting performance, and noise transmission? This study's aim is to diagnose and optimize IEQ in temperate Indian institutional buildings. Physical measures of the environment (temperature, humidity, air speed, illuminance, noise) will be recorded over a range of timeframes, and occupants' level of satisfaction with these same environmental measures will be recorded and correlated to define a micro-climactic comfort standard and provide solutions and strategies for implementing climate-responsiveness and improving overall building performance.

METHODOLOGY

Study Area

According to the National Building Code of India,[17] South Bengaluru is classified as a temperate climate region, with summer temperatures between 28 and 34°C and 50–70% relative humidity, and winter temperatures between 15 and 28°C and 55–70% relative humidity. The area receives a substantial amount of rain from the monsoon, between 900 and 1,000 mm of annual precipitation, according to the ISHRAE[18] climate data and other meteorological records. With multiple decades' worth of educational institutions and expanding campuses with new infrastructure, South Bengaluru offers a dynamic built landscape. The building chosen for the current study has a substantial number of glass façades. This building measures 29.5 m wide by 64.2 m long (with the longer dimension facing east-west), is an 8-story academic building (ground floor plus 7 upper levels) intended for education beyond secondary level, has an area of 1,792 m^2 per level (total area of 14,337 m^2), and has a height of 24.0 m (with a clear height between floors of 3.0 m). The lower-middle levels (1st–4th floors) house BBA/B.Com classrooms and faculty spaces, while the upper levels (5th–6th floors) host the postgraduate MBA/M.Com programs, advanced research labs, and student welfare governance [Figure 1].

Methods

This study utilized a mixed-methods research design, combining objective environmental monitoring with subjective occupant surveys and physical observations to evaluate the IEQ of an educational building. Data collection was done during regular academic hours of 9.00 am to 4.00 pm, to capture the operational and occupancy conditions. Quantitative data were gathered through simultaneous indoor and outdoor environmental monitoring alongside a structured occupant satisfaction survey. Qualitative insights were gathered concurrently through physical observations of space utilization and building operations. Integrating these diverse datasets facilitated data triangulation, cross-verifying the objective physical metrics against the real-world comfort experiences of the building occupants.

The physical monitoring framework systematically measured five IEQ parameters: Air temperature (°C), relative humidity (%), air speed (m/s), illuminance (lux), and noise levels (dB(A)). To account for daily temporal shifts in solar exposure, occupancy density, internal heat gains, and building operations, readings were collected across three specific time slots: Morning (9:30 am–10:30 am), afternoon

Figure 1: Details of the surveyed reference academic building. (a) Site plan; (b) view of the building elevation, (c) typical floor plan, and (d) classroom view

(1:00 pm–2:00 pm), and evening (3:00 pm–4:00 pm). Spatially, measurements were taken across three vertical floors: The ground, middle, and top floors. On each floor, sampling focused on six specific rooms chosen by orientation: The four corner rooms and the two central rooms on the east and west axes. Within each selected room, data points were captured at two distinct spatial depths: A perimeter zone close to the external wall or window, and a core zone near the internal corridor. This multi-temporal and multi-spatial configuration ensured mapping of environmental fluctuations throughout the structure.

Subjective IEQ data were gathered through a structured questionnaire distributed to 89 participants, including both faculty and students occupying the monitored rooms. Respondents rated 12 distinct comfort and ergonomic variables using a standardized five-point satisfaction Likert scale,[19] ranging from "Very Unsatisfactory" to "Very Satisfactory." The survey evaluated thermal comfort (temperature and air movement), IAQ (air freshness), visual comfort (daylight, artificial lighting, and glare), acoustic comfort (noise levels and speech audibility), and spatial ergonomics (board visibility, seating comfort, personal space, and crowding). Concurrently, physical observations documented contextual field conditions, such as window operations, air conditioning usage, sunlight penetration, and spatial density. All collected quantitative data from the environmental meters and occupant surveys were compiled, organized, and analyzed using Microsoft Excel. Statistical analysis in Excel focused on descriptive statistics, including calculating averages, tracking parameter ranges, and generating cross-tabulations to identify trends, isolate environmental variances, and directly correlate objective physical measurements with subjective user satisfaction scores.

Results and Discussion

The IEQ assessment data in the contemporary educational building located in South Bengaluru were sourced from multiple sensors spread out across both time and space. Using these sensor-based assessments, comparisons were made against data provided by 89 building occupants during an indicated period of time. The multi-level building consisted of large areas of glass, passively ventilated and experiencing microclimates, which were reflected through varying vertical levels, differing time periods, different depths, and varying face exposures to sun. The baseline physical measurements taken during this assessment included dry-bulb temperature (°C), relative humidity (%), average air velocity (m/s), average daylight (lux), and average A-weighted sound levels (dB-A). These physical measurements found evidence of thermal build-up, inconsistent daylight distribution, and low-level acoustic vulnerability.

The temporal analysis of thermal performance data, as shown in Table 1, shows evidence of a large gap between indoor and outdoor thermal conditions during the forenoon. During the forenoon hours from 9:30 am until 10:30 am, while the external environmental conditions are cool at 26.0°C, the average classroom internal temperature is a high 31.3°C; thus, creating an immediate +5.3°C due to structural thermal heat ingress. In addition, in the case of relative humidity (60.49%) and internal air velocity (0.22 m/s) creates a high likelihood of dissatisfaction from an occupant comfort perception standpoint. A strong correlation exists between perceived temperature comfort (Q1) and perceived air movement (Q2) so that both scores drop to just below the acceptable level of 2.10 and 2.43, respectively. By the afternoon hours from 1:00 pm until 2:00 pm, the internal dry bulb temperatures peak at 32.4°C and equal the outdoor ambient dry bulb temperatures of 32.0°C. This condition represents the greatest peak thermal stress to the structural envelope of the building. Even though the mechanical ceiling fans raise the average internal air speed to 0.48 m/s, the air movement perception (Q2) is at its annual low of 2.37; therefore indicating that low velocity air motion is not efficient for removing heat from an internal space once the internal space temperature has exceeded comfort limits. In the evening transition period between 3:00 pm and 4:00 pm, the temperature indoors decreases a temperature of 31.8°C, and ceiling-mounted fans driven by occupants increase the localized rate of air flow in their respective areas to 0.80 m/sec, effectively returning an air movement score of 3.0 (neutral). Conversely, there is a substantial increase in the relative humidity indoors at 67.4%, which greatly limits the ability of metabolic sweat to evaporate, creating a low final satisfaction score for temperature (2.62).

The spatial distribution of luminous performance, as shown in Table 2, establishes an evident visual discernment between various depths of the room. Indeed, perimeter areas observing daylight near the windows (1.50 m or less) display a mean illuminance of 338.57 lux, exceeding the minimum reading/writing illuminance target level. The high light level of this boundary area has also yielded a positive perceived satisfaction rating (Q4) about the amount of daylight (3.62). However, the high amount of light introduces high levels of visual contrast and direct exposure to solar light during the day. Unfiltered daylight produces noticeable glare on work surfaces and whiteboards, therefore reducing compliance with Q6 to only 2.96 (Vision Glare). In contrast, areas located further back into the core of the layout have a much lower amount of daylit space, as locations deeper into the layout have a significant drop in low level of illuminance, as evidenced by a mean indoor illuminance of 241.65 lux. Furthermore, because of this increased darkness at deeper core lengths, fewer visual disturbances are present from glare; thus, this has yielded a higher satisfaction rating (Q6 = 3.25) regarding glare disturbances. However, satisfaction rating regarding daylight (Q4 = 3.14) is impacted substantially, requiring a high level of reliance on energy-intensive, permanent fluorescent lighting systems for a basic level of visibility to occur.

The vertical building profile has been shown through acoustic monitoring [Table 3] that lower levels of buildings suffer from significant vulnerabilities with regard to noise pollution from the surroundings. The first floor (1F) has been acoustically compromised more than any other zones, with measured indoor levels of 69.00dB(A) being approximately 2.20dB(A) above the measured outdoor traffic noise level of 71.20 dB(A). The high level of noise in this area has resulted in disruption to classroom activities and the perceived acoustic comfort of occupants (Q7)

Table 1: Diurnal variations in thermal parameters and occupant satisfaction

Time slot	*Mean indoor temp (°C)*	*Mean outdoor temp (°C)*	*Mean indoor RH (%)*	*Mean air speed (m/s)*	*Perceived temp comfort (Q1)*	*Perceived air movement (Q2)*
9:30–10:30 am	31.32	26.00	60.49	0.22	2.10 (Unsatisfactory)	2.43 (Unsatisfactory)
1:00–2:00 pm	32.40	32.00	50.83	0.48	2.60 (Neutral-Poor)	2.37 (Unsatisfactory)
3:00–4:00 pm	31.80	31.07	67.38	0.80	2.62 (Neutral-Poor)	3.00 (Neutral)

and speech audibility of occupants in these classrooms (Q8) being rated at critical levels, Q7 = 2.67 and Q8 = 3.10, respectively. The ground floor (0F) and the fourth floor (4F) exhibit similarly high levels of indoor noise (65.71dB(A) and 68.31dB(A), respectively) with the perceived acoustic comfort of occupants (Q7 = 3.2, Q8 = 3.2) being rated below neutral and corresponding to severe challenges for occupants: They may choose to open windows for passive ventilation, and suffer from noise disruption from the surroundings, in their classrooms, or they must completely seal their classrooms for acoustic isolation, and create a condition in which their classrooms are rapidly becoming thermally stagnant. The noise levels appear to dissipate on the seventh floor (7F) of the building, where indoor noise levels are much more comfortable (55.54dB(A)) and the perceived acoustic comfort of occupants (Q7 = 3.21, Q8 = 3.78) is significantly greater than that of lower levels of the building.

Table 4 provides a summary of the interaction between physical metrics and user spatial contexts. The first floor (1F) had the highest levels of spatial congestion, averaging 52.0 per classroom session; 1F also consistently had the lowest scores on all three of the measures of seating comfort (2.67), personal space satisfaction (2.67), and overall indoor comfort (Q12 = 2.83) compared to any other floor level. On the other hand, the seventh floor (7F) had much lower average occupancy levels (32.1 persons per room), and as a result, both layout and internal heat generation had lower levels of crowding. In addition, top-tier respondents rated 7F higher than any other floor for measures related to: Seating comfort (3.21), personal space satisfaction (3.14), and overall indoor comfort (3.43).

The building's envelope orientation determines the amount of solar radiation received on a daily basis. Table 5 exhibits the varying spatial quadrants and their associated micro-environmental issues. The East-Mid space experiences significant cross-micro-environmental stressors; it exhibited the highest indoor comfort temperature (32.5°C), with the highest average dominant luminance, at 402.79 lux, from morning solar radiation at low angles. Consequently, classrooms in this area will become uncomfortably hot before beginning each day and experience the largest dramatic changes in perceived brightness. Therefore, the comfort temperature for this micro-climate is a dangerously low 2.10. The North-West quadrant receives the highest solar gains in the afternoon; consequently, the indoor temperature reached 32.3°C, and perceived glare was rated the poorest (2.84), although daylighting was rated excellent in this area (3.94). The North-East orientation is the most resistant to changing micro-climatic conditions, with an average indoor temperature of 31.2°C and the highest temperature comfort rating of 3.05, therefore confirming that spaces with shields blocking direct solar paths will inherently perform better during South Bengaluru's temperate climate.

Table 6 identifies the physical systems in the building and compares them with the actual field performance, drawing attention to the mechanical failures that reduce total user satisfaction. Almost all the spaces have operable windows (83%), but the noise from the surroundings limits their practical use. This limits the amount of natural ventilation into the building, which adds to the amount of stale air created, which is problematic for occupants. Mechanical air conditioning is only available in specific labs; therefore, all other classrooms cannot be mechanically conditioned to respond to fluctuations in outside temperatures. In addition, classrooms, on average, have 6.2 ceiling fans, which do not produce adequate airflow at the start of the day (0.22 m/s). The unshaded glass of the east and west elevations allows for

Table 2: Spatial depth analysis of luminous metrics and glare perception

Position relative to window	*Mean indoor illuminance (lux)*	*Perceived daylight sufficiency (Q4)*	*Perceived glare disturbance (Q6)*
Perimeter zone (Near)	338.57	3.62 (Satisfactory)	2.96 (Neutral/Noticeable)
Core zone (Away)	241.65	3.14 (Neutral)	3.25 (Comfortable/Low Glare)

Table 3: Acoustic environment and audibility across vertical floor levels

Floor designation	*Mean indoor noise level [dB (A)]*	*Mean outdoor noise level [dB (A)]*	*Perceived acoustic comfort (Q7)*	*Classroom audibility rating (Q8)*
Ground floor (0F)	65.71	68.45	2.81	3.22
First floor (1F)	69.00	71.20	2.67	3.10
Fourth floor (4F)	68.31	70.15	2.78	3.35
Seventh floor (7F)	55.54	58.90	3.21	3.78

Table 4: Spatial ergonomics and overall comfort profile by building tier

Floor level	*Mean occupancy (persons)*	*Seating comfort (Q10)*	*Personal space rating (Q11)*	*Overall indoor comfort (Q12)*
Ground floor (0F)	48.2	2.84	2.81	3.00
First floor (1F)	52.0	2.67	2.67	2.83
Fourth floor (4F)	44.6	2.86	2.84	2.95
Seventh floor (7F)	32.1	3.21	3.14	3.43

Table 5: Environmental profiles categorized by structural orientation

Facade orientation	*Mean indoor temp (°C)*	*Mean luminous level (lux)*	*Temperature comfort (Q1)*	*Daylight comfort (Q4)*	*Glare satisfaction (Q6)*
East Mid (EM)	32.50	402.79	2.10	2.90	3.00
North West (NW)	32.25	338.07	2.21	3.94	2.84
South East (SE)	31.92	259.45	2.26	3.33	3.33
South West (SW)	31.87	280.62	2.10	3.10	2.90
West Mid (WM)	31.69	228.59	2.50	3.14	3.36
North East (NE)	31.20	262.80	3.05	3.43	3.14

Table 6: Operational features and building performance summary

Key architectural feature	*Documented metric/field count*	*Primary observed operational issue*	*Impact on overall comfort (Q12)*
Operable windows	Present in 83% of spaces	High external noise restricts window usage	Negative
Air conditioning	Only available in specific computer/seminar labs	Limited mechanical cooling in general classrooms	Negative
Ceiling fans	Average 6.2 fans per room	Low air speed (0.22 m/s) during morning hours	Negative
Direct sunlight	Observed across East/West zones	Extreme morning and evening heat gains	Negative

direct, intense sunlight to enter the building and raise the internal temperature, and have a cumulative negative effect on overall occupant comfort (Q12).

Discussion: Interpretation and Insights

Despite its location being in a temperate climate of South Bengaluru's contemporary academic block has a high internal thermal penalty. The block's average indoor temperature of 31.8°C and morning indoor temperature of 31.3°C compared to an outdoor temperature of 26.0°C [Table 1] indicate that the building design functions as a structural heat trap [Table 1]. The architectural design of this structure consists of a large concrete block with many floor-to-ceiling glass facades and no shading. The structural design allows the building to retain thermal energy throughout the day without dissipating that thermal energy during the evening hours. This structural heat retention has created a microclimate that is consistently uncomfortable for all students and faculty. Between the hours of 1:00 pm and 2:00 pm, the indoor temperature of the block rises to 32.4°C [Table 1] as a result of the high ambient outdoor temperature and metabolic loads generated by the occupants. The low velocity of air movement (0.22 m/s) inside the block during the morning indicates a lack of cross-ventilation and therefore explains why the occupants rated the air movement (Q2) a low score of 2.43. Evening indoor air movement increases at 0.80m/s due to ceiling fan use; however, increased relative humidity (67.38%) [Table 1] has a negating effect because part of thermal comfort is lost to lack of evaporation through sweating (2.62).

Visual comfort data [Figure 2] indicates that there is a marked difference between the spaces adjacent to windows versus further in from the perimeter, as well as significant differences among various orientations. Perimeter spaces receive sufficient amounts of daylight, averaging 338.57 lux [Table 2], which meets daylight sufficiency criteria and received an average of 3.62 for user satisfaction. However, due to the abundance of daylight in perimeter spaces, direct glare occurs. Perimeter occupants reported difficulty with glare (Q6) at an average of 2.96 due to having unfiltered sunlight directly on their desks or on the whiteboards. Even though the distance from daylight makes it necessary for occupants in the deeper core spaces to rely on artificial light during class, the average amount of daylight received in these zones (241.65 lux as shown in Table 2) was below the minimum acceptable requirement for achieving satisfactory levels of daylight indoors (3.14). Building orientation plays a very significant role in the thermal and visual performance of the building. The North West and East Mid (EM) zones had the highest recorded temperatures (32.5°C and 32.25°C, respectively) at the time that the measurements were taken [Table 5]. Furthermore, much of the direct solar radiation that impacted the EM zone came in early morning, which resulted in the zone being heated before the start of classes.

In addition, the visual performance profile demonstrates that the east-facing orientation suffers from an inadequate amount of

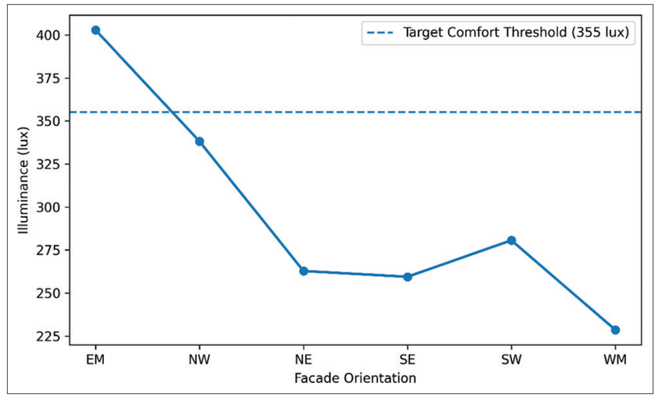

Figure 2: Visual performance profile versus target comfort threshold

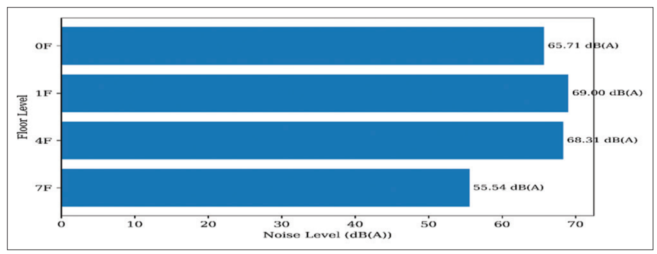

Figure 3: Vertical acoustic profile

light (average of 402.79 lux), with the resultant extreme amount of contrast being detrimental to projector screen output and reducing the effectiveness of teaching through the projection of information. On the other hand, part of the issue with the northwest corner is that it is subjected to excessive amounts of sun during the afternoon; this results in extremely low thermal comfort ratings (2.10 and 2.21). The quadrant that performed the best was the northeast quadrant, where the average temperature was 31.2°C, and there was a relatively high level of comfort (3.05). These results support the idea that areas shielded from direct solar exposure will perform better than those exposed to direct sunlight; such an effect can be seen in the South Bengaluru temperate climate.

From an acoustical perspective [Figure 3], the lower levels of the building suffer from significant interference due to urban noise generated around the building. As shown in Table 3, indoor noise levels were measured at 69.00 dB(A) on 1F and 68.31 dB(A) on 4F based on the vertical acoustic profile. This level of noise comes from outdoor noises (71.20 dB(A)) when windows are open. Occupants have to make the difficult decision to open windows for fresh air ventilation or keep them closed to avoid outdoor noise from intruding into their activity space. The low acoustic satisfaction score for 1F (2.67; [Table 2.3]) is a direct result of the acoustic disruption caused by noise from outside the building. As seen on 7F, indoor noise levels dropped significantly to 55.54 dB(A), thus allowing occupants to experience increased satisfaction (3.21) and audibility (3.78) [Table 3].

The data provide insight into the relationship between the number of occupants per floor, their vertical location within a building, and an occupant's overall satisfaction with the indoor environment. The highest number of people, on average 52 people per room, live on the first floor and rate their personal comfort (2.67) and overall comfort (2.83) as low [Table 4]. High occupant density results in an excess of internal heat load and stale air accumulation, thereby increasing the level of thermal discomfort. In contrast, the seventh floor has an average of 32.1 people per room and a high level of airflow, leading to the highest overall comfort rating (3.43) [Table 4]. This data indicates that occupant comfort is directly influenced by the building's architectural design, the indoor environment, and the management of occupants within that indoor environment.

Alignment with Literature: Comparative Context

Results from this study on user satisfaction with thermal conditions within the academic building, in terms of dissatisfaction levels and heat retention through passive ventilation methods (natural), correspond with those of previous studies focusing on institutional buildings. The documented trend of indoor temperatures exceeding outdoor baseline temperatures for naturally ventilated areas throughout the study is consistent with findings published by Kapoor *et al*.,[9] who observed that school facilities made of cement (e.g., concrete) within India have a tendency to retain heat, resulting in high levels of dissatisfaction. The low (0.22 m/s) levels of air movement during the morning hours and corresponding low level of user satisfaction correlate with the findings of Miranda *et al*.[7] who demonstrated that passive ventilation methods do not produce sufficient airflow during the peak use times (i.e., largest number of occupants). In addition, the lack of thermal comfort (e.g., use of window openings) due to noise pollution also supports the findings of Lamberti *et al*., 2024[20] who indicate that urban educational institutions compromise IAQ to achieve acceptable levels of acoustic comfort. The results from this study oppose what has been established as the traditional adaptive comfort models for temperate climates.[4] Adaptive comfort models assume that moderate external climatic conditions will lead to the creation and persistence of comfortable indoor environments. In high-density academic building environments, the research findings found through this investigation do not support the assumption that architecturally planned elements, such as shading and building orientation, are not required to create comfortable indoor spaces, even with a moderate external climate. The study demonstrates that when projects are designed without consideration of these elements, the existence of moderate external climate conditions will still create uncomfortable indoor spaces. In addition, per Budaniya *et al*.,[1] occupants located in close proximity to windows are generally more satisfied with their indoor environment due to connectivity to natural scenery. However, this study found that the presence of large, unshaded windows caused glare and heat (overall satisfaction score of 2.96 as shown in Table 2) and therefore reduced comfort. There is a clear indication that effective daylighting strategies need to be developed in the design of buildings.

Implications: Theoretical and Practical Transitions

Adaptive comfort theory has been enhanced with this research through findings indicating that in educational institutions located in high-density areas, climatic conditions will not solely determine comfort numerically. The occurrence of varying heat and occupant density can have a greater impact on indoor comfort than prevailing outdoor weather conditions. The results of this research also emphasize that specifically developed models to reflect comfort within institutional buildings in temperate climates are critical and should exist beyond generalized regional standards. This research provides architects and institutional administrators with clear and concise recommendations to improve occupant comfort:

- Use solar shading techniques: Install exterior shading devices and/or automatic shades on East- and West-facing facades to reduce thermal gain due to solar exposure in the morning and afternoon [Table 5].
- Provide noise barriers: Install double glazing into lower floors (0F–4F) to create noise barriers while allowing for a change in use of space from time to time [Table 3].
- Utilize smart ventilation systems: When establishing locations for ceiling fan installations, consider placing fans in locations that provide for consistent air movement (>0.5 m/s) to each zone of the room during periods of high occupancy (e.g., morning classes when occupied) [Table 1].

Limitations: Boundaries of the Present Assessment

Although this study offers valuable insight into the benefits of this type of environmental monitoring, the following limitations should be borne in mind while interpreting results:

- Short-term data: Environmental monitoring was done over a period of time only during regular academic sessions, and therefore seasonal variations were not addressed. For example, there was no consideration of the significant seasonal changes, such as the monsoon transition and the very hot summer months that occur in this region (South Bengaluru).
- No air quality parameters: The study relied on physical parameters and user surveys to assess the success of the physical environment, as there were no objective measures of air quality, that is, CO_2 levels, PM 2.5, etc. A complete analysis of the air quality of the room during the study was not possible because no objective measures were taken.
- Limited sample size: The sample being analyzed in this study includes a total of 89 occupants from the same contemporary-style building. By being so specific to this set of occupants/setting, the results of this study cannot be generalized to older styles of institutional buildings or other types of architectural style in this area.

Conclusion and Future Work

Key Findings

This empirical investigation has revealed a significant gap between the relatively moderate condition of the external environment in South Bangalore and the IEQ of a current naturally ventilated academic establishment. Field measurements have indicated numerous instances of elevated indoor temperatures compared to external ambient air, with the average value of 31.8°C for indoor temperature determined by the average external temperature of 29°C. In essence, the structure appears to function as a thermal heat sink; that is, there is an indoor-outdoor temperature disparity as early as the morning hours (31.32°C for indoors versus 26.00°C for outdoors) but increasing to a maximum of 32.40°C later in the afternoon hours. Consequently, these thermal conditions correspond to significant user dissatisfaction based on low temperature comfort scores (Q1 measured between 2.10 and 2.62). Furthermore, based on spatial analysis, the extensive use of glass facade has created a spatial microclimatic separation whereby perimeter zones have ample daylighting (measured at 338.57 lux) but suffer from substantial glare conditions (Q6 measured at 2.96). Conversely, the core deep zones experience a dramatic decline in daylighting measured at only 241.65 lux and, thus, require the continual use of artificial lighting to maintain satisfactory levels of illumination during periods of occupancy. In light of acoustic conditions, the lower levels of urban traffic noise create a 1st floor (1F) indoor acoustic penalty of approximately 69.00 dB(A), which corresponds with occupants' perceptions of low acoustic comfort (Q5 calculated at 2.67). By contrast, the 7th floor (7F) has reduced urban traffic noise levels to approximately 55.54 dB(A), providing occupants with higher perceived overall comfort levels (Q5 calculated at 3.43) due to lower occupant densities.

Expanding on the adaptive comfort theory by demonstrating that, contrary to the typical assumption that a region's temperate climate provides comfortable indoor environments for high-density institutions, structural heat retention, occupant density, and urban noise pollution work in conjunction to support the notion that localized physical conditions can trump regional climatological conditions by presenting an example of how to measure and document these variables. The need for microclimatic comfort standards at the building level as opposed to regional template standards is highlighted by this documentation. The development of a data-driven framework for institutional administrators and designers for utilization within rapidly urbanizing Indian microclimates is anticipated to be of great importance. The empirical results of this research will serve as a basis for assisting stakeholders in addressing issues related to natural ventilation and acoustic insulation, creating optimum classroom layouts based on orientation, and developing target retrofits (e.g., using external shade on East-West facades and using double-glazing units on lower levels of buildings) to reduce energy consumption and improve the quality of learning environments.

Future Directions

Although our results establish a microclimatic baseline, there are many avenues available for future work. The first logical step would be to expand upon our environmental monitoring efforts to encompass a full year – this will allow researchers to document seasonal climate changes (e.g., monsoon seasons or peak summertime temperatures). Objective IAQ measurements (e.g., CO_2 concentrations, total volatile organic compounds (TVOCs), and PM2.5) could also be added to future analysis so that researchers can correlate objective measures of the chemical quality of the air with the occupants' metabolic rates. In addition, expanding the current study to compare/contrast between two building types (i.e., traditional concrete with low amounts of glass and modern buildings with glass façades) to obtain a clear picture of how modern versus traditional building designs affect climate resilience. All of this information will be invaluable when computer modelling building energy use and smart retrofitting (i.e., automatic shading devices, use of mixed-mode heating and cooling systems) using sophisticated energy modeling software, such as EnergyPlus.

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Ethical Statement

This study did not involve any human or animal subjects and, therefore, did not require ethical approval.

Declaration

The authors declare that this manuscript is original and has not been published or accepted for publication elsewhere, in print or electronic format.

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