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CONFERENCE PAPER · LOW-CARBON BUILDINGS

Characterisation of Bedroom Thermal Microclimates Influencing Sleep Quality in Diverse Residential Settings in Kerala: Integrating Indoor Environmental Monitoring, PMV and Sleep Assessment

Anagha Ashok[1]*, Deepa Rani R[1]

[1] Department of Architecture and Planning, College of Engineering Trivandrum, Thiruvananthapuram, Kerala, India

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ABSTRACT

Sleep quality in Kerala's warm-humid climate is strongly influenced by night-time temperatures, persistent humidity, and restricted natural ventilation—factors that directly affect human thermoregulation and the stability of circadian rhythms. As traditional, well-ventilated homes are increasingly replaced by compact urban dwellings with restricted airflow, indoor environments are gradually diverging from climate-responsive design principles that historically supported nocturnal comfort. Therefore, this study investigates how bedroom thermal microclimates characterised by localised variations in temperature, humidity, airflow, and indoor air quality shape sleep quality across diverse residential settings in Kerala. A mixed-method approach is employed, integrating continuous environmental monitoring (temperature, humidity, and CO_2 levels), thermal comfort assessment using Predicted Mean Vote (PMV) indices, smart watch-based sleep tracking, and subjective evaluations through the Pittsburgh Sleep Quality Index (PSQI) in selected bedrooms in residential buildings. The results reveal a clear inverse relationship between thermal discomfort and deep sleep duration. As PMV values increase, indicating warmer and more uncomfortable conditions, deep sleep duration consistently decreases, a trend that remains evident even after accounting for age-related variations in sleep duration. Nights with PMV values exceeding 1.6 are associated with significantly reduced deep sleep (approximately 0.42 hours), whereas more moderate conditions with PMV values in the range of 1.2–1.3 correspond to higher deep sleep durations (approximately 0.55–0.60 hours). These findings establish PMV as a meaningful indicator linking indoor thermal conditions with sleep quality outcomes in warm-humid residential environments, demonstrating that elevated temperature and humidity significantly compromise sleep efficiency and continuity.

KEYWORDS Warm-humid climate, Sleep quality, Thermal comfort, Predicted mean vote (PMV), Indoor environmental quality (IEQ), Bedroom microclimate, Pittsburgh Sleep Quality Index

1. Introduction

Sleep is a fundamental physiological process essential for maintaining physical health, cognitive function, and emotional well-being. Poor sleep quality has been associated with adverse health outcomes, including cardiovascular disease, metabolic disorders, and impaired cognitive performance (Buysse *et al.* 1989). Since individuals spend approximately one-third of their lives indoors during sleep, the bedroom environment plays a critical role in influencing sleep quality.

Among indoor environmental factors, the thermal environment is particularly important because sleep is closely linked to human thermoregulation. During sleep onset, the body dissipates heat through peripheral vasodilation and a reduction in core body temperature. Elevated indoor

* Corresponding author. Email address: anaghasubhadram@gmail.com (Anagha Ashok)

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temperatures and excessive humidity interfere with this process, leading to delayed sleep onset, reduced deep sleep, and increased nocturnal awakenings (Okamoto-Mizuno and Mizuno 2012). In warm-humid climates, where night-time temperatures remain high and humidity restricts evaporative cooling, maintaining a comfortable sleeping environment becomes especially challenging.

Kerala's tropical climate is characterised by persistently high temperatures and relative humidity throughout much of the year. Traditionally, residential buildings incorporated climate-responsive features such as large openings, courtyards, and high ceilings to enhance natural ventilation. However, rapid urbanisation has led to compact residential developments with reduced airflow and increased heat retention, potentially affecting indoor thermal comfort and sleep quality.

Recent studies have demonstrated that bedroom ventilation and indoor environmental quality significantly influence sleep outcomes. Fan *et al.* (2023) found that improved bedroom ventilation enhanced objectively measured sleep quality, while Akimoto *et al.* (2025) reported that inadequate ventilation and elevated indoor CO_2 concentrations were consistently associated with poorer sleep performance. These findings highlight the importance of assessing multiple indoor environmental parameters rather than temperature alone.

Despite growing research on thermal comfort and sleep, field-based studies investigating bedroom thermal microclimates in naturally ventilated residential buildings within tropical climates remain limited, particularly in the Indian context. This study addresses this gap by characterising bedroom thermal microclimates across diverse residential settings in Kerala and examining their influence on sleep quality. A mixed-method approach integrating continuous monitoring of temperature, relative humidity, carbon dioxide concentration, thermal comfort assessment using Predicted Mean Vote (PMV), smart watch-based sleep tracking, and the Pittsburgh Sleep Quality Index (PSQI) was employed. The findings aim to provide evidence for climate-responsive residential design strategies that promote healthier indoor sleeping environments.

2. Materials and methods

This study adopted a mixed-method approach to characterise bedroom thermal microclimates and evaluate their influence on sleep quality in diverse residential settings across Kerala. Objective environmental measurements were integrated with subjective and objective sleep assessments to establish relationships between indoor thermal conditions and sleep outcomes. The methodology comprised continuous monitoring of bedroom environmental parameters, thermal comfort assessment using the Predicted Mean Vote (PMV) model, smart watch-based sleep monitoring, and subjective evaluation using the Pittsburgh Sleep Quality Index (PSQI).

2.1. Study Area and Sample Selection

Ten naturally ventilated bedrooms located in different districts of Kerala were selected to represent diverse residential settings and ventilation conditions. Participants belonged to two age groups (24–35 years and 36–50 years), were in good general health, and did not use sleep medication. Both single-occupancy and shared bedrooms were included to capture variations in residential sleeping environments.

Bedroom ventilation was classified into four categories based on the configuration of windows and doors during the sleeping period: V1 (window and door open—cross ventilation), V2 (window open and door closed), V3 (partially open window), and V4 (window closed).

Table 1. Ventilation types adopted for the surveyed bedrooms.

Code	Description
V1	Window open + door open
V2	Window open + door closed
V3	Window partially open
V4	Window closed

Other characteristics of the surveyed rooms were observed and tabulated as follows:

Table 2. Characteristics of the surveyed bedrooms.

Cases	Location	Floor level	Bed orientation	Ventilation type	Mechanical ventilation (ceiling fan)	Occupancy
Room 1	Trivandrum	First	North	V2	on	Double
Room 2	Thrissur	First	East	V3	on	Double
Room 3	Thrissur	First	South	V1	on	Single
Room 4	Trivandrum	Ground	North	V2	on	Single
Room 5	Kochi	Second	East	V1	on	Single
Room 6	Trivandrum	First	South	V4	on	Single
Room 7	Kochi	Second	South	V1	on	Single
Room 8	Kochi	Third	North	V4	on	Single
Room 9	Kannur	Ground	East	V1	on	Single
Room 10	Kannur	Second	West	V4	on	Single

2.2. Environmental Monitoring and Thermal Comfort Assessment

Night-time environmental conditions were monitored using a Lutron WBGT-2010SD data logger and a Testo Smart Meter. Air temperature, relative humidity, carbon dioxide (CO_2) concentration, and air velocity were recorded during the sleeping period to characterise the bedroom thermal microclimate. Environmental and sleep data were synchronised for each monitored night to facilitate comparative analysis.



Figure 1. Testo Smart Meter used to measure indoor air temperature, relative humidity, and air velocity.



Figure 2. WBGT meter used to periodically measure air temperature, globe temperature, relative humidity, and wet bulb globe temperature in the surveyed bedrooms during night-time field measurements.

Table 3. Measured indoor environmental and occupant-related parameters for each surveyed bedroom.

Room	Location	Age Group (years)	Met value	Air temperature Ta (°C)	Relative Humidity (%)	Clo value
R1	Trivandrum	36–50	0.85	27.8	79	0.4
R2	Thrissur	36–50	0.85	28.4	82	0.4
R3	Thrissur	24–35	0.90	26.9	75	0.4
R4	Trivandrum	36–50	0.85	28.6	83	0.4
R5	Trivandrum	24–35	0.90	26.2	72	0.4
R6	Trivandrum	36–50	0.85	28.8	84	0.4
R7	Kochi	24–35	0.90	26.6	74	0.4
R8	Kochi	36–50	0.85	28.3	81	0.4
R9	Kannur	24–35	0.90	25.9	70	0.4
R10	Kannur	36–50	0.85	28.5	83	0.4

Thermal comfort was evaluated using the Predicted Mean Vote (PMV) model developed by Fanger and implemented through the CBE Thermal Comfort Tool, following the procedures outlined in ISO 7730 (ISO 2005) and ASHRAE Standard 55 (ASHRAE 2023). PMV calculations incorporated measured environmental variables together with sleeping-specific assumptions, including a metabolic rate of approximately 0.7 met and clothing/bedding insulation representative of typical sleeping conditions.

Table 4. Corresponding PMV values from CBE thermal comfort tool.

Room	Vent Class	Air Speed (m/s)	PMV	Thermal Sensation
R1	V2	0.20	1.38	Warm
R2	V3	0.15	1.62	Warm
R3	V1	0.35	1.05	Slightly warm
R4	V2	0.20	1.55	Warm
R5	V1	0.35	0.92	Near neutral to slightly warm
R6	V4	0.10	1.78	Very warm
R7	V1	0.35	1.00	Slightly warm
R8	V4	0.10	1.70	Warm to very warm

Table 4. (continued)

Room	Vent Class	Air Speed (m/s)	PMV	Thermal Sensation
R9	V1	0.35	0.85	Near neutral
R10	V4	0.10	1.72	Warm to very warm

2.3. Sleep Quality Assessment

Objective sleep quality was assessed using smart watch-based sleep tracking. Participants record their average sleep statistics from the past week, as tracked by their smart watch. This includes total sleep duration, the amount of time spent in REM, deep, and light sleep, sleep efficiency percentage, average sleep and wake times, and the number of awakenings per night. These objective measures provide a more accurate picture of sleep quality than self-reports alone.

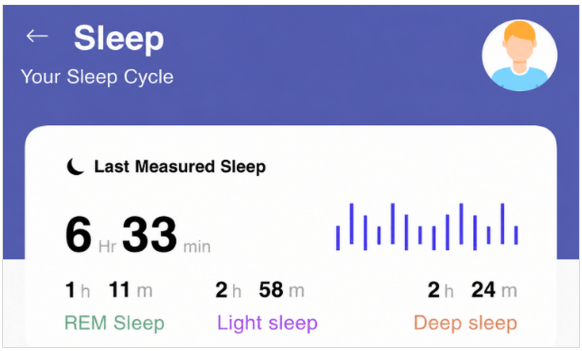

Figure 3. Sleep cycle duration as measured by smart watch as shown in the respective android app, provided by the respondents.

Table 5. Sleep cycle duration as measured by smart watch as shown in the respective android app, provided by the respondents.

Cases	Age group	Total sleep duration(hrs)	Deep sleep(hrs)	Light sleep (hrs)	REM sleep(hrs)
Room 1	36–50	6	0.6	3.48	1.92
Room 2	36–50	6	0.36	3.96	1.68
Room 3	24–35	6.5	0.78	3.58	2.15
Room 4	36–50	6	0.48	3.72	1.8
Room 5	24–35	6.5	0.98	3.25	2.28
Room 6	36–50	6	0.36	3.96	1.68
Room 7	24–35	6.5	0.98	3.25	2.28
Room 8	36–50	6	0.36	3.96	1.68
Room 9	24–35	6.5	0.98	3.25	2.28
Room 10	36–50	6	0.36	3.96	1.68

Subjective sleep quality was evaluated using the Pittsburgh Sleep Quality Index (PSQI), a validated self-administered questionnaire developed by Buysse *et al.* (1989). The PSQI evaluates sleep quality over the previous month through 19 self-rated items, which are grouped into seven components: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction.

Each component is scored on a 0–3 scale, where 0 indicates no difficulty and 3 indicates severe difficulty. The seven component scores are summed to obtain a global PSQI score ranging from 0 to 21, with lower scores representing better sleep quality. A global score of ≤5 indicates good sleep quality, whereas a score of >5 indicates poor sleep quality.

Table 6. PSQI score and its implications.

Total PSQI Score	Description	Implication
0–4	Good sleep quality	Normal, healthy sleep patterns
5–9	Poor sleep quality	Some sleep problems, not severe
10–14	Moderately Poor Sleep	Noticeable sleep issues that may affect daytime functioning
15–21	Severe Sleep Problems	Significant, likely chronic sleep disturbance

The findings from the participants were tabulated as follows:

Table 7. The observations from the participants and their respective PSQI scores.

Cases	Age group	Total sleep duration(hrs)	Sleep quality
Room 1	36–50	6	Mild disturbance
Room 2	36–50	6	Moderate disturbance
Room 3	24–35	6.5	Near good
Room 4	36–50	6	Mild disturbance
Room 5	24–35	6.5	Good sleep
Room 6	36–50	6	Moderate-severe
Room 7	24–35	6.5	Good sleep
Room 8	36–50	6	Moderate
Room 9	24–35	6.5	Very good
Room 10	36–50	6	Moderate-severe

2.4. Data Analysis

The monitored environmental parameters were analysed alongside PMV values, smart watch-derived sleep metrics, and PSQI scores to identify relationships between bedroom thermal microclimates and sleep quality. Comparative analyses were performed across different ventilation categories and residential settings to evaluate the influence of thermal conditions on deep sleep duration and perceived sleep quality.

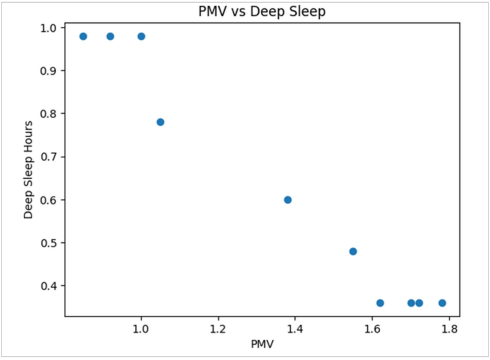

Figure 4. The scatter plot illustrates the relationship between predicted mean vote (PMV) and deep sleep duration for the ten surveyed bedrooms.

The scatter plot indicates a distinct negative association, where increasing PMV values correspond to progressively shorter deep sleep durations. Bedrooms with PMV values closer to thermal neutrality (0.85–1.00) consistently exhibited longer deep sleep durations, whereas rooms with higher PMV values (>1.50), representing warmer thermal conditions, showed a marked reduction in deep sleep.

Table 8. Relationship between PMV and deep sleep duration.

PMV Range	Deep Sleep Duration (h)
0.85–1.00 (V1 rooms)	0.98
1.05–1.38	0.60–0.78
1.55–1.62	0.36–0.48
≥1.70 (V4 rooms)	0.36

Overall, the scatter plot demonstrates that deep sleep duration decreases as PMV increases, highlighting the importance of maintaining bedroom conditions closer to thermal neutrality during the night. The findings also emphasize that passive design strategies such as effective cross-ventilation can improve thermal comfort and contribute to healthier sleep in naturally ventilated residential buildings in Kerala.

3. Results and discussion

The results obtained from environmental monitoring and sleep assessments were analysed to investigate the relationship between bedroom thermal microclimates and sleep quality in diverse residential settings across Kerala. The observed relationship is also consistent with thermal comfort theory. As PMV increases above the comfort range, occupants experience greater thermal stress, leading to physiological responses such as increased perspiration, elevated skin temperature, and more frequent sleep disturbances. These responses can reduce the duration of slow-wave (deep) sleep, which is the most restorative stage of the sleep cycle.

The present results therefore support the research indicating that warmer sleeping environments negatively affect sleep architecture by reducing deep sleep while increasing the likelihood of fragmented sleep. The findings contribute empirical evidence to support the integration of sleep-oriented thermal comfort considerations into residential building design and provide a basis for future research involving larger sample sizes, seasonal investigations, and a broader range of residential typologies to further strengthen climate-responsive housing design guidelines.

Declarations

Author contributions. Anagha Ashok: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing (original draft), Visualization, Validation, Software, Resources, Writing (review and editing). Deepa Rani R: Conceptualization, Methodology, Writing (review and editing), Supervision, Resources, Software, Project administration.

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Data availability. All data generated or analysed during this study are included in this paper.

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