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Evaluating and comparing objective and subjective thermal comfort in a malaysian green office building: A case study

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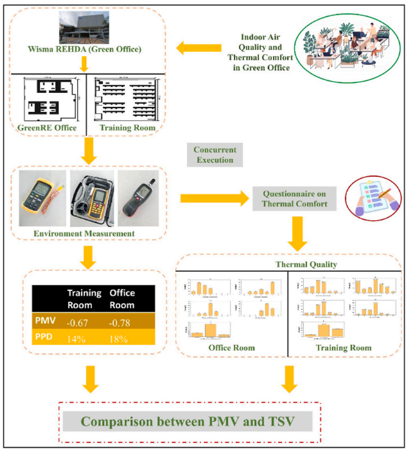
GRAPHICAL ABSTRACT



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ABSTRACT

This study examined thermal comfort in a sustainable office building in Malaysia, with the goal of understanding how objective environmental data relates to occupants' subjective experiences. The study utilized established thermal comfort models, such as the predicted mean vote (PMV), in conjunction with occupant surveys to evaluate the indoor environment. Objective data aligned with thermal comfort criteria, but subjective thermal sensation vote (TSV) showed a notable difference. The environment felt colder than anticipated by the occupants. This study emphasises

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the drawbacks of depending exclusively on conventional thermal comfort models, especially in tropical settings. The research emphasises the importance of considering individual variability (physiological and psychological), localised environmental variables, and potential adaptive comfort mechanisms impacted by regional climate. This research aims to develop a thorough understanding of green buildings' inside climates to inform design methods for achieving optimal thermal comfort, energy efficiency, and reduced carbon emissions. The results provide guidance on methods for emphasising occupant-centered design in sustainable buildings located in tropical areas. This study focuses on filling the knowledge gaps regarding the dynamics of thermal comfort in green buildings located in tropical regions. Combining empirical data with subjective feedback emphasises the need for design strategies that focus on occupant well-being in addition to energy efficiency goals.

List of abbreviations

ASHRAE	American Society of Heating, Refrigeration Air-Conditioning Engineers
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
TSV	Thermal Sensation Vote
CBE	Center for Built Environment
RH	Relative Humidity
ISO	International Organization for Standardization

1. Introduction

People typically spend around 90 % of their time indoors, with considerable time spent in office settings. Establishing a healthy and comfortable interior environment is crucial. It highlights the need to maintain suitable indoor environmental conditions for occupants. Optimal conditions are critical for occupant pleasure and well-being and for preventing potential health issues. Green building approaches strive to achieve this objective while also decreasing energy usage. The construction of green buildings has surged in recent years due to the urgent difficulties posed by the energy crisis and global warming. Green building projects focus on constructing high-performance buildings that emphasise energy efficiency and provide a healthy and comfortable indoor environment. Tens of thousands of certified green office buildings operate worldwide, emphasising energy and environmental conservation as their primary principles. The designs of these structures aim to minimize energy consumption and lessen their environmental impact. The main goal is to optimise energy, water, land usage, and material conservation across the building's whole lifecycle, including planning, design, construction, and continuous operation. Green office buildings focus on optimising energy efficiency to minimize pollution and safeguard the environment while providing inhabitants with a healthy and comfortable workplace. Sustainable, high-performance buildings are becoming increasingly popular and serve as a crucial measure for assessing worldwide sustainable development efforts.

Extensive research has investigated different aspects of green office buildings, including green building technologies, building energy efficiency assessments, indoor environmental quality (IEQ), and post-occupancy evaluations. Studies have investigated the efficiency and long-term viability of green roof and wall technologies with economic advantages and reduction of carbon emissions. These studies emphasise their role in enhancing energy efficiency and providing thermal comfort in buildings [1–3]. However, Widiastuti et al. [4] propose that green facades could raise interior relative humidity, which might cause discomfort. The green building movement is placing more emphasis on IEQ issues and how they affect the health and comfort of occupants. Research by Zhao et al. [5] has explored the impact of acoustic quality, lighting, thermal comfort, indoor air quality (IAQ), and IEQ on building occupants. Kaarlela-Tuomaala et al. [6] and Abd Jalil et al. [7] suggest that open-plan workplaces may not be acceptable for professional workers due to noise disturbances and interruptions. Consequently, modifications are necessary to accommodate different types of work. Several studies [8–10] demonstrate that indoor lighting and illumination improvements can enhance visual comfort and reduce eye strain for occupants. Furthermore, research by Kosonen and Tan [11]; Mahbob et al. [12]; Mohamed and Srinavin [13] have found that there is a direct relationship between optimal thermal comfort, enhanced IAQ, and health, well-being, and productivity of occupants in both traditional and environmentally-friendly buildings. Su et al. [14] and Wu et al. [15] indicate that green office buildings have a tangible impact on improving IAQ. Furthermore, the level of green certification obtained by these buildings is directly proportional to the quality of indoor air.

Many studies have also examined the thermal comfort of individuals in both conventional and green buildings [11–13]. The results of these investigations establish a strong association between how well people execute tasks and how they perceive the temperature of their surroundings, as shown using correlation and regression analysis. Thermal indicators have been utilized to construct predictive models for worker productivity. Lu et al. [16] discovered variations in thermal comfort thresholds across green buildings in different climatic regions. Green office buildings provide a twofold advantage: simultaneously contribute to energy efficiency to reduce carbon emissions and enhance user productivity and efficiency, making them a precious economic asset [17]. Nevertheless, the influence of Indoor Environmental Quality (IEQ) on those working in green office buildings has become a significant matter of concern. IEQ is affected by various factors, such as indoor air temperature, relative humidity, wind speed, airflow patterns, pollutant concentrations, odours, noise, and lighting [18]. Past studies have classified the concept of IEQ into four primary domains: thermal comfort, IAQ, visual comfort, and acoustic comfort [19–21]. Due to its crucial importance in IEQ, the thermal environment and thermal comfort of green buildings should be given greater emphasis [22–24]. Moreover, numerous studies have underscored the importance of thermal comfort in office buildings [25–28]. Unfavourable comfort conditions can give rise to adverse effects on occupants, influencing their conduct, well-being, efficiency, and the calibre of their work performance. Occupants may experience fatigue in hot office spaces, whereas freezing temperatures can instigate discomfort and lead to distractions [29]. As indicated in the study by Abass et al. [29], the investigation of indoor thermal comfort in buildings serves dual vital objectives. Firstly, it aims to provide occupants with a satisfactory and conducive indoor environment. Secondly, it is oriented towards optimising energy consumption and promoting energy efficiency within the building. Researchers conducted multiple studies in Malaysia, to identify the appropriate indoor thermal comfort levels for tropical climates. Previous studies before the 1990s indicated that the widely acknowledged range of indoor air temperatures deemed acceptable for air-conditioned office buildings typically fell within 23–26 °C [30]. Similarly, Ahmad [31] delved into the realm of thermal comfort, this time with the objective of discerning strategies for energy efficiency within an office setting. The outcomes of this study pinpointed a range of comfort that extended from 24.5 °C to 28.0 °C, all while maintaining a relative humidity of 73 %. Similarly, in another study conducted within an office edifice, it was divulged that upholding an average indoor air temperature of 23.6 °C, alongside a relative humidity of 50 %, engendered a condition of thermal contentment among occupants [32]. Shaharon and Jalaludin [33] conducted research to assess worker contentment in a Low Energy Office Building in Malaysia. The outcomes unveiled that indoor thermal conditions adhered to ISO7730's acceptable range (23–26 °C), with temperatures lower than MS 1525's standards. Similarly, Damiati et al. [34] approximated a comfortable temperature range of 25.60 °C for air-conditioned office buildings in Malaysia.

On the other hand, Elnaklah et al. [35] investigated the experiences of 120 employees transitioning from a conventional office building to a green building. Their study employed surveys to assess occupant perceptions. While the green building adhered to recommended thermal comfort standards, the findings indicated lingering concerns regarding potential negative impacts on occupant comfort and health arising from efforts to improve thermal performance and energy efficiency. Similarly, previous studies comparing indoor environments in conventional and green buildings reported potential benefits of green buildings for overall IEQ and occupant comfort but lacked conclusive evidence. A review of the existing literature reveals a research gap related to the specific influence of thermal comfort within the broader realm of IEQ studies in green buildings. While scholars have extensively explored various IEQ aspects, factors directly impacting thermal comfort, such as the indoor thermal environment, appear less well-investigated [36–38]. Further supporting this notion, Liang et al. [36] identified office temperature as a primary source of occupant dissatisfaction and discomfort. Despite this, traditional thermal comfort models predominantly focus on tangible environmental and personal factors, often overlooking the subjective nature of comfort and the profound impact of psychological elements on individual experiences. There is a growing body of research highlighting the importance of psychological variables such as mood state, expectations, environmental control, and adaptability in shaping thermal perceptions. These aspects contribute to the discrepancies often observed between calculated predicted mean votes (PMV) and actual thermal sensation votes (TSV). The work of Özbey and Turhan [39] offers a promising avenue by proposing a mood state correction factor within thermal comfort models. This factor integrates psychological influences into PMV calculations, recognizing the varying effects of individuals' mood states on their perception of thermal conditions. While this represents a notable advancement, challenges persist in accurately quantifying psychological factors and addressing individual and cultural differences. Additionally, incorporating psychological motivations for behavioral adaptations could further enhance the refinement of thermal comfort models, leading to more personalized and accurate assessments of comfort in built environments.

Therefore, this study investigates the thermal comfort and IEQ of green office buildings in Malaysia. To comprehensively understand the gap between design goals and actual performance. This study aims to assess the indoor thermal environment and occupant thermal comfort in green office buildings and compare the objectively measured indoor thermal environment with the subjectively reported thermal comfort of occupants within green office buildings. The research employs a combined approach utilising both objective and subjective measurements. Objective measurements of temperature, humidity, and airflow will be conducted to assess the physical characteristics of the indoor thermal environment within the buildings. Complementing these objective assessments, subjective occupant surveys will gather data on thermal comfort levels and experiences. By analyzing this combined dataset, the study aims to achieve a more nuanced understanding of Malaysia's current state of green office buildings. This knowledge will be valuable for informing the development of design and operational strategies for green buildings that can achieve a balance between improved energy efficiency, reduced carbon emissions, and a healthy and comfortable indoor environment for occupants.

2. Methods

2.1. Location and building information

The present research utilises Wisma REHDA, a three-story office building in Kelana Jaya, Petaling Jaya, Selangor, certified as GreenRE Gold as shown in Fig. 1. This certification indicates the building's dedication to sustainable design and operation. The main characteristics of this building are its southern orientation, which reduces solar exposure, efficient energy and water systems, and passive ventilation. The building's double-skin facade, designed to reduce heat gain, is particularly noteworthy. In addition, the strategic positioning of office areas towards the north and east provides shielding from direct sunshine. The mean annual temperature in the Selangor region is 28 °C, accompanied by an average humidity level of 86 %. It highlights the significance of efficient indoor environmental control in this tropical climate. Two rooms, an office area and a training room, were chosen within Wisma REHDA to measure indoor environmental parameters and conduct a questionnaire survey. The office room is a relatively spacious area located on the first

Fig. 1. Location of the green building. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

level of the building. It is commonly utilized for both independent and cooperative tasks. The office was cooled by four ceiling cassette air conditioners operated during the working period (9-6 PM) with a constant temperature setting of 24 °C. The training room is more prominent on the second floor and primarily used for group instruction and presentations. 6 ceiling cassette air conditioners cool the training room and operate during the working period (9-6 PM) with a constant temperature setting of 24 °C. These spaces were selected due to their contrasting sizes, occupancy patterns, and orientations within the building, potentially leading to variations in indoor environmental conditions. Fig. 2 depicts the two distinct areas of interest: the training room and the office room within the green office building.

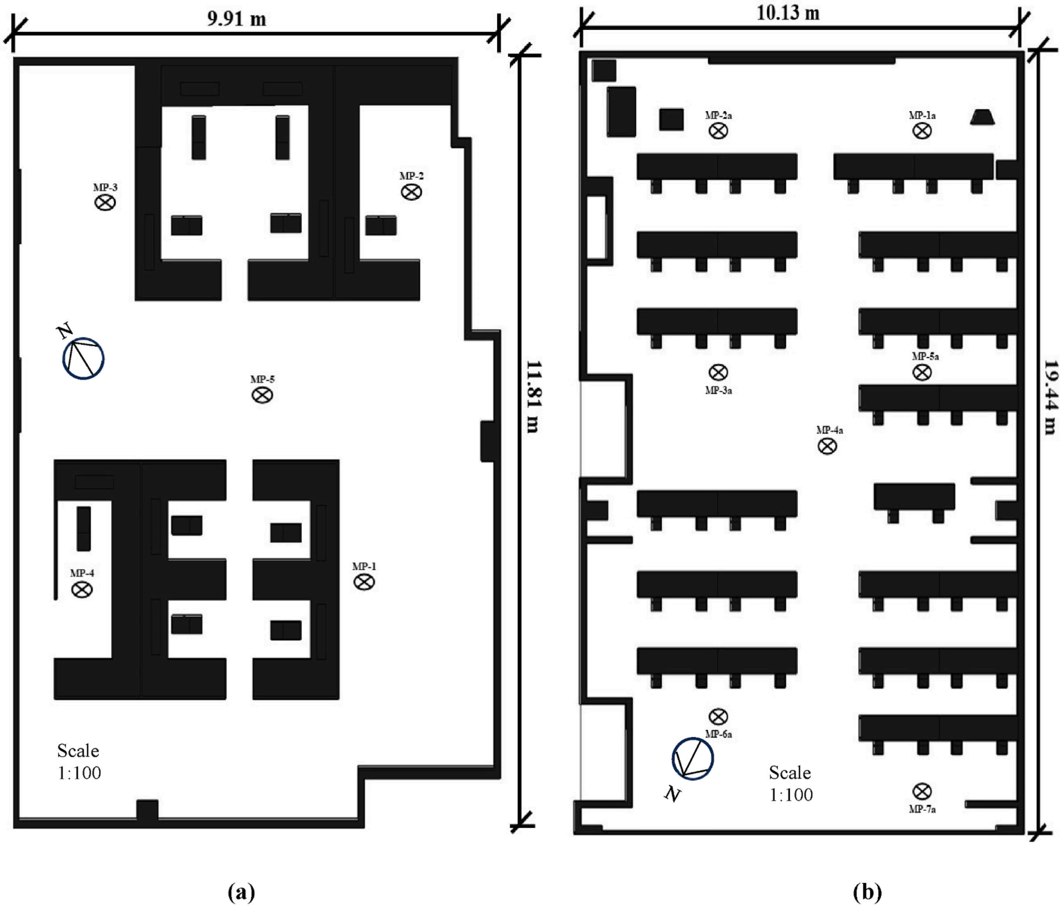

Fig. 2. Layouts of the designated areas within the building and measuring points. (a) Training room (located on the 2nd floor); (b) Office room (located on the 1st floor).

Malaysia falls under the Koppen's climatic classification of "equatorial fully humid," as depicted in Fig. 3 consequently, Malaysia experiences consistently high temperatures throughout the year, with typical averages ranging from 25 °C to 33 °C and minimal seasonal fluctuation. Furthermore, the Intertropical Convergence Zone (ITCZ) brings a high volume of precipitation exceeding 2000 mm annually without a distinct dry season. Coupled with the persistent heat, this rainfall pattern results in consistently high humidity levels, frequently exceeding 80 %.

2.2. Measurement of indoor environment parameters

The physical measurement was undertaken in the Training and Office rooms over three months, from February 13th to April 14th, 2023. Before commencing the measurements, suitable spots were carefully identified for data collection. Following the protocols outlined in ISO 16000–1 [40] for physical measurements conducted at seated positions situated 1.1 m above floor level, calibrated instruments were utilized to measure specific thermal parameters intricately. These parameters encompassed variables like air temperature (T_a), air velocity (m/s), and relative humidity (RH). Further, operative temperature (T_{op}), an index widely used in thermal comfort studies considering the effects of air temperature, mean radiant temperature and air velocity on human thermal comfort, was used and calculated by equation (1) given in the ASHRAE 55 standard [41].

$$T_{op} = AT_a + (1 - A)\, T_{mrt} \tag{1}$$

T_a is the air temperature (°C), and T_{mrt} is the mean radiation temperature (°C). A is a dimension less constant. Furthermore, concerning the mean radiant temperature, T_{mrt} was determined using the following equation (2) :

$$T_{mrt} = T_1A_1 + T_2A_2 + \ldots + T_nA_n / (A_1 + A_2 + \ldots + A_n) \tag{2}$$

Where T is the surface temperature, and A is the room surface area.

The data collection took place from 9:30 a.m. to 6 p.m. Fig. 2 visually represents the deliberate arrangement of measurement points, facilitating a thorough grasp of the authentic thermal comfort conditions experienced throughout the working hours. For accurate measurements of thermal parameters, the experiment utilized a thermocouple thermometer, anemometer, and thermo-hygrometer, as shown in Fig. 4, whereas Table 1 demonstrates the equipment specifications.

2.3. Subjective questionnaire

Due to individual differences, perceptions of the indoor environment vary among individuals. To understand office workers' experiences of thermal comfort, this study employed a subjective questionnaire survey alongside objective measurements of environmen-

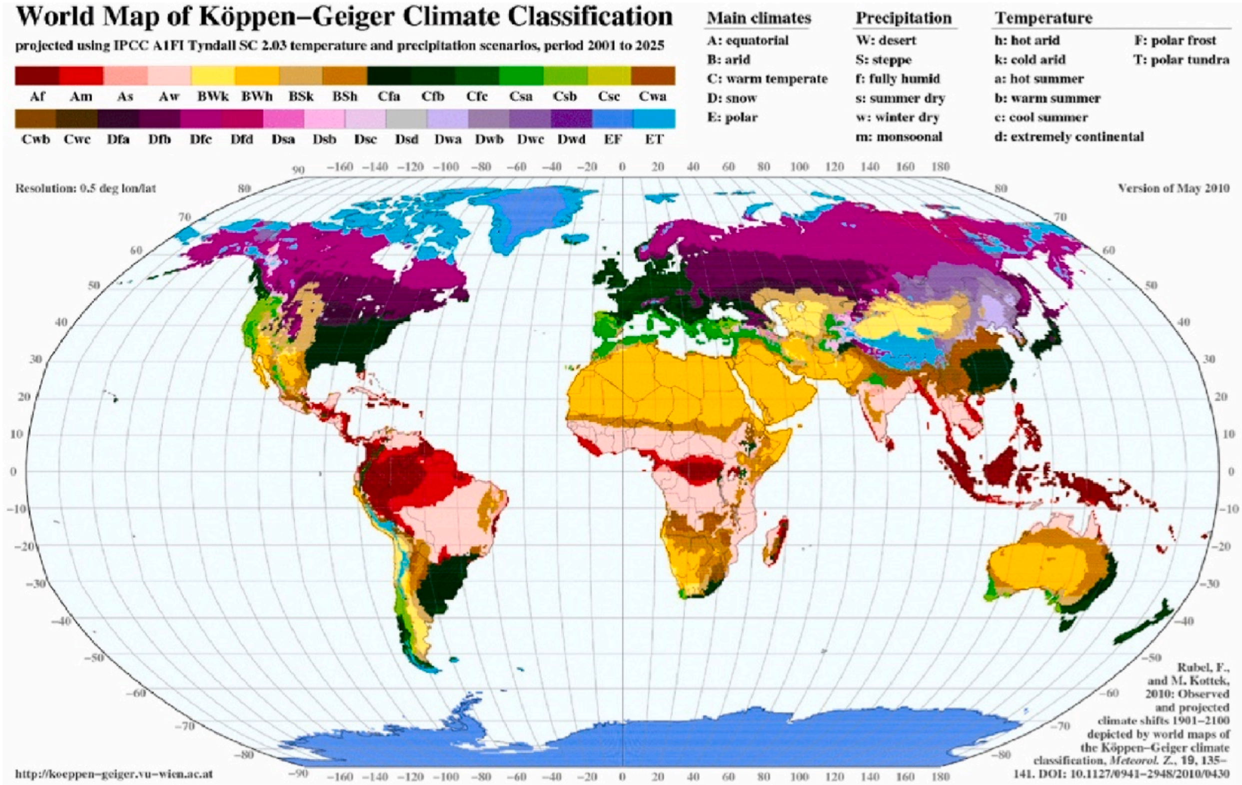

Fig. 3. World Map climate classification.

(a) (b) (c)

Fig. 4. Measurement tools. (a) Thermocouple thermometer with type k thermocouple (b) Anemometer (c) Thermo-hygrometer.

Table 1
Instrument specification.

Parameter	Equipment	Accuracy	Range
Air temperature (Ta)	Thermocouple thermometer	± [0.05 % + 0.3 °C]	−200 to 1372 °C
Air velocity (m/s)	Anemometer	±3 % ± 0.1	0 m/s – 45 m/s
Relative humidity (RH)	Thermo-hygrometer	T: ±1 °C RH: ±4 %	T: −20 °C–70 °C; RH: 0 %–100 %

tal parameters. A comprehensive survey was carried out, encompassing online and paper-based questionnaires distributed among the office room staff and the trainees in the training room. The survey took place throughout the entire span of the comprehensive measurement period until April 14th. On each designated survey day, occupants were provided with questionnaires as they began their work hours, and these questionnaires were later retrieved from their respective tables when the work hours concluded. This method is widely acknowledged as the most effective and systematic approach for investigating and analyzing the reciprocal interactions between the building and occupants' requirements, as supported by previous research [42]. The questionnaire items were assessed using a seven-point scale, following the guidelines outlined in ASHRAE 55 Standard [41]. Table 2 thoroughly summarises the data collected through the questionnaire, while basic subject information is tabulated in Table 3.

The present research successfully collected fifty-one valid responses from all trainees in the training room, and an additional ten responses were gathered from the staff members occupying the office room. Within the training room, females comprised 49 % of the responses, while males constituted 51 %. Moreover, 51 % of the respondents reported being 30 years or above, whereas 49 % reported being under 30. Interestingly, only 11.8 % of the participants reported sitting near windows.

In the Office room, females represented 90 % of the responses, while males accounted for 10 %. Similarly, 80 % of the respondents reported being 30 years or above, whereas 20 % reported being under 30. Notably, a minority of 20 % of the participants mentioned being near windows. Further insights into the distribution of respondents, encompassing their respective occupations, can be found in Table 3.

2.4. Thermal comfort model for calculation

Within this research investigation, an evaluation was undertaken to gauge the thermal environmental conditions within a training room and an office situated within a green building. This assessment was conducted using the Center for Built Environment thermal comfort tool [43], which adheres to the principles outlined in the ASHRAE 55 Standard [41]. This evaluation's predictive aspect involved utilising the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. These indices encompassed a comprehensive array of six input parameters, which include "air temperature," "mean radiant temperature," "air velocity," "relative humidity," "metabolic rate," and "clothing insulation." All these parameters were thoroughly considered within this research's scope. Metabolic rate calculations are complex; therefore, estimations derived from activity intensity are often used [44]. This study attrib-

Table 2
Overview of the information obtained through the questionnaire.

Category	Question
Demographic detail	Gender, Age, Occupation, Seated close to a window
Thermal comfort	How comfortable is the thermal environment?
Thermal sensation	How are you currently experiencing your state or condition?
Thermal and air movement preferences	What specific temperature sensation would you currently prefer the most?
	How would you prefer the level of air movement in your environment?
Air Humidity	How would you describe indoor humidity?

Table 3
Demographic details of the respondents.

		Training Room		Office Room	
		N	%	N	%
Gender	Male	26	51.0	1	10.0
	Female	25	49.0	9	90.0
Age	Under 30	25	49.0	2	20.0
	30 and above	26	51.0	8	80.0
Occupation	Contractor	4	7.8	1	10.0
	Supplier	6	11.8	0	0.0
	Consultant	15	29.4	0	0.0
	Administrative staff	3	5.9	0	0.0
	Developer	19	37.3	0	0.0
	Green Manager	2	3.9	0	0.0
	Academician	2	3.9	0	0.0
	Executive Director	0	0.0	1	10.0
	Manager	0	0.0	1	10.0
	Assessor	0	0.0	4	40.0
	Training Manager	0	0.0	1	10.0
	Training Assistant	0	0.0	1	10.0
	Sales/Marketing Manager	0	0.0	1	10.0
	HR/Admin Executive	0	0.0	1	10.0
Is your desk located near a window?	Yes	6	11.8	2	20.0
	No	45	88.2	8	80.0

uted a metabolic rate of 1.1 met to all participants, considering their primarily sedentary work activities, such as sitting and typing [45,46] while clothing insulation values were sourced from comparable studies [45,47,48], specifically adopting a value of 0.61 clo.

The internationally recognised standards, such as ISO EN-7730 [49] and ASHRAE 55 standard [41], emphasise the significance of keeping circumstances within a specific range to provide thermal comfort. According to these criteria, the appropriate limit for thermal comfort states that the PPD number should not exceed 10 %. On the other hand, the PMV value must be between −0.5 (representing a little cool feeling) and +0.5 (representing a slightly warm feeling). The validation and applicability of these limits have been verified, considering the intrinsic physiological differences among individuals. Fig. 5 presents the analytical framework of study.

3. Findings

A comprehensive analysis of the collected data was performed, yielding results presented in two primary sub-sections: (1) objective measurement and (2) subjective measurement. The objective measurement section provides insights into the outcomes of the thermal analysis, accompanied by discussions informed by relevant studies and standards. Simultaneously, the subjective measure-

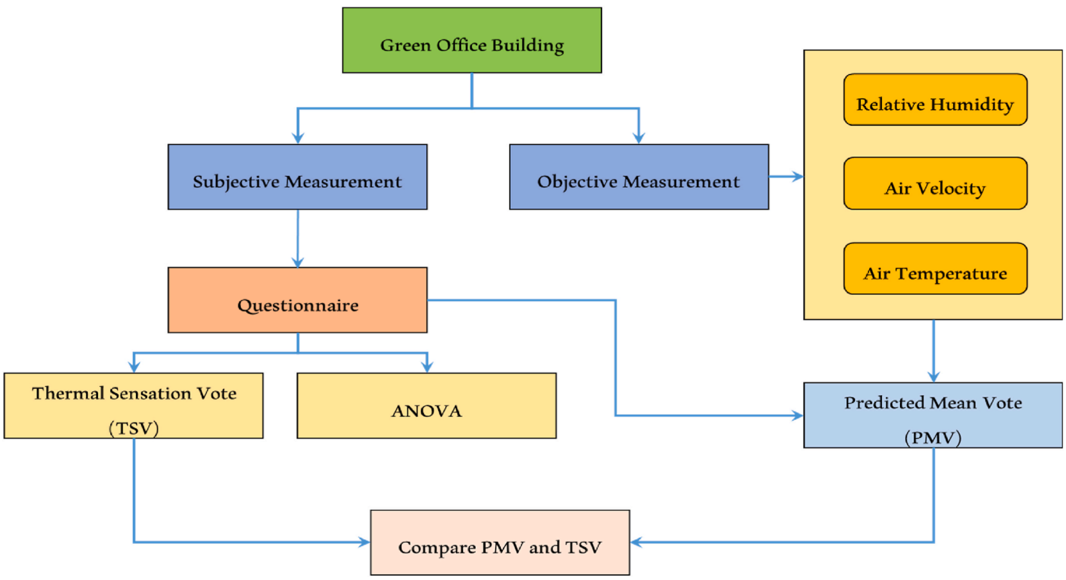

Fig. 5. Analytical framework of study.

ment subsection encompasses findings from the survey analysis, incorporating occupants' thermal perceptions and related analyses, which are further examined and discussed in detail.

3.1. Objective measurement

Precise measurements were taken to determine the indoor environmental parameters necessary for estimating the thermal comfort range of the mechanical ventilation system when the air conditioning is in operation. These readings were further analysed compared to the allowable range suggested by ISO 7730 [49], ASHRAE 55 [41], and MS-1525 [50] standards. The assessed parameters included air temperature, relative humidity, and air velocity.

According to the statistics shown in Table 4, The air temperature in the training room (24 ˚C–26 ˚C) falls within the acceptable comfort range specified by the analysed criteria. Conversely, the temperature in the office room dropped significantly below the permissible range of 23 ˚C–26 ˚C as stated in MS 1525 [50]. This deviation emphasises the possibility of spatial disparities within a building and the significance of preserving comfortable environments in various sections. Studies indicate that extended periods spent in conditions that are not ideal, especially colder temperatures, can result in the development of respiratory diseases and asthma [51]. This phenomenon arises due to the constriction of airways caused by lower ambient temperatures, rendering them more vulnerable to irritation and inflammation. In addition, lower temperatures have the potential to weaken the immune system, which may make individuals more susceptible to respiratory illnesses [51]. Hence, it may be imperative to consistently monitor and make appropriate modifications to the mechanical ventilation system to guarantee compliance with the recommended temperature ranges in all occupied areas.

In addition, the recorded average relative humidity (*RH*) in the training and office rooms is beyond the permissible range of 50 % – 70 %, as specified in MS 1525 [50]. Elevated humidity levels can facilitate the proliferation of mould, germs, and viruses in indoor settings, presenting possible health hazards [51]. The Institute of Medicine (US) [52] has established a correlation between exposure to mould and the development of respiratory difficulties, allergic reactions, and neurological concerns. In addition, elevated humidity levels might foster the proliferation of bacteria and viruses, potentially heightening the likelihood of transmitting infectious diseases, temporary exposure to increased humidity can also result in detrimental health consequences, such as respiratory difficulties, dizziness, and fatigue [53]. The results indicate that the existing mechanical ventilation system may be inadequate in regulating humidity levels in the building. To ensure comfort and reduce potential health hazards caused by high humidity in tropical climates, strategies such as dehumidification or increasing air circulation rates may be required.

Regarding air velocity, the office room displayed an average measured value of 1.00 m/s, whilst the training room indicated a reading of 0.98 m/s. These statistics indicate that the airspeeds are higher than the recommended limit for comfortable travel in hot and humid areas. Air circulation can worsen discomfort, especially when coupled with elevated humidity. Although air movement is important for preserving thermal comfort and indoor air quality, overly high air velocity in office areas can have negative consequences. An important issue is the production of drafts. Drafts are specific areas where cold air flows, which can cause a feeling of coldness and discomfort for people, even if the general temperature of the space is within the tolerable range [41]. In addition, keeping air circulation rates overly high requires the HVAC system to use more energy. The increased energy requirement results in elevated operational expenses and a more substantial ecological impact for the building [54]. Adjusting air velocity to the recommended levels can greatly enhance the overall energy efficiency of a building, resulting in substantial economic and environmental advantages.

3.2. Subjective measurement

In both the training room and office room, a questionnaire survey was employed to assess various factors of thermal quality. To achieve this, the variables were rated on a seven-point Likert scale, as specified by ASHRAE 55 Standard [41]. The scale ranged from −3 to 3. The distribution of responses regarding thermal sensation (a), thermal comfort (b), thermal preference (c), air movement preference (d), and air humidity (e) is depicted in Figs. 6 and 7.

3.2.1. Thermal sensation vote and thermal comfort vote

In the context of the training room, it is noteworthy that merely a minority of trainees (31.36 %) indicated satisfaction with the overall comfort of the thermal conditions, as indicated by a mean vote of −0.21, as depicted in Fig. 6b. ASHRAE 55 Standard [41] stipulates a minimum satisfaction rate of 80 % for thermal quality, and it is essential to note that this rate is significantly lower in the case of the training room. The primary cause for the lower satisfaction level is the prevalence of relaxed environments. This is evident from the thermal sensation mean vote of −0.94, with 41.17 % of occupants expressing discomfort, as illustrated in Fig. 6a. For the office room, most staff members (60 %) reported overall comfort with thermal quality with a mean vote of 0.80, as shown in Fig. 7g.

Table 4
Environmental parameters and comparison with standards.

Parameter	Location		Standards		
	Training Room	Office Room	ASHRAE 55	MS-1525	ISO 7730
Average Air temperature (°C)	24.12	23.02	23–26	24–26	23–26
Average Relative humidity (%)	70.29	71.97	50	50–70	30–70
Average Air velocity (m/s)	0.98	1	< 0.15	0.15–0.50	< 0.40

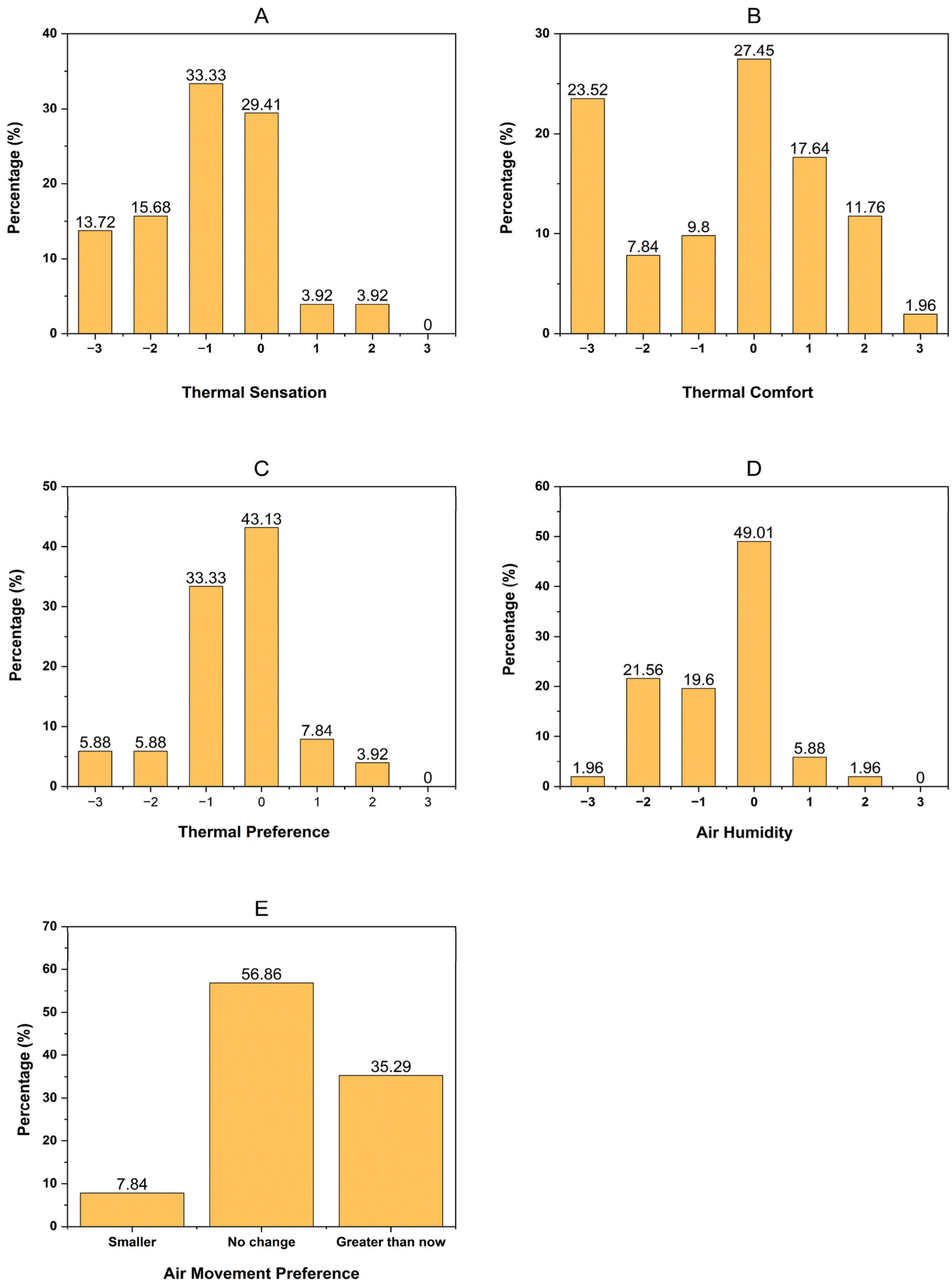

Fig. 6. Distribution of thermal quality variable votes among occupants in the training room (a) thermal sensation vote; (b) Overall thermal comfort; (c) thermal preference vote; (d) air humidity; (e) Air movement preference.

However, in Fig. 7f, most staff members (80 %) stated they were feeling cold, and none of the staff members experienced warm feelings. Mean TSV of −1.40, indicating a prevailing tendency towards perceiving the environment as cooler.

3.2.2. Thermal preference, air humidity, and air movement preference vote

In the case of the training room, most trainees preferred to cool down (45.09 %), and only a limited number of trainees wanted to warm up (11.76 %), as depicted in Fig. 6c. Moreover, for air movement, the majority of trainees (56.86 %) did not need a change in

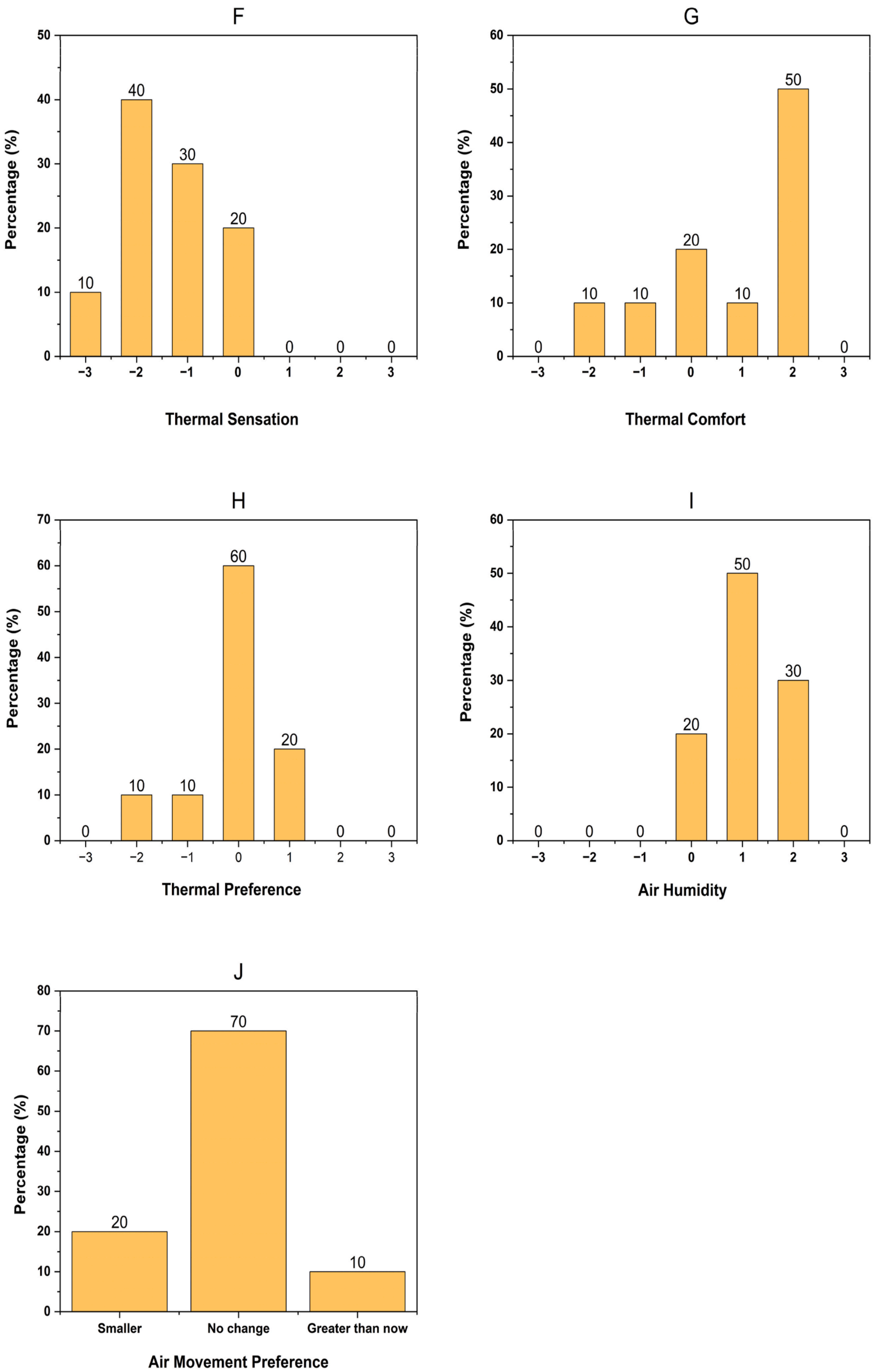

Fig. 7. Distribution of thermal quality variable votes among occupants in the office room (f) thermal sensation vote; (g) overall thermal comfort; (h) thermal preference vote; (i) air humidity; (j) air movement preference.

air movement and limited number of trainees (35.29 %) wanted a change in air velocity, and very few numbers of trainees (7.84 %) wanted lower air velocity in the training room as shown in Fig. 6e. Whereas most trainees (43.14 %) reported dry indoor air, only a limited number of trainees (7.84 %) reported humid indoor air, as demonstrated in Fig. 6d.

The case of the office room illustrates that a significant majority of staff members (60 %) are content with the existing thermal environment and do not seek any changes. Conversely, a noteworthy portion of 20 % preferred a cooler environment, while another 20 % indicated a slight preference for a warmer setting. Moreover, as depicted in Fig. 7j, most staff members (70 %) did not express a need for lower air velocity, with only a tiny fraction (10 %) indicating a desire for higher air movement rates. The data also suggests a correlation between respondents desiring a cooler office space and a preference for increased air movement rates.

3.3. Thermal analysis considering characteristics of occupants

The responses provided by trainees in the training room and office staff members regarding thermal variables were subjected to statistical analysis to determine whether significant differences existed based on their characteristics. These characteristics encompass age, gender, and proximity to a window. Independent sample t-tests and one-way ANOVA were used to test the following hypotheses:

Null Hypothesis (H_0): There is no significant difference in thermal perception based on individual characteristics (age, gender, proximity to window).

Research Hypothesis (H_1): There are significant differences in thermal perception based on individual characteristics (age, gender, proximity to window).

The findings indicated that there were no statistically significant differences ($p > 0.05$) were observed for most variables. The results suggest that these individual characteristics did not significantly influence thermal comfort responses. This finding suggests that the characteristics of the occupants did not have a notable impact on their responses. Table 5 demonstrates statistically significant differences in the responses from the training room occupants concerning gender and their preferences for air movement; thus, the null hypothesis is rejected. Notably, respondents who expressed a desire for a cooler office environment exhibited a preference for an increase in air movement rates. In addition, Table 6 demonstrates that the responses from the office room are statistically different regarding gender over thermal comfort; the null hypothesis is rejected. A parallel observation was made in a study conducted by Maykot et al. [55], where a statistically significant difference was identified based on gender concerning thermal comfort in an office building situated within the tropical climate of Brazil. In the present study, the responses showed statistically significant changes in relation to the distance from the window, thereby rejecting the null hypothesis. Specifically, individuals farther away from the window reported a sensation of comfort, whereas those closer to the window expressed discomfort.

3.4. PMV-PPD model

The PMV is a model commonly utilized and established to predict the average thermal sensation experienced by a group of individuals inside a particular setting. From −3 (cold) to +3 (hot), a PMV of 0 signifies thermal neutrality. The PPD, an index derived from the PMV, estimates the percentage of people likely to feel thermally dissatisfied. Calculating PMV necessitates carefully considering six key factors: air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate [56]. In this study, data for these factors were systematically collected. Operative and mean radiant temperatures were derived using equations (1) and (2). The detailed results are presented in Table 7. These values and other environmental and occupant-related data were inputted into the CBE Thermal Comfort Tool. This online tool leverages the established PMV model and its associated equations to generate PMV and PPD values. The CBE tool calculated PMV values of approximately −0.78 for the office and −0.68 for the train-

Table 5
Impact of occupant characteristics on the perception of thermal variables (Training Room).

	Gender		Age		Near window	
	Male	Female	Under 30	30 and above	Yes	No
%	51	49	49	51	11.8	88.2
Overall Thermal Comfort	t	0.112	1.393		0.661	
	df	49	49		49	
	Sig	0.911	0.170		0.512	
Thermal Sensation	t	−0.343	−1.010		−0.123	
	df	49	49		49	
	Sig	0.733	0.317		0.903	
Thermal Preference	t	0.849	0.460		−1.305	
	df	49	49		49	
	Sig	0.400	0.647		0.198	
Air Humidity	t	0.351	−0.080		0.646	
	df	49	49		49	
	Sig	0.727	0.937		0.521	
Air Movement	t	−2.511	0.525		0.975	
	df	49	49		49	
	Sig	0.015*	0.602		0.334	

* Significant when $p < 0.05$.

Table 6
Impact of occupant characteristics on the perception of thermal variables (Office Room).

	Gender		Age		Near window	
	Male	Female	Under 30	30 and above	Yes	No
%	10	90	20	80	10	90
Overall Thermal Comfort	t	−2.53	0.843		2.806	
	df	8	8		8	
	Sig	0.035*	0.424		0.026*	
Thermal Sensation	t	1.673	−0.632		−0.155	
	df	8	8		8	
	Sig	0.133	0.545		0.881	
Thermal Preference	t	0.144	0.144		1.095	
	df	8	8		8	
	Sig	0.912	0.912		0.305	
Air Humidity	t	1.342	1.342		−0.203	
	df	8	8		8	
	Sig	0.217	0.217		0.845	
Air Movement	t	0.175	−1.897		−1.131	
	df	8	8		8	
	Sig	0.865	0.094		0.291	

* Significant when $p < 0.05$.

Table 7
PMV and PPD results.

Location	Parameter	Values
Office Room	Average Air temperature (°C)	23.02
	Mean radiant temperature (°C)	27.17
	Average Relative humidity (%)	71.97
	Average Air velocity (m/s)	1
	Operative Temperature (°C)	25.09
	PMV	−0.78
	Sensation	Slightly Cool
	PPD	18 %
Training Room	Average Air temperature (°C)	24.12
	Mean radiant temperature (°C)	26.79
	Average Relative humidity (%)	70.29
	Average Air velocity (m/s)	0.98
	Operative Temperature (°C)	25.45
	PMV	−0.67
	Sensation	Slightly Cool
	PPD	14

ing room, falling within the “slightly cool” range of the PMV scale, as shown in Table 7. This suggests a near-neutral thermal sensation for most occupants. The resulting PPD values were consistently low (below 20 %), indicating high satisfaction with the thermal conditions within both spaces, as described in Table 7. To gain a more granular understanding of occupant experience, Interestingly, the TSV results revealed a discrepancy with the PMV predictions. In both the training room (−0.94) and the office room (−1.4), the average TSVs indicated that occupants were experiencing a cooler sensation than the PMV model predicted. This highlights the importance of considering potential contributing factors such as individual variations in thermal sensitivity, localized drafts or radiant temperature differences not reflected in average measurements, and the potential for adaptive comfort mechanisms specific to the climate.

This study effectively demonstrates the value of combining predicted thermal comfort modelling (PMV) with subjective reports of thermal sensation (TSV). The findings emphasise that while PMV provides valuable insights into predicted average responses, individual experiences can deviate from the model. Understanding the potential factors contributing to discrepancies between PMV and TSV, such as localized environmental variations, individual differences, and climate-based adaptations, is crucial for creating truly comfortable and occupant-responsive thermal environments.

3.5. Comparison between PMV and TSV

The average calculated PMV index values for both the training room and the office room are presented in Table 8. In the context of the training room, the calculated average PMV value was determined to be −0.67. At the same time, the corresponding TSV was estimated to be −0.94, signifying a “slightly cool” thermal sensation. Similarly, the calculated average PMV index value for the office room was found to be −0.78, with the estimated thermal sensation indicating a “slightly cool” state at −1.4. Several factors can lead to discrepancies between PMV and TSV values. Individual variations play a significant role. People naturally exhibit physiological dif-

Table 8
Thermal comfort prediction based on the average value measures.

	Training Room	Office Room
PMV	−0.67	−0.78
TSV	−0.94	−1.4
PPD	14 %	18 %

ferences in metabolic rates, body composition, and temperature sensitivity, causing them to experience the same thermal environment differently. Psychological factors like mood, stress, and personal preferences influence thermal perception.

Additionally, the PMV model relies on simplified assumptions about a standardized person and their activity levels or clothing. It cannot fully account for the nuances of individual variations. Furthermore, PMV does not directly incorporate all factors that influence thermal comfort, such as localized drafts, direct sunlight, or recent thermal history (a person's prior exposure to warmer or cooler environments). In contrast, TSV reflects a person's subjective thermal sensation at a particular moment. The immediate assessment of the situation may vary from the longer-term average predicted by PMV. TSV depends on individuals providing accurate self-reports of their thermal comfort levels, which could potentially introduce bias or misinterpretation of the intended scale.

Table 8 graphically illustrates the difference between the PMV and TSV readings. Several studies have additionally demonstrated a comparable disparity between PMV and TSV over time [57–59]. In addition, it has been reported that the difference between predicted and actual sensations can be as significant as 1.3 units [60]. According to Maiti [57], the difference could be due to the tropical climate of Malaysia. Several studies conducted in regions with climates analogous to Malaysia offer insights into why occupants might perceive temperatures as cooler than predicted by the PMV model. For example, Damiati et al. [34] in Singapore found that localized drafts from natural ventilation and the influence of high humidity on thermal perception played a role in discrepancies between PMV and TSV.

Similarly, Shooshtarian et al. [61], in a subtropical region, noted the impact of adaptive thermal comfort (where people in warmer climates may have a broader comfort range) and uneven solar radiation on occupant perception. Fernandez et al. [62] highlighted the influence of clothing adaptation and localized air movement from ceiling fans. These studies suggest key factors potentially contributing to PMV/TSV discrepancies in Malaysian studies: drafts and air movement, the impact of humidity on thermal perception, clothing choices specific to the climate, and the potential for adaptive thermal comfort mechanisms.

4. Discussion

This study aimed to assess indoor thermal environments and occupant comfort in green office buildings in Malaysia, combining objective and subjective measurements. The results provide valuable insights into the present condition of green building design and operation in this environment.

4.1. Objective measurements & standards

The objective measurements identified compliance and discrepancies from the stated thermal comfort standards in the mechanically ventilated green office building. Although the air temperature in the training room was within the recommended range, the temperature in the office room marginally fell below it. Significantly, the relative humidity levels in both rooms surpassed the permissible guidelines. The air velocity values exceeded the optimum range for tropical climates. The results presented underline several essential factors to take into consideration:

The disparities between global benchmarks and actual measurements highlight the possible necessity for standards specifically designed for tropical areas. Malaysia's MS-1525 standard, compared to more international standards, provided recommendations that were more closely matched to the temperature range in this study. Conducting additional research to assess the appropriateness of current thermal comfort requirements for different climatic regions would be highly beneficial. The observed discrepancies from the recommended levels necessitate thoroughly examining the mechanical ventilation system's design and performance. To achieve thermal comfort and preserve energy economy, optimising factors such as temperature set points, dehumidification procedures, and air circulation patterns within the building is essential. The studies conducted by Lin et al. [63]; Zoure and Genovese [64] have shown that integrated ventilation techniques that include dehumidification and optimised airflow are highly beneficial in attaining thermal comfort and energy savings in humid areas. It is important to note that localised changes in drafts, uneven airflow patterns, and radiant heat sources may be present even in rooms where the average air temperature, humidity, and air velocity are within acceptable limits. Subsequent research that includes precise measurements of microclimatic conditions in the office setting could accurately identify and tackle the underlying factors responsible for discomfort. Research that examines explicitly the dispersion of air and radiant heat in different places can help identify specific locations where modifications to temperature or airflow may be necessary. Individuals residing in regions with higher temperatures may exhibit more comprehensive comfort ranges than those often considered in standardised thermal comfort models [65]. This adaptation can arise from physiological alterations, as well as behavioural or psychological modifications. An understanding of adaptive comfort can guide building design techniques that prioritise occupant well-being instead of rigidly following criteria that may not be suitable for different climate conditions [66].

This study emphasises the significance of customising green building design and mechanical ventilation systems to suit the particular circumstances of tropical regions. An important factor to consider is efficient control of humidity, which is essential for the well-being and satisfaction of occupants. Possible strategies could involve using specialised dehumidification devices, enhanced air circulation, or a combination of both approaches. They guarantee consistent and efficient airflow to alleviate specific discomfort under appropriate overall circumstances. Examples of such measures may encompass the installation of ceiling fan diffusers or implementing personalized ventilation control systems at individual workstations. Integrating design features that provide localised control over temperature or air circulation could empower individuals to customise their thermal surroundings, particularly considering potential variations depending on gender. Consistently monitoring environmental factors within a building enables proactive modifications to maintain optimal thermal comfort while maximising energy efficiency.

4.2. Subjective measurements

The study findings provided subjective insights into how people perceive thermal comfort in the green office building, revealing disparities between the training and office rooms.

Most trainees (68.64 %) expressed discontent with the heat conditions. The training room has a mean TSV of −0.94, indicating that the prevailing feeling in the room is coolness. The discrepancy between the current environmental conditions and the desired thermal preferences of the occupants indicates that either the mechanical ventilation system or the thermal control strategy in the training room needs to be modified. Possible physiological reasons for trainee discomfort may include.

a. Vasoconstriction: In response to colder temperatures, the body narrows the blood vessels in the skin to retain heat [67]. It might result in a sensation of coldness and decreased blood circulation to the limbs, which may cause discomfort.
b. Shivering: The body may start shivering to produce heat when exposed to colder temperatures [68]. This involuntary muscular activation can cause discomfort and interrupt concentration during training sessions.
c. Suppressed Immune System: Research indicates that extended exposure to colder temperatures can inhibit the immune system's functioning, potentially heightening susceptibility to respiratory infections [69].

A study by Sikram et al. [27] has documented similar observations of inhabitants feeling discomfort due to cold temperatures in mechanically ventilated buildings in hot and humid areas. According to their research, people living in hot areas may have higher air temperature preferences than standardised comfort models, often based on studies conducted in temperate locations.

Responses from the office room survey were more polarised. Most staff members (60 %) reported feeling comfortable with the current temperature environment. However, 20 % wished for a colder atmosphere, while another 20 % indicated a slight preference for a warmer setting. The variation in the feeling of thermal comfort highlights the impact of individual factors such as clothing preferences, levels of physical activity, and metabolic rates [45]. Notably, the average TSV in the office room was −1.40, indicating an overall inclination to perceive the environment as cooler than the neutral temperature despite the varied individual reactions regarding thermal comfort. The difference between the average TSV and individual comfort responses may be attributed to:

Habituation: The individuals in the office area may have adapted to the cooler atmosphere over time, decreasing their neutral thermal comfort zone [70].

Microclimatic Variations: The survey data represents average responses across the office room. However, localized variations in temperature, air movement, and radiant heat sources can exist within a space [71]. Specific individuals may be situated close to windows with lower temperatures or subjected to air currents, which may influence their feeling of cool even if the overall room temperature falls within the recommended range.

A significant link was observed between the preference for thermal conditions and airflow in the training and office rooms. The inclination towards lower temperatures coupled with a demand for enhanced air circulation. This discovery is consistent with well-established concepts of thermal comfort in hot and humid conditions, where air circulation improves the process of evaporative cooling from the body's surface [72]. It implies that improving the air circulation patterns in the mechanically ventilated system could increase comfort, especially for occupants who prefer lower temperatures.

Most individuals in the training room assessed the indoor air as lacking moisture. These findings indicate that the humidity levels in the training environment may fall below the suggested comfort range for tropical regions, generally between 50 % and 70 %. Inadequate levels of humidity can lead to sensations of dryness and irritation of mucosal membranes [51]. Moreover, decreased humidity can facilitate the transmission of respiratory viruses through the air [73]. Ensuring optimal humidity levels in the mechanically ventilated system is vital for the well-being and comfort of occupants in tropical conditions.

These results emphasise the significance of considering individual variability in thermal comfort preferences when designing and operating indoor spaces. Although standardised thermal comfort models offer a structure, obtaining occupant feedback through surveys or real-time monitoring devices is essential for customising interior environments to enhance their overall health [74]. The preference for cooler environments in both locations suggests the presence of adaptive comfort mechanisms in the tropical environment. Occupants in warmer climates may have adapted to higher ambient temperatures, leading to broader comfort ranges than those in temperate climates [48]. Additional research focusing on adaptable comfort among this particular group of occupants could provide valuable insights for developing thermal comfort standards tailored to specific climatic conditions. Comprehending the significance of physiological and behavioural adaptation with green buildings in tropical climates is essential for formulating energy-efficient design solutions that prioritise the comfort and well-being of occupants. Granting flexibility or individualised regulation of air temperature and airflow within the green office building could effectively mitigate the fluctuations in thermal preferences identified in this study [75]. This can be accomplished by implementing user-controlled thermostats or adjustable air diffusers at each workstation. By incorporating localised control features, occupants can adjust their thermal environment according to their preferences. This can lead to higher levels of pleasure and greater focus on their tasks.

It is crucial to recognise that survey responses are subjective and can be affected by variables other than the local thermal environment, such as prior thermal experiences or expectations.

To gain a more detailed knowledge of individual differences in thermal comfort and how they affect subjective responses, future studies should include measures of clothing insulation and occupants' metabolic rate during the survey time. Enhancing quantitative surveys with qualitative interviews or focus groups can provide a more comprehensive understanding of occupants' motivations for thermal preferences and experiences of discomfort. This qualitative data could provide valuable insights to inform specific enhancements to the indoor environment.

4.3. Occupant characteristics

The statistical analysis of the responses from the occupants produced fascinating findings on possible relationships between individual characteristics and perceptions of thermal comfort in the green office building. For most variables, the study showed no statistically significant changes in thermal perception depending on age, gender (except air movement preference in the training room), or proximity to windows (except in the office room). This shows that factors other than the demographic characteristics examined in this study may be responsible for individual differences in thermal comfort responses. The kind and quantity of clothing occupants wear, which significantly impacts how they perceive the thermal environment, is one potential component that could influence thermal comfort [75]. Individuals dressed in thicker garments in a cold setting may feel uneasy because their ability to release heat is limited.

In contrast, those dressed in lighter garments in a hot setting may experience discomfort. Differences in heat generation within the body are influenced by variations in activity levels, which in turn impact perceptions of thermal comfort [76]. Individuals involved in physically demanding activities will produce a greater amount of heat and may prefer lower temperatures compared to those who participate in sedentary work. Subjective thermal comfort responses can be influenced by stress levels, mood, and personal expectations [77]. For example, those experiencing stress may have heightened sensitivity to changes in temperature or view their surroundings as less comfortable compared to those in a relaxed state.

A substantial correlation was found between gender and air movement preference in the training room. More precisely, individuals in the training room who wanted a colder atmosphere also favoured higher air circulation. This discovery is consistent with well-established concepts of thermal comfort, in which air circulation improves the process of evaporative cooling from the body's surface. This results in coolness under hot and humid conditions [78]. This emphasises the significance of considering gender-specific requirements for thermal comfort when designing or operating mechanically ventilated buildings in tropical regions. The findings from the office room study also indicated a statistically significant disparity in the feeling of thermal comfort between genders. The results of this study support previous research conducted by Parkinson et al. [79,80], which also found gender-related differences in how individuals perceive thermal comfort in office environments in tropical climates.

Potential rationales for these gender disparities may include the following: Women exhibit a slightly higher baseline metabolic rate in comparison to men, resulting in increased heat production. This can result in women perceiving the same environment as having a higher temperature than men. Social conventions and expectations can influence gendered clothing choices. Women in professional office environments often choose to wear attire that is deemed more formal. However, this clothing may also be less breathable and lead to higher levels of body heat retention. Gender may lead to variations in psychological expectations for the indoor temperature environment. Women may exhibit a predilection for office environments that are slightly lower in temperature than men. A significant relationship was found between the distance from windows and the thermal comfort perception. Individuals situated at a greater distance from windows reported a higher level of comfort, whereas those close to windows reported a feeling of uneasiness. This discovery indicates that being close to windows can result in specific areas of indoor surroundings experiencing temperature discomfort. Possible justifications encompass: Windows can emit solar radiation, especially when exposed to sunlight. Individuals close to windows may experience increased amounts of radiant heat, which can lead to discomfort, particularly in tropical regions[81]. Windows can contribute to the presence of drafts, especially in mechanically ventilated or older structures with inadequate sealing.

This study emphasises the complex nature of thermal comfort and highlights the importance of considering a more comprehensive array of individual parameters beyond basic demographic information. The results regarding the impact of closeness to windows emphasise the significance of resolving small-scale climatic differences inside a room to maximise thermal comfort for all individuals present. Possible strategies to consider the installation of external shading devices or the application of window film. These measures can effectively decrease the amount of solar heat entering via windows, reducing discomfort for nearby individuals. Strategic design of air diffusers and ventilation systems to minimize drafts can enhance thermal comfort, especially for individuals close to windows. Based on the reported disparities between genders, it appears advantageous to investigate design interventions that cater to the individual thermal comfort requirements of each gender in indoor settings. Although additional research and attention are necessary to prevent detrimental generalisations, potential approaches could involve Offering localised temperature regulation options, such as personal fans or adjustable air vents, that enable occupants to customise their environment based on their unique preferences. Implementing relaxed dress regulations in corporate environments can allow individuals to select attire that maximises their comfort, taking into account their degree of physical activity and thermal preferences. This study exclusively examined the variables of age, gender, and proximity to windows. In order to gain a more thorough knowledge of how individual variances affect the feeling of thermal comfort, future studies should include assessments of clothing insulation, metabolic rate, and psychological aspects. Accurate microclimatic measurements within the building are crucial to identify the reasons for localised discomfort. Data-collecting may encompass air temperature mapping, radiant temperature measurements, and draft analysis. Enhancing statistical analysis with qualitative methods such as occupant interviews or focus groups can yield significant insights into the underlying causes of individual preferences and experiences of discomfort.

4.4. PMV and TSV discrepancy

The PMV calculations and TSV analysis uncovered a significant disparity in the green office block. The PMV values for the office and training room were −0.78 and −0.68, respectively, indicating a nearly neutral temperature experience for most occupants. However, the TSV data showed that occupants regarded the environment as cooler, with values of −1.4 for the office and −0.94 for the training room. This discrepancy emphasises the constraints of exclusively depending on PMV for thermal comfort evaluations. It highlights the significance of considering individual differences and specific circumstances to multiple factors contributing to disparities between PMV and TSV, and analysing these aspects can provide valuable insights for enhancing thermal comfort in green buildings, especially in tropical regions.

The PMV model assumes a standardised individual with a typical metabolic rate, body composition, and heat sensitivity. Nevertheless, individuals display notable physiological variations [46]. For example, an individual with a greater basal metabolic rate, which is the body's energy at rest, will produce more heat and may feel that the same environment is colder compared to someone with a lower metabolic rate. Similarly, differences in body composition, such as the amount of muscular mass, can affect how we perceive temperature. Subjective temperature sensation can be strongly influenced by mood, stress levels, and personal preferences, which affect TSV responses [82]. An individual experiencing anxiety or stress may perceive a given environment as having a lower temperature compared to someone who is feeling relaxed under the same circumstances. Gaining insight into these psychological elements can facilitate the establishment of surroundings that foster physical comfort and enhance the well-being of occupants. The PMV model employs mean environmental data throughout a certain area. Nevertheless, the PMV model fails to properly account for localised differences commonly found in real-world contexts.

Leaky windows, air conditioning vents, or holes in the building might result in drafts, creating specific areas of coolness even if the overall temperature falls within the comfort range defined by the PMV [83]. In the same way, an imbalanced distribution of air in a given area can cause specific individuals to perceive a lower temperature than others, even if the average PMV indicates thermal neutrality. On the other hand, areas that do not receive enough solar heat during colder months may result in specific cold spots that are not accounted for in the PMV. The PMV model is mainly based on research undertaken in temperate climates. Individuals residing in tropical regions such as Malaysia may have an expansion in their tolerance for comfortable temperatures due to their adaptation to higher ambient temperatures [48]. This concept is adaptive comfort. Consequently, individuals in the green building may feel the environment colder than the PMV model predicts, as it does not entirely consider the thermal comfort expectations influenced by the Malaysian climate.

Analysing the factors contributing to disparities between PMV and TSV might provide valuable insights for developing design strategies for environmentally-friendly buildings in tropical regions. Although PMV is essential, it should not be the only metric to determine thermal comfort. Real-time methods for gathering occupant feedback, such as TSV surveys or thermal comfort monitoring systems, can provide valuable insights for customising the indoor environment to meet the occupants' needs. Design features like adjustable diffusers and personal fans allow occupants direct control over temperature and airflow. This enables individuals to customise their environment according to their physiological needs and personal preferences [84]. By prioritising measures such as addressing localised drafts and unequal radiant heat sources (such as window shading) and ensuring uniform air distribution, the overall thermal comfort within green buildings can be significantly improved. The importance of regional specificity and additional investigation into adaptive comfort mechanisms tailored to the Malaysian context could provide insights for creating climate-specific thermal comfort criteria for green building design in tropical regions. Customising standards to suit certain local climates would more accurately align with individuals' expectations and comfort preferences.

Potential areas for further research in order to develop green buildings that are both thermally comfortable and responsive in tropical climates include sensor integration and monitoring: By including sensors and thermal cameras, the gathering of data can be extended to continuously detect specific environmental factors such as air temperature fluctuations, drafts, and radiant heat sources inside a given region. This approach enables the identification of locations that exhibit microclimatic variations. By integrating data from evaluations of clothing insulation and metabolic rate, presumably collected by wearable sensors, understanding elements that affect individual thermal comfort in green buildings in tropical environments would be enhanced. Comprehending the perceptions of those occupying a space gathering qualitative data through interviews or focus groups with occupants in green buildings in Malaysia might yield significant insights. This study further investigates the factors influencing individuals' perceptions of coolness and examines particular ways to improve thermal comfort in different contexts. Exploring adaptation conducting longitudinal studies that monitor occupant heat perceptions over lengthy periods, such as throughout several seasons, could offer valuable insights into how occupants adapt within green buildings in tropical locations. This information can assist designers in comprehending how indoor climates can be modified seasonally to satisfy initial thermal perceptions and evolving comfort requirements over the year.

Future green building projects in tropical climates can optimise occupant well-being and productivity by overcoming the limitations of the PMV model, focusing on occupant-centric design, conducting climate-specific research, and studying occupant adaptive behaviours. These projects can create thermally comfortable and responsive environments while meeting energy-efficiency standards.

5. Limitations

The present research acknowledges multiple limitations requiring careful attention when interpreting its results. Over the course of two months, occupant comfort and the interior temperature environment were compared. This limited duration may not comprehensively encompass the influence of seasonal fluctuations on occupants' sense of thermal comfort. Future research should include several seasons to investigate potential changes and develop evaluation models that may be applied in varied climatic circumstances.

Moreover, there were limitations faced during the process of gathering data. Due to the inability to get permission for a comprehensive building study, field tests were limited to particular floors. To obtain a more thorough understanding of thermal comfort in the green office space, it is necessary to collect data from all areas of the building. Furthermore, the occupant surveys were restricted to only two months. Extending the survey duration to include several seasons might enhance the potential to apply the findings to a broader population. The main objective of this study was to examine the thermal conditions within green office buildings. Additional factors of IEQ, such as lighting and air quality, were not thoroughly investigated. Future research should adopt a comprehensive approach, investigating the interaction among several aspects that contribute to the overall well-being and happiness of occupants in green buildings. Although there are limitations, this study seeks to provide significant insights into the current debate on green buildings in Malaysia. This country is seeing tremendous construction expansion and a growing acceptance of green building grading systems. The results of this study have the potential to stimulate additional research and potentially influence changes in policies. In addition, incorporating regular post-occupancy evaluations into the green building certification procedure would yield helpful information regarding the enduring sustainability of such buildings following their construction and during their operation.

6. Conclusion

This study thoroughly examined thermal comfort in a green office building located in Malaysia. The study employed a comprehensive strategy, methodically integrating objective environmental measures with subjective occupant questionnaires to understand occupant thermal experience thoroughly. The acquired environmental data from the green office building was analysed using established thermal comfort methods, specifically the PMV score. The PMV values calculated for the office (−0.78) and training room (−0.68) indicate that the thermal conditions were slightly cold. This suggests that a significant number of occupants experienced a near-neutral temperature sense. The connection with recognised thermal comfort criteria suggests that the green building can save energy while consistently maintaining acceptable temperature levels. However, the research further explored the topic by including subjective TSV directly obtained from the building occupants. The TSV data exhibited a significant disparity from the PMV estimates. The occupants experienced a cooler sensation (−1.4 in the office and −0.94 in the training room) compared to what was expected based on the PMV model. This notable disparity emphasises the constraints of exclusively depending on standardised thermal comfort models and the significance of considering occupant-centric elements that impact subjective thermal perception.

In order to understand the difference between PMV and TSV, the study carefully examined several elements that affect thermal comfort, going beyond the assumptions of a standardised model. The PMV model is based on the assumption of a standardised individual with average values for metabolic rate, body composition, and heat sensitivity. Nevertheless, inhabitants have notable physiological changes. For example, an individual with a greater basal metabolic rate may experience colder surroundings since they produce more heat than someone with a lower metabolic rate. The study recognises that mood, stress levels, and personal thermal preferences can considerably influence subjective thermal feeling. An individual experiencing anxiety may perceive a given environment as having a cooler temperature compared to someone who is feeling calm under the same circumstances. Gaining insight into these psychological elements can guide the creation of spaces that enhance physical comfort and the overall well-being of occupants. The PMV model employs mean environmental data throughout a particular area. Nevertheless, the PMV model fails to properly account for the localised differences commonly found in real-world contexts. Leaky windows or uneven air distribution can induce drafts, resulting in localised chilly areas, even if the average temperature falls within the comfort range defined by the PMV.

Likewise, unequal radiant heat sources emerging from windows can lead to discomfort among individuals nearby. The PMV model was primarily generated from investigations conducted in temperate climates. Occupants in warm climates like Malaysia may develop broader comfort ranges through acclimatization to hotter temperatures. Occupants in tropical climates like Malaysia might expand their comfort zones by acclimating to higher temperatures. Consequently, occupants of the green building may perceive the space to be colder than what the PMV model predicts, which may not adequately account for Malaysian climate-influenced thermal comfort expectations.

By shedding light on the disparity between PMV and TSV and investigating the underlying causes, this study provides significant knowledge for enhancing the thermal comfort of environmentally sustainable buildings in tropical regions. These insights contribute to developing design strategies prioritising occupant-centric considerations rather than relying solely on standardised models. Although PMV is a valuable instrument, it should not be the only metric to assess thermal comfort. By utilising real-time occupant feedback mechanisms such as thermal comfort monitoring systems or TSV surveys, indoor environments can be better adapted to the requirements of occupants. By integrating design components that grant occupants localised regulation of temperature or airflow—such as adjustable diffusers or personal fans—individuals can be empowered to modify their surroundings following their personal preferences and physiological variations.

By prioritising efforts to reduce localised drafts and uneven radiant heat sources, such as window shading, and by ensuring uniform air distribution, the overall thermal comfort within green buildings can be significantly improved. Additional investigation into adaptive comfort mechanisms tailored to the Malaysian context could provide insights for establishing climate-specific thermal comfort criteria for green building design in tropical countries. Customising standards based on local conditions would more accurately align with the expectations and comfort preferences of inhabitants in particular areas while still meeting energy efficiency goals. To summarise, this study emphasises the complex nature of thermal comfort and underscores the significance of prioritising occupant-centered design concepts for environmentally friendly buildings in tropical climates. Researchers and building designers can work together to develop thermal settings that enhance occupant well-being, boost productivity, and contribute to sustainable building practices by studying the interaction between objective data, individual preferences, and regional climatic conditions.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Research Committee of the University Tunku Abdul Rahman (Malaysia) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate

All authors listed have participated to the study.

Consent to publish

All authors listed have agreed and approved the submission.

Availability of data and materials

All data supporting the findings of this study can be obtained from the corresponding author upon request.

CRediT authorship contribution statement

Muhammad Tarique Lakhiar: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Shalini Sanmargaraja:** Writing – review & editing, Supervision. **AbdulLateef Olanrewaju:** Writing – review & editing, Supervision. **Chong Hooi Lim:** Writing – review & editing, Supervision. **Vignes Ponniah:** Writing – review & editing, Supervision. **Anselm Dass Mathalamuthu:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare there are no conflicts of interest.

Data availability

The data that has been used is confidential.

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