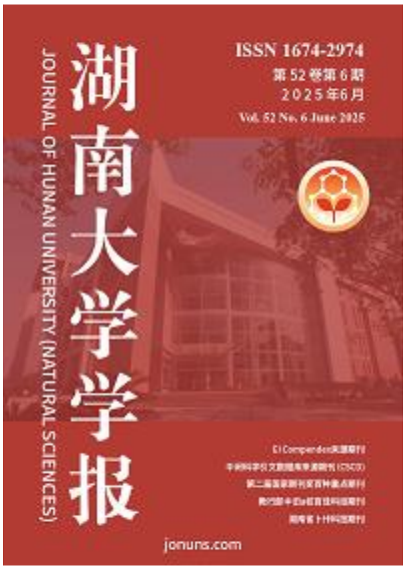

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Diurnal Thermal Comfort Variations and Model-User Perception Gaps in a Tropical Peatland Campus

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Abstract: This study investigates the diurnal variation of outdoor thermal comfort and the discrepancy between the Predicted Mean Vote (PMV) and the Thermal Sensation Vote (TSV) in a humid tropical campus environment. The research was conducted at Lambung Mangkurat University, located in a wetland area with dense tropical vegetation. Data collection combined microclimatic measurements—air temperature, relative humidity, wind speed, and solar radiation—with thermal perception surveys administered to 150 students during two time intervals: 11:00–12:00 and 15:00–16:00 over five days. The purpose of this study is to evaluate the diurnal variation in thermal comfort and examine the discrepancy between model-predicted and user-perceived sensations. The novelty of this study lies in its integration of objective PMV calculations with subjective TSV responses in a tropical peatland context, revealing critical model limitations and informing adaptive design strategies. Results indicate that midday PMV values ranged from +0.88 to +1.30, exceeding ASHRAE-defined comfort thresholds and reflecting "warm to slightly hot" conditions. In the afternoon, PMV values dropped to a more neutral range (0.00 to +0.50). However, TSV responses revealed greater discomfort, particularly at midday, with most respondents reporting sensations from "slightly warm" to "warm" (TSV +1 to +2). This indicates a notable gap between model predictions and actual user perceptions. These findings highlight limitations of the PMV model in representing outdoor comfort in humid tropical contexts and suggest the need for locally adapted or adaptive-based models. Recommendations include implementing time-sensitive design strategies, increasing effective vegetative shading in active areas, and incorporating semi-permanent architectural elements such as pergolas and porous canopies. Such interventions support climate-responsive campus design and contribute to sustainable development goals in tropical higher education settings.

Keywords: thermal comfort; predicted mean vote; thermal sensation vote; tropical campus; outdoor microclimate.

热带泥炭地校园热舒适性昼夜变化与模型感知差异分析

摘要：本研究探讨了潮湿热带校园环境中户外热舒适性的昼夜变化，以及预测平均投票值（PMV）与热感觉投票值（TSV）之间的差异。研究地点为印度尼西亚兰邦马格拉特大学，该校位于一个植被茂密的湿地区域。数据收集结合了微气候参数的测量——空气温度、相对湿度、风速和太阳辐射——以及在五天内、每天两个时间段（11:00–12:00 和 15:00–16:00）对150名学生进行的热感知问卷调查。本研究的目的是评估热舒适性的昼夜变化，并分析模型预测与用户感知之间的差异。本研究的创新之处在于将客观的PMV计算与主观的TSV感知相结合，应用于热带泥炭地环境，从而揭示传统模型的关键局限性，并为适应性设计策略提供依据。研究结果表明，中午时段的PMV值在+0.88至+1.30之间，超出ASHRAE所定义的舒适阈值，反映出“温暖至略热”的感受。下午时段，PMV值下降至更接近中性范围（0.00至+0.50）。然而，TSV的反馈显示出更高的不适感，特别是在中午，大多数受访者的热感从“略热”到“热”（TSV +1 至 +2）。这表明模型预测与实际用户感知之间存在明显差距。这些发现强调了PMV模型在潮湿热带户外环境中表达热舒适性时的局限性，指出了需采用本地化或基于适应性的模型的必要性。建议包括实施具有时间敏感性的设计策略、增加活跃区域的有效植被遮荫，以及引入如棚架和透气遮阳设施等半永久性建筑元素。此类干预措施有助于打造对气候有响应能力的校园设计，并推动热带地区高等教育机构实现可持续发展目标。**关键词**：热舒适性；预测平均投票值；热感觉投票值；热带校园；户外

关键词：热舒适性；预测平均投票值；热感觉投票值；热带校园；户外微气候

1. Introduction

Thermal comfort is a key factor in creating healthy, productive, and inclusive learning environments, particularly in tropical regions. In the context of higher education, thermal comfort not only shapes subjective perceptions of space but also directly affects cognitive capacity, academic performance, and students' motivation to engage in daily activities—both indoors and outdoors. Outdoor activities such as walking between buildings, informal discussions, waiting for classes, or resting in campus gardens are strongly influenced by the thermal quality of the surrounding environment [1,2,3].

Humid tropical climates, such as that of South Kalimantan, are characterized by high air temperatures (averaging above 30°C), relative humidity often exceeding 70%, and year-round intense solar radiation. This combination generates a high environmental thermal load, especially during midday periods that typically coincide with peak student activity on campus [4,5,6]. The transition between air-conditioned indoor spaces and open, unshaded outdoor areas often leads to abrupt thermal shifts. Prolonged exposure to such conditions may induce thermal stress, which can impair students' concentration and academic productivity [7,8].

To date, most thermal comfort research has focused on indoor environments, typically within temperate or arid climate contexts. Outdoor thermal comfort (OTC) studies remain limited and have mostly concentrated on urban public or commercial spaces rather than educational campuses in tropical regions. Moreover, many of these studies rely heavily on microclimatic parameters and predictive models like Predicted Mean Vote (PMV), while neglecting users' subjective perceptions such as the Thermal Sensation Vote (TSV) [9,10,11].

This issue becomes even more significant in tropical campuses situated on peatland ecosystems, such as Lambung Mangkurat University (ULM). Peatland environments possess unique thermal properties, including extreme moisture levels, high soil heat capacity, and poor drainage performance. These characteristics interact with physical campus elements—such as vegetation, surface materials, and building orientation—to produce complex and dynamic microclimates. Inadequate vegetation or dense building configurations may further hinder natural ventilation and elevate local surface temperatures [9,12]. Despite these challenges, there is a notable lack of research explicitly examining how ecological typologies like peatland influence thermal comfort in campus environments.

This study aims to address this research gap by evaluating the diurnal variation of outdoor thermal comfort in a humid tropical campus, with a focus on midday and afternoon conditions. It further examines the extent to which the PMV model can accurately reflect students' actual thermal perceptions as measured by TSV. By combining quantitative measurements and perceptual surveys, this study seeks to provide empirical insight into the real-world thermal conditions of a tropical peatland campus and to propose time-based thermal design strategies that are responsive to local climatic conditions. These findings are expected to contribute not only to improved user comfort but also to the broader agenda of developing sustainable and climate-resilient campuses in the tropics.

2. Literature Review

Thermal comfort is a critical indicator in the design of healthy, productive, and sustainable built environments. According to international standards such as ASHRAE Standard 55 [13], thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment." This concept is determined not only by air temperature but also by environmental variables such as relative humidity, wind speed, and solar radiation, as well as human factors including clothing insulation (clo) and metabolic rate (met) [6,14].

Two commonly used approaches for evaluating thermal comfort are the Predicted Mean Vote (PMV) and the Thermal Sensation Vote (TSV). PMV, developed by Fanger, is a mathematical model that predicts the average thermal sensation of a population based on thermo-physical environmental conditions and user physiological characteristics [4]. The PMV scale ranges from -3 (cold) to +3 (hot), with 0 representing a neutral state. Due to its quantitative and measurement-based nature, PMV has become a widely adopted metric in building design and thermal comfort standards.

Conversely, TSV is a subjective approach that relies on individual perception of actual thermal conditions, typically collected through field surveys or questionnaires. Although it lacks objectivity, TSV excels in capturing the psychophysiological responses of users within specific spatial and temporal contexts. Numerous studies have shown that PMV often fails to accurately predict comfort in outdoor environments, especially in humid tropical climates where direct solar radiation, heated ground surfaces, and limited air circulation significantly influence perceived thermal conditions [1,3,9].

This mismatch between PMV and TSV in humid tropical contexts has been widely reported and is often referred to as the "model–perception gap" [10,15]. One primary reason is that the PMV model was originally developed for indoor environments in temperate climates with stable temperature control, making it less sensitive to microclimatic fluctuations such as heat-retaining surfaces or the absence of natural shading.

Additionally, the time of day plays a major role in shaping outdoor thermal comfort. During midday (especially between 11:00 and 13:00), air temperature and solar radiation peak, increasing the thermal load experienced by users. In contrast, conditions become more comfortable in the afternoon as solar exposure decreases and wind flow improves. Studies by Yao et al. and Yang et al. indicate that outdoor thermal comfort can vary significantly within just a few hours, emphasizing the importance of time-sensitive thermal design approaches [5,9].

In the context of a humid tropical campus situated on peatland—such as Lambung Mangkurat University—this issue becomes particularly relevant. Peatlands exhibit distinctive thermal characteristics, including high soil moisture, latent heat capacity, and airflow restrictions due to dense vegetation or compact building arrangements. The interaction between ecological elements and campus design creates unique microclimatic conditions that are often beyond the scope of conventional thermal comfort models [8,12].

However, systematic research addressing the suitability of PMV models and actual TSV perceptions in humid tropical campus environments—particularly on wetland-based terrain—remains limited. This study aims to bridge this gap by integrating objective microclimatic measurements with direct user perception data. The findings are expected to strengthen the empirical foundation for developing more context-sensitive thermal comfort models and to support the design of tropical campuses that are both adaptive and responsive to climate change.

3. Methodology

This study employed a quantitative approach through field measurements conducted at the campus of Lambung Mangkurat University, Banjarbaru, South

Kalimantan. The site was selected due to its characteristic tropical wetland environment with relatively high vegetation cover, which significantly influences microclimatic dynamics. Lambung Mangkurat University was selected due to its location in a representative humid tropical peatland ecosystem, providing a relevant case for analyzing outdoor thermal comfort in such environmental conditions.

3.1 Data Collection Period

The study was carried out over a five-day period in July 2024, coinciding with the dry season, when solar radiation typically reaches its annual peak. This timing was intentionally chosen to represent the extreme thermal conditions frequently encountered on tropical campuses, where high temperatures and intense solar exposure pose significant challenges to outdoor comfort. Measurements were taken at selected strategic points across the campus, including pedestrian pathways heavily used by students, shaded green open spaces used for recreation, and covered walkways between academic buildings. These locations were chosen to reflect the diversity of outdoor microclimatic conditions experienced by campus users. Data collection was conducted during two key intervals representing the daily thermal cycle: 11:00–12:00 (typically the peak thermal load period) and 15:00–16:00 (when radiation begins to decline but residual heat remains high). These intervals were strategically selected to capture the variation in thermal comfort typically encountered during outdoor academic and non-academic activities.

3.2 Measured Parameters

Measured variables were divided into two main categories: microclimatic parameters and respondent characteristics, representing objective and subjective aspects of outdoor thermal comfort. The microclimatic parameters were measured directly in the field and included:

- Air temperature (°C): indicating the thermal intensity of ambient air.
- Relative humidity (%): affecting sweat evaporation and cooling efficiency.
- Wind speed (m/s): influencing convective and evaporative cooling.
- Solar radiation (W/m²): the primary source of direct thermal load on human bodies and surfaces.

Measurements were taken using calibrated instruments as follows:

- Data logger: for simultaneous recording of air temperature and relative humidity.
- Anemometer: to measure wind speed at standard height.
- Solar power meter: to quantify solar radiation intensity.
- SNDWAY thermal imager: to detect and visualize surface temperature distribution.

In addition to environmental conditions, respondent characteristics were recorded to understand thermal perception. These human-related parameters included:

- Physical activity (metabolic rate, met): categorized based on observed actions (sitting, standing, walking), contributing to internal heat production.
- Clothing insulation (clo): estimated based on garments worn, following international insulation classification standards.
- Thermal sensation perception: collected via direct student surveys using a 7-point thermal sensation scale from -3 (cold) to +3 (hot), based on ASHRAE 55.

This approach integrates objective environmental measurements with subjective user perception, enabling a comprehensive assessment of thermal comfort in outdoor campus spaces.

3.3 Participants

A total of 150 students actively participated as respondents during the five-day observation period. Respondents were selected purposively, based on their presence in outdoor campus areas during measurement intervals. This ensured that thermal perception data reflected the actual experiences of students engaged in daily outdoor activities.

Each participant completed a short questionnaire designed to capture three key aspects:

- The physical activity being performed during the survey (e.g., sitting, walking, standing).
- The type of clothing worn, representing thermal insulation level (clo value).
- Perceived thermal sensation and comfort level, rated using the Thermal Sensation Vote (TSV) scale aligned with ASHRAE 55 standards (-3 to +3).

The data obtained from these questionnaires served as the subjective component of thermal comfort evaluation and were compared with the objectively measured microclimatic parameters to assess the gap between perceived and predicted thermal conditions.

3.4 Data Analysis

Microclimatic data and user characteristics were analyzed using the Predicted Mean Vote (PMV) formula, calculated through an ASHRAE-standard thermal comfort calculator. The analysis consisted of: (1) descriptive statistics (mean and standard deviation) for each parameter; (2) diurnal comparison between midday and afternoon conditions; (3) PMV–TSV gap analysis to evaluate model accuracy; and (4) Pearson correlation analysis to assess the relationship between environmental factors and students' thermal perceptions. This integrated approach enabled a comprehensive evaluation of both objective and subjective thermal comfort in a tropical outdoor campus environment.

4. Results

This study yielded empirical data indicating significant differences in thermal conditions between midday and afternoon periods, as shown through both physical measurements (PMV) and subjective user perceptions (TSV).

4.1 Predicted Mean Vote (PMV) Values

The Predicted Mean Vote (PMV) is a quantitative representation of an individual's thermal comfort level, derived from a combination of environmental parameters (microclimate) and personal physiological characteristics such as metabolic rate and clothing insulation. In this study, PMV values were calculated using field-measured data including air temperature, relative humidity, wind speed, and solar radiation, combined with estimated activity levels and clothing insulation values based on respondents' actual conditions during observation.

Observations conducted between 11:00 and 12:00 revealed PMV values ranging from +0.88 to +1.30, with an average of +1.10. These values indicate "warm to slightly hot" thermal conditions, exceeding the ASHRAE 55 comfort range (−0.5 to +0.5), suggesting that most individuals would begin to feel thermally uncomfortable during this period. The elevated PMV values were directly associated with high solar radiation levels (often exceeding 1500 W/m²), high relative humidity (approximately 69–78%), and low wind speeds (generally <0.75 m/s), which collectively impede effective heat dissipation from the body. In humid tropical climates, this thermal load is exacerbated by reduced sweat evaporation efficiency due to high humidity, diminishing the body's cooling mechanism and resulting in increased thermal discomfort.

In contrast, during the 15:00–16:00 interval, PMV values dropped significantly. The recorded PMV range was 0.00 to +0.50, with an average of +0.30, falling within the ASHRAE 55 thermal comfort zone. This improvement can be attributed to two main factors: first, a sharp reduction in solar radiation intensity (to below 300 W/m² by 15:30–16:00), and second, a notable increase in wind speed (reaching 1.01 m/s by 15:45), which promoted convective and evaporative cooling from the skin surface. The gradual decrease in air temperature, reaching around 29.9°C, also contributed to the more comfortable thermal environment during the afternoon.

Overall, the significant contrast in PMV values between midday and afternoon underscores the importance of time of day as a determining factor in outdoor thermal comfort dynamics in tropical climates. These findings have critical implications for campus outdoor space design, particularly in relation to microclimatic adaptation. Design strategies such as enhancing vegetation for shade, incorporating artificial shading elements, and orienting open spaces to support natural ventilation are highly relevant in mitigating heat stress during peak daytime activity. Thus, the PMV values obtained in this study serve not only as indicators of actual thermal conditions but also as strategic tools for evaluating and improving campus microclimate design in response to the diurnal rhythm of humid tropical environments.

Table 1. Summary of PMV values at two observation periods (Source: Field measurements and ASHRAE Standard 55)

Time	PMV Range	Average PMV	Thermal Comfort Interpretation	Dominant Influencing Factors
11:00–12:00	+0.88 to +1.30	+1.10	Warm to slightly hot (outside ASHRAE comfort)	High radiation, high humidity, low wind speed
15:00–16:00	0.00 to +0.50	+0.30	Neutral to slightly warm (within ASHRAE comfort)	Decreased solar radiation, increased natural wind speed

4.2 Thermal Sensation Vote (TSV) Values

The Thermal Sensation Vote (TSV) represents users' subjective perceptions of thermal comfort at the time of measurement and is obtained through field surveys based on the standard ASHRAE 55 thermal sensation scale. This scale ranges from -3 (cold) to +3 (hot), with a value of 0 indicating a thermally neutral state considered physiologically comfortable by the majority of people.

During the midday interval (11:00–12:00), respondents' thermal perceptions indicated a high level of discomfort. Survey results collected over five consecutive days revealed the following TSV distribution: 27% of respondents reported neutral conditions (TSV 0), 43% felt slightly warm (TSV +1), and 30% felt warm (TSV +2). This indicates that approximately 73% of respondents experienced thermal sensations outside the comfort zone, specifically in the slightly warm to warm categories. These findings reinforce the objectively measured PMV values and correspond with microclimatic conditions such as high solar radiation levels exceeding 1500 W/m², ambient air temperatures reaching 32°C, consistently high relative humidity levels (>70%), and low wind speeds (<0.75 m/s). The combination of these factors significantly impairs the body's ability to dissipate heat through sweat evaporation, resulting in thermal accumulation and heightened thermal stress.

In contrast, the afternoon interval (15:00–16:00) showed a shift toward more comfortable thermal conditions. TSV distribution during this period revealed that 17% of respondents felt slightly cool (TSV -1), 50% felt neutral (TSV 0), and 33% felt slightly warm (TSV +1). Notably, no respondents reported feeling hot (TSV +2), indicating that 67% of participants fell within an acceptable thermal comfort range. This improvement can be attributed to more moderate microclimatic conditions in the afternoon, including a significant reduction in solar radiation (below 300 W/m²), increased natural wind speed (exceeding 1.0 m/s), and lower air temperatures (approaching 29°C). Additionally, residual heat from hard surfaces began to dissipate, contributing to the overall cooling effect in the outdoor environment.

The comparison between midday and afternoon perceptions highlights the strong influence of time-dependent microclimatic variations on outdoor thermal comfort, especially in humid tropical regions. While PMV provides a predictive model based on environmental parameters, TSV captures the actual thermal experience of users. The integration of these objective (PMV) and subjective (TSV) data offers a more comprehensive understanding of thermal comfort conditions.

These findings underscore the importance of responsive and adaptive outdoor campus design strategies aligned with the diurnal rhythm of tropical climates. Recommended approaches include enhancing vegetation as natural shading elements, selecting surface materials with low thermal mass, and optimizing spatial configurations to promote natural ventilation. Such strategies not only improve outdoor comfort but also support sustainable academic activity amid the challenges posed by tropical climate conditions.

Table 2. Distribution of respondents' thermal sensation votes over 5 days (Source: Field measurements)

Time	TSV -1	TSV 0	TSV +1	TSV +2	Respondents
11:00–12:00	0	40	65	45	150
15:00–16:00	25	75	50	0	150

4.3 Model–Perception Gap

A comparison between Predicted Mean Vote (PMV) values and Thermal Sensation Vote (TSV) responses reveals a clear discrepancy between model-based thermal predictions and users' actual perceptions of outdoor thermal comfort. This gap reflects the difference between thermally calculated conditions and the thermal sensations directly experienced by the human body in real-world environments.

During the midday interval (11:00–12:00), the average PMV was recorded at +1.10, while the average TSV reported by respondents reached +2, with most responses falling within the TSV +1 to +2 range. While the PMV model suggests "warm to slightly hot" conditions, respondents perceived them as more extreme—"slightly warm to warm." This indicates that the PMV model tends to underestimate thermal discomfort during peak daytime hours in humid tropical climates. One of the main reasons for this gap is that PMV does not fully account for the direct impact of solar radiation on the body's surface, nor does it incorporate psychological adaptation and local acclimatization factors that influence thermal perception.

In contrast, during the afternoon interval (15:00–16:00), the average PMV dropped to +0.30, while the average TSV was around +1, with responses more evenly distributed around the thermal neutral range (TSV -1 to +1). This smaller gap suggests that the PMV model becomes significantly more accurate under more stable and moderate microclimatic conditions. The reduction in solar radiation, lower ambient temperatures, and increased wind speed during the afternoon contribute to environmental conditions that align more closely with PMV assumptions, thereby reducing the discrepancy between predicted and perceived comfort.

These findings underscore that the reliability of the PMV model is highly contextual and dependent on microclimatic conditions at the time of measurement. Under extreme midday conditions in tropical environments, PMV demonstrates clear limitations in capturing the complexity of real thermal loads—particularly when direct solar radiation dominates outdoor settings. Therefore, incorporating TSV data alongside PMV calculations is essential, as it provides subjective validation of model predictions and enriches the understanding of user comfort perceptions.

In summary, the PMV–TSV gap in this study serves as a critical indicator for identifying extreme thermal conditions where predictive models may fall short. It also offers strategic insight for developing more responsive microclimate design interventions that better reflect actual user experiences in humid tropical outdoor environments.

5. Discussion

The results of this study reveal a significant diurnal variation in thermal conditions between midday and afternoon periods within a tropical campus environment. During midday, air temperature, relative humidity, and solar radiation intensity reach their peak levels, while wind speed tends to be low. The combination of these parameters creates extreme thermal conditions that exceed the thermal comfort thresholds defined by ASHRAE Standard 55 [13], which specifies a neutral thermal zone within the PMV range of −0.5 to +0.5. The average midday PMV in this study was recorded at +1.10, substantially above the upper comfort limit.

These findings are consistent with previous studies [5,8], which emphasized the critical role of time-of-day as a determinant in developing thermal comfort mitigation strategies, particularly in humid tropical settings. The observed midday thermal conditions underscore the need for adaptive design interventions that address high heat exposure during peak hours, highlighting the importance of integrating temporal dynamics into microclimate-sensitive design approaches in educational environments.

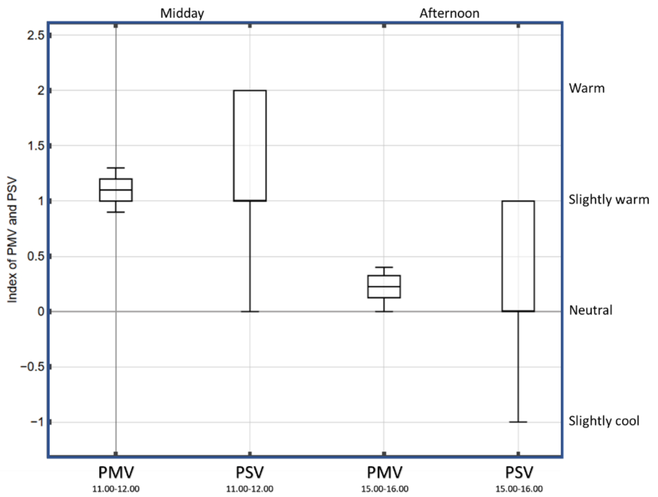

Figure 1. Diurnal variation of thermal comfort indices (PMV and TSV) in outdoor (Source: Field measurements)

Although the Lambung Mangkurat University campus features relatively extensive vegetation coverage, its effectiveness in reducing thermal load during midday remains limited. This is attributed to several key factors: (1) high humidity levels hinder the body's cooling process through sweat evaporation; (2) vegetative shading is unevenly distributed across key activity zones; and (3) the use of low-reflectance ground surfaces that absorb and retain substantial heat. These observations are supported by studies [9,12], which emphasize that the effectiveness of vegetation is highly dependent on species type, canopy structure, and its integration with human activity areas.

Furthermore, a noticeable gap was observed between PMV and TSV values, particularly during midday. While PMV estimated "warm to slightly hot" conditions (+1.10), actual user perceptions captured through TSV indicated sensations of "slightly warm to warm," with an average TSV close to +2. This suggests that the PMV model tends to underestimate actual thermal discomfort, as it does not fully account for the effects of direct solar radiation on the human body, elevated surface temperatures of hard materials, or psychological factors such as individual adaptation and heat tolerance. These findings align with previous studies [5,10], but provide greater emphasis on the underestimation of thermal discomfort by the PMV model during midday in humid tropical campuses. Several studies have also documented systematic bias in PMV performance when applied to outdoor tropical settings, reinforcing the need for local calibration or the development of adaptation-based comfort models [1,4,10,15].

In contrast, during the afternoon period, both PMV (+0.30) and TSV (+1) reflected more moderate and thermally acceptable conditions. Reduced solar radiation (<300 W/m²), increased wind speed (>1.0 m/s), and lower air temperatures created a more stable microenvironment, allowing user perceptions to align more closely with model predictions. Thus, the discrepancy between PMV and TSV serves as a critical indicator of the dominant influence of time and microclimatic conditions on outdoor thermal comfort.

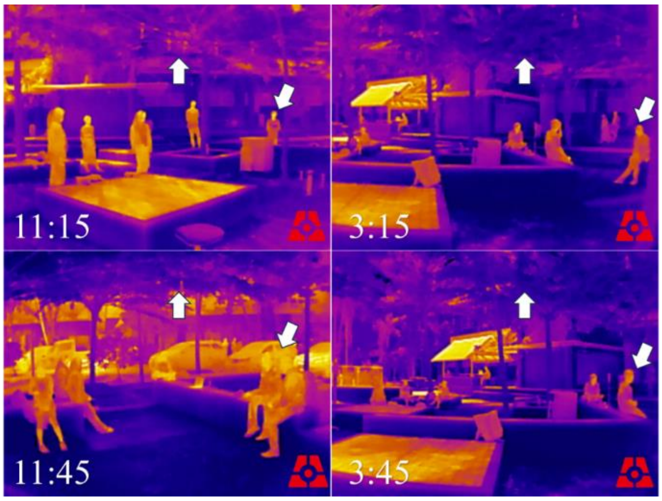

Figure 2. Diurnal thermal distribution of outdoor campus spaces based on infrared imaging (Source: Field measurements)

Overall, these findings affirm that outdoor thermal comfort strategies must be not only functional but also transformative—contributing to the development of more adaptive, energy-efficient, and sustainable campus environments. Such strategies align with Sustainable Development Goal (SDG) 4 on Quality Education and SDG 13 on Climate Action. The integrative approach that combines PMV and TSV data provides a robust empirical foundation for designing more human-centered and climate-resilient tropical wetland campuses.

6. Conclusion and Recommendations

This study evaluated the diurnal variation of thermal comfort in outdoor campus environments located within a tropical peatland context, while also analyzing the discrepancy between objective thermal comfort predictions (Predicted Mean Vote / PMV) and actual user perceptions (Thermal Sensation Vote / TSV). Conducted at the campus of Lambung Mangkurat University (ULM), Banjarmasin, the research focused on two critical time intervals—midday and afternoon—

to capture microclimatic dynamics influenced by solar radiation, air temperature, humidity, and wind speed.

Measurement results showed that thermal conditions during midday were extreme, with PMV values ranging from +0.88 to +1.30, indicating "warm to slightly hot" sensations that fall outside the comfort zone defined by ASHRAE 55 standards. In the afternoon, PMV values declined to a more acceptable range (0.00 to +0.50), falling within thermal comfort limits. T SV responses confirmed this trend but also revealed that the PMV model consistently underestimates actual discomfort, particularly under conditions of intense solar exposure and low wind circulation.

These findings emph asize that PMV has significant limitations in representing thermal comfort in humid tropical outdoor environments. The inability of the model to capture the combined effects of radiant heat, elevated ground surface temperatures, and individual heat adaptation responses suggests the need for complementary approaches based on local perception and environmental context.

While campus vegetation has helped form cooler microzones, its spatial distribution and shading performance were found to be insufficient in mitigating thermal loads during peak midday hours. These insights support the development of adaptive strategies that combine objective measurements with contextual user feedback to guide spatial interventions.

The contribution of this study lies in providing a perception-informed and time-sensitive framework for campus thermal comfort planning. By integrating quantitative thermal indices with field-based user responses in a tropical peatland setting, the study offers a practical basis for rethinking outdoor learning environments in Southeast Asian universities.

The following recommendations are proposed to enhance outdoor thermal conditions and promote more climate-responsive campus planning:

- Outdoor activities such as sports, field lectures, and informal gatherings should be scheduled for the afternoon, when solar intensity decreases and wind speeds increase, reducing heat stress and enhancing user productivity [5,6]. This aligns scheduling with circadian rhythms and observed microclimate stability.
- Introducing broad-canopy trees along pedestrian paths and public areas, as well as using understory and shrub vegetation, can create distributed "cool spots" and improve soil evaporation, thereby supporting thermal balance [12,16]. When layered appropriately, this vegetation also offers co-benefits including biodiversity and stormwater control.
- Semi-permanent structures such as pergolas, lightweight canopies, and ventilated vertical screens should be integrated into transitional spaces between buildings and outdoor areas. Reflective, light-colored materials are recommended to minimize heat accumulation and promote ventilation [10].
- Future masterplans should consider the orientation of open spaces, use of high-albedo materials, permeable surfaces, and thermal drainage strategies to lower surface temperatures and enhance natural air circulation [3,11]. These spatial configurations can extend thermal comfort zones across the campus.

This study provides a reference for future designs of thermally comfortable and resilient campuses in humid tropical climates. Further research should include computational simulation techniques, such as Computational Fluid Dynamics (CFD), and expand site diversity to strengthen the applicability of the findings. Through an integrative method that values both measured conditions and human experience, outdoor environments can be more human-centered, adaptive, and ecologically attuned to Southeast Asia's unique climate challenges.

Declarations

Author Contributions

A.R. conceptualized and led the study design and manuscript writing. F.R. contributed to the theoretical framework and cross-national data analysis. M.T. assisted in field data collection and statistical modeling. M.H.N.F. handled survey administration and graphical visualization. All authors reviewed and approved the final manuscript.

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Conflicts of Interest

The author declares no conflicts of interest with respect to the research, authorship, or publication of this article. All academic integrity principles—including plagiarism avoidance, data accuracy, responsible authorship, and ethical compliance—have been strictly followed.

Institutional Review Board Statement
Ethical review and approval were not required for this study, as it involved non-invasive observational data collection and did not include any interventions involving human or animal subjects.

Informed Consent Statement
Informed consent was obtained from all student participants involved in the perception survey component. Participants were informed that their responses would be used anonymously for academic research purposes only.

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