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Children's Thermal Comfort and Passive Thermal Performance of Semi-Outdoor Classrooms in a Tropical Climate

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Abstract

This study investigates passive thermal performance and children's thermal comfort in semi-outdoor classrooms in Aceh, Indonesia, integrating physical environmental measurements, thermal perception surveys, and thermal imaging observations. Measurements were conducted over three consecutive days across six classrooms (C1–C6) at Aceh Islamic Nature School, encompassing air temperature (Ta), relative humidity (RH), air velocity (Va), Mean Radiant Temperature (MRT), and Effective Temperature (ET). Thermal perceptions were collected through a seven-point Thermal Sensation Vote (TSV) questionnaire administered simultaneously to 37 students and homeroom teachers during morning and midday sessions. Results indicate that although air temperature reached 34.3°C and MRT exceeded tropical comfort thresholds during midday, ET values remained within 25.0–28.0°C, reflecting the important role of passive design elements, including natural ventilation, shading, and vegetation, in mitigating perceived heat loads. The shift in students' thermal perception from neutral in the morning toward warm during midday aligned with rising ET and MRT values, yet remained within tolerable limits. The study further identifies a gap between students and teachers; the findings suggested a tendency for teachers to perceive students' thermal discomfort differently, particularly during midday, which may be related to physiological differences between children and adults. These findings underscore the importance of explicitly positioning children's thermal perceptions as the primary reference in managing learning environments within tropical climates.

Keywords: thermal comfort; children; tropical climate; passive thermal performance; semi-outdoor classroom.

Introduction

Children spend approximately 30–50% of their daily time in school environments, making the thermal quality of classrooms an important factor affecting their concentration, health, and well-

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being [1]. In tropical regions such as Indonesia, these environments are characterized by high air temperatures, high relative humidity, and year-round solar radiation, which may cause indoor temperatures to exceed recommended comfort thresholds. Semi-outdoor classrooms with natural ventilation have become an increasingly adopted design approach, not only as an energy-efficiency strategy but also as a response to the need for interaction between learning spaces and the surrounding natural environment [2].

Dependence on air-conditioning (AC) systems is considered inconsistent with environmental sustainability principles due to their high energy consumption and contribution to increased emissions [3,4]. Most schools in developing tropical regions operate without AC and without adequate passive design strategies, a condition that directly exposes students to the risk of chronic thermal discomfort during learning hours [5]. Therefore, optimizing passive thermal performance, defined here as the effectiveness of passive design elements such as building orientation, opening systems, envelope materials, vegetation, and shading in regulating indoor thermal conditions, represents an approach that is both ecologically relevant and socially equitable [6].

In this context, the adaptive comfort theory developed by Humphreys and Nicol [7] serves as a vital theoretical foundation, suggesting that occupants consistently exposed to natural thermal conditions expand their comfort tolerance through physiological and behavioral adaptation. This phenomenon is explicitly demonstrated through children’s Thermal Sensation Votes (TSV), where students in tropical regions often report feeling "neutral" despite high air temperatures that exceed standard comfort thresholds. Supporting this, empirical research on children in Indonesia reveals a thermal neutral temperature of approximately 27.1°C, significantly higher than conventional indoor standards. Furthermore, a persistent discrepancy of approximately 0.8 points has been identified between the actual TSV (or Actual Mean Vote) and PMV predictions, reinforcing the argument that static models consistently overestimate children's sensitivity to heat [2]. Consequently, relying on subjective TSV provides a more accurate representation of children's comfort in semi-outdoor tropical classrooms than conventional objective indices.

Children possess physiological characteristics that differ from those of adults. Their larger body surface area-to-mass ratio and higher metabolic rate cause them to absorb environmental heat more rapidly [2,9]. This condition is further exacerbated by children's limited ability to recognize and independently respond to thermal conditions [10], while teachers, who are responsible for thermal adaptation decisions in classrooms, are generally less accurate in identifying the actual thermal conditions experienced by students [9,11,12]. Ironically, studies that explicitly compare the thermal perceptions of students and teachers simultaneously within the context of tropical semi-outdoor classrooms remain very limited. Yet thermal adaptation decisions in classrooms, such as opening windows, operating fans, and adjusting activity schedules, are entirely under the teachers’ control. If significant perceptual gaps and heat accumulation are still found in schools that have been designed responsively, conditions in other tropical schools with more enclosed environments may be considerably more concerning.

This study aims to analyze passive thermal performance and children's thermal comfort in semi-outdoor classrooms in Aceh by integrating measurements of physical environmental parameters, thermal sensation vote (TSV) surveys, and thermal imaging observations. By directly comparing the perceptions of students and teachers, this study seeks to identify thermal perception gaps and their implications for learning environment management, while also providing an empirical basis for passive thermal design strategies that are more responsive to the physiological needs of children in tropical climates.

Materials and Methods

Study Site and Classroom Characteristics

The study was conducted at Aceh Islamic Nature School, a privately operated elementary school located on Jalan Kerukun, Pangu Deah Village, Ulee Kareng District, Banda Aceh, Indonesia (**Figure 1**). The school occupies a land area of 5,760 m². The research took place in classroom spaces within the school building, which is situated in a tropical climate context characterized by high air temperatures, high humidity levels, and continuous solar radiation throughout the year. Banda Aceh has an average temperature of approximately 26–27°C, with maximum temperatures reaching up to 33°C. These climatic conditions formed the environmental background of this study, particularly in relation to semi-outdoor classrooms that have direct interaction with the outdoor environment.

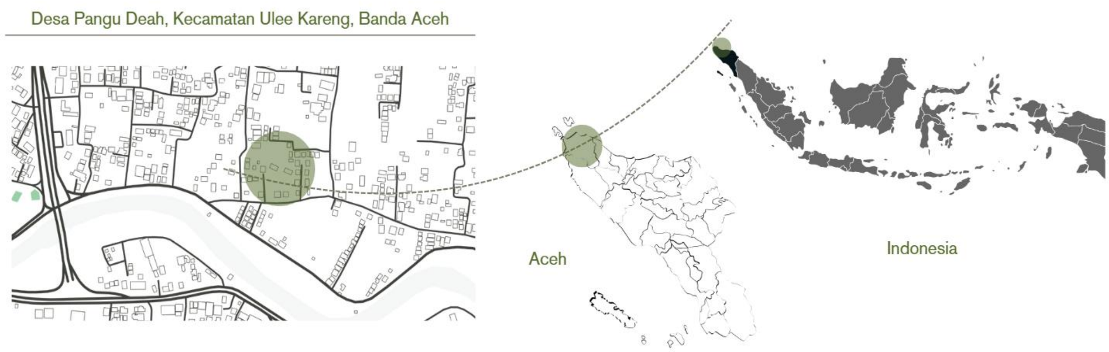

Figure 1. Study site (The study was conducted in Pangu Deah Village, Aceh, Indonesia)

Figure 2 presents an overview of the semi-outdoor classroom conditions in the tropical environment where the study was conducted.

Figure 2. Documentation of the Classrooms (Source: Author's Documentation)

Building A is a two-story structure functioning as the main classroom with a semi-open concept, characterized by large wall openings and the absence of mechanical cooling systems. Building B is a two-story structure, with the upper floor serving as a supplementary learning space for grades 5 and 6. In addition to these two primary masses, the site is also equipped with open areas comprising a courtyard and green spaces that function as transitional zones between the interior and the outdoor environment (**Figure 3** and **Table 1**).

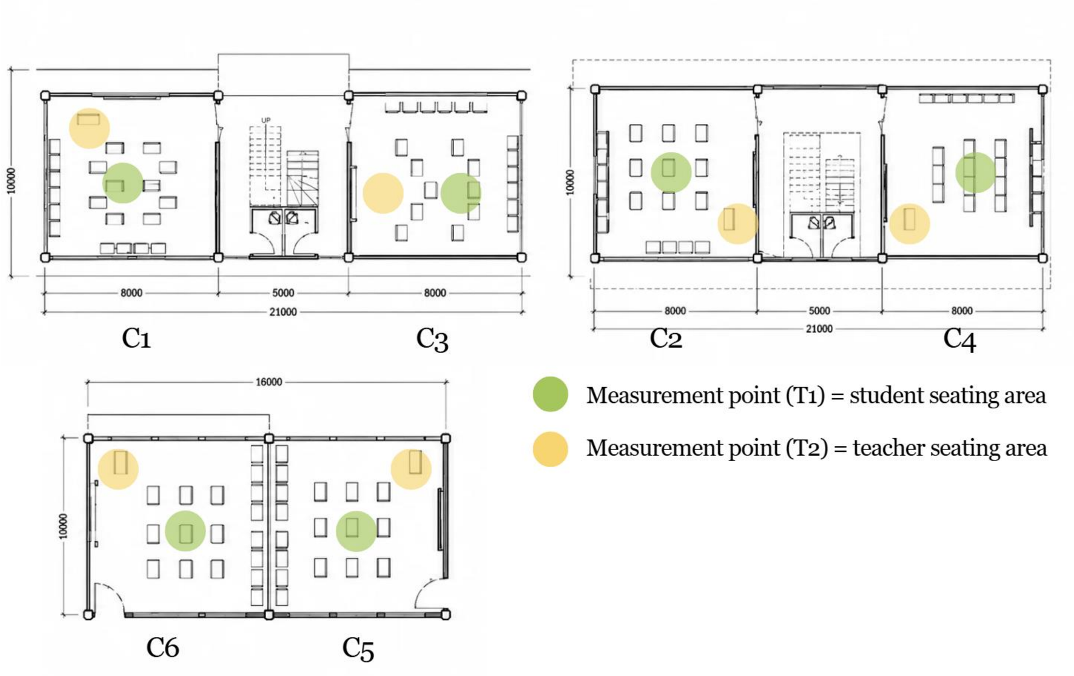

Figure 3. Classroom layout showing the measurement points T1 (Children Zone) and T2 (Teacher Zone)

Table 1. Classroom Description

Class No.	Building	Value
C1	Floor 1 – Building A	- Adjacent to Classroom 1 with a similar design. - Not directly exposed to sunlight.
C2	Floor 2 – Building A	- Equipped with operable windows that can be opened and closed. - Secondary skin surrounding the space to protect against direct heat exposure.
C3	Floor 1 – Building A	- Vegetation functions as shading and a heat barrier. - Open walls with side exposure to direct sunlight.
C4	Floor 2 – Building A	- Adjacent to Classroom 2 with a similar design. - Open walls and a secondary skin serving as heat protection.
C5	Floor 2 – Building B	- Glass walls provide natural lighting, reducing electricity use in the morning. - Presence of tall vegetation that may act as shading to reduce heat. - Operable windows for air circulation.
C6	Floor 2 – Building B	- Adjacent to Classroom 5 with a similar design. - Glass walls for natural lighting. - Tall vegetation and several small operable windows.

Environmental Measurements

Thermal environmental parameters were measured over three consecutive days during the period from 08:00 to 13:00 WIB, covering active learning hours from morning to early afternoon (**Table 2**). The three-day consecutive measurement period was selected to obtain sufficient data for identifying consistent thermal condition patterns while capturing reasonable day-to-day variations typical of tropical climates. This approach is consistent with common practices in field-based thermal comfort studies conducted in school environments, where structured measurements during active learning periods are considered representative of the typical thermal conditions experienced by occupants. Practical considerations related to minimizing disruption to teaching and learning activities also influenced the selection of this measurement duration.

In each classroom, measurements were conducted at two locations distinguished according to occupant activity zones: the student zone as Point 1 (T1) and the teacher zone as Point 2 (T2), as shown in Figure 3. This distinction was intended to identify potential differences in thermal conditions between the two zones, considering that variations in spatial position, orientation relative to openings, and activity types between teachers and students may influence the distribution of temperature, radiation, and airflow within the classroom.

Table 2. Thermal Parameters Measured in The Study

No	Parameter	Symbol	Instrument	Unit
1	Air Temperature	Ta	Digital Thermometer	°C
2	Relative Humidity	RH	Digital Hygrometer	%
3	Air Velocity	Va	Anemometer	m/s
4	Globe Temperature	Tg	Globe Thermometer	°C
5	Mean Radiant Temperature	MRT	Derived from Tg, Ta, Va	°C
6	Effective Temperature	ET	Derived from Ta, RH, Va	°C

(Source: Compiled by the author based on ISO 7726 and ASHRAE 55 (2017))

This method was selected because a globe thermometer is capable of simultaneously integrating the radiative effects of all surrounding surfaces, making it a recommended approach for evaluating thermal environments in semi-outdoor spaces [13]. Mean Radiant Temperature (MRT) was used as an indicator to identify the level of radiant heat load, particularly among more vulnerable occupant groups such as children.

The placement of measurement instruments was adjusted to the characteristics of the occupants, who were primary school children. ASHRAE 55 (2017) and ISO 7726 (1998) recommend measurement heights ranging from 0.6 to 1.1 m; however, these standards are based on adult anthropometric characteristics. Given that the subjects of this study were children aged 7–12 years, who have different body proportions, measurements were conducted at heights between 0.8 and 1.0 m above floor level. This height range was selected to represent the breathing zone and thermal exposure at the head level of seated children, which is physiologically the area most sensitive to environmental thermal conditions. This approach is consistent with previous thermal comfort studies involving children in school environments that employed similar measurement heights in field investigations [14].

Thermal Perception Survey and Observation

The thermal perception survey was conducted among 37 students from Grades 1 to 6 (aged 6–12 years), in which the study population was equivalent to the number of respondents, as well as the homeroom teachers of each classroom included in the study. This dual-respondent approach was adopted to obtain a more comprehensive perspective by integrating children's perceptions as the primary users of the space and teachers' assessments as observers who are familiar with the students' characteristics and daily behaviors.

The questionnaire was administered at two different times during the day: the morning session (08:00–10:00) and the midday session (11:00–13:00), in order to examine differences in students' thermal perceptions between these two periods. The questionnaires were completed simultaneously by students and teachers using identical respondent codes, enabling the alignment of responses between respondent pairs for comparative analysis (**Figure 4**).

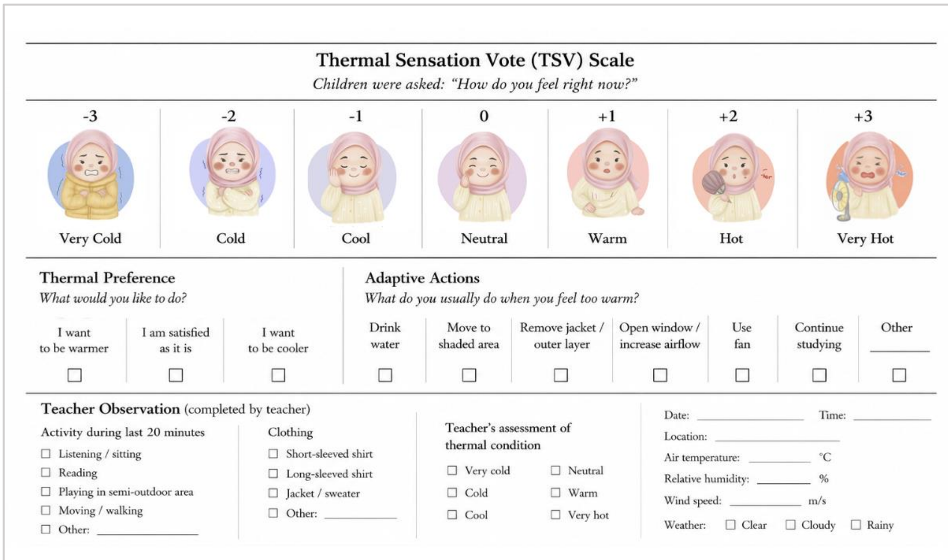

Figure 4. Questionnaire Administered to Respondents

The questionnaire instrument consisted of three main sections: (1) respondent demographic information for classification purposes, (2) homeroom teachers' assessments of students' comfort conditions based on daily classroom observations, and (3) students' direct perceptions of the thermal conditions within the learning environment, including thermal sensation, thermal comfort, and thermal preference. Thermal comfort levels were evaluated using the Thermal Sensation Vote (TSV) based on the seven-point ASHRAE 55 scale, ranging from −3 (very cold) to +3 (very hot). The questionnaire employed a visual presentation format inspired by previous studies, as it facilitates children's ability to focus on imagining their thermal comfort sensations during the survey process [15]. The TSV values were subsequently analyzed to determine the mean thermal sensation, the distribution of perceptions, and overall comfort tendencies under specific environmental conditions.

To examine the relationship between air temperature and thermal sensation, linear regression analysis was applied to the TSV data collected from both students and teachers. The regression model used air temperature (Ta) as the independent variable and TSV as the dependent variable, producing a regression equation and coefficient of determination (R^2) for each respondent group. From the regression equation, the neutral temperature, defined as the air temperature at which the predicted TSV equals zero, was derived for each group, enabling direct comparison of thermal neutrality between students and teachers.

To complement these subjective perception data, thermal imaging observations were conducted simultaneously using a thermal camera in all six classrooms (C1–C6) during both measurement sessions. Thermal images were captured at the same locations as the environmental parameter measurements (T1 and T2), allowing the imaging results to be directly examined alongside the measured air temperature, relative humidity, air velocity, and Mean Radiant Temperature (MRT) data. Thermal imaging was used to visualize the surface temperature distribution around the buildings [16]. Comparisons of thermal images among classrooms provided a visual representation of the increasing radiant heat load experienced by each classroom as solar radiation intensity increased.

The teacher assessment was conducted by the homeroom teacher, who was considered to have sufficient familiarity with the students through regular daily interaction. Teachers were asked to estimate each child's thermal comfort based on their observed facial expressions, behavioral responses, and their overall judgment of the child's perceived thermal condition at the time of the survey. This assessment was intended to provide an external evaluation of the child's thermal state rather than a direct measurement of the child's subjective perception. To facilitate comparison between teacher assessments and children's self-reported responses, each teacher questionnaire was assigned the same identification code as the corresponding child's questionnaire, allowing paired analysis of the two datasets.

The integration of subjective perception survey data and objective thermal imaging data was intended to provide a more comprehensive understanding of the relationship between the physical surface conditions of the space, radiant heat load, and occupants' thermal responses, particularly in evaluating the effectiveness of passive design elements such as shading, vegetation, and opening systems in each classroom.

Results

Thermal Characteristics of Semi-Outdoor Classrooms

The results of thermal parameter measurements in the six classrooms (C1–C6) revealed variations in thermal conditions influenced by measurement time and the design characteristics of each space (**Table 3**). In general, a consistent pattern of increasing thermal conditions from morning to midday was observed, reflecting the intensification of solar radiation throughout the learning period.

Table 3. Results of Calculated Parameters

Class No.			Ta (°C)	Tg (°C)	Rh (%)	Va (m/s)	MRT	ET
C1	T1	Min	28.2	22.7	46.5	0.03	22.6	25.0
		Mean	30.9	30.5	57.0	0.05	30.5	26.6
		Max	34.3	34.5	65.1	0.07	34.5	28.0
	T2	Min	28.3	28.3	47.1	0.01	28.3	25.0
		Mean	30.7	31.3	57.6	0.03	31.3	26.3
		Max	33.2	34.5	67.6	0.05	34.4	27.6
C2	T1	Min	29.3	23.1	51.4	0.01	23.1	25.3
		Mean	30.9	30.2	57.5	0.07	30.2	26.3
		Max	33.3	33.1	65.1	0.17	33.1	27.8
	T2	Min	29.2	29.1	50.1	0.01	29.1	25.4
		Mean	30.8	31.0	57.6	0.04	31.0	26.5
		Max	32.8	32.0	64.8	0.10	32.0	27.6

C3	T1	Min	29.8	28.5	54.6	0.07	28.5	25.8
		Mean	30.7	30.9	57.9	0.12	30.9	26.4
		Max	31.7	33.5	64.5	0.24	33.5	27.0
	T2	Min	29.7	28.7	55.3	0.02	28.7	25.5
		Mean	30.6	30.7	58.2	0.17	30.7	26.6
		Max	31.6	33.3	63.2	0.09	33.3	27.8
C4	T1	Min	28.4	28.9	50.0	0.01	28.9	25.2
		Mean	30.7	30.7	58.2	0.07	30.7	26.4
		Max	32.8	33.2	66.6	0.11	33.2	27.5
	T2	Min	28.4	27.3	49.9	0.01	27.3	25.2
		Mean	30.6	30.6	58.3	0.05	30.6	26.6
		Max	32.0	34.1	66.9	0.09	34.1	27.8
C5	T1	Min	30.6	19.9	49.7	0.01	19.8	26.2
		Mean	31.9	32.1	55.4	0.04	32.1	26.2
		Max	33.7	36.8	58.6	0.08	36.9	26.2
	T2	Min	30.6	30.3	49.5	0.00	30.3	26.1
		Mean	31.8	33.3	55.6	0.03	33.3	26.1
		Max	33.7	36.8	58.2	0.05	36.8	26.1
C6	T1	Min	30.8	29.5	49.2	0.01	29.5	26.2
		Mean	32.0	32.4	55.2	0.05	32.4	26.2
		Max	33.7	36.6	58.6	0.09	36.7	26.2
	T2	Min	30.7	29.8	49.0	0.00	29.8	26.0
		Mean	31.9	32.5	56.1	0.03	32.5	26.0
		Max	33.7	36.4	66.1	0.06	32.5	26.0

Table 3 presents the calculated environmental parameters across six classrooms during two observation periods (T1 and T2). Air temperature (Ta) generally ranged from 28.2°C to 34.3°C, while globe temperature (Tg) varied between 19.9°C and 36.9°C. Relative humidity (RH) remained within a moderate range of approximately 46.5% to 67.6%, indicating consistently humid conditions throughout the study period. Air velocity (Va) was relatively low in most classrooms, with average values commonly below 0.20 m/s. Mean radiant temperature (MRT) followed trends similar to globe temperature, reflecting variations in surface heat exposure and radiant conditions within the semi outdoor classrooms. Effective temperature (ET) remained relatively stable, with mean values generally ranging from 26.0°C to 26.6°C.

Among the observed classrooms, C5 and C6 exhibited the highest temperature values, with maximum globe temperatures reaching 36.8°C and 36.9°C, respectively. In contrast, classrooms C1 to C4 showed lower thermal fluctuations and more moderate environmental conditions. Although temperature and humidity levels varied among classrooms and observation periods, the effective temperature remained within a relatively narrow range, suggesting that the combined influence of air temperature, humidity, air movement, and radiant heat produced comparable overall thermal conditions (**Figure 5**). These results indicate that while individual environmental parameters differed across locations and times, the overall thermal environment experienced by occupants remained relatively consistent throughout the study. In addition, the variation in average MRT increases among classrooms and between measurement periods can be compared.

Air velocity (Va) across all classrooms remained relatively low, ranging from 0.03 to 0.24 m/s. Classrooms C1 to C4 recorded higher air velocity values than C5 and C6. At most measurement points, Va values were below 0.1 m/s.

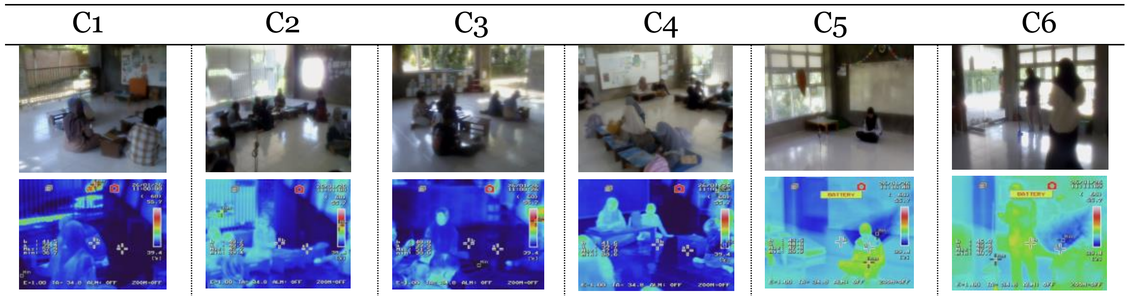

Figure 5. Thermal Imaging Results (Source: Author's Documentation)

Thermal imaging results revealed lower, more uniform surface temperature distributions in C1–C4 than in C5 and C6. During the midday session, increases in surface temperature were predominantly observed in areas directly exposed to solar radiation, particularly on roofs, walls, and floors, with the most prominent heat accumulation points (hot spots) appearing in C5 and C6, consistent with the high MRT and Ta values recorded in these spaces. Meanwhile, the semi-outdoor characteristics of C1–C4, the presence of shading, and the use of materials with greater capacity to reduce heat absorption resulted in lower and more stable surface temperatures in these classrooms. In contrast, Classroom C3, which utilized vegetation as a shading element, showed a more uniform and lower surface temperature distribution, indicating the effectiveness of natural shading in passively reducing radiant heat loads. The thermal images visually supported the field measurement results by illustrating higher surface heat accumulation in classrooms with greater solar exposure and limited external shading.

These observations are consistent with the environmental measurements and thermal perception results, where classrooms exhibiting lower surface heat accumulation generally recorded lower MRT values and a higher proportion of children reporting neutral or comfortable thermal sensations. This agreement suggests that reducing radiant heat through passive design strategies contributes to improving both the measured thermal environment and occupants' thermal experience.

Thermal Performance and Adaptive Comfort

Effective Temperature (ET) values across all classrooms ranged from 25.0 to 28.0°C, despite air temperatures (Ta) reaching 34.3°C and MRT exceeding recommended tropical comfort thresholds. The lowest ET values were recorded during the morning session at approximately 25.0°C and increased to nearly 28.0°C during the midday session. Classroom C3 recorded lower ET and MRT values than C5 and C6.

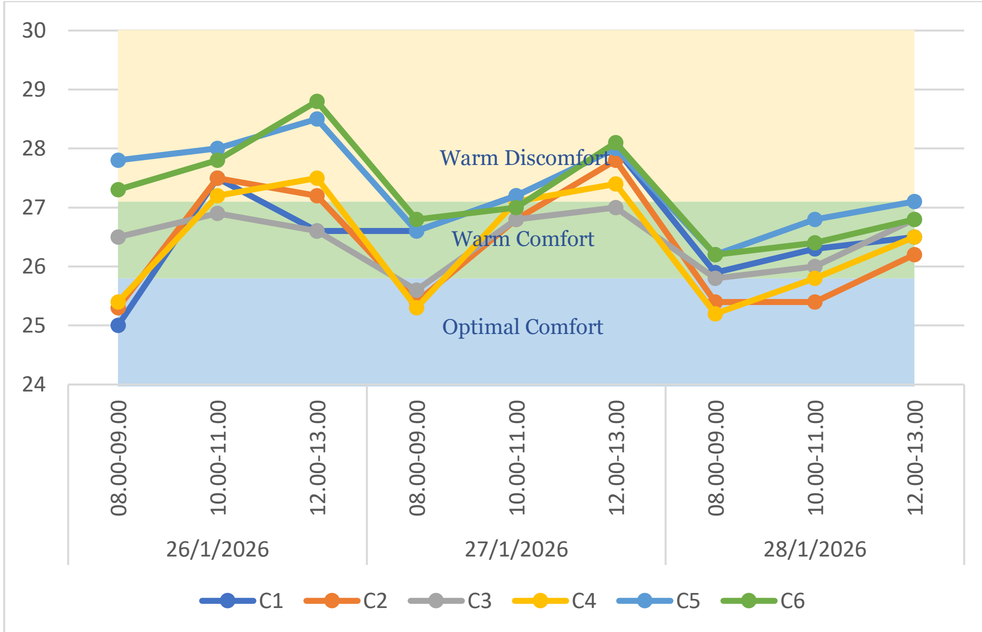

Figure 6. Effective Temperature (ET) in Classroom Measurements

Figure 6 shows that Effective Temperature (ET) values across all classrooms ranged from approximately 25.0°C to 28.9°C during the measurement period. ET generally increased from the morning to the midday session, with the highest values recorded in Classrooms C5 and C6 and the lowest in Classroom C3. Most measurements fell within the optimal comfort and warm comfort zones, while several midday measurements in C5 and C6 approached or exceeded the warm discomfort threshold.

The relationship between the physical conditions of the classrooms and occupants' thermal responses was also reflected in the distribution of students' Thermal Sensation Vote (TSV) values. During the morning session (08:00–10:00), when ET was at its lowest level of approximately 25.0°C, the distribution of students' TSV responses was dominated by the neutral category, indicating thermal conditions that remained within acceptable comfort limits. During the midday session (11:00–13:00), as ET increased to nearly 28.0°C and MRT reached its peak, students' thermal perceptions shifted toward the warm category, with a small proportion of responses reaching the very hot category. Nevertheless, the overall thermal conditions remained within tolerable limits, partly due to the limited duration of classroom occupancy until 13:00, before the period of peak daily solar radiation exposure, which generally occurs between 14:00 and 15:00. Field observations also recorded adaptive behaviors among students during the measurement sessions, such as relocating to areas closer to airflow sources or shaded zones within the classroom.

Children's Thermal Perceptions and Teachers' Predictions

A comparison of TSV values between students and teachers revealed a consistent thermal perception gap, particularly during the midday session. During the morning session (08:00–10:00), the TSV distributions of both groups were relatively balanced, with the majority of respondents falling within the neutral category. No respondents from either group selected the very cold category throughout the measurement period, reinforcing the characterization of the study environment as a hot-humid climate that does not reach extremely cold conditions. During the midday session (11:00–13:00), the difference between the two groups became more apparent. Students exhibited a shift in TSV responses toward higher positive values, whereas teachers tended to maintain assessments within the neutral category when evaluating the conditions experienced by students.

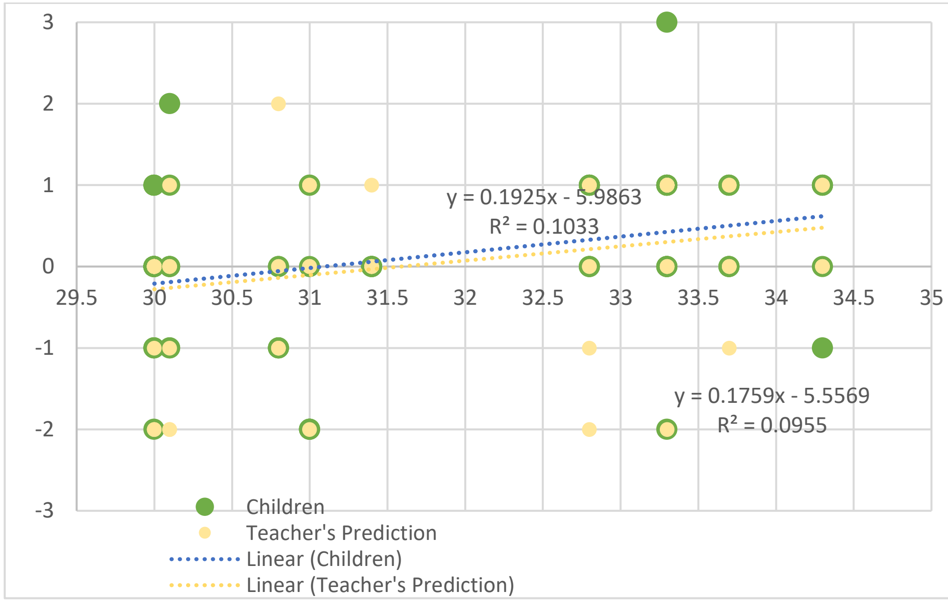

Figure 7. Thermal Sensation Vote (TSV) Results of Teachers and Students

Figure 7 shows Thermal Sensation Vote (TSV) among children and teachers. TSV values for both groups were distributed across an air temperature range of approximately 30–34°C. Linear regression analysis produced the equation $y = 0.1925x - 5.9863$ with $R^2 = 0.1033$ for children and $y = 0.1759x - 5.5569$ with $R^2 = 0.0955$ for teachers. The TSV values reported by children ranged from −2 to +3, whereas those reported by teachers ranged from −2 to +2. The estimated neutral temperature (TSV = 0), derived from the regression equations, was approximately 31.1°C for children and 31.6°C for teachers.

The difference in TSV values between students and teachers was not merely subjective but was supported by fundamental physiological factors. Children have a larger body surface area-to-mass ratio (BSA) and a higher metabolic rate than adults [9], causing them to absorb environmental heat more rapidly. Consequently, under identical thermal conditions, students tend to experience warmer thermal sensations and report higher TSV values than teachers. This physiological difference becomes more pronounced during the midday period when environmental heat loads increase and is consistent with previous studies demonstrating that adults' assessments often fail to accurately represent children's actual thermal experiences [11]. This perception gap has important practical implications. Thermal adaptation measures in classrooms, such as opening windows, operating fans, or adjusting activity schedules, are generally implemented based on teachers' assessments. If teachers consistently underestimate the heat conditions perceived by students, necessary adaptive actions may be delayed or not implemented at all.

Statistical analysis of TSV values from both groups further reinforced this pattern, with the mean TSV difference between students and teachers showing a more consistent divergence during the midday session than during the morning session. These findings highlight the importance of explicitly incorporating children's thermal perceptions as a primary reference in decisions regarding the management of learning environments, rather than relying solely on teachers' assessments as a proxy for students' thermal conditions.

Discussion

The findings of this study reveal that the thermal conditions of semi-outdoor classrooms in tropical climates cannot be explained solely by air temperature as a single parameter. Although Ta reached 34.3°C and exceeded conventional comfort thresholds, ET remained within the range of 25.0–28.0°C, which was still acceptable to most students. The discrepancy between these two parameters indicates that natural ventilation, air humidity, and air movement play important roles in shaping occupants' thermal perceptions. In the context of semi-outdoor spaces, ET appears to provide a more comprehensive representation of perceived thermal conditions than air temperature alone because it accounts for the interaction of multiple environmental parameters simultaneously [17]. Therefore, thermal comfort assessments based solely on Ta may overestimate the actual level of discomfort experienced by occupants of semi-outdoor spaces.

Comparisons among classrooms highlight the importance of passive design strategies in controlling environmental heat loads. Classrooms incorporating a combination of more open configurations, shading vegetation, and protection from direct solar radiation tended to maintain lower MRT and ET values than spaces characterized by extensive glazed surfaces and limited shading protection. Classrooms C1 to C4, which adopted a more open semi-outdoor concept with adequate vegetation and shading elements, exhibited lower MRT and ET values than C5 and C6, which were dominated by glass walls without effective external shading. This pattern was reinforced by thermal imaging results, which identified the highest concentration of hot spots in C5 and C6, indicating greater radiant heat accumulation due to the limited passive design strategies implemented in these classrooms. These findings are consistent with previous studies demonstrating that vegetation, shading systems, and natural ventilation contribute significantly to reducing radiant heat loads and improving thermal comfort in educational buildings located in tropical and subtropical regions [4,18].

Interestingly, substantial increases in MRT were not always accompanied by proportional increases in thermal discomfort. This suggests that natural ventilation and opportunities for behavioral adaptation may compensate for some of the negative effects of radiant heat exposure [3]. In semi-outdoor environments, occupants do not merely experience thermal conditions passively but actively adjust their body positions, select more comfortable locations, and take advantage of available airflow. The combination of these factors likely contributed to maintaining ET values and thermal perceptions within a tolerable range. Beyond physiological differences, measurement data indicate that MRT values at T1 (student zone) tended to be higher with lower air velocity compared to T2 (teacher zone). This condition was further compounded by the density of students sitting in proximity to one another, generating higher metabolic heat accumulation, while teachers positioned at the periphery of the classroom tended to have better access to airflow [11,12].

The conditions observed at AINS, as a school that seeks to implement a nature-based design approach through the use of semi-outdoor spaces, vegetation, and natural ventilation, provide an important example of this relationship. Nevertheless, this study still identified substantial increases in MRT during the midday period, as well as heat accumulation in several classrooms. These findings indicate that thermal comfort challenges may persist even in learning environments that have adopted various passive design strategies. Consequently, schools with lower levels of passive design implementation may face even more challenging thermal conditions. Therefore, the results of this study may serve as an empirical reference for evaluating and improving the design quality of tropical schools more broadly.

Moving from the physical dimension to the perceptual dimension, the TSV results showed that students reported warmer thermal sensations than teachers' assessments of the same conditions, with the perception gap becoming more pronounced during the midday session. This difference has a strong physiological basis. Children's larger BSA ratio and higher metabolic rate cause them to absorb environmental heat more rapidly than adults [5,6]. Consequently, even under identical thermal conditions, children may be physiologically subjected to greater thermal stress than teachers, despite occupying the same space [15]. These findings are consistent with previous studies showing that adults' assessments, including those of teachers and parents, do not always accurately represent children's actual thermal experiences [12].

This perception gap has implications that extend beyond differences in TSV values. In everyday classroom management, thermal adaptation measures, such as opening windows, operating fans, or adjusting physical activity schedules, depend almost entirely on teachers' initiative. If teachers systematically underestimate the heat conditions perceived by students, necessary adaptive actions may be delayed or not implemented at all, resulting in students being exposed to uncomfortable thermal conditions for longer periods [11]. Such conditions may affect concentration and learning performance [5], although in the context of this study, these effects did not exceed critical thresholds because classroom use ended before the period of peak daily solar radiation exposure.

The findings of this study also support previous research that questions the suitability of the PMV model for evaluating children's thermal comfort in tropical semi-outdoor environments. PMV was developed based on adult populations in relatively controlled indoor environments and therefore, may not fully represent children's physiological characteristics or the adaptive responses that emerge in naturally ventilated settings. In this study, the spontaneous adaptive behaviors observed among students, such as moving to shaded areas or positioning themselves closer to airflow sources, indicate that behavioral responses play an important role in shaping occupants' actual thermal experiences [19,20]. Therefore, thermal comfort evaluations in children's learning environments should consider the integration of physical parameters, subjective perceptions, and users' adaptive behaviors simultaneously.

Conclusion

This study demonstrates that passive thermal performance in semi-outdoor classrooms plays an important role in maintaining tolerable thermal conditions for students in tropical climates. Although air temperature and MRT exceeded conventional comfort thresholds during midday periods, ET remained within an acceptable range due to the influence of natural ventilation, shading, and vegetation. These findings highlight the importance of passive design strategies in reducing dependence on mechanical cooling systems in tropical schools.

Classrooms with adequate vegetative shading and cross-ventilation consistently exhibited better thermal performance, whereas glass-dominated classrooms without effective external shading experienced higher radiant heat loads. The thermal perception gap identified between students and teachers further emphasizes the need to consider children's thermal perceptions when implementing classroom thermal adaptation measures.

This study has several limitations. Measurements were conducted over only three days in a single school, limiting the generalizability of the findings and the representation of seasonal variations. Future studies involving longer monitoring periods, multiple school settings, and additional variables would provide a more comprehensive understanding of children's thermal comfort in tropical learning environments.

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Conflict of Interest

The authors declare no conflicts of interest.

Author Contribution Statement

Aci Astriana: Conceptualization, Investigation, Data curation, Writing original draft. **Abdul Munir**: Supervision, Methodology. **Laina Hilma Sari**: Supervision, Methodology. **Siti Norbaya Mohd Konar**: Writing – review & editing.

Data Availability Statement

The data used to support the findings of this study are included within the article. Additional data derived from interviews and field observations are not publicly available due to confidentiality and privacy considerations of the participants. Questionnaire participation was voluntary and anonymous, and no personal identifying information was collected from respondents.

Ethics Approval

Permission to conduct the study was obtained from the school administration and participating teachers.

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