RESEARCH ARTICLE

Evaluation of Thermal Comfort in Outdoor Learning Spaces of a University Campus in Hot-Humid Climate, Malaysia

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Abstract

The underutilisation and poor design of outdoor spaces on university campuses have limited their effectiveness as learning environments due to inadequate planning and thermal discomfort. By analysing the relationship between thermal comfort and user satisfaction, the study aims to improve the design and planning of outdoor areas, hence increasing their usefulness as effective learning environments. Surveys on 500 respondents and field measurements were conducted across five outdoor learning spaces on a university campus in a hot and humid climate region from March to September 2024. Results showed that the mean air temperature for outdoor learning spaces is 28.9 °C, and the neutral overall thermal comfort temperature is much higher at 37.1 °C. This reflects that the students in a hot-humid climate demonstrate greater adaptability to elevated air temperatures in outdoor learning spaces. There are significant differences in thermal comfort for different outdoor learning spaces, with tree-shaded sites having high heat levels and dissatisfaction rates exceeding 90%. Roof-shaded and courtyard sites showed moderate thermal comfort, although dissatisfaction remained above 50%. Semi-open spaces were the most comfortable, with respondents preferring cooler, shaded areas. The study concludes that optimising thermal conditions can improve the usability and integration of outdoor learning spaces.

Keywords: *Hot and humid Climate, Outdoor Learning Space, Thermal Comfort, Thermal Comfort Indices, University Campus*

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Introduction

The physical environment of higher education should be regarded as a complex network of interconnected learning spaces. Various learning processes, encompassing diverse pedagogies, venues, technology, cultures, communities and academic mentality circumstances, make up the complex components of the higher education environment (Radcliffe et al., 2008; Wang et al., 2024; Zandvliet, 2014). Typically, individuals do not utilise the outdoor spaces that are essentially “leftover” between buildings (Azhar et al., 2022). However, there is an opportunity to develop learning spaces in the “leftover” spaces between buildings (Radcliffe et al., 2008).

Radcliffe et al. (2008) introduced the “Learning Spectrum Model,” inspired by a student-centred learning approach. Based on the goal of the learning approaches, active learning or reflective learning approaches, the learning spaces in his Learning Spectrum model can be organised or unstructured. This concept suggests that every square meter of outdoor campus space can facilitate activities and the overall learning process (Prince & Diggory, 2024). Unstructured learning settings are suited for individual work, group collaboration, peer education and self-directed study, while structured spaces are intended for teacher-led instruction.

The campus environment significantly influences students' daily experiences, where access to outdoor activities is vital for performance and well-being (Barfield et al., 2021; Brent Jackson et al., 2021; Coventry et al., 2021; Zhu et al., 2022). Outdoor open spaces, often referred to as "squares" serve as a crucial location for campus activities. Unfortunately, these spaces are typically viewed mainly as representations of university culture and authority. Consequently, the regulation of microclimates and thermal comfort is often overlooked in the design of campus squares. With increasing emphasis on students' physical and mental well-being, it is essential to analyse and design campus squares with a focus on environmental quality (Ghorbanzadeh, 2019).

Thermal comfort refers to the psychological state where an individual is satisfied with the surrounding thermal environment. The built environment influences the outdoor thermal conditions through factors such as anthropogenic heat (Ichinose et al., 1999), ground surface materials (Lin et al., 2007), evaporation and evapotranspiration of plants (Robitu et al., 2006) and shading from trees and artificial objects (Binabid & Anteet, 2024). Outdoor thermal comfort represents a multifaceted interaction of atmospheric variables, encompassing physical, physiological, psychological and behavioural aspects. These factors and elements combine to shape responses and thermal sensation, commonly discussed in human biometeorology studies (Chen & Ng, 2012).

Research shows that excessive heat adversely affects students' health, which in turn impacts their academic performance. The effects of heat on cognitive development are expected to be more severe in countries such as India, where temperatures and poverty levels are both high (Park et al., 2020). Prolonged exposure to high outdoor temperatures throughout the year may result in health issues (Salata et al., 2016) such as eye fatigue, vertigo, shortness of breath and tachycardia (Xiong et al., 2015). More severe symptoms of heat stress include swelling, rashes, and heat strokes, which can be associated with neurological disorders when body temperature reaches 40.6 °C (McGugan, 2001).

A study on the thermal comfort of shaded outdoor areas was carried out in 2010 at Universiti Putra Malaysia in Malaysia by Makaremi et al. (2012). They discovered that environmental factors, thermal adaptation and psychological parameters strongly affect human thermal comfort levels in outdoor spaces. Additionally, Lau et al. (2019) carried out a study at the National University of Singapore from 2015 to 2017 to compare thermal comfort in learning spaces using three different ventilation strategies that include air-conditioning, hybrid and natural ventilation. Their findings showed that hybrid spaces have significant advantages over air-conditioning and natural ventilation spaces in terms of a higher rate of neutral thermal sensation votes, temperature satisfaction levels, and overall thermal comfort levels. Similarly, in 2018, Ghaffarianhoseini et al. (2019) conducted a study on the thermal comfort conditions of outdoor spaces on the campus of University Malaya in Malaysia. The study debates improving the outdoor comfort conditions for campus users while attempting to identify the thermally uncomfortable areas and their physical and design characteristics. Consequently, recommendation is made to enhance the design quality of outdoor areas by optimising their thermal comfort conditions are proposed. The study concludes that by properly considering the important effects of vegetation and shade, outdoor areas in the tropics can be redesigned to be more comfortable and used frequently.

Building on these insights, the present study integrates four types of outdoor learning spaces: tree-shaded, roof-shaded, courtyard-type and semi-open spaces, into a holistic campus network. By incorporating these spaces with indoor learning areas, the study aims to reduce the physical separation created by bitumen roads, car parks, and other hardscape features, thereby improving outdoor thermal comfort.

This study contributes to three meaningful findings to the body of literature. First, it demonstrates how the four types of outdoor learning space types can be systematically integrated into the campus network as a whole. Second, it applies an advanced methodology based on environmental measures because WS3 data at user level are utilised in capturing actual experience of students in terms of their thermal comfort in outdoor learning spaces. Third, it investigates the relationship between user-level responses and out-of-building operating temperature more elegantly than before and provides insight into microclimatic effects on learnability of learning environments. Collectively, these developments bridge the gap between under-sought “leftover” spaces and the promise of well-designed OLS to maximise learning and flourishing at university scale.

Research Methodology

This research was conducted in two phases. The first phase involved measuring the thermal environment of selected outdoor learning spaces to investigate the on-site conditions. The second phase is to conduct subjective thermal comfort questionnaire survey to capture the responses of outdoor learning space users.

Climate Conditions

The research was conducted on a university campus in Kuala Lumpur, Malaysia (3° 13’ 10.3” N 101° 43’ 33.9” E) between 1 March 2024 and 6 September 2024, spanning approximately six months. Kuala Lumpur lies in the equatorial region and experiences a tropical climate year-round. The mean outdoor air temperature and relative humidity during the study period were 28 ±2 °C and 80 ±7%, respectively. These climate conditions posed challenges to thermal comfort in outdoor learning spaces that were not regulated by any cooling systems. Malaysia experiences two monsoon seasons: the Southwest Monsoon (from late May to September) with drier weather and the Northeast Monsoon (from November to March) with heavier rainfall. March, April and May are generally the hottest months, with temperatures potentially reaching over 37 °C in some regions.

Investigated Outdoor Learning Spaces

Beyond weather conditions, the thermal comfort of outdoor learning spaces (OLS) depends highly on the surrounding setting, including landscaping, buildings and shading. Five OLSs representing four categories were selected within the Tunku Abdul Rahman University of Management and Technology (TAR UMT) (Figure 1). The first OLS (S1) is an open park, surrounded by two to three-storey buildings and densely shaded by tall Casuarina trees (Figure 2a). The second OLS (S2) is a partly shaded area with canopy trees, bordered by a four-storey building on the east side and facing a large open space to the west (Figure 2b). S1 and S2 are tree-shaded OLSs and receive direct sunlight through gaps between trees and buildings. The third OLS (S3) is a roofed grandstand located within a park (Figure 2c). This is a popular space among students for learning and interactive activities. It is well-shaded from direct sunlight and well-ventilated from all sides. The fourth OLS (S4) is a courtyard enclosed within a four-storey building (Figure 2d). It receives sunlight primarily at noon through the top opening, with limited shading provided by coconut trees. Poor ventilation was identified for the S4 due to the buildings surrounding it the four sides. The last OLS (S5) is a semi-open space located on the ground floor of a three-storey building (Figure 2e). S5 is well-ventilated from all four sides and fully shaded by the first-floor slab.

Figure 1: Location of Investigated Outdoor Learning Spaces within the TAR UMT Campus. (Google Maps, 2024)

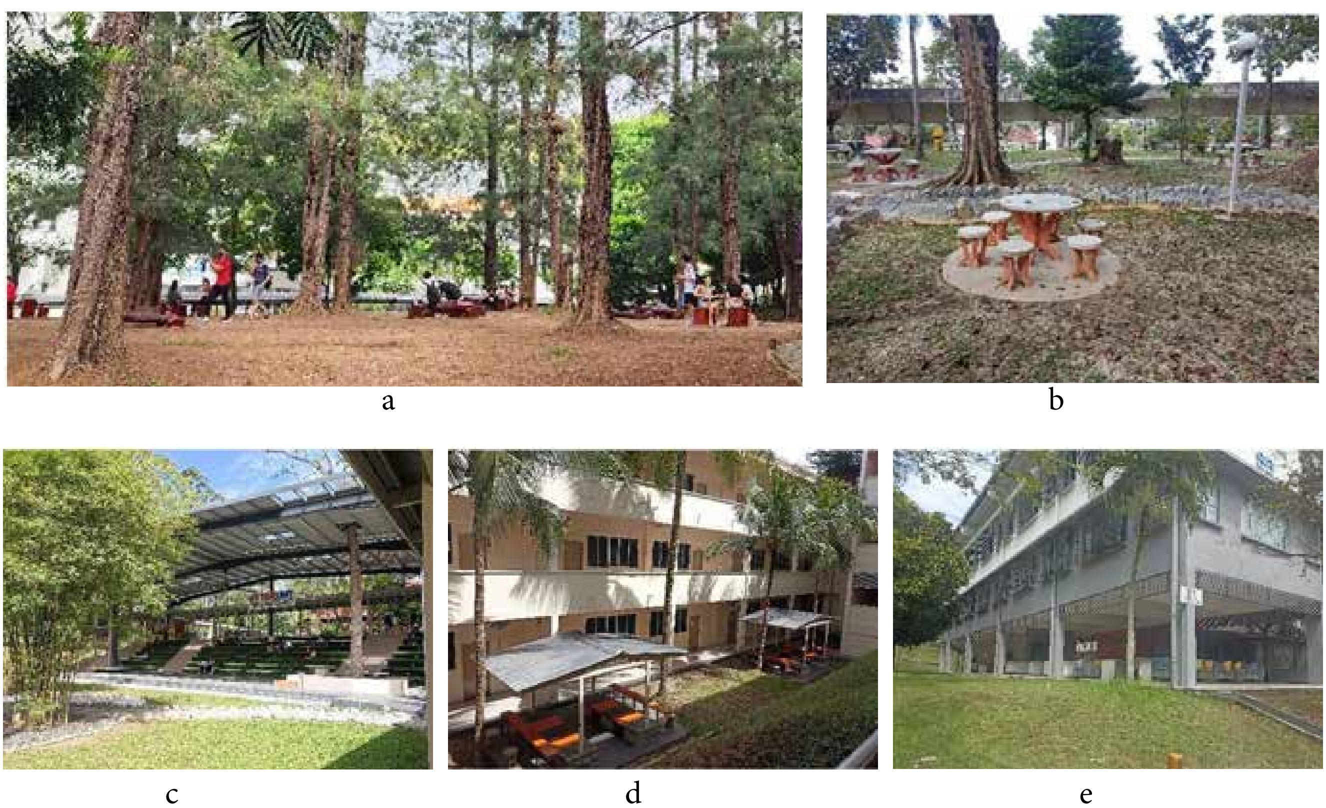


Figure 2: Views Of the Five Investigated OLSs at the TAR UMT Campus. (a) S1 - Tree-Shaded Outdoor Learning Space; (b) S2 - Tree-Shaded Outdoor Learning Space; (c) S3 - Roof-Shaded Outdoor Learning Space; (d) S4 - Courtyard-Type Outdoor Learning Space; (e) S5 - Semi-Open Outdoor Learning Space

Data Collection

Questionnaire surveys were administered on OLS users to collect their subjective responses to the thermal environment at that specific moment. At the same time, field measurements were conducted to measure the thermal environment of the OLSs. The data collection process was carried out between March to September 2024 in a sequence from S1 to S5. Random sampling was used to choose 100 respondents from the users of each outdoor learning space. In total, 500 samples were collected. The survey was conducted from 9 am to 5 pm on Monday to Friday when students occupied the space. No surveys were conducted during weekends, and semester breaks due to the lack of space users.

Thermal Environment Measurements

The instruments used in the field measurements are shown in Table 1. Two units of Delta Ohm Meteo compact station HDMCS-200 weather stations were set up on the campus to measure the thermal environment of the investigated OLSs. The first unit (WS1) was permanently set up on the rooftop of a five-storey administrative building on the campus (Figure 3a) to record the prevailing weather conditions of the area. Air temperature (T_a), relative humidity (RH), globe temperature (T_g), solar radiation (SR), wind speed (V_a), wind direction and precipitation at 30-second intervals. The weather station's second unit (WS2) is a movable unit that can be placed on the ground level in each selected OLSs to measure the microclimate throughout the data collection period (Figure 3b). The environmental parameters measured by the WS2 are the same as the WS1, excluding precipitation. In addition, a portable thermal comfort data logger (WS3), Delta Ohm HD32.3TC (Figure 3c), was placed adjacent to each respondent to measure the air temperature (T_a), relative humidity (RH), globe temperature (T_g) and air velocity (V_a). In addition, the thermal comfort index's predicted mean vote (PMV) index and predicted percentage of dissatisfaction (PPD) index were calculated automatically by the data logger. The purpose of the three weather stations is to investigate any significant differences in locating the weather station when conducting a thermal comfort study.

Table 1: List of Instruments Used in the Field Measurement.

Instrument	Manufacture	Parameter	Resolution	Range	Accuracy
Delta Ohm Meteo compact station HDMCS-200	Delta Ohm, Italy	Air temperature	0.1 °C	-40 to 60 °C	± 0.15 °C ± 0.1% of measurement
		Relative humidity	0.1%	0 to 100% RH	± 1.5%RH 0…90%RH), ± 2%RH (remaining range)
		Wind speed	0.01 m/s	0 to 50 m/s	± 0.2 m/s or ± 2%, the greatest (0…35 m/s), ± 3% (> 35 m/s)
		Wind direction	0.1°	0 to 359.9°	± 2° RMSE from 1.0 m/s
		Solar radiation	1 W/m^2	0…2000 W/m^2	2nd Class Pyranometer
		Precipitation	0.1 – 0.2 or 0.5 mm/tip	-	± 2 %
Delta Ohm HD32.3TC	Delta Ohm, Italy	Air temperature and Relative humidity	0.1 RH	T= -40 to 100 °C UR= 0 to 100%	RH = ±2% (90 to 100% RH) @ T=15 to 35°C (±1.5 + 1.5% of the measurement) % @ T=remaining range
		Globe temperature	0.1 °C	-30 to 120 °C	Class 1/3 DIN
		Air velocity	0.01 m/s	0.05 to 5 m/s	± (0.05+0.5% of the measurement) m/s

a b c

Figure 3: (a) Delta Ohm Meteo Compact Station HDMCS-200 Set Permanently on the Rooftop of A 5-Storey Building. (b) The Movable Delta Ohm Meteo Compact Station HDMCS-200 Is in the Investigated Outdoor Learning Space. (c) Portable Delta Ohm HD32.3TC Data Logger Setup Adjacent to the Respondent.

Subjective Thermal Comfort Questionnaire

The questionnaire survey consisted of three parts. The first part is focused on respondents' sociodemographic information and the physical activity they engaged in before participating in the survey. In addition, the survey date, time and prevailing weather conditions were recorded. The second part addressed the type of clothes worn during the interview to determine respondents' clothing insulation levels. The third part focused on the respondents' subjective evaluations of thermal sensation, satisfaction, preference and overall thermal comfort level. Thermal sensation was evaluated using the 7-point ASHRAE scale. Thermal satisfaction was assessed using a 5-point Likert scale. Temperature preference was measured with a 3-point McIntyre preference scale. Overall thermal comfort of the respondents was evaluated on a 7-point scale, as shown in Table 2.

Table 2: Descriptions of the Thermal Comfort Survey Questionnaire Scales.

Scale	Thermal sensation	Scale	Thermal satisfaction	Scale	Temperature preference	Scale	Overall thermal comfort
3	Hot					7	Very comfortable
2	Warm	5	Very satisfied			6	Comfortable
1	Slightly warm	4	Satisfied	3	Cooler	5	Slightly comfortable
0	Neutral	3	Neutral	2	No change	4	Neutral
-1	Slightly cool	2	Unsatisfied	1	Warmer	3	Slightly uncomfortable
-2	Cool	1	Very unsatisfied			2	Uncomfortable
-3	Cold					1	Very uncomfortable

All data were collected through voluntary participation, with informed consent obtained and clear information provided regarding the study's purpose. Participants had the right to withdraw at any point during the survey. Participants' information was kept confidential and anonymized to protect their privacy throughout the research.

The overall profile of respondents is shown in Table 3. Most respondents are students aged 17 to 24, primarily from the Chinese ethnic group, with 55.8% female. The majority surveys (93.8%) were conducted in the afternoon from 12 pm to 5 pm when the outdoor temperatures were their highest. With respect to weather conditions, 59.2% of the surveys were conducted on sunny days, 38% were on cloudy days, 19.4% on windy days and 9.4% on rainy days. As shown in Table 4, the mean clothing insulation for all respondents was 0.4 clo, a low insulation level typical of summer clothing in temperate climate, while the mean metabolic rate was 1.36 met (between standing and walking). The results of the ANOVA test (Table 4) indicated no significant differences in clothing insulation among respondents from the five different OLSs. However, significant differences in metabolic rate were observed among the five OLSs.

Table 3: Profile of Respondents Based on the Outdoor Learning Space.

	S1	S2	S3	S4	S5	Total	Percentage (%)
Age							
17-18	0	3	26	17	13	59	11.8
19-20	16	46	40	28	43	173	34.6
21-22	67	29	29	42	32	199	39.8
23-24	15	15	3	11	7	51	10.2
>24	2	7	2	2	5	18	3.6
Total	100	100	100	100	100	500	100
Gender							
Female	59	57	47	60	56	279	55.8
Male	41	43	53	40	44	221	44.2
Total	100	100	100	100	100	500	100
Ethnic							
Chinese	98	82	91	90	90	451	90.2
Malay	0	4	0	1	1	6	1.2
Indian	1	11	8	8	9	37	7.4
Others	1	3	1	1	0	6	1.2
Total	100	100	100	100	100	500	100
Survey time							
Before 12 pm	12	4	0	1	14	31	6.2
12 – 3 pm	59	91	22	39	46	257	51.4
After 3 pm	29	5	78	60	40	212	42.4
Total	100	100	100	100	100	500	100
Weather condition*							
Sunny	70	67	48	63	48	296	59.2
Cloudy	33	31	47	35	44	190	38.0
Windy	21	15	27	7	27	97	19.4
Rainy	4	5	10	17	11	47	9.4

*Respondents are allowed to select more than one condition.

Table 4: Mean Clothing Insulation, Metabolic Rates

	S1	S2	S3	S4	S5	Mean	ANOVA Test
Clothing insulation (clo)	0.40±0.02	0.41±0.02	0.40±0.03	0.44±0.03	0.40±0.03	0.41±0.03	F(4, 495) = 0.7, p = 0.564
Metabolic rate (met)	1.17±0.01	1.06±0.01	1.45±0.24	1.47±0.23	1.16±0.13	1.26±0.12	F(4, 495) = 28.2, p < 0.001

Notes On ANOVA Test: F: F-Statistic; P: P-Value. Values in Brackets Denote the Degrees of Freedom Between Groups and Within Groups.

Figure 4 presents box plots illustrating the distribution of clothing insulation, height, weight and age among female and male respondents. As shown in Figure 4a, females (median = 4.5 clo) exhibited higher clothing insulation than males (median = 0.31 clo), with both distributions skewed toward higher values and containing some outliers. Generally, males (median = 1.725 m) were taller than females (median = 1.6 m) in height (Figure 4b) and males (median = 62 kg) were also heavier than females (median = 50 kg) in weight (Figure 4c). Both female and male respondents had the same median age of 21 years old.

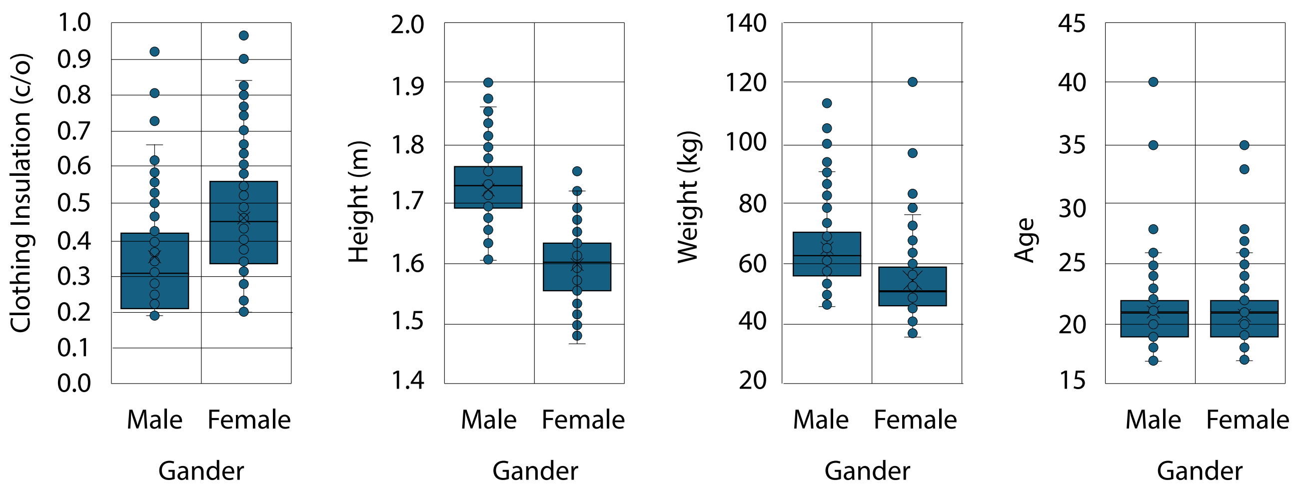


Figure 4: Distribution of Clothing Insulation (4a), Height (4b), Weight (4c), and Age (4d) Between Female and Male Respondents.

Results and Discussion

Thermal Environment

A summary of the environmental parameters measured by the three weather stations across the five OLS is presented in Table 5. Solar radiation (SR) was not recorded by WS3. The maximum air temperature (T_a) recorded on campus was 36.3 °C and the minimum was 23.6 °C, with relative humidity (RH) ranging from 34.7% to 100% and a mean of 28.9 °C. The highest wind speed (V_a) recorded was 7.7 m/s. S1 and S2 recorded the highest mean T_a at 28.9 °C while S5 recorded the lowest at 27.2 °C. As shown in Figure 5, variations between WS1 and WS2 were minor, ranging from 0.2 to 0.4 °C. However, temperatures recorded by WS3 near the respondents were substantially higher than those from WS1 and WS2, by 3.9 to 5.5 °C. Standard deviations indicated that WS1 and WS2 exhibited much greater variation in environmental parameters than WS3. Table 6 presents the ANOVA results analyzing significant differences among the five OLSs in mean environmental parameter values collected from WS1 and WS2. The results indicated that the mean values of T_a, RH, V_a and SR for both WS1 and WS2 were statistically significant.

Table 5: Mean Values of Environmental Parameters Taken from WS1, WS2, And WS3

OLS	Date	T_a (°C)			RH (%)			V_a (m/s)			SR (MJ/day)	
		WS1	WS2	WS3	WS1	WS2	WS3	WS1	WS2	WS3	WS1	WS2
S1	1/3/2024-20/4/2024	28.9 (3.0)	28.9 (3.3)	34.1 (1.3)	75.2 (16.9)	77.3 (28.3)	50.7 (6.2)	1.5 (1.1)	0.4 (0.3)	0.7 (0.4)	22.8 (5.6)	11.8 (3.0)
S2	23/4/2024-15/5/2024	28.5 (3.0)	28.3 (3.0)	33.8 (0.9)	82.9 (15.1)	85.9 (15.2)	57.2 (3.9)	1.3 (0.9)	0.5 (0.4)	0.7 (0.5)	19.7 (3.9)	8.6 (2.1)
S3	5/7/2024-19/7/2024	27.9 (2.8)	28.1 (3.0)	31.8 (1.7)	79.9 (14.3)	80.5 (15.1)	60.5 (7.5)	1.4 (0.9)	0.5 (0.4)	0.5 (0.3)	17.3 (5.0)	9.8 (2.7)
S4	30/7/2024-13/8/2024	27.5 (2.9)	27.7 (3.1)	31.5 (2.1)	80.7 (14.9)	80.7 (15.6)	59.0 (14.0)	1.4 (0.9)	0.7 (0.5)	0.3 (0.2)	18.6 (5.2)	9.7 (3.1)
S5	16/8/2024-6/9/2024	27.6 (3.0)	27.2 (3.0)	31.0 (1.5)	81.2 (15.4)	85.0 (15.0)	62.6 (8.3)	1.3 (0.9)	0.5 (0.5)	0.8 (0.5)	19.6 (4.4)	8.6 (1.9)
Overall Maximum		36.3	35.7	-	99.8	100	-	7.7	1.3	-	-	-
Overall Minimum		24.0	23.6	-	35.9	34.7	-	0.4	0.1	-	-	-
Overall Mean		28.9	28.9	-	75.2	77.3	-	1.5	0.4	-	-	-

Notes: WS1: Weather Station 1; WS2: Weather Station 2; WS3: Weather Station 3; S1: Site 1, S2: Site 2; S3: Site 3; S4: Site 4; S5: Site 5; T_a: Air Temperature; RH: Relative Humidity; V_a: Air Speed; SR: Solar Radiation

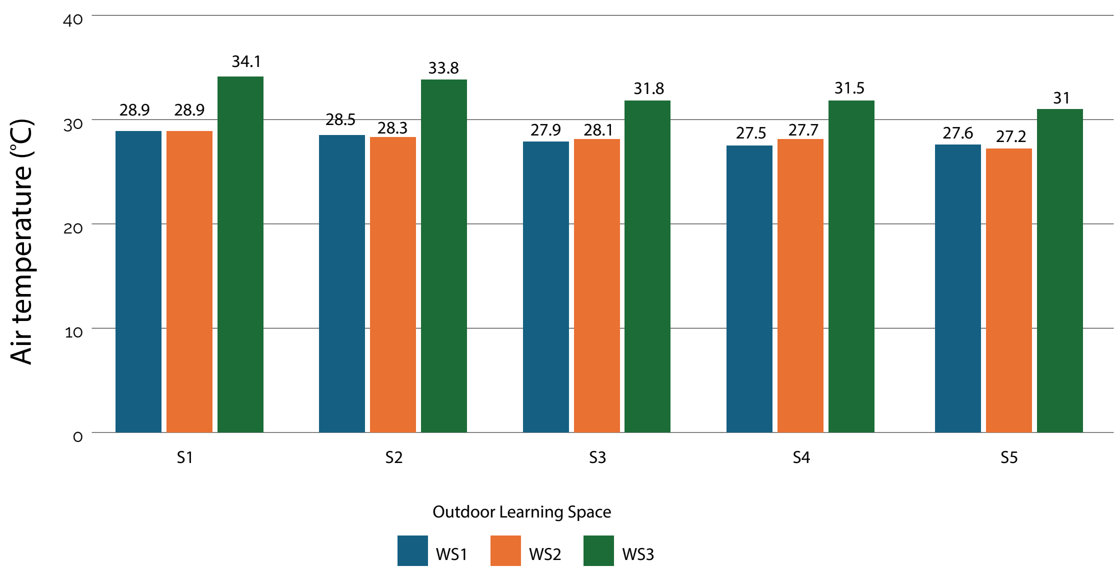


Figure 5: Comparison of Mean Air Temperature Between WS1, WS2 and WS3

Table 6: ANOVA Test on the Significance of Differences Between Five OLSs

ANOVA Test	T_a	RH	V_a	SR
WS1	F(4, 3036) = 29.8, p <0.001	F(4, 3039) = 31.1, p <0.001	F(4, 3039) = 31.1, p <0.001	F(4, 3035) = 10.5, p <0.001
WS2	F(4, 3036) = 30.2, p <0.001	F(4, 3036) = 36.0, p <0.001	F(4, 3036) = 36.0, p <0.001	F(4, 3035) = 63.8, p <0.001

Notes: WS1: Weather Station 1; WS2: Weather Station 2; T_a: Air Temperature; RH: Relative Humidity; V_a: Air Speed; SR: Solar Radiation, F: F-Statistic; P: P-Value

Table 7 shows the environmental parameters recorded by WS3, including T_a, T_g, T_{mrt} and T_{op}. As shown in Figure 6, no significant differences among T_a, T_g, T_{mrt} were observed for S3, S4 and S5. However, for S1 and S2, T_{mrt} and T_g were substantially higher than T_a. This indicates elevated radiant heat from the surroundings due to the high T_a when the field measurements for S1 and S2 were conducted. The ANOVA test further confirmed that the T_a, T_g, T_{mrt}, and T_{op} differed significantly among the five OLSs.

Table 7: Mean Values of the Additional Environmental Parameters Taken from the Portable Delta Ohm HD32.3TC Data Logger

OLS	T_a (°C)	T_g (°C)	T_{mrt} (°C)	T_{op} (°C)
S1	34.1 (1.3)	35.6 (2.0)	39.4 (4.7)	35.7 (2.1)
S2	33.8 (0.9)	35.2 (1.7)	38.3 (4.1)	35.2 (1.7)
S3	31.8 (1.7)	32.1 (1.9)	32.8 (2.5)	32.1 (1.9)
S4	31.5 (2.1)	31.9 (2.3)	32.5 (2.6)	31.8 (2.2)
S5	31.0 (1.5)	31.2 (1.5)	31.6 (1.5)	31.2 (1.5)
ANOVA Test	$F(4, 495) = 83.8$, $p < 0.001$	$F(4, 495) = 115.1$, $p < 0.001$	$F(4, 495) = 121.0$, $p < 0.001$	$F(4, 495) = 118.9$, $p < 0.001$

Notes: T_a: air temperature; T_g: globe temperature; T_{mrt}: mean radiant temperature; T_{op}: operative temperature. Values in brackets indicate the standard deviation.

Notes on ANOVA Test: F: F-statistic; p: p-value. Values in brackets denote the degrees of freedom between groups and within groups.

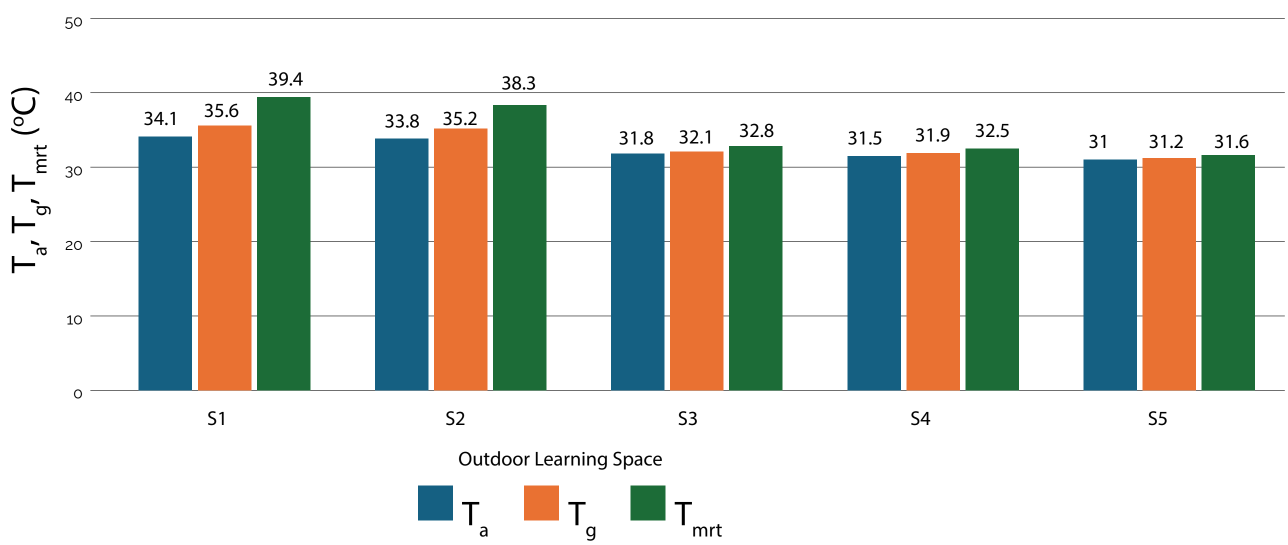
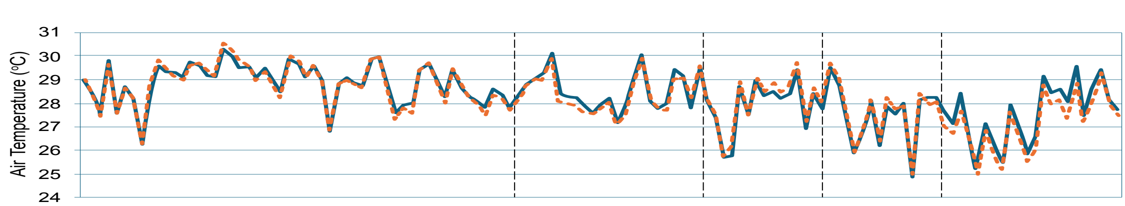
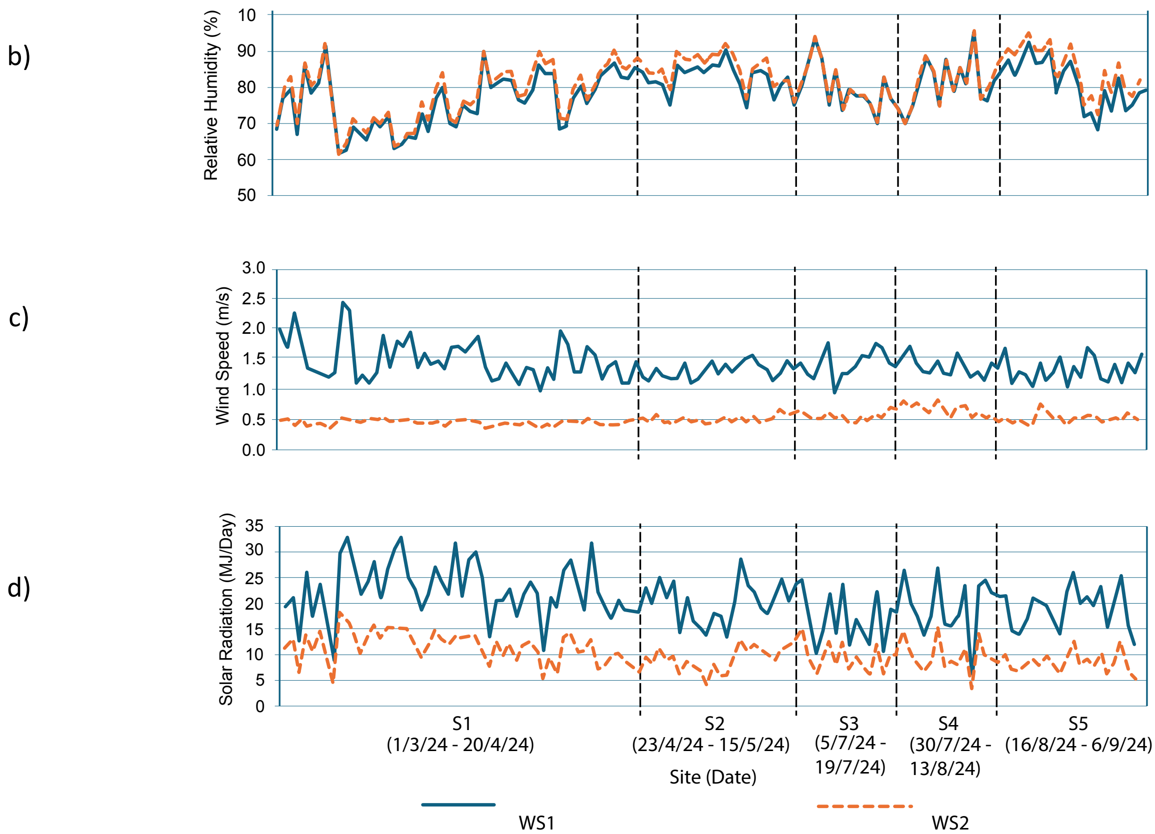


Figure 6: Comparison Between T_a, T_g, And T_{mrt} Taken from WS3 for S1 to S5.

Figure 7 compares data from WS1 and WS2 to examine differences between a rooftop-mounted weather station and a portable unit positioned adjacent to the investigated OLS at ground level. Comparison of air temperature (Figure 7a) and relative humidity (Figure 7b) revealed no significant differences between the two stations. However, significant differences were observed in mean wind speed (Figure 7c) and solar radiation (Figure 7d). WS1 at the rooftop recorded a higher wind speed (1.4 m/s), while WS2 at the ground level recorded a lower mean wind speed (0.5 m/s). A similar pattern was observed for mean solar radiation, with 20.5 MJ/day at WS1 and 10.1 MJ/day at WS2. The differences were attributed to shading from surrounding trees and buildings, which blocked the wind flow and solar radiation reaching the OLS.

a)





Notes: WS1: Weather Station 1; WS2: Weather Station 2; WS3: Weather Station 3; S1: Site 1, S2: Site 2; S3: Site 3; S4: Site 4; S5: Site 5

Figure 7: Comparison of Environmental Parameters Taken from WS1 and WS2.

Subjective Evaluations and Predicted Comfort Level

Table 8 summarises the mean values of the four subjective evaluation parameters that is thermal sensation (TS), thermal satisfaction (TA), thermal preference (TP) and overall thermal comfort (OC) across different space types, along with the two predicted thermal comfort indices, PMV and PPD. The ANOVA results indicate that all subjective parameters differed significantly across the five OLSs.

Table 8: Mean Values of Subjective Parameters, PMV And PPD

OLS	TS	TA	TP	OC	PMV	PPD (%)
S1	2.1 (1.1)	2.5 (0.9)	2.7 (0.7)	3.2 (1.2)	2.7 (0.5)	93 (14.3)
S2	2.2 (1.0)	2.5 (0.9)	2.7 (0.6)	3.5 (1.2)	2.6 (0.4)	92.6 (9.8)
S3	1.9 (1.2)	2.6 (0.9)	2.6 (0.7)	3.5 (1.3)	1.6 (0.8)	54.2 (31.0)
S4	2.1 (1.3)	2.4 (1.0)	2.6 (0.7)	3.4 (1.3)	1.8 (0.7)	64.8 (29.1)
S5	1.1 (1.7)	3.1 (0.9)	2.2 (0.8)	4.3 (1.1)	1.0 (0.8)	37.5 (22.8)
ANOVA Test	F(4, 495) = 13.5	F(4, 495) = 11.9	F(4, 495) = 7.3	F(4, 495) = 13.1	F(4, 495) = 113.6	F(4, 495) = 110.9

Notes: TS: Thermal Sensation; TA: Thermal Satisfaction; TP: Thermal Preference; OC: Overall Thermal Comfort; PMV: Predicted Mean Vote; PPD: Predicted Percentage of Dissatisfaction.

Notes on ANOVA Test: F: F-Statistic; P: P-Value. Values In Brackets Denote the Degrees of Freedom Between Groups and Within Groups. P < 0.001

Thermal Sensation

As shown in Table 8, the mean thermal sensation (TS) for all spaces is on the warmer side of the scale, ranged between 1.1 and 2.2. Generally, S1 and S2, with tree-shaded outdoor learning spaces, recorded higher TS votes between 2.1 and 2.2, corresponding to 'warm' to 'hot'. The next highest TS was observed in S4, the courtyard-type outdoor learning space, with a mean value of 2.1 (warm). S3, the roof-shaded outdoor space, recorded a slightly lower mean TS of 1.9. The semi-open outdoor learning space S5, recorded the lowest mean TS of 1.1.

Figure 8 (left) presents a bar chart summarising TS vote, providing an overall view of subjective responses from OLS users. After consolidating the three warm and cool categories, Figure 8 (right) shows that 85-95% of votes indicated a warm sensation for S1 and S2. S4 exhibited a similar distribution, with 84% of responses falling in the warm category. In contrast, S3 had 68% of responses in the warm category and a higher proportion of 24% in the neutral category. However, S5 showed a different pattern, with 62% responses indicating a cool sensation.

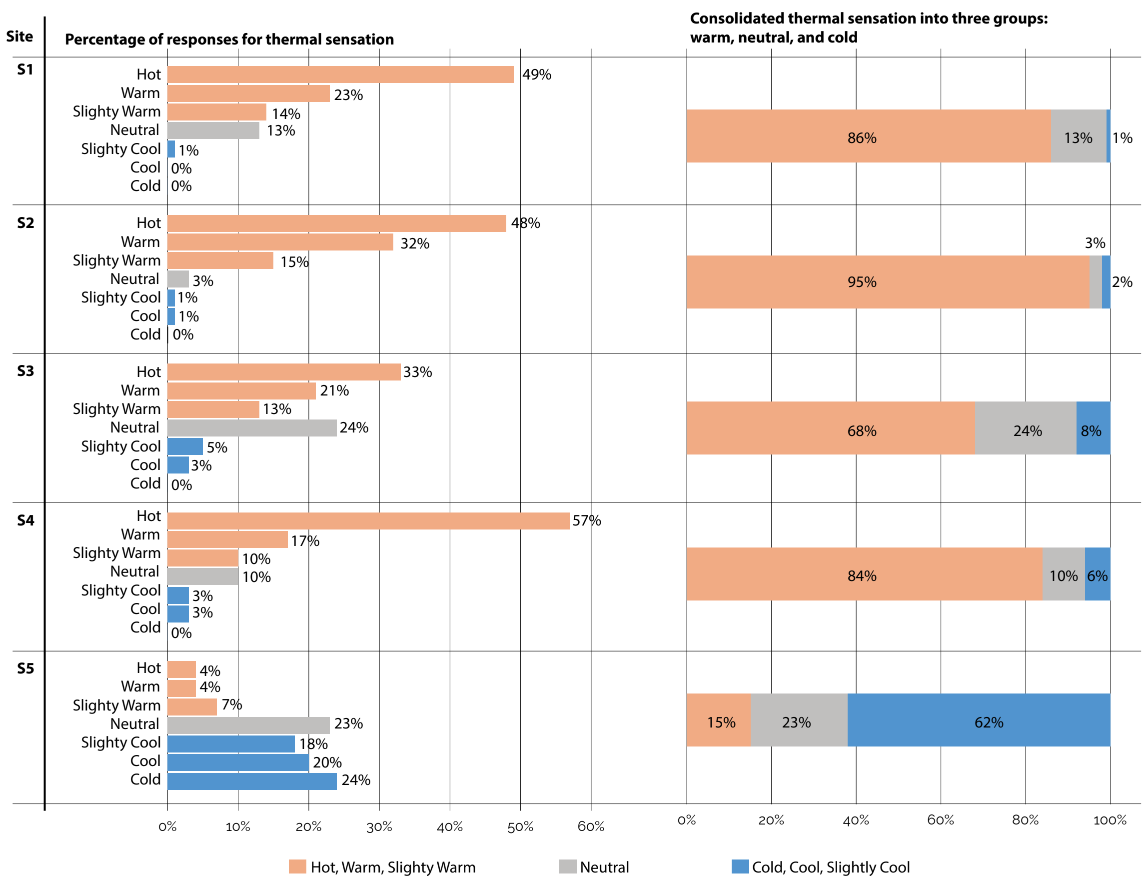


Figure 8: Percentage of Responses for Thermal Sensation on a 7-Point Scale and Consolidated Thermal Sensation into Three Groups: Warm, Neutral, and Cold.

Thermal satisfaction

With the exception of S5, most spaces showed low thermal satisfaction (TA) (Figure 9). In S1 and S2, 50% of respondents reported dissatisfaction with thermal conditions, while in S4 the figure was 59%. By contrast, S3 and S5 recorded a lower dissatisfaction rate of 31% and 20%, respectively. Overall, the average TA ranged from 2.4 to 3.1, corresponding to a level between 'unsatisfied' and 'neutral' regarding respondents' thermal satisfaction (Table 8).

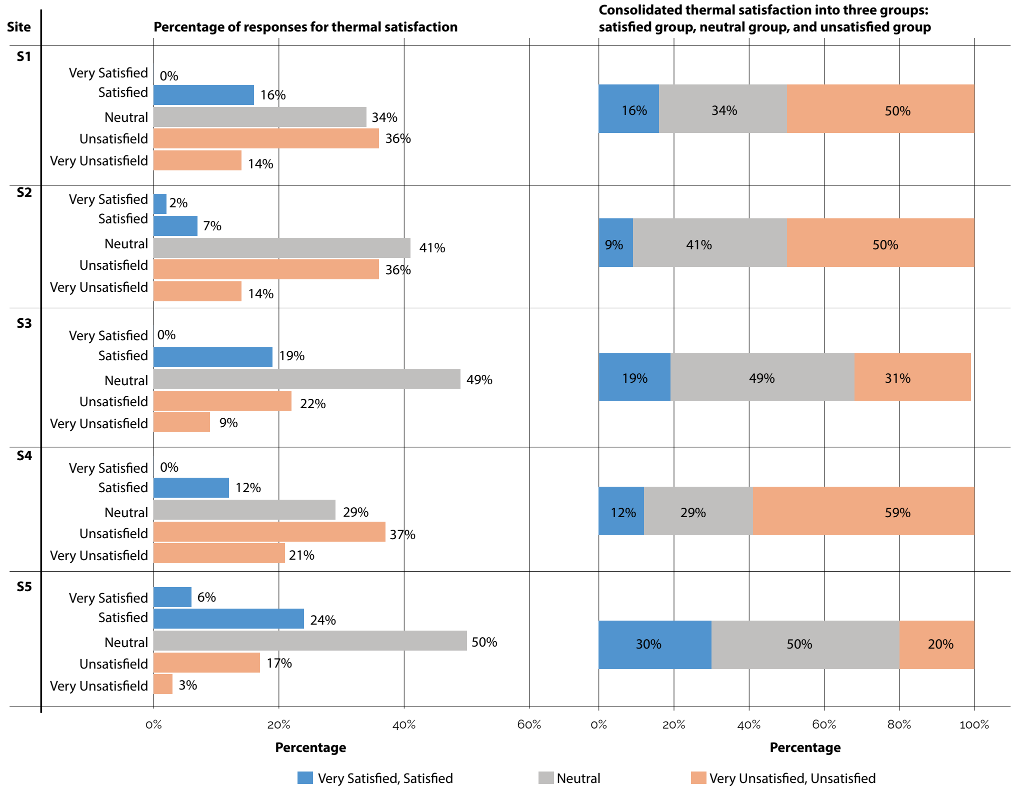


Figure 9: Percentage of Responses for Thermal Satisfaction on a 5-Point Scale and Consolidated Thermal Satisfaction into Three Groups: Satisfied Group, Neutral Group, and Unsatisfied Group.

Temperature Preference

Figure 10 illustrates respondents' temperature preference (TP) across the five different OLSs. Respondents across all OLSs preferred a cooler thermal environment, with average TP values ranging from 2.2 to 2.7.

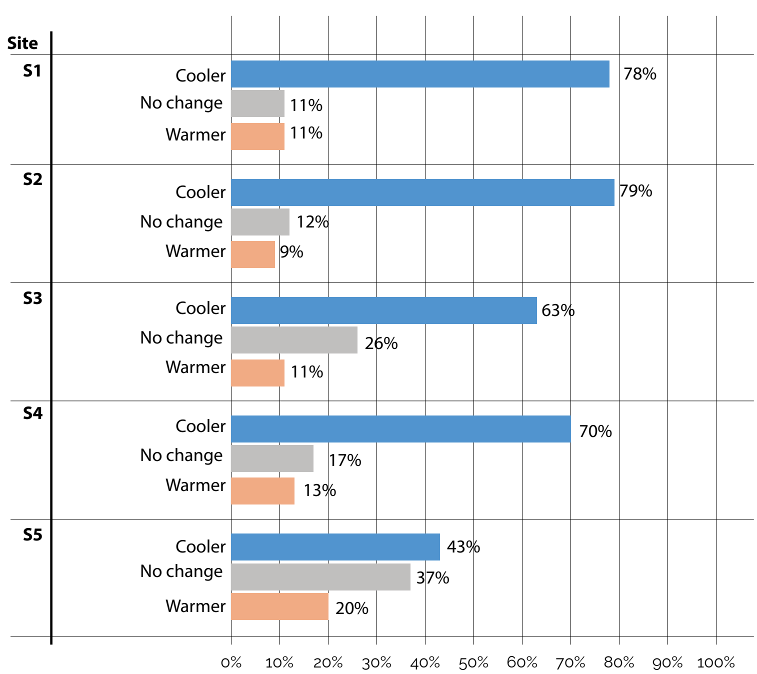


Figure 10: Percentage of Responses for Thermal Preference on a 3-Point Scale.

Overall Thermal Comfort

Figure 11 shows the overall thermal comfort (OC) across the four types of OLS. Most respondents reported feeling neutral regarding OC, 65% to 79% expressing neutrality across the different OLS. The average OC score ranged from 3.2 (slightly uncomfortable) and 4.3 (neutral) (Table 7). S5 recorded the highest OC of 4.3, indicating that the semi-open outdoor learning space was the most thermally comfortable among the OLS.

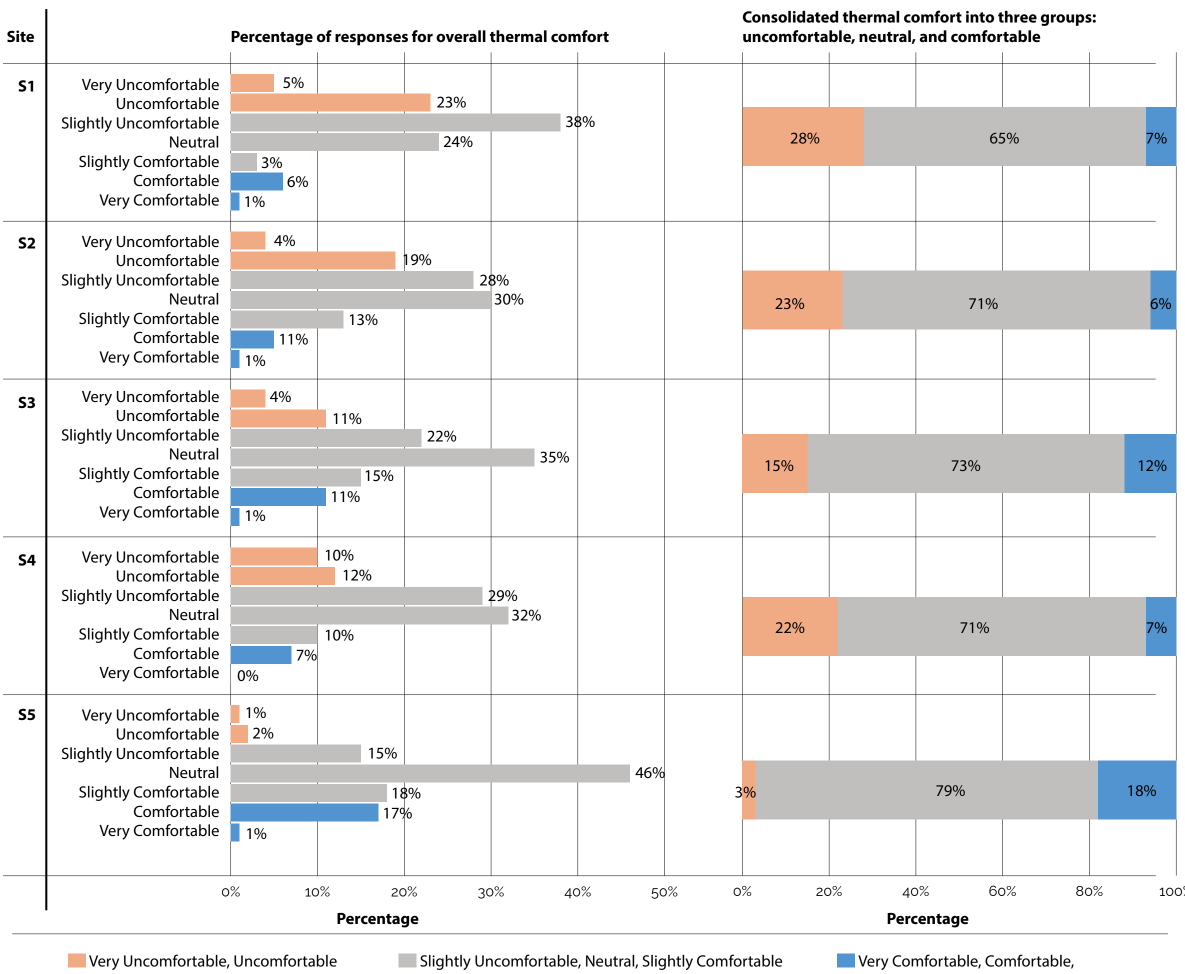


Figure 11: Percentage of Responses for Overall Thermal Comfort on a 7-Point Scale, Consolidated into Three Groups: Uncomfortable, Neutral, and Comfortable.

Figure 12 presents the relationship between subjective evaluations of thermal comfort and operative temperature (T_{op}) in the OLS. Thermal sensation was strongly associated with changes in operative temperature (R^2 = 0.1948) (Figure 12a). A neutral T_{op} was identified at 26.2 °C, beyond which users were predicted to feel warm. For thermal satisfaction (Figure 12b), the neutral T_{op} was 30.2 °C, beyond which users were predicted to feel dissatisfied with the thermal conditions. For thermal preference (Figure 12c), the neutral T_{op} was 20.5 °C, with all respondents preferring cooler conditions below this threshold. Based on subjective evaluations, the neutral T_{op} for overall thermal comfort (Figure 12d) was 37.1 °C, higher than the mean T_a of 28.9 °C and the maximum T_a of 36.1 °C.

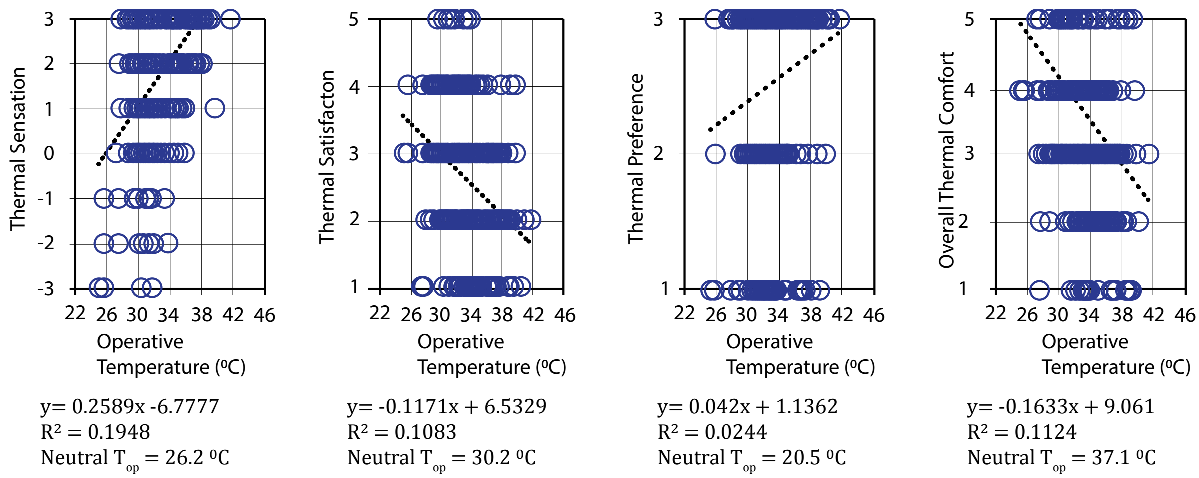


Figure 12: Scatter Plots of Operative Temperature Versus Thermal Sensation, Thermal Satisfaction, Thermal Preference and Overall Thermal Comfort for All Outdoor Learning Spaces.

Compared with the mean T_a (28.9 °C) and maximum T_a (36.1 °C), the suggested neutral temperature for overall thermal comfort (Figure 12d) was 37.1 °C, an excessively high value. The linear regression model (R^2 = 0.11) indicates a weak relationship, suggesting that this finding should be interpreted with caution. This spurious value was likely caused by extrapolation beyond measured range. The result reflects low variation and weak correlation in discomfort responses, rather than a true comfort threshold. A neutral temperature of 37.1 °C is neither practically nor physiologically plausible. Evidence from previous studies in similar tropical climates (e.g., Ghaffarianhoseini et al., 2019; Makaremi et al., 2012; Sadakorn et al., 2025) consistently demonstrates mid-outdoor comfort temperatures ranging from 24 °C to 30 °C. Therefore, this value should be regarded as a model artifact, highlighting the limitations of using regression to gauge neutrality when response variance is low, rather than as an indication of actual thermal comfort.

PMV and PPD

The predicted mean vote (PMV) provides a qualitative assessment of the average thermal sensation reported by respondents across the five OLSs, ranging from -3 (very cold) to +3 (very hot), with 0 indicating thermal neutrality. In contrast, the predicted percentage dissatisfied (PPD) quantifies the proportion of students dissatisfied with thermal comfort in the five OLSs, ranging from 0% (none dissatisfied) to 100% (all dissatisfied). A higher PPD value indicates a greater proportion of students likely to be dissatisfied with the thermal comfort of an outdoor learning space.

As shown in Figure 13, the PMV values for S1 and S2 are 2.7 and 2.6, respectively, falling between the warm and hot categories. For S3 and S4, the PMVs are 1.6 and 1.8, corresponding to the slightly warm to warm range. The PMV for S5 is comparatively better, with a value of 1.0, corresponding to the slightly warm category. Regarding PPD, 93% of respondents in S1 and 92% in S2 were predicted to be dissatisfied with the thermal conditions. For S3 and S4, the PPD exceeded 50%, at 54.2%, and 64.8%, respectively. By contrast, the PPD for S5 was lower, at 37.5%

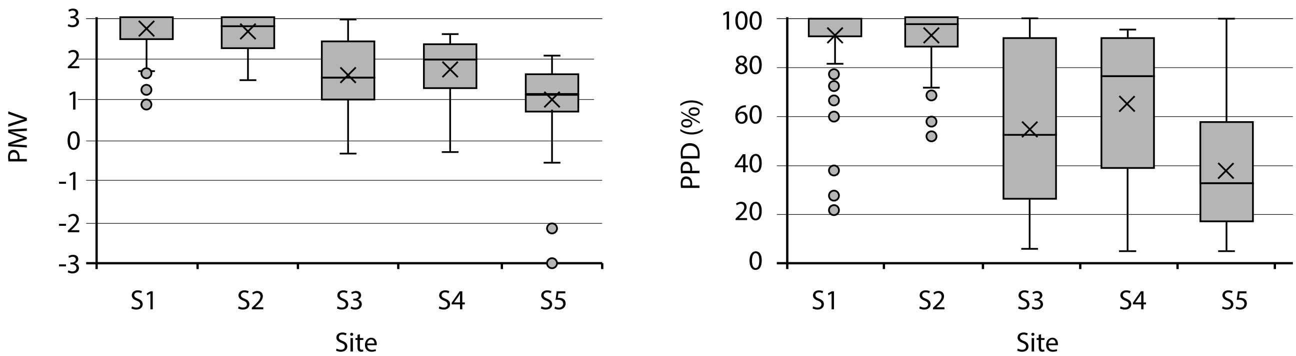


Figure 13: Box Plots of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) by Site.

The findings of this study complement and reinforce the previous research on outdoor thermal comfort in higher education settings. For instance, Makaremi et al., 2012, who emphasized the significance of psychological and environmental adaptation factors in thermal comfort. The results indicate that users exhibit behavioural adaptation and that subjective reactions vary across different types outdoor learning spaces (OLS). The integration of semi-open and shaded spaces in this study provides the similar advantage for outdoor environments, offering transitional spaces that mitigate thermal stress. This aligns with Lau et al. (2019), who highlighted the benefits of hybrid approaches in indoor environments. Additionally, while Ghaffarianhoseini et al., (2019) emphasised vegetation and shading being primary drivers, this study operationalises these factors by systematically employing four OLS typologies which are tree-shaded, roof-shaded, courtyard-type and semi-open rather than treating them as isolated interventions. Unlike previous studies, that primarily focused on environmental measurements or space typologies, this study presents an evidence-based framework of the usability threshold for OLS by integrating microclimatic analysis with user-level WS3 data and correlating operative temperature with thermal sensation. In hot-humid climates, these contributions work towards accentuating the need to break free from passive open-space design to a network of interrelated climate-responsive adaptive learning spaces.

Recommendation to Improve Thermal Comfort

Table 9 presents recommendations to improve thermal comfort for each OLS on the TAR UMT campus, considering their current conditions. Some recommendations are based on factors that may influence the thermal comfort of the outdoor learning space, such as vegetation, natural shading, artificial shading and surrounding building height and materials as recommended by Cung & Rosetia, 2023 and Tetiranont et al., (2024) to improve thermal comfort in hot and humid climate regions.

Table 9: Recommendations to Improve Thermal Comfort Based on the Existing Condition of Each Site

OLS	Operative Temperature T_{op} (°C)	PMV Value	PPD Value	Issue	Recommendation
S1	35.7 (2.1)	2.7	93%	S1 recorded the highest mean temperature of 28.9°C, indicating exposure to direct sunlight through gaps between buildings and trees. Despite dense shading from Casuarina trees, users experience reduced thermal comfort during peak hours due to direct sunlight penetration.	Measures such as improving ventilation, introducing cooling systems and increasing shading can be considered. Adding more vegetation and taller trees amplify the cooling effect and improves shading. These trees would also act as a windbreak and contribute to a cooler microclimate. Installing shade structures like pergolas or canopies can provide extra shade during peak sun hours. Implementing reflective surfaces along its surrounding pathways can minimize heat absorption.
S2	35.2 (1.7)	2.6	92.6%	S2 is exposed to direct sunlight through openings and experiences inconsistent shading due to its surrounding environment, which leads to discomfort. In addition, airflow is obstructed by the nearby four-story building. Consequently, users reported higher thermal sensation values (2.2).	Measures to improve S2 include enhancing ventilation and introducing cooling systems, as well as increasing shading through additional tree coverage or installing retractable awnings. Vertical gardens will be introduced on nearby façades to cool the surrounding air through evapotranspiration.
S3	32.1 (1.9)	1.6	54.2%	Despite being well-ventilated and shaded, S3 still experiences elevated temperatures during peak hours. Overcrowding of students can negatively impact thermal comfort by increasing body heat and reducing airflow.	Measurements include enhancing comfort by optimizing ventilation or wind flow and adjusting seating arrangements to maximise airflow while minimising heat accumulation from body heat during crowded events. A misting system can be installed during high-usage periods to lower the ambient temperature and further enhance thermal comfort. Light coloured finishes can be applied to surfaces to reduce heat retention.
S4	31.8 (2.2)	1.8	64.8%	S4 experiences poor ventilation due to being surrounded by buildings on all sides. The surrounding walls of the nearest building trap heat and potentially lead to higher temperatures, especially in hot weather and during the day.	Measures include enhancing comfort by optimizing current ventilation conditions or wind flow. Options include improving ventilation by incorporating louvres and movable panels or creating openings on the walls of the nearby surrounding buildings. Light-coloured building materials for the surrounding wall can be considered to reflect solar radiation. Water features such as fountains or ponds may also be incorporated to help cool the air through evaporation.
S5	31.2 (1.5)	1.0	37.5%	S5 still experiences temperature fluctuations even though it is well-ventilated and shaded by the first-floor slab, which can impact users' thermal comfort.	Measures include improving natural ventilation, adding landscaping and utilizing thermal mass to further enhance S5. All sides should remain unobstructed to allow airflow. Operable windows, panels, or vents can be installed for adjustable ventilation. Landscaping can improve air quality and shading. Localized cooling systems may also be considered to address individual preferences.

Conclusions

This study examined users' thermal comfort in five different outdoor learning spaces on a university campus, focusing on different surrounding settings. A total of 500 respondents participated in the survey. The conclusions of this study are as follows:

Air temperatures in the outdoor learning spaces ranged from a maximum of 36.3 °C to a minimum of 23.6 °C, with a mean of 28.9 °C.

Thermal sensation votes were closely correlated with operative temperature. The model suggested a neutral overall thermal comfort temperature of 37.1 °C.

The predicted mean votes (PMV) for S1 and S2 were high at 2.7 and 2.6, reflecting elevated air and operative temperatures. By contrast, S5 recorded a lower PMV of 1.0 due to cooler conditions. The predicted percentage of dissatisfaction (PPD) was high for S1 and S2, at 93% and 92.6% respectively, while for S5, which is much lower at 37.5%.

Thermal sensation votes indicated that S1 and S2 were perceived as warm to hot (2.1 to 2.2), S4 as warm (2.1) and S3 as slightly warm (1.9). S5 recorded the lowest thermal sensation at 1.1.

Most outdoor learning spaces (OLSs) showed low thermal satisfaction, except S5. Dissatisfaction levels were 50% in S1 and S2, 59% in S4, 31% in S3, and 20% in S5.

Respondents in all OLSs expressed preference for cooler conditions. The overall comfort vote ranged from 3.2 (slightly uncomfortable) to 4.3 (neutral). S5 scored the highest comfort score, suggesting that semi-open spaces are thermally more comfortable.

Acknowledgements

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