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A Comparative Study of Cooling Performance and Thermal Comfort under Street Market Shades and Tree Canopies in Tropical Savanna Climate

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Abstract: Walking through street markets is the most popular outdoor activity in Thailand, promoting local economies and tourism. In the year-round hot and humid conditions, living outdoors with long heat exposure throughout the midday can result in heat-related illness. Artificial shade structures and tree shade canopies are typical cooling strategies to protect market sellers and pedestrians from direct sun exposure and improve outdoor human thermal comfort in the street market. This study investigates microclimate conditions and cooling benefits of typical street market shade structures with different settings—three roofing materials, two roof shapes, and surrounding trees with dense and sparse canopies. The dimension of the single artificial shade was 2 m × 2 m with heights varying 2–2.5 m. The vertical air temperature and sky view factor profiles were measured on winter and summer days. The calculated physiological equivalent temperatures (PET) and thermal comfortable hours beneath different shade structures were assessed using RayMan 1.2 software. A cluster of trees with a dense canopy provided more effective cooling (with a satisfied thermal condition of 9 h) than artificial shade structures. Thermal conditions under the galvanized steel roofing and HDPE tarpaulin plastic roofing shades were cooler than those of polycarbonate roofing shade. Meanwhile, the space beneath the sparse tree canopy had the warmest condition. The temperature reductions beneath the artificial shade structure varied throughout the day, with the maximum reduction occurring during midday and the lowest reduction found in the late morning and late afternoon. Our study demonstrates that the tree canopies and artificial shade structures had limited application for providing comfortable conditions throughout midday. To reduce such extreme heat, a combination of shade structures with other cooling techniques is suggested, which should be the focus for further studies.

Keywords: microclimate; thermal comfort; shading structure; canopies; tree shade

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1. Introduction

High temperatures in cities have been associated with negative consequences for human health and well-being, including increased illnesses and deaths during the summer months [1]. Shade structures have been studied as a strategy for mitigating the impacts of urban heating and as a method for improving outdoor human thermal comfort [2–7]. Temporary shade structures in urban space affect thermal comfort and are closely related to behavioral adaptation to climatic conditions. One of the fundamental dimensions in assessing the cooling capacity of natural and artificial shade types is outdoor thermal comfort during diurnal range conditions. It has considerable potential to be optimized via shade structure design, especially in the hot-humid climate of Asian cities.

Trading in outdoor markets, known as street vending in market stalls and market stands, is an economic activity prevalent in many urban settings across Thailand. Moreover, Thailand has a tropical wet and dry or savanna climate with the monthly average air temperature ranging 24–29 °C and 184–253 mm average rainfall in summer and rainy seasons. High solar radiation is the primary source of thermal stress perceived by the human body in outdoor spaces. Thus, shade plays an important role in designing pedestrian-friendly outdoor spaces in many cities of Thailand. Shade structures such as metal roofing sheets and canvas shades are typically used to attenuate sunlight in semi-outdoor environments. However, heat can penetrate beneath the shade structures with the lower sun angles, leading to an unacceptable thermal condition for Thailand's outdoor market and vendor stalls (Figure 1).

Figure 1. Samples of temporary canopies provide thermal comfort for Thai's outdoor market and vendor stalls.

2. Studies of Outdoor Shade Structures

Several studies have shown that tree canopy or building shades help to attenuate the heat from direct solar radiation [8–13]. However, a small number of studies have investigated the thermal condition and cooling benefits of using artificial shade structures, including contemporary ramadas [2] and permanent shelter canopies [14]. Moreover, the structural materials used for shading covered in previous research included solar cells [15], membranes [16], shelters [17–19], concrete [20], nylon [21], aluminum–acrylic [21], and sun sails with tissue properties including various colors and thickness [22]. Additionally, the effects of various shapes and sizes of the canopies on semi-outdoor thermal comfort have also been studied [2,15,16,23]. The effects of shade characteristics and environmental factors that improve cooling performance and thermal comfort underneath have been studied, as follows:

2.1. Effects of Tree Canopies and Artificial Shade Structures on Cooling Benefits and Improving Thermal Comfort Conditions

Canopy shading structures provide different potentials in heat reduction and improvement of thermal comfort in semi-outdoor areas. For example, during the daytime hours, canopy shade could lower the air temperature by 2.3–8.7 °C [24,25] and reduce the mean radiant temperature by 20–22 °C [26]. Moreover, the canopy shade could reduce the physiologically equivalent temperature (PET) by 4–12 °C [22,26,27]. The maximum heat reduction is at midday when the sun's position is directly overhead [27].

Moreover, the reduction in the air and mean radiant temperatures are dependent on the type of roofing materials, heights, locations, and climate conditions. Middel et al. [15] conducted field investigations of thermal comfort conditions in the space beneath solar cells and tree canopy shades in Arizona, USA, which has a hot and arid climate. Their study showed that air temperature reduction in both canopy shades was not different. However, Lee et al. [17] found that the shade of buildings could provide a better temperature reduction than the shade from trees and umbrellas. This is because the buildings could completely prevent sun radiance from penetrating the usage spaces [2]. This finding contrasts with the investigation by Rahman et al. [28] that showed the temperature and PET reductions under tree shades were 1 °C higher than the building shade. Furthermore, many studies compared the cooling benefits among trees and different kinds of shade structures [29–31]. The air temperature, mean radiant temperature, and PET values beneath trees were lower than those beneath artificial shades [27]. The study results point out that trees can absorb the solar heat and reduce the radiant heat penetrating the space beneath better than any artificial shades. The studies also revealed that large trees with dense canopies could reduce heat stress under their shade more than those with sparser canopies [32–34].

As for the effect of different shading materials on preventing radiant solar heat from penetrating through, Paolini et al. [35] revealed that roofing materials with low light transmission and high solar reflection properties (more than 0.80) could significantly reduce the amount of radiant heat penetrating the living space below. Furthermore, similar to Garcia-Nevado et al. [14], the shading materials in dark colors could block more sunlight transmission to the shaded area than light colors.

Moreover, the roof shapes and the size of shade structures can also affect the microclimate conditions beneath the shades. Jafarian et al. [16] evaluated the outer thermal comfort of buildings beneath six different types of lightweight membrane canopies in Iran, with its hot and arid climate. The assessment was conducted through field observations and by computer simulation. The study concluded that a shade structure of 5 m $\times$ 5 m and 3 m in height could provide maximum cooling because it can provide complete shade. In addition, the study found that a conical shade structure could reduce the air temperature more than a flat-roof structure. The air temperature reduction under an umbrella structure was higher than the saddle-type structure because it allows the hot air to escape to the roof quickly, which effectively improves outdoor human thermal comfort. The Iran study provided a result similar to Elnabawi and Hamza [25], which compared the vertical air temperature profiles at various height levels within shade structures in Cairo, Egypt. They found that the air temperature increased noticeably with the increase in height as the hot air rose higher and accumulated at the roof's top. Therefore, air vents on the roof could ventilate the hot air. However, the design of air vent panels must comply with the protection requirements of preventing direct solar heat from penetrating the areas beneath the shade structures. Our literature reviews shows that the cooling performance of artificial shade structures varies depending on the weather conditions, shading materials, and design characteristics [2,15,23]. Therefore, these factors should be considered before applying the shade structures for use in any specific local context to determine appropriate design parameters.

2.2. Environmental Factors Affecting the Cooling Performance under Artificial Shade Structures

Chen and Ng [19] revealed that an increase in solar radiation by 164 W/m^2 could raise air temperature by 2.4 °C beneath a shade. Furthermore, they assessed the influence of wind speed affecting the thermal sensation of people seated under the shelter with a windscreen and without the windshield. It was found that people sitting under the shelter with the windscreen felt warmer than those without the windshield. Moreover, an increase in wind speed from 0.3 to 1 m/s could reduce the air temperature under the shelter by up to 2 °C. Johansson et al. [36] showed that increasing wind speed could cool the globe temperature and reduce the PET value. According to the review of other studies, the thermal comfort survey and cooling performance under shade structures were primarily conducted for a couple of hours or steady-state conditions using computer modeling, typically during the midday with extreme conditions [2,23,32]. However, cooling performance beneath the shade structure may differ due to the solar direction and local climatic conditions changing throughout the day.

As a conclusion from the reviews, it is necessary to study the relationships among the variables mentioned above. Most field research was also performed in warm temperate climates, while the least performed were field investigations in hot and arid climate areas. No study has investigated the cooling effect of artificial shade structures in tropical savanna climates. Furthermore, the study of roofing material used for the shade structure varies with the specific location context and its purpose. However, those materials and the shade structure size do not cover those typically used in Thailand's outdoor market and vendor stalls. Most shading studies have experimented with a couple of hours, which had the peak thermal condition. However, variations in solar radiation intensity, air temperature, and wind speed across an entire day may affect the cooling performance under the shade structures. As a consequence, the purpose of this study is to fill gaps in existing research and includes addressing the following questions. (i) How do different local shading material structures and local tree canopies reduce hourly air temperature and mean radiant temperature in the usage space beneath? (ii) How do artificial shade structures and tree canopies provide an hourly acceptable comfortable condition for activities in outdoor markets in Thailand? The study findings can help designers better understand shade structures and their proper application in the specific tropical climate of Thailand.

3. Methods

3.1. Study Location

The field measurements were conducted in December 2019 and April 2020. Because of COVID-19 control in Thailand with the local travel restrictions, this experiment was conducted in a university campus parking lot (located at 14°04′05.8″ N 100°36′31.7″ E) in Pathum Thani, Thailand, as shown in Figure 2. The weather condition in Pathum Thani is classified under the Köppen system as a tropical savanna climate or tropical wet and dry climate (Aw), with high air temperature all year round (the air temperature ranging 22–40 °C and relative humidity 62–80%). In this study, the micrometeorological data were recorded for three days, representing winter and hot summer conditions. The winter condition was conducted during 20–22 December 2019, and the data collection in summer condition was conducted during 10–16 April 2020. The settlement of three artificial canopies was at the center of the parking lot (Location A), an open environment without any effect from nearby trees or building shades. The trees with dense and sparse canopies are in Locations B and C, respectively. The micrometeorological records of environmental data of unshaded conditions were taken from Location D.

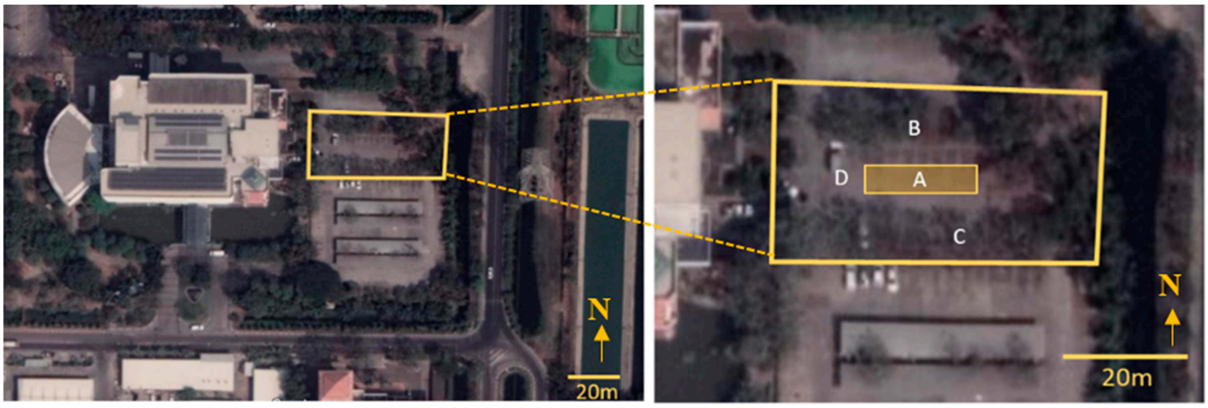


Figure 2. Study location and surrounding environment. (Image modified from https://www.google.co.th/maps/, last accessed 12 January 2021).

3.2. Characteristics of Shade Structures and Instrumentation Installation

This study conducted the field measurement with open shade structures. The experimental setting comprises two parts: (1) roofing materials and (2) roof shapes.

3.2.1. Shade Structure Setting with Different Roofing Materials

The effect of different artificial shades and tree canopies on microclimate beneath the shades was investigated for the first setting. The flat roofing shade (dimension 2 m × 2 m with 2 m in height) with three different roofing materials: polycarbonate sheet, galvanized metal sheet, and HDPE tarpaulin plastic roofing sheet, was setup as presented in Figure 3. Those are the most common shading materials in Thai outdoor markets. The thermal properties of the roofing materials are presented in Appendix A. In this study, two leaf area indexes (LAI) of *Pterocarpus macrocarpus* trees were selected to measure their effects on the cooling performance (see trees located at points B and C in Figure 2). *Pterocarpus macrocarpus* tree is a large tree native to Southeast Asia, often cultivated as an ornamental shade tree along the streets and in the parks of cities. On-site tree height measurements were performed with a Nikon 550 Forestry Pro laser rangefinder, and hemispherical photos of each tree were taken and processed using Hemisfer software to estimate the LAI (Hemisfer, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Switzerland, 2016). The crown base height of the first tree at 3.5 m had a LAI value of 4.2 m^2 m^{-2} (dense canopy at location B). For the second tree, the LAI was low, 3.8 m^2 m^{-2} (3 m tree height at location C) (Figure 3).

Under each shade structure, the air temperature was recorded at 0.1, 0.6, 1.1, and 1.6 m in height above the ground. Radiation-shielded iButton data loggers (DS1922L and DS1923 models) with aluminum foil, as referred to in Liu et al.'s investigation [37], were mounted on a tripod to measure air temperature at the center of the shade structures (Figure 3). The relative humidity and globe temperature measurements were conducted at 1.1 m above grade. The average air temperature, air velocity, and globe temperature at 1.1 m in height were then used to calculate the mean radiant temperature. One iButton (DS1922L) was attached to the roof sheet materials to measure the surface temperature. All sensors were placed at the north side to ensure that the sensors were in the shaded area, not exposed to direct solar radiation. The data of unshaded conditions and tree canopies were read at the same position as those of the artificial shade structures, with each record taken at 10 min intervals. All sensors were precalibration by the manufacturer. Global solar radiation data were obtained from a nearby local weather station of the Thai Meteorological Department (TMD).

Sky view factor (SVF) measurement was conducted at noon on 10 April 2020. SVF refers to the ratio of visible sky area to the area obstructed by the nearby environment, for example, buildings and trees. SVFs can be calculated via importing the hemispherical image using the fisheye lens to the RayMan 1.2 software [38].

In this study, the photographs were taken at four heights: 0.1, 0.6, 1.1, and 1.6 m at the center of the shade canopies. Table 1 summarizes the measurement parameters and the accuracy of the sensors used in the field measurement.

Table 1. Type of sensors used for data collection and the measurement accuracy and installation height.

Instrument	Measurement Range	Accuracy	Height
Temperature/RH smart sensor (S-THB-M00x)	−40 °C to 75 °C 0–100% RH at −40° to 75 °C	0.2 °C over 0° to 50 °C ±2.5% from 10% to 90% RH	1.1 m (unshaded condition)
Globe temperature T-type thermocouple sensor attached to HOBO-U12-014 data logger	−250° to 350 °C	±1 °C or ±0.75%	1.1 m (shaded and unshaded conditions)
Wind speed/direction smart sensor (Part-S-WCA-M003)	0 to 44 m/s (0 to 99 mph)	±0.5 m/s (±1.1 mph) ±3% 17 to 30 m/s	1.6 m (unshaded condition)
iButton data logger DS1923	−20 °C to +85 °C 0 to 100% humidity	±0.5 °C: −10 °C to +65 °C ±5%RH	1.1 m (shaded condition)
iButton data logger DS1922L	−40 °C to +85 °C	±0.5 °C: −10 °C to +65 °C	0.1, 0.6, 1.6 m, and surface material (shaded condition)
SVF using a fisheye lens	-	-	0.1, 0.6, 1.1, and 1.6 m (shaded and unshaded condition)

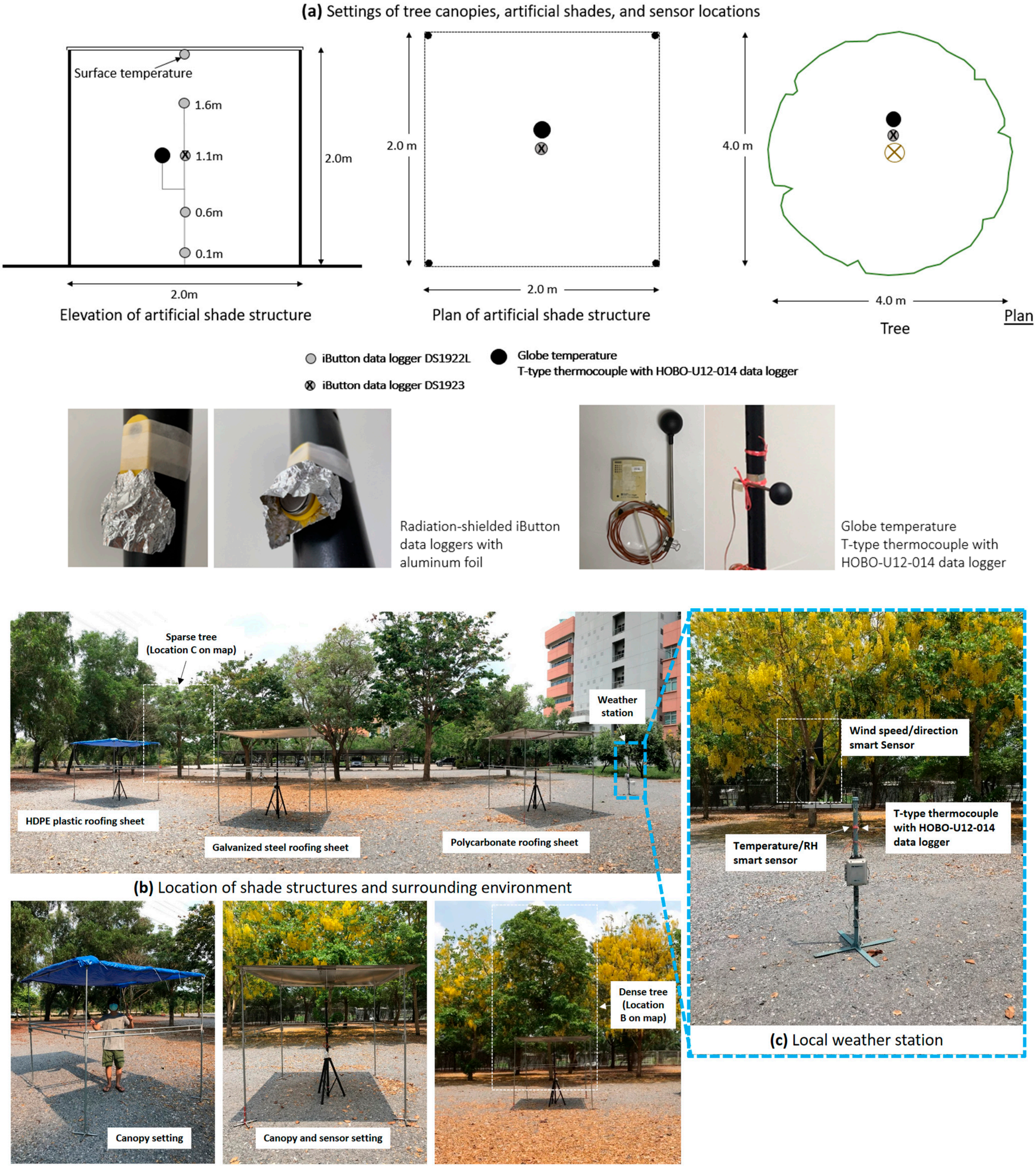


Figure 3. (**a**) Settings of tree canopies and artificial shade with different roofing materials and sensor locations. (**b**) Location of shade structures and surrounding environment. (**c**) Local weather station.

3.2.2. Shade Structure Setting with Different Roof Shapes

The second experiment (conducted 14–16 April 2020) assessed the effect of two roof shapes with different heights on the microclimate condition under the canopies. The shade structure setting is presented in Figure 4. The most common roof shapes found in outdoor markets are flat roofs with a height of 2 or 2.5 m, while another typical one is a gable roof 2.5 m in height. All sensors were installed at the exact locations as those in the previous experiment. In this test, the roofing material used for all shade structures was a tarpaulin plastic roofing sheet.

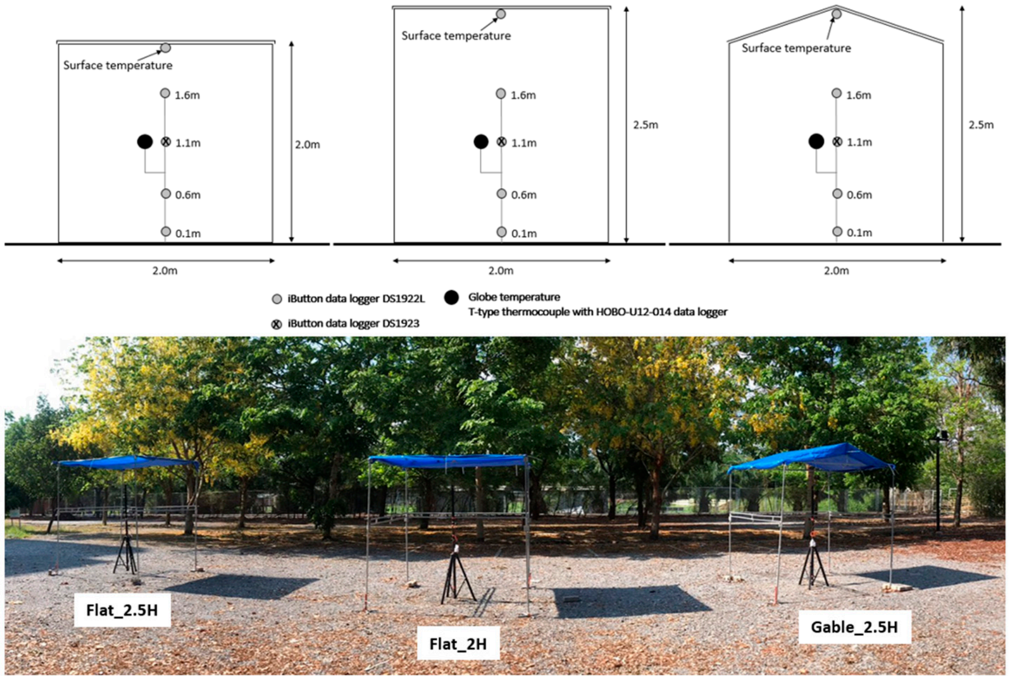


Figure 4. The setting of artificial shade structures with different roof shapes and sensor locations.

Table 2 presents the mean, minimum, and maximum air temperatures, relative humidity, solar radiation, and wind speed during the test days from 6 a.m.–6 p.m. The air temperatures were high on winter days, similar to those in the summer days. The mean wind speeds in summer ranged from 0.3 to 0.7 m/s and 0.4 m/s for winter days. The wind directions were mainly from the south in summer and from the northeast in winter. The peak solar irradiation in the summer days was higher than in the winter; however, the mean values were similar.

Table 2. Measured weather data from 6 a.m.–6 p.m. during the test dates.

Test Dates	Air Temperature (°C)			Relative Humidity (%)			Solar Radiation (Watt/m^2)			Wind Speed (m/s)		
	Max	Average	Min	Max	Average	Min	Max	Mean	Min	Max	Mean	Min
Winter condition 20–22 December 2019	39.5	36.9	27.7	88.8	53.4	44.4	620.7	321.5	0	0.8	0.4	0.0
Summer condition 10–13 April 2020	39.4	38.2	27.2	78.9	47	39.1	836.8	300.0	0.4	0.9	0.7	0.2
Summer condition 14–16 April 2020	39.9	38.7	28.4	80.4	45.8	41.7	839.0	329.6	2.6	0.5	0.3	0.0

3.3. Thermal Comfort Evaluation Calculation

Several indices have been used to assess human thermal comfort in outdoor and semi-outdoor conditions [2,15,25,39]. In all of the previous studies, a mathematical thermal index (mostly physiological equivalent temperatures or PET) has been applied to understand the impacts of shade on the outdoor thermal sensation of pedestrians. Not every study has attempted to directly link the actual thermal sensation collected through a thermal sensation survey and microclimatic parameters measured locally. Consequently, this study examines the correlations between the microclimatic variables and cooling benefits of shade on Thai residents' thermal acceptable range to understand how microclimate influences outdoor thermal comfort in a tropical context. The PET is based on a simplification of the human energy balance model using the Munich energy balance model for individuals (MEMI), which has been widely used as the thermal comfort index in outdoor and semi-outdoor thermal comfort studies [36]. Moreover, it describes the effect of the thermal environment on the human body by means of the commonly used Celsius scale dimension of temperature (°C), which facilitates the interpretation of the results [40,41].

From our reviews, only one study investigated the acceptable comfort condition of people living in semi-outdoor and outdoor areas in Thailand [42]. Their survey was conducted with 600 respondents living in a university campus environment in Pathum Thani province. The study revealed that the respondents accepted comfort conditions for outdoor living within 25.1–35.2 °C PET. However, the respondents residing in the semi-outdoor areas had higher tolerance to higher temperatures with an acceptable upper limit of 37.3 °C PET. Although this acceptable range differs from other comfort standards, it can better represent people's actual comfort satisfaction levels with the local environment. Consequently, the personal data were obtained from Srivanit and Jareemit's work [42] to calculate PET using the RayMan model. It assigned a 35-year-old male with a standard height of 1.66 m, weighting 58 kg, wearing static clothing insulation of 0.43 clo, and doing light activity (metabolic rate of 80 W/m^2).

This study used the calculation method to assess thermal comfort under different tree canopies and artificial shades instead of the survey method. The study chose PET as the index to assess outdoor thermal comfort conditions as compared to the acceptable thermal comfort range surveyed in previous work [42]. The RayMan model was used to calculate the hourly PET value. The model requires the input of environmental conditions, including average hourly air temperature (Ta), relative humidity (RH), mean radiant temperature (Tmrt), and sky view factor (SVF), in which all data were collected at 1.1 m aboveground under different shade canopies. The calculation of mean radiant temperature was determined using Equation (1) according to ISO 7726 [43] standard (expressed in °C) [44]. Equation (1) represents globe temperature, which, in this study, the globe diameter is 0.005 m, and its emissivity (ε) is 0.95. The average wind speed (V_a) was used from the micrometeorological station located next to the shade structures. It was assumed that the wind speeds under shade structures were the same as those of unshaded conditions.

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.335 \times 10^8 V_a^{0.71}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{1/4} - 273.15 \quad (1)$$

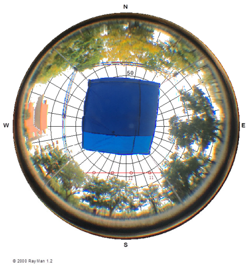
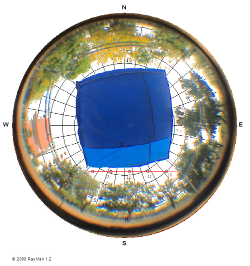
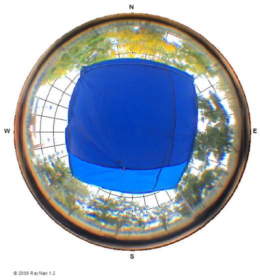
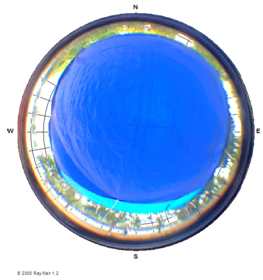
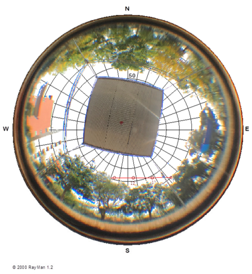
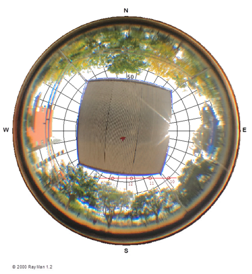
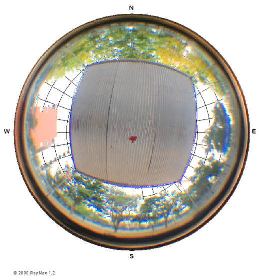
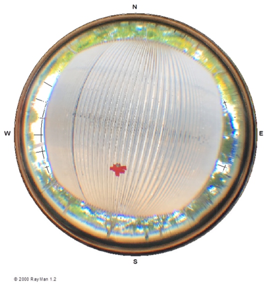
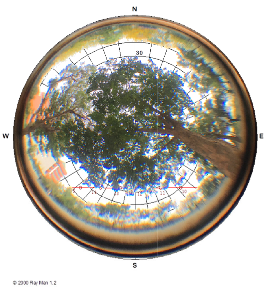
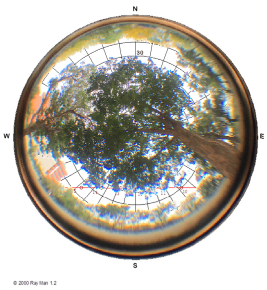
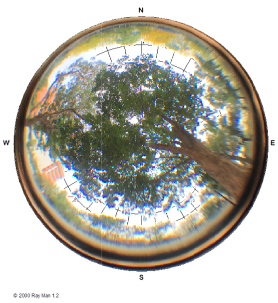
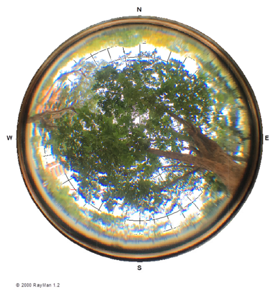
Basic data processing utilized the standard methods of descriptive statistics. The paired samples *T*-test method was used to evaluate the significant difference in microclimate condition and acceptable thermal comfort hours between artificial shade and tree canopies. The mean differences between the groups used a significant level at p-value < 0.05. The correlation between the heat reduction and microclimate data under the shade structures and tree canopies was evaluated using linear regression to understand the effects of these variables on the cooling performance.

4. Results

4.1. Sky View Factor (SVF)

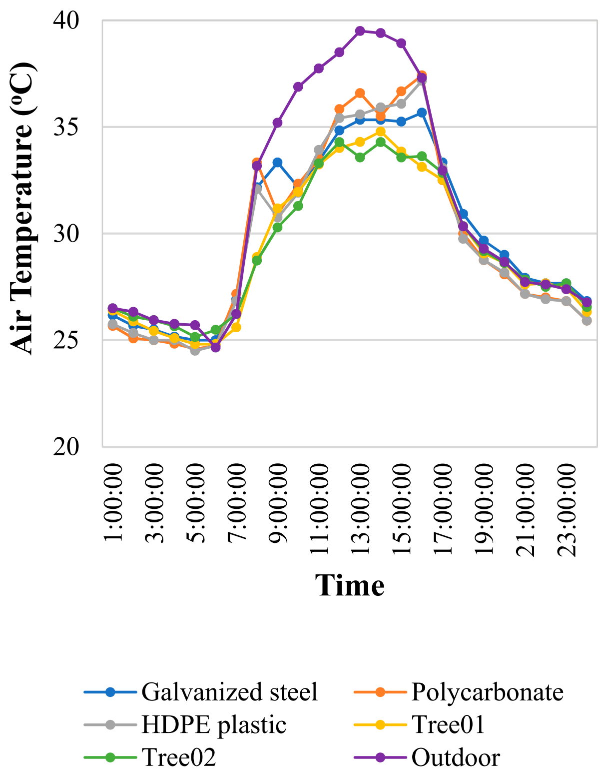
Table 3 presents the fisheye images under the artificial shade and tree canopies at four different heights. The SVF value ranges from 0 to 1, where 0 means complete obstruction, while 1 represents no obstruction. The calculated SVF in the unshaded area is 0.49 (see more detail in Appendix B). High SVFs (0.14–0.25) occurred at 0.1 m height, and those values decreased in line with the height level. The lowest values (0.02–0.06) were at 1.6 m, where the area was almost completely shaded. However, under the trees with a sparse canopy (Tree02), the SVF values at different height levels were similar (0.22–0.28). Thus, conditions under shade structures (except for 1.6 m height) in the semi-outdoor areas could be classified as mostly medium sky obstruction (0.10 ≤ SVF < 0.79), as referred to by Zaki et al. [45].

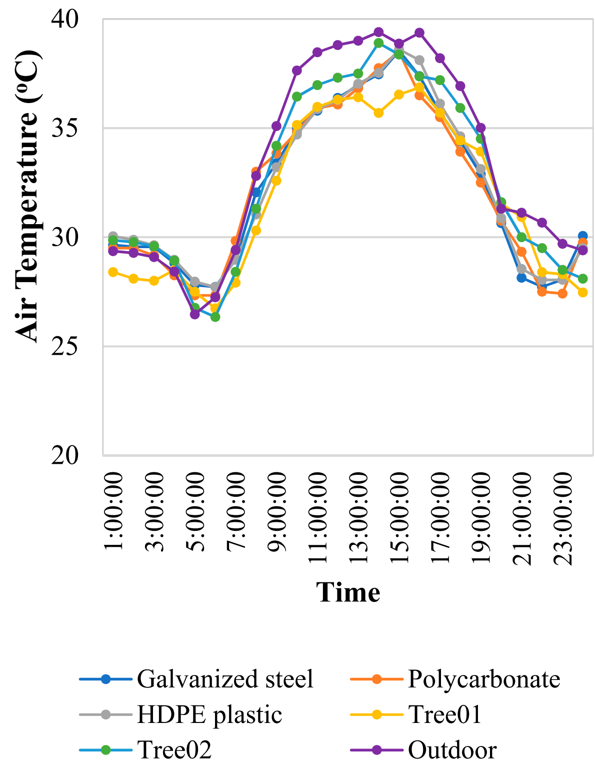
Table 3. Examples of fisheye images and calculated SVFs in the unshaded area and different height levels under artificial shade structures and dense tree canopy.

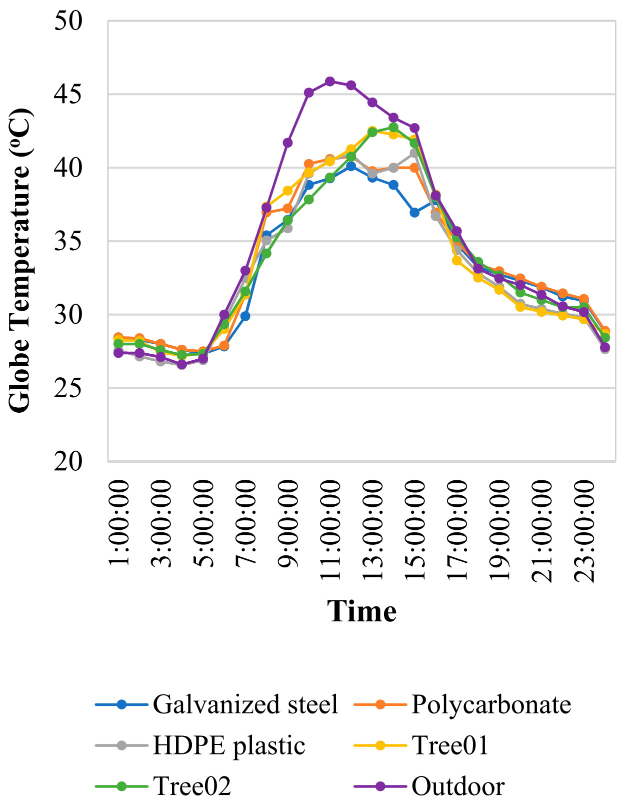
Date: 11 April 2020, Time: 12 p.m.			
Fabric 0.1 m_SVF = 0.23	Fabric 0.6 m_SVF = 0.19	Fabric 1.1 m_SVF = 0.11	Fabric 1.6 m_SVF = 0.06
			
Metal 0.1 m_SVF = 0.25	Metal 0.6 m_SVF = 0.19	Metal 1.1 m_SVF = 0.11	Metal 1.6 m_SVF = 0.03
			
Tree01 0.1 m_SVF = 0.13	Tree01 0.6 m_SVF = 0.13	Tree01 1.1 m_SVF = 0.07	Tree01 1.6 m_SVF = 0.02
			

4.2. *Effect of Roofing Materials on Thermal Condition and Cooling Performance Underneath*

The effect of roofing materials at 1.1 m height on the thermal condition underneath was compared to unshaded conditions on winter and summer days. Average hourly air temperature and globe temperature gradually started to increase from 6 a.m. and decline from 2 p.m., which correlated with the solar radiation profile. The air temperatures on winter and summer days were slightly different, whereas the nighttime temperatures on the winter days were approximately 4 °C lower than those in summer. The average hourly globe temperature under the shade structures and trees was slightly different with 1–2 °C (Figure 5). In the daytime, the relative humidity under artificial and tree canopies was slightly higher than in the unshaded condition.







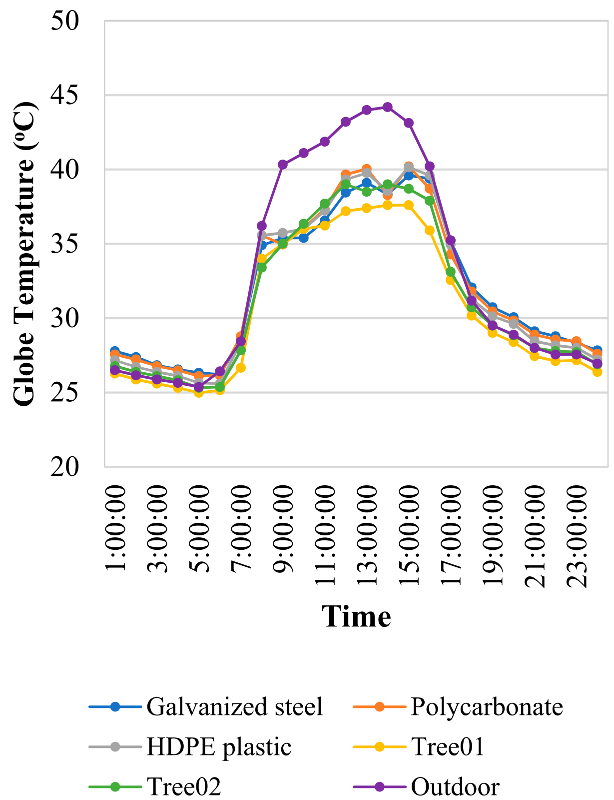
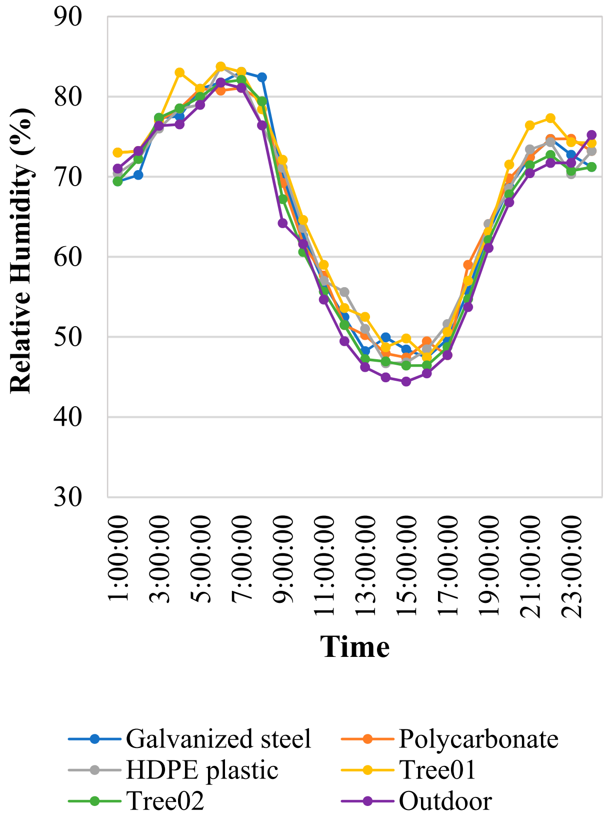


Figure 5. *Cont.*



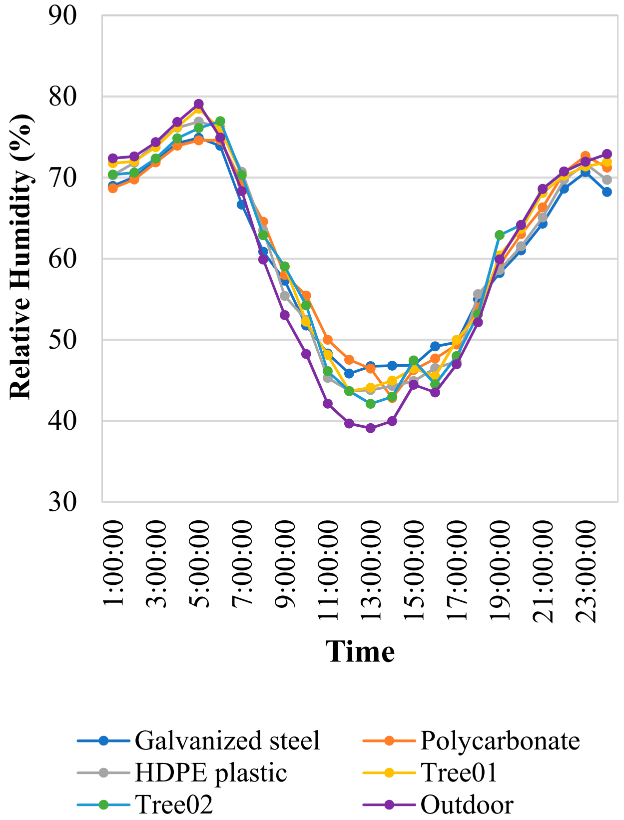


Figure 5. Diurnal patterns of air temperature, globe temperature, and relative humidity profile at 1.1 m height under artificial and tree canopy shades compared with unshaded conditions on winter days (**Left**) and summer days (**Right**).

The tree with dense canopy (Tree01) provided the coolest performance for winter and summer days with the temperature reduction (Tout–Tshade) of 2.3–3 °C, while the temperature reductions beneath the sparse canopy ranged from 0.1 to 0.4 °C (see Appendix C). The temperature reductions under different artificial shades showed a similar performance with 2.3 ± 2.1 °C on winter days and 1.6 ± 2.3 °C on summer days, and their temperature reductions were larger than those of the sparse tree canopy.

The study of roof shape effect was conducted on 14–16 April 2020. The air temperature and globe temperature distributions under the shade structures were lower than the unshaded conditions, while the relative humidity was slightly higher (Figure 6). Compared to the shade performance, the thermal conditions and relative humidity under various roof-shape canopies showed no statistically significant difference (p-value > 0.05).

The diurnal pattern of mean radiant temperature under various artificial shadesand tree canopies at 1.1 m height was calculated and is presented in Figure 7. The mean radiant temperature in the early morning and late afternoon rose close to the outdoor condition due to the sensors being directly exposed to sunlight. Artificial shades and tree canopies had a crucial effect on the mean radiant temperature reductions. It was found that Tree01 had the lowest mean radiant temperature. The mean radiant temperature reductions beneath Tree01 were 6.3 ± 3.3 °C on winter days, while significant reductions of 11.6 ± 7.7 °C occurred on summer days. This is because of the effect of the dense canopy absorbing solar radiation and blocking it from the space beneath the canopy. The reduction under the galvanized steel roofing sheet and tarpaulin plastic sheet (HDPE) was 4.6–8.5 °C, higher than that of the polycarbonate-roofing sheet. Meanwhile, Tree02 had the lowest temperature reduction (2.9 ± 2.1 °C on winter days and 4.1 ± 8.1 °C on summer days) because the solar heat could penetrate through the sparse leaves.

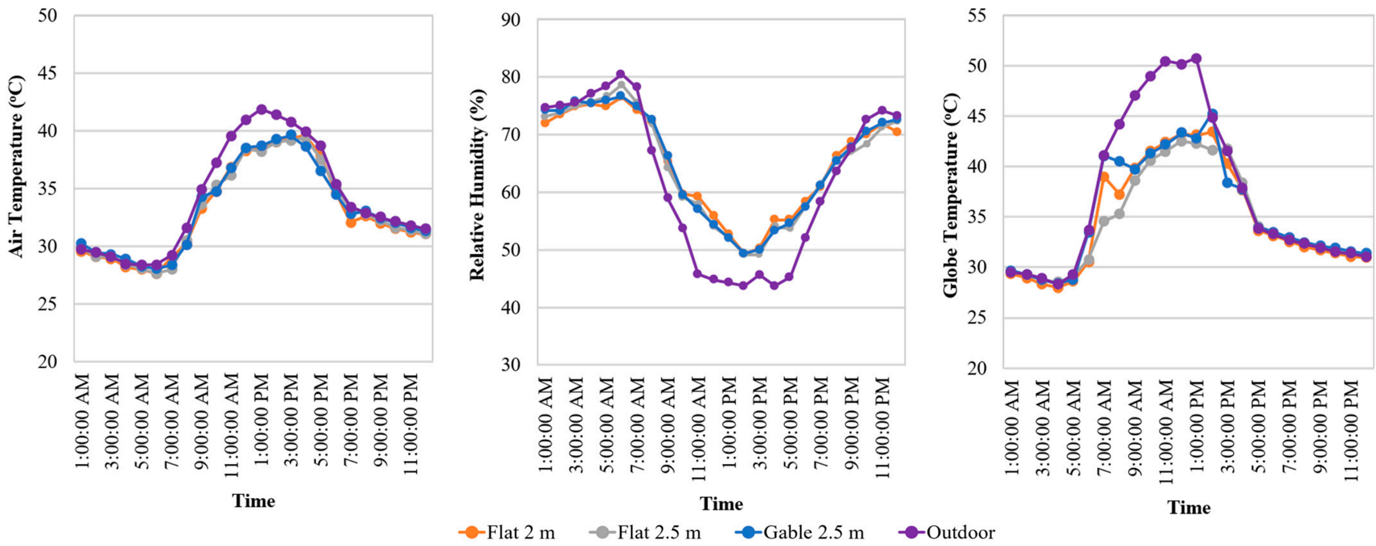


Figure 6. Diurnal patterns of air temperature, globe temperature, and relative humidity profile at 1.1 m height under various roof-shape canopies compared with unshaded conditions on summer days.

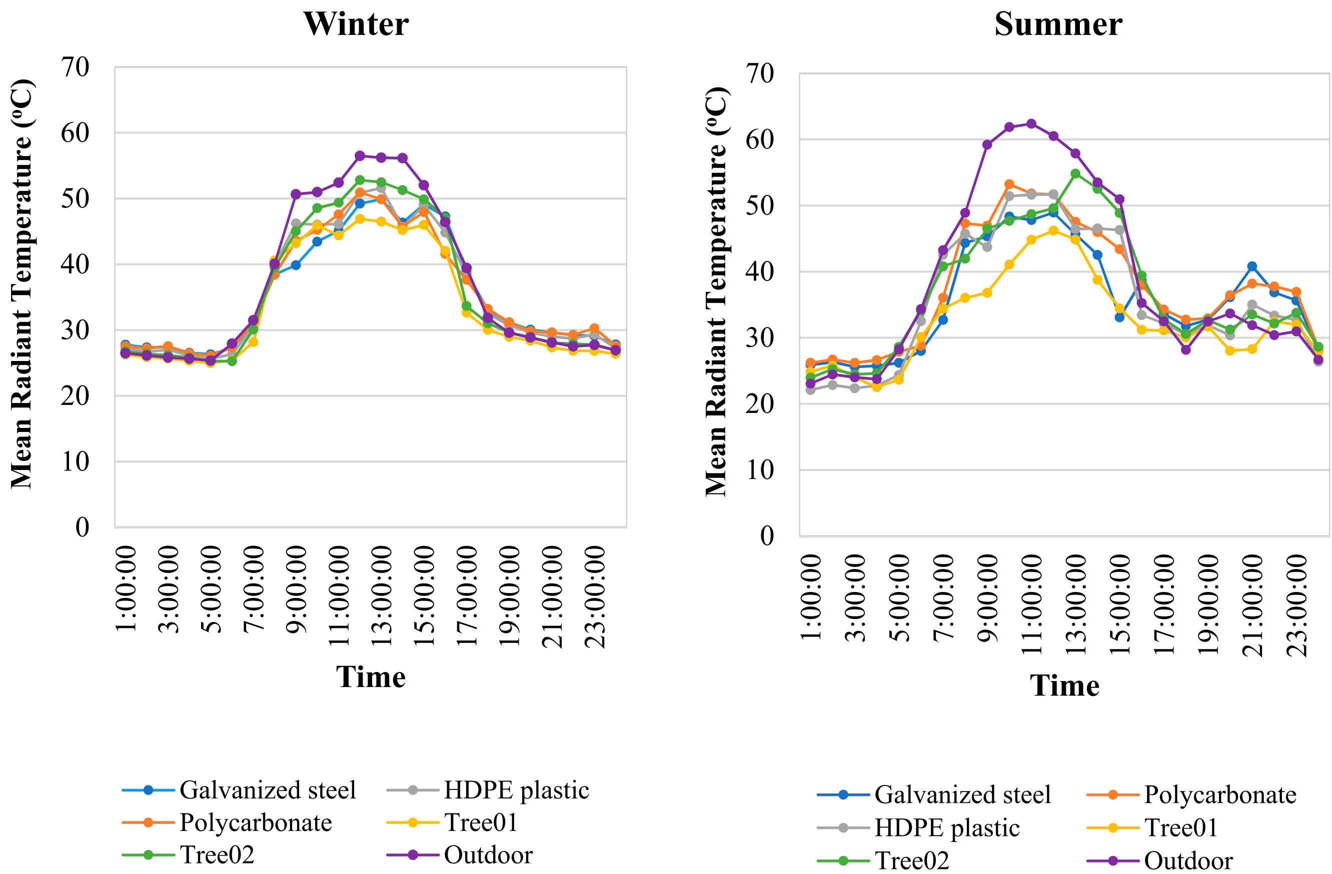


Figure 7. Diurnal pattern of mean radiant temperature at 1.1 m height under artificial shades and tree canopies compared with the unshaded condition on winter days (**Left**) and summer days (**Right**).

Considering the effect of roof shapes on the cooling performance, the largest reduction in mean radiant temperature (4.9 ± 5.5 °C) occurred in the flat roof at 2.5 m height, approximately 0.5 °C higher than for other roofs (see Figure A1a in Appendix D). However, a paired samples *T*-test showed that this difference had no statistical significance (*p*-value = 0.45).

4.3. Vertical Cooling Performance under Artificial Shades and Tree Canopies

The air temperatures were measured beneath the artificial shades and tree canopies at different vertical heights (0.1, 0.6, 1.1, and 1.6 m) (see Figure 8). The maximum reduction in air temperatures under the artificial canopies and Tree01 showed at 1.6 m height, 1.5–3 °C lower than the unshaded condition (T_{out}). The air temperatures beneath the artificial shades and dense tree canopy (T_{shade}) increased alongside a decrease in height, which correlated with the SVF profile. The paired samples *T*-test showed a significant difference in vertical temperature profiles between Tree01 and the artificial shade structures. Meanwhile, there was no statistically significant difference between the galvanized steel roofing sheet and the tarpaulin plastic sheet (t = −0.378–2.931, *p*-value > 0.05). It signifies that the thermal condition under the polycarbonate roofing sheet was warmer than those of two other materials. Considering the roof shape effect, the vertical air temperature profile under the canopies showed similar performance (see Figure A1b in Appendix D).

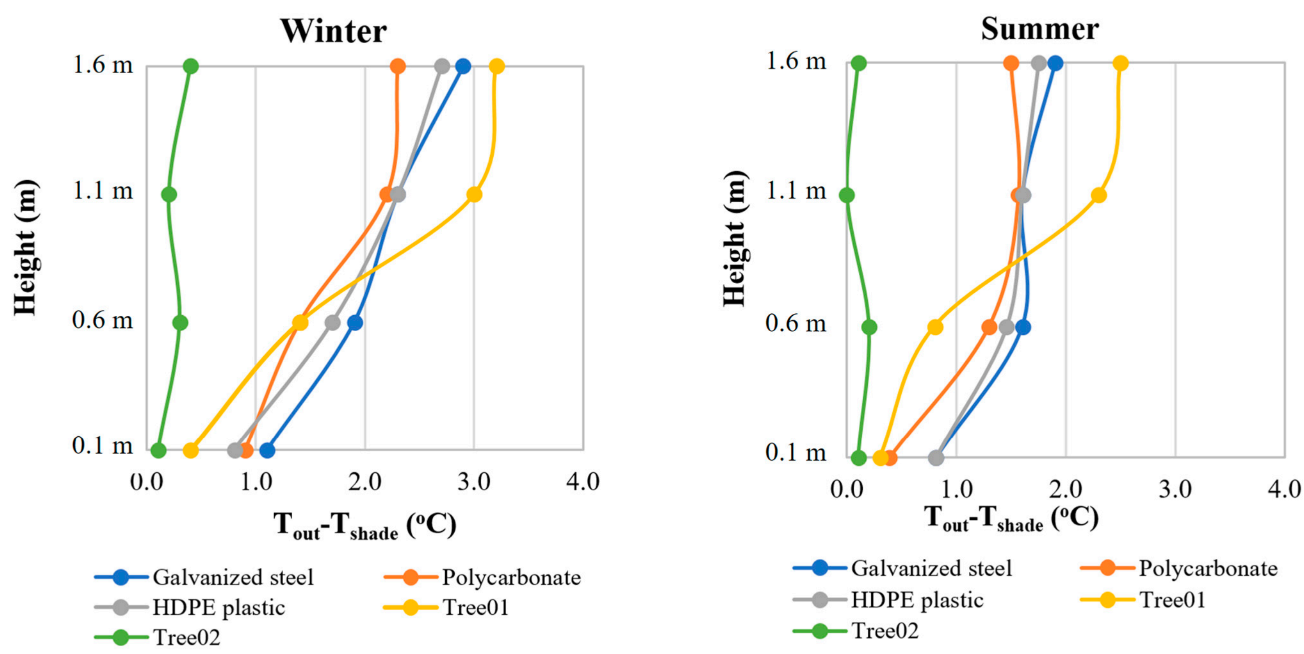


Figure 8. Vertical profiles represent air temperature differences under artificial shades and tree canopies compared with unshaded conditions on winter days (**Left**) and summer days (**Right**).

4.4. Thermal Comfort Performance Calculation

A calculation of hourly PET values under artificial shades and tree canopies from 6 a.m.–6 p.m. is shown in Figure 9. The highest PETs occurred in unshaded conditions, where the acceptable thermal comfort condition was presented for only 2 h in the early morning and 2 h in the late evening. During midday, artificial shades could reduce the maximum PET by 7–9.8 °C while the PET reduction under Tree01 and Tree02 was 11.4–15.5 °C and 6.4–8.2 °C, respectively. A maximum comfortable condition occurred in Tree01, lasting for 9 h (accounting for 69% of daytime), which could expand thermal comfort conditions by two more hours in the late morning (9 a.m.–10 a.m.) and 2 h late afternoon (3 p.m.–4 p.m.) as compared to the unshaded condition. The number of acceptable comfort conditions under the galvanized steel roofing structure was 6 h (accounting for 46% of daytime), which was statistically similar to that of tarpaulin plastic roofing shade (t = −0.707, *p*-value = 0.493). Even though the PET values under the polycarbonate roofing shade and Tree02 were lower than those of the unshaded condition, they had a similar percentage of acceptable thermal comfort hours. The PET values under different roof-shape canopies are not presented in this paper since there was no significant difference (t = −1.808–1.507, *p*-value > 0.05) in the calculated PET values under those shade structures.

(a)

Winter (Time)	Galvanized steel	Polycarbonate	HDPE plastic	Tree01	Tree02	Outdoor
6:00:00 AM	26.9	26.8	26.3	25.8	26.1	27.0
7:00:00 AM	29.2	29.3	29.2	29.1	28.3	29.1
8:00:00 AM	35.4	36.5	36.8	35.7	35.7	37.3
9:00:00 AM	36.9	37.5	37.0	36.2	38.5	43.0
10:00:00 AM	37.6	39.5	38.7	37.4	39.4	44.8
11:00:00 AM	39.4	42.0	40.0	38.6	42.1	46.2
12:00:00 PM	42.1	43.8	43.5	39.5	42.7	50.9
1:00:00 PM	42.9	44.0	44.0	42.3	42.1	51.1
2:00:00 PM	40.5	43.0	41.3	42.3	41.3	49.8
3:00:00 PM	42.3	43.2	43.3	37.4	38.5	46.9
4:00:00 PM	39.4	40.5	39.8	33.8	37.6	42.9
5:00:00 PM	36.3	35.6	34.5	32.7	33.4	36.4
6:00:00 PM	32.5	32.2	31.7	30.7	31.2	31.6
No. of comfort hour	6 hours	5 hours	6 hours	7 hours	5 hours	5 hours

(b)

Summer (Time)	Galvanized steel	Polycarbonate	HDPE plastic	Tree01	Tree02	Outdoor
6:00:00 AM	27.7	27.9	30.0	28.1	29.9	30.6
7:00:00 AM	29.6	31.9	34.4	29.4	33.0	35.0
8:00:00 AM	37.7	40.0	37.5	31.4	35.9	40.6
9:00:00 AM	39.1	40.3	38.2	33.2	38.6	47.7
10:00:00 AM	42.1	44.5	38.5	35.8	39.7	51.3
11:00:00 AM	42.4	44.6	40.0	37.5	41.9	52.2
12:00:00 PM	43.4	44.7	42.5	38.9	44.0	51.4
1:00:00 PM	42.1	42.9	45.1	39.7	47.3	50.1
2:00:00 PM	41.1	43.0	43.0	39.6	47.5	48.4
3:00:00 PM	37.2	42.2	43.7	36.4	44.9	46.3
4:00:00 PM	37.0	38.0	37.1	35.1	39.4	38.9
5:00:00 PM	35.2	35.4	34.7	33.9	35.6	36.0
6:00:00 PM	33.6	33.8	33.1	32.7	33.8	33.2
No. of comfort hour	6 hours	4 hours	5 hours	9 hours	5 hours	4 hours

XX Within acceptable comfort hour

XX Exceed acceptable comfort hour

Figure 9. Hourly distribution of PET values and acceptable thermal comfort conditions under different shades, compared with the unshaded condition on winter days (**a**) and summer days (**b**).

The patterns of thermal comfortable hours under the shade structures and tree canopies varied depending on the season owing to different sun positions. On winter days, the comfortable hours occurred mainly in the morning, while those conditions in summer days shifted to the afternoon. In our investigation, artificial shade structures and tree canopies could not protect against the extreme thermal conditions occurring during midday.

4.5. Relationship between Environmental Factors, Air Temperature, and Mean Radiant Temperature Reductions Beneath the Canopies

With corresponding regression lines, the air temperature reduction at different heights positively correlates with the SVF values (Figure 10a). This relationship is stronger throughout the midday, except for the sparse tree canopy (Tree02). The smaller SVFs, found in the almost completely shaded area, provide a more significant cooling effect. The difference between outdoor and in-the-shade mean radiant temperatures increased significantly with the increase in solar radiation (Figure 10b).

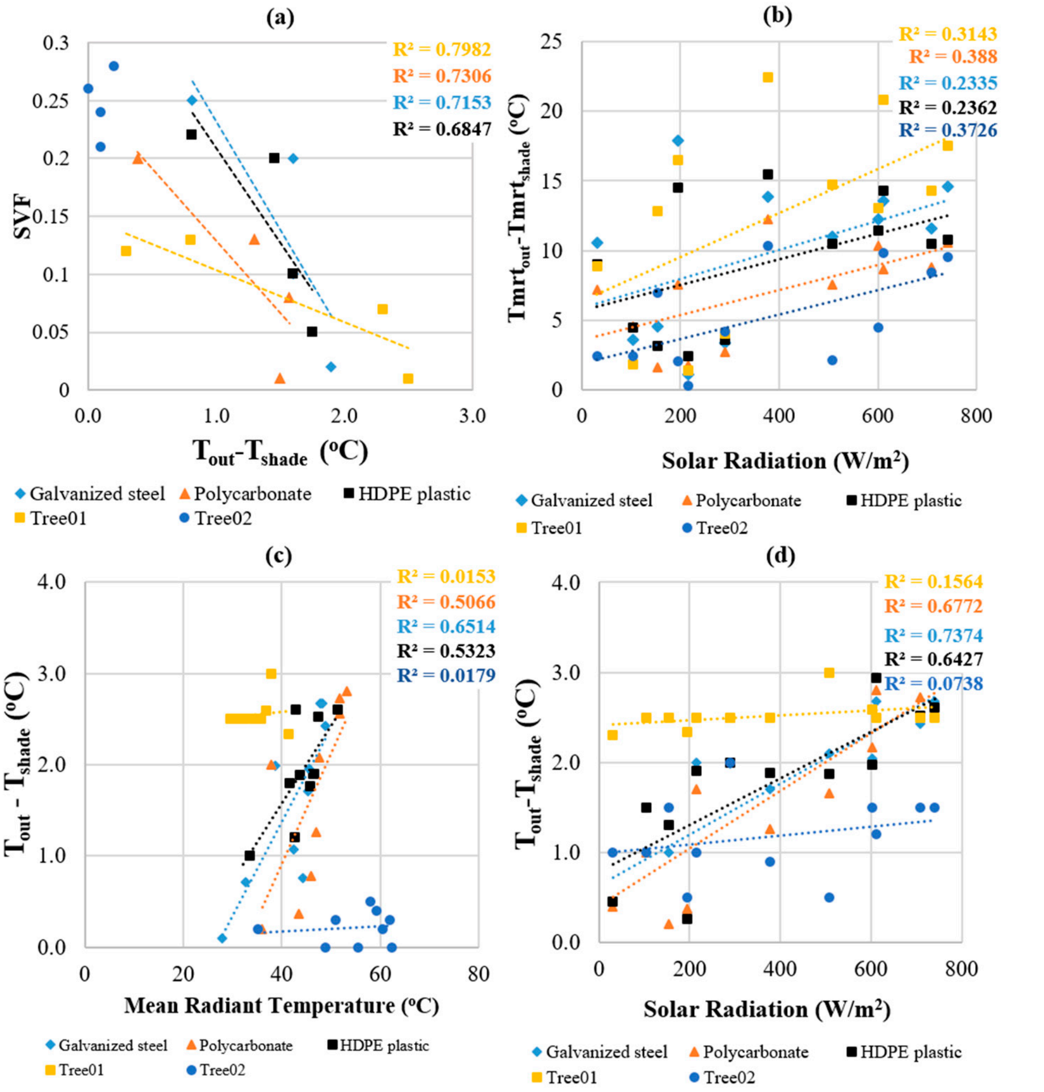


Figure 10. Relationship between two environmental variables: SVFs and temperature reductions (**a**), mean radiant temperatures and solar radiations (**b**), temperature reductions and mean radiant temperatures (**c**), and temperature reductions and solar radiations (**d**) beneath the tree canopies and artificial shades.

The air temperature reductions had a moderate positive relationship with the mean radiant temperatures under the shade structures (R^2 = 0.51–0.65), as shown in Figure 10c. The more significant reductions in air temperature occurred at midday, and correspond to the solar intensity, except for the tree canopies (Figure 10d). The air temperature reductions beneath a dense tree canopy were relatively stable because the tree canopy could absorb direct solar radiation and reduce radiated heat beneath the canopy.

5. Discussion

This present study investigated the microclimate conditions and cooling performance beneath tree canopies and various artificial shades with a dimension of 2 m × 2 m at a height of 2–2.5 m. Previous work [15] did compare thermal conditions under different shading types in Arizona, USA. The study showed solar cells and tree canopy shades provided the same shading effect. However, another study [27] investigated the impact of lower sun sail and a sparse tree canopy at Széchenyi Square in Pécs, Hungary. The sparse canopy (SVF = 0.188) could reduce thermal conditions more effectively than the artificial canopy (SVF = 0.014–0.068). Similar to Colter et al.'s investigation [2], that compared the effect of ramada and tree shades on human thermal comfort in Phoenix, Arizona, USA, the study revealed that the tree canopies provided greater thermal comfort conditions than those under the ramada shade. In our research, the dense tree canopy (Tree01, SVF = 0.07) provided the maximum cooling benefit (2.3–3 °C air temperature reduction), which was larger than a sparse tree canopy (Tree02, SVF = 0.27). This finding is similar to those reported in Armson et al. [46], Kántor et al. [27], and Colter et al. [2]. An increase in leaf density resulted in temperature and PET reductions. The dense tree can absorb more solar heat and provide more transpiration cooling [47,48]. Contrary to the findings of [2,15,27], in our experiment the thermal condition under the sparse tree canopy (Tree02, SVF = 0.27) was higher than artificial shade structures (SVF = 0.05–0.11). The tree canopy with a low leaf area allows more solar radiation to penetrate into the space beneath.

Considering the cooling effect of artificial shades, the study of impact of shading in Hungary (mainly a humid continental climate) by Kántor et al. [27] and in Nagoya, Japan, (a humid subtropical climate) by Watanabe and Ishii [24] reported that the air temperature reductions under overhead shades were as much as 9 and 16.2 °C, respectively. However, in this study, the artificial shades could reduce the air temperature in a range 1.6–2.3 °C. Such temperature reductions are close to values obtained in previous studies that also investigated thermal conditions under constructed shades and tree canopies in a hot and arid area [2,15,25]. Those small temperature reductions might be due to the small shade structures and radiated heat from the surrounding environment.

The thermal condition beneath the polycarbonate roofing shade is warmer than the other two roofing materials. It is because of two effects: (1) transmitting solar radiation through the dark gray transparent sheet and (2) sensible heat flux from the roof material. From our measurements, the surface temperature of the polycarbonate roofing sheet was 5–8 °C higher than those of the other two roof materials. Galvanized steel sheet has a good conductivity that could allow more heat energy to flow through the material. However, that sensible heat flux has a small effect on the air temperature and mean radiant temperature beneath the shade structures, owing to heat reduction by convection from the environmental wind. Such findings appear to corroborate previous works [18,25,36,47,49], revealing that reduced wind velocity resulted in a warming effect accumulated beneath the shade structures. Consequently, complete-shade roofs and environmental wind significantly improve the cooling benefits of the artificial shades. With the limited data of the emissivity coefficient of the inner surface of the roof materials, the effect of the emissivity coefficient of the materials on the mean radiant temperatures should be examined in future works.

Previous studies assessed the cooling performance under different natural and artificial shade structures exposed to extreme heat conditions during a couple of hours [2,17,22]. This study provides new insights into the relationship between diurnal temperature reduction, mean radiant temperature, and solar radiation intensity. The cooling benefit of artificial shade structures is associated with shade mean radiant temperature, and they both have a crucial link to the solar radiation profile. The minimum temperature reduction beneath the artificial shade structures was found in the late morning and late afternoon, while the maximum cooling performance occurred during midday. Compared with the tree canopies, the temperature reductions are not significantly different across an entire day. Comparing our results to Kántor et al. [27], the diurnal temperature reduction profile shows a different pattern.

Because of the COVID-19 pandemic in Thailand, our study was prevented from collecting data from the local outdoor markets. Consequently, we decided to switch to field testing at an institutional campus. By conducting the experiment at the actual location, other environmental variables, for example, the density and arrangement of the shade structures and shade coverage area, could be taken into account. These variables may affect the thermal conditions beneath.

The investigation was conducted with a few days in thermally stressful locations for a particular range of summer thermal comfort. The different tree types, fabric colors, and artificial shading materials with varying levels of shade imply that solar radiation may affect the suitability of PET for evaluating thermal comfort in an outdoor environment.

A long-term investigation could provide more evidence for the effect of artificial shade structures on the thermal performance and hourly thermal comfort condition in the space beneath. With a 2 m × 2 m size of the shade structure, to avoid discomfort from the sun's rays entering at a lower height (0.1–0.6 m height above ground), the shade structure's size could be increased [16]. Unfortunately, this study was limited to the single shade structure. The shade structures could provide a greater cooling effect if the shade structures are aligned. Furthermore, a better understanding of the cooling effect beneath the shades, more roofing materials, and variation in its sizes should be examined to compare the thermal performances and cooling benefits in different scenarios. Moreover, future studies should perhaps test this result and compare PET and its relationship with subjective human sensation votes to other thermal comfort indices, such as the universal thermal climate index (UTCI) and standard effective temperature (SET*), within spaces differing greatly in solar radiation and different climates.

6. Conclusions

This paper investigated microclimate conditions and cooling performance beneath a cluster of tree shades and various artificial shades with a dimension of 2 m × 2 m and at 2–2.5 m height. The experiments were conducted in hot and humid conditions on winter and summer days. In addition, the PET was calculated, and acceptable thermal comfort hours under various shades were investigated based on the previously calculated acceptable comfortable range. The findings from this investigation are summarized as follows:

The artificial shades and tree canopies could improve the thermal environment in hot and humid conditions. The maximum air temperature reduction (2.3–3 °C) occurred beneath the dense tree canopy (Tree01). The air temperature reduction beneath three artificial shades provided a similar performance level with the reduction ranging from 1.6 to 2.3 °C. A small temperature reduction (1.2–1.4 °C range) was found beneath the sparse trees canopy owing that the direct solar radiation could penetrate through the sparse leaves. In our investigation, the difference among roof shape canopies and their heights showed no statistical effect on thermal condition in the usage space beneath. Our major finding presents that the temperature reductions under artificial shades varied throughout the day depending on the shade mean radiant temperature and solar radiation intensity, in which the maximum reduction occurred during the midday. However, those thermal variations under the tree canopies are small.

The dense tree canopy provided the maximum cooling condition for 9 h (accounting for 69% of daytime), followed by galvanized steel roofing-sheet canopy and HDPE tarpaulin plastic roofing shade, which both had the same comfortable conditions of 6 h (46% of daytime). Furthermore, except for the sparse tree canopy, the thermal comfort condition under the canopy shades could be expanded by 1–3 h more in the late morning on winter days and in the late afternoon on summer days. However, these results highlight that the artificial shade structures still have their limited applications to protect from the extreme heat condition during the midday. It is because of the difference in physiological parameters and physiological adaptation of Thai residents, which may have different thermal responses to the outdoor thermal environment compared to other countries. Consequently, in hot and humid conditions, a combination of shading and other cooling strategies, such as evaporative cooling and cooling the surrounding environment, may reduce more effectively the extreme heat during midday. These design combinations for appropriate use and the consequent impacts on human thermal comfort in humid climates should be further investigated.

The findings of this study can provide a better understanding of microclimatic conditions and cooling benefits beneath a cluster of tree canopies and artificial canopies. This major finding opens avenues for active shade management strategies in tropical savanna climates to mitigate heat stress on people staying in an outdoor environment. This can change usage patterns of public spaces with significant social interaction and economic benefits, and may be a suitable strategy for cities hoping to better adapt to tropical climates and remain attractive to tourism.

Author Contributions: Conceptualization, methodology, formal analysis, investigation, data curation, resources, writing—original draft, writing—review and editing, visualization, funding acquisition, D.J.; formal analysis, investigation, resources, data curation, writing—original draft, writing—review and editing, M.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Thermal properties of roofing materials.

Roof Material	Specific Heat Capacity	Thermal Conductivity	Source
Galvanized steel roof sheet	470 J/kg-°C	52.0 W/m-K	Manufacturing data
Polycarbonate sheet	1200 J/kg-°C	0.19–0.22 W/m-K	Manufacturing data
HDPE plastic sheet	1750–1810 J/kg-°C	0.45–0.52 W/m-K @23C	Manufacturing data

Appendix B

Table A2. Fisheye images and calculated SVFs in the unshaded area and different height levels under artificial shade structures and tree canopies.

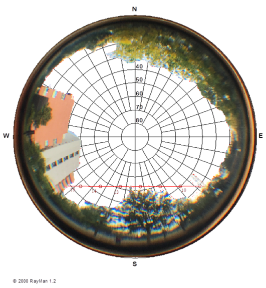
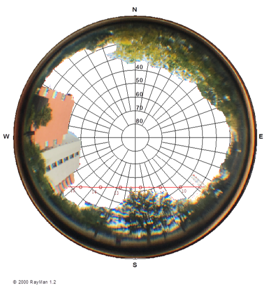
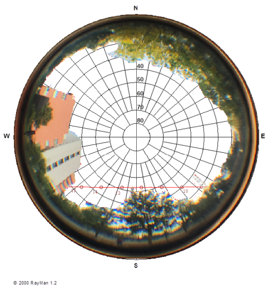
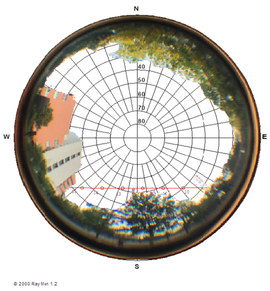
Date: 11 April 2020, Time: 12 p.m.			
Unshaded area 0.1 m__SVF = 0.49	Unshaded area 0.6 m_SVF = 0.49	Unshaded area 1.1 m_SVF = 0.49	Unshaded area 1.6 m_SVF = 0.49
			

Table A2. *Cont.*

Date: 11 April 2020, Time: 12 p.m.			
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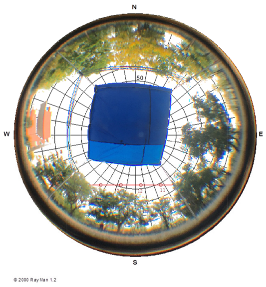	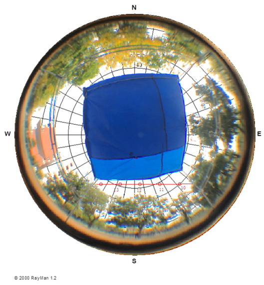	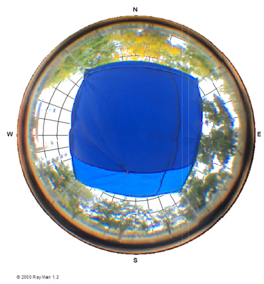	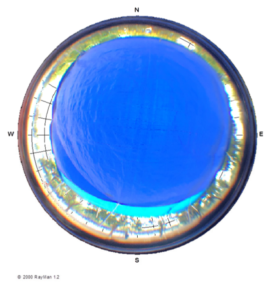
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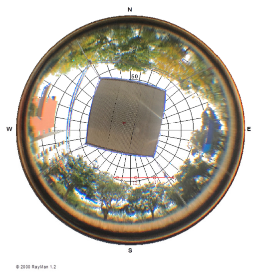	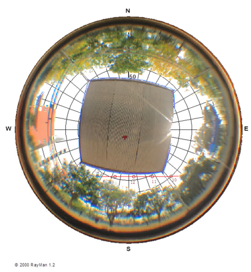	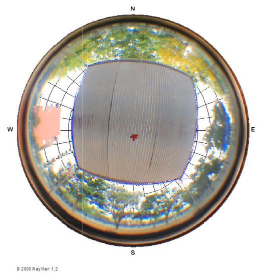	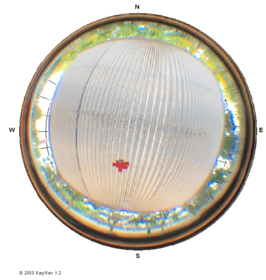
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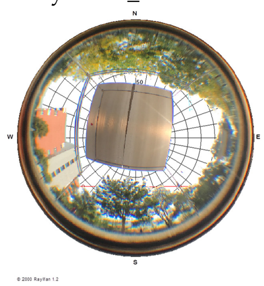
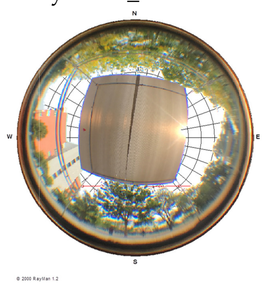
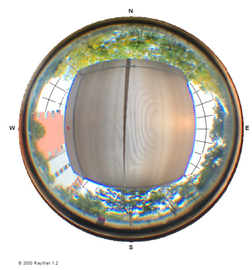
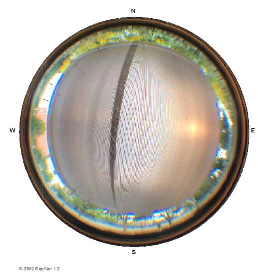
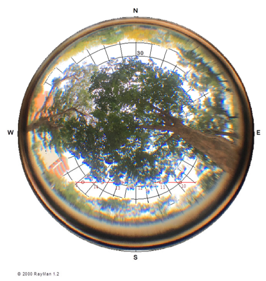
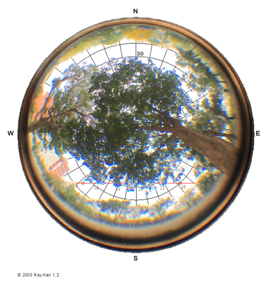
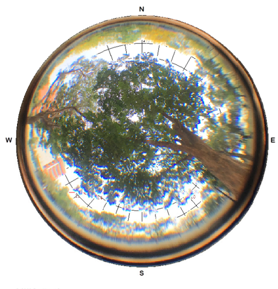
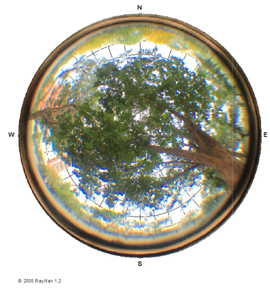
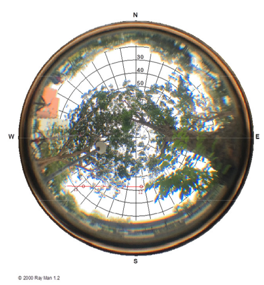
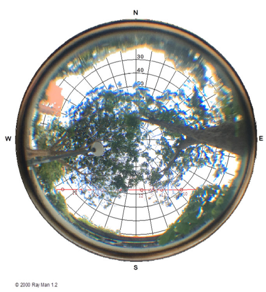
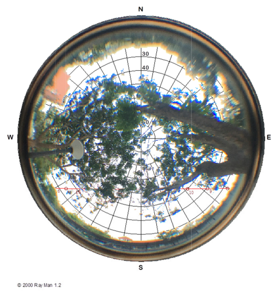
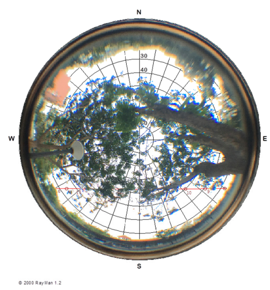
			
Tree01 0.1 m_SVF = 0.13	Tree01 0.6 m_SVF = 0.13	Tree01 1.1 m_SVF = 0.07	Tree01 1.6 m_SVF = 0.02
			
Tree02 0.1 m_SKV = 0.22	Tree02 0.6 m_SKV = 0.28	Tree02 1.1 m_SKV = 0.27	Tree02 1.6 m_SKV = 0.24
			

Appendix C

Table A3. Average reduction (±standard deviation) in microclimate conditions at 1.1 m height beneath various shade structures and tree canopies in the winter and summer days.

Winter Season	**Unshaded Condition–Shaded Condition 20–22 December 2019**								
	Unit	**Galvanized Steel**	**Polycarbonate**	**HDPE Plastic**	**Tree01**	**Tree02**			
Air temperature	°C	2.3 ± 2.1	2.0 ± 2.0	2.3 ± 2.0	3.0 ± 2.3	1.4 ± 2.3			
Globe temperature	°C	12.9 ± 9.3	12.4 ± 9.4	11.8 ± 9.3	13.5 ± 8.6	11.6 ± 8.8			
Relative humidity	%	−3.3 ± 1.8	−2.7 ± 1.6	−3.3 ± 2.1	−4.2 ± 1.9	−1.5 ± 1.2			
Mean radiant temperature	°C	4.8 ± 4.3	3.8 ± 3.1	4.6 ± 3.2	6.3 ± 3.3	2.9 ± 2.1			
Summer Season	**Unshaded Condition–Shaded Condition 10–12 April 2020**						**Unshaded Condition–Shaded Condition 14–16 April 2020**		
	Unit	**Galvanized Steel**	**Polycarbonate**	**HDPE Plastic**	**Tree01**	**Tree02**	**Flat 2 m**	**Flat 2.5 m**	**Gable 2.5 m**
Air temperature	°C	1.6 ± 1.1	1.6 ± 1.3	1.6 ± 1.0	2.3 ± 0.6	1.2 ± 0.4	1.5 ± 1.0	1.7 ± 1.0	1.5 ± 1.0
Globe temperature	°C	3.6 ± 2.4	2.8 ± 2.0	2.9 ± 2.1	4.8 ± 2.4	2.5 ± 2.6	4.0 ± 3.1	4.1 ± 4.0	3.9 ± 3.7
Relative humidity	%	−3.9 ± 5.3	−4.5 ± 2.9	−5.3 ± 3.2	−3.8 ± 1.8	−3.0 ± 1.7	−5.7 ± 4.6	−5.6 ± 4.3	−5.9 ± 5.2
Mean radiant temperature	°C	8.5 ± 7.2	4.6 ± 5.6	6.9 ± 5.4	11.6 ± 7.7	4.1 ± 8.1	4.4 ± 4.3	4.9 ± 5.5	4.3 ± 5.0

Appendix D

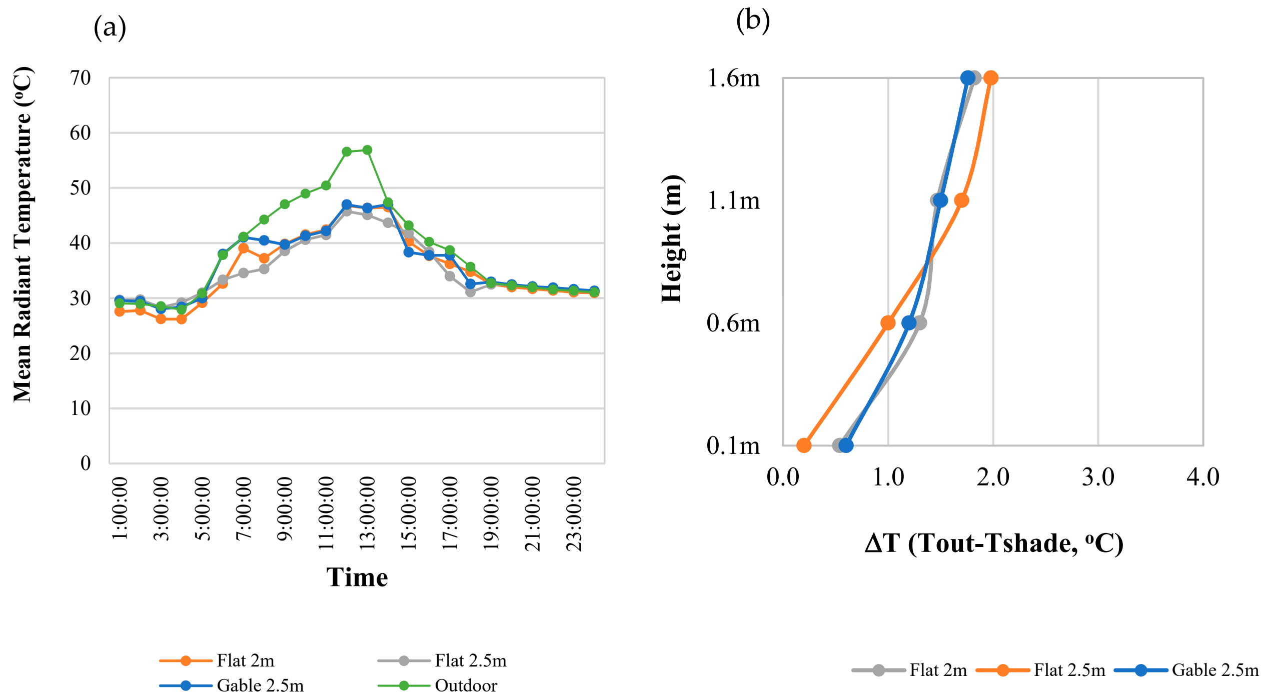


Figure A1. (**a**) Diurnal pattern of mean radiant temperature at 1.1 m height under different shade structures compared to unshaded condition in summer days (14–16 April 2020). (**b**) Vertical profiles represent air temperature reduction under different roof shape structures on summer days.

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