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The Effects of Design Combinations of Surface Materials and Plants on Outdoor Thermal Conditions during Summer around a Single-Detached House: a Numerical Analysis

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ABSTRACT

Suburban areas with low-density buildings are subject to only limited shading from adjacent buildings. As a result, these areas have more surface area absorbing more radiation, which has the effect of increasing urban temperatures compared with built-up high-density areas. This study aims to assess the combinations of landscape design, namely the integration of wall-paint colors, used to influence the outdoor thermal conditions around a single house in a housing cluster in suburban Bangkok, Thailand. The investigation used the ENVI-met model to perform diurnal profiles of the air temperature (Ta), relative humidity (RH), direct and diffuse solar radiation, and wind speed (WS) in summer. The results show that only a single design element adversely affected the cooling effect, while other combinations of landscape design significantly improved outdoor thermal conditions. It was found that a combination of light wall-paint colors and trees planted near the house provided the maximum reduction in Ta of 0.7°C (1.6% from the base case), and a 2.7% reduction in the noon solar radiation. High-reflectance wall-paint was found to have a secondary influence of up to 0.2°C on the Ta, while the temperature reductions from changing the ground-cover materials had only a slight impact. Finally, landscape designs integrating wall-paint colors to promote a cooler outdoor environment are proposed.

Keywords: air temperature reduction, outdoor thermal conditions, ENVI-met, plants, surface material

INTRODUCTION

Urbanization in Thailand is dominated by Bangkok, which became one of the world's megacities in 2018 (United Nations Department of Economic and Social Affairs [UN DESA], 2018). The expansion of land used for urban construction and impervious surfaces in and around Bangkok neighborhoods has resulted in rising air temperature (Ta) (Arifwidodo & Tanaka, 2015; Takkanon & Chantarangul, 2019), and has also led to an urban heat island (UHI) effect. Previous studies have shown that the maximum temperature difference between Bangkok's urban and rural areas was 7ºC, which is the highest recorded difference in the last ten years (Arifwidodo & Chandrasiri, 2019, 2020). This situation has led to an increase in both heat-related illnesses and in energy consumed to cool buildings. In addition, the high level of energy consumption is also raising the future global temperature, which is one of the most important causes of climate change.

Landscape design can significantly improve the microclimate and enhance human comfort in outdoor areas, mitigating the UHI effect (Ignatius et al., 2015; Mohammad et al., 2021; Xu et al., 2017) , and resulting in a decrease in the demand for cooling of buildings (Akbari et al., 1992; Hamdan & Oliveira, 2019; Kolokotroni et al., 2007; Xu et al., 2017). A few studies have investigated the cooling impact of trees and vegetation on outdoor Ta due to the evaporation ability and shading effects of vegetation. Farhadi et al. (2019) found that increasing the vegetation coverage area by 10% could reduce Ta by a maximum of 0.56°C in Tehran, Iran. In line with a study by Huang et al. (2016) in Xi-an, China, it was found that Ta could be dropped by 0.3°C by increasing the vegetation coverage. In Montreal, Canada, Wang and Akbari (2016) reported that the reductions in Ta from planting street trees was 0.2–0.3°C during the day, and 0.03–0.19°C at night. Shahidan et al. (2012) also suggested that increasing the number of trees by 50% and a higher canopy density could lower Ta by 2.7°C in Putrajaya, Malaysia. Yang et al. (2018) found that combining trees with natural grass surfaces could reduce Ta by 0.75°C in a residential area in Singapore. In addition, the cooling effect of trees has been considered in energy consumption studies. It has been concluded that many trees or urban parks could significantly drop the local Ta by 0.5-1°C, which could lower the cooling demand by 2-4% (Akbari et al., 1992). According to the literature reviewed, increased vegetation and tree planting are important strategies to promote energy savings and cooler cities; however, the cooling effect from the studied designs differs depending on the context of the implementation.

Besides tree planting and vegetation coverage, the albedo and solar reflectivity of surface materials significantly impact the surrounding air conditions. The effect of albedos on outdoor Ta reductions was incorporated into the assessment of building energy consumption (Akbari et al., 2001; Doulos et al., 2004). Higher albedo values and solar reflectance notably reduce Ta more than do lower albedo values. For example, Farhadi et al. (2019) revealed that raising the albedo of a street pavement from 0.3 to 0.6 could lower the maximum Ta by 0.36°C in Tehran, Iran. Meanwhile, in Brasília, Brazil, Werneck and Romero (2017) reported that increasing a walkway pavement's albedo from 0.3 to 0.8 and a street pavement's albedo from 0.2 to 0.5–0.6 reduced Ta by 0.75°C and 1.0°C, respectively. Furthermore, they also found that combining high albedo surfaces with trees on the walkway resulted in the maximum reduction in Ta of 1.1°C. From studies in Eilat, Singapore, Adelaide, and Göteborg, in open space or shallow street canyons, which are defined by the building's height to street's width ratio (H/W ratio ≤ 0.1), surface materials reduce Ta by 70% more than those in deep canyons (H/W ≥ 2) (Erell et al., 2014). However, Salvati et al. (2022) investigated the thermal environment in the typical street canyon by applying high solar reflectance materials to the road and building's facades, and found that designs that incorporate a great deal of high solar reflectance materials worsen thermal comfort conditions. It might be that interreflections between the road pavement and building façade materials lead to rising mean radiant temperatures and Ta. To avoid that detrimental impact, integrating high-reflectivity streets with low-reflectivity in the lower façades would be the best strategy for UHI mitigation. In summary, using cool surface pavements may reduce Ta, but the potential negative effect of those designs applied in some specific contexts needs some consideration.

In line with the strategic plan to achieve the 2030 Agenda and Sustainable Development Goals (SDGs), including solving the global temperature issue, the Bangkok Metropolitan Administration (BMA) launched the Green Bangkok 2030 Project, with a focus on SDG-11 and SDG-13 to enhance sustainable urbanization and reduce the environmental impact of cities. The BMA project aims to increase the ratio of green space and urban tree canopies in the city areas (Bangkok Metropolitan Administration, & Faculty of Political Sciences, Chulalongkorn University, 2020). However, based on our review, it seems that other urban design elements such as streetscapes or building materials have not been considered in that strategic plan. Furthermore, those mitigation strategies have not been implemented for private residential-neighborhoods, which are primarily located in low-density built-up areas with less shade from adjacent buildings. Such areas account for the largest proportion of urban settlement in suburban Bangkokand the large exposed surface areas of these settlements could absorb more solar radiation, thus increasing urban heat.

To fill the gaps in implementing and expanding the heat mitigation strategies in low-density built-up areas, this study aimed to investigate how landscape design and outdoor material surfaces could affect the outdoor microclimate and improve thermal conditions in those areas. This study chose a detached-housing estate in a Bangkok suburb as a case study. The microclimate parameters were investigated using a microclimate analysis model that includes Ta, WS, RH, and direct solar radiation. The study findings could provide design guidelines to improve the outdoor microclimate around a group of single-detached houses. This kind of clarity on such design strategies is important for landscape architects and property owners in reducing the Ta. However, the influence of outdoor microclimate on outdoor thermal comfort and energy consumption is not within the study's scope, and requires further investigation.

METHODOLOGY

Figure 1 presents the framework of this research and the work conducted in the previous study (Leetongin et al., 2017). In this study, the landscape components, including plant types, floor surface materials, and exterior wall-paint colors, are used in the design scenarios. In addition, the study presents a procedure and simulation tool for evaluating the impact of each design scenario on the local microclimate around the studied house. Finally, designs for promoting an outdoor cooling environment are proposed.

Studied Location

In this study, purposive sampling was used to select the studied area. A single-detached housing estate in a Bangkok suburb was selected for the case study, and used for the model validation (see Figure 2). This site was chosen because the managers of this housing estate project provided permission to collect the field experiment data. In addition, this new construction project had few landscape elements, meaning that this simple model could provide more accurate results. This housing project provides a representative case because the single-detatched house layout, land plot size, and house size are within the range of the typical housing projects found in the suburban areas investigated by Jareemit et al. (2016).

The houses in the case study have two stories, typically comprising three bedrooms, a living room, a kitchen, and two bathrooms. With the inclusion of outdoor terraces, laundry, and car parking, they have a total floor area ranging from 136–165 m^2, and the land plot sizes vary from 200–240 m^2. The main roads in front of the houses are 6 m wide.

Information on the Base Case and Design Scenarios

For the representative case (base case), the researchers ascertained that the house's exterior walls are a lightweight concrete system painted in a dark color. The roof construction is covered with concrete roof tiles, and the roof eaves are 1 m wide. The main road and parking areas are covered with concrete pavement (see Figure 3). The outdoor terraces and landscape around the house are covered with granite floor tiles and ceramic tiles, respectively.

For the proposed design solutions, the ground surface material, the number of trees planted, and the wall paint color were varied in order to assess their impact on the outdoor thermal conditions surrounding the house. The researchers initially identified the types of surface materials and tree planting patterns commonly found in Thai housing estates. During their occupation, most homeowners upgrade and change the floor pavement and landscaping around their houses to enhance the functional use of the outdoor space. The ground-cover grass, the shaded area in Figure 4(a), is typically replaced with artificial pavements such as ceramic tiles and concrete floors to increase the functional outdoor area. Different designs of shrub and tree plantings are presented in Figure 4(b). Combinations of these design variables provided the 16 design scenarios presented in Table 1. Table 2 summarizes the material properties of the existing design conditions and our proposed design scenarios from the material database provided in the ENVI-met model.

Figure 1

The Research Framework of the Study

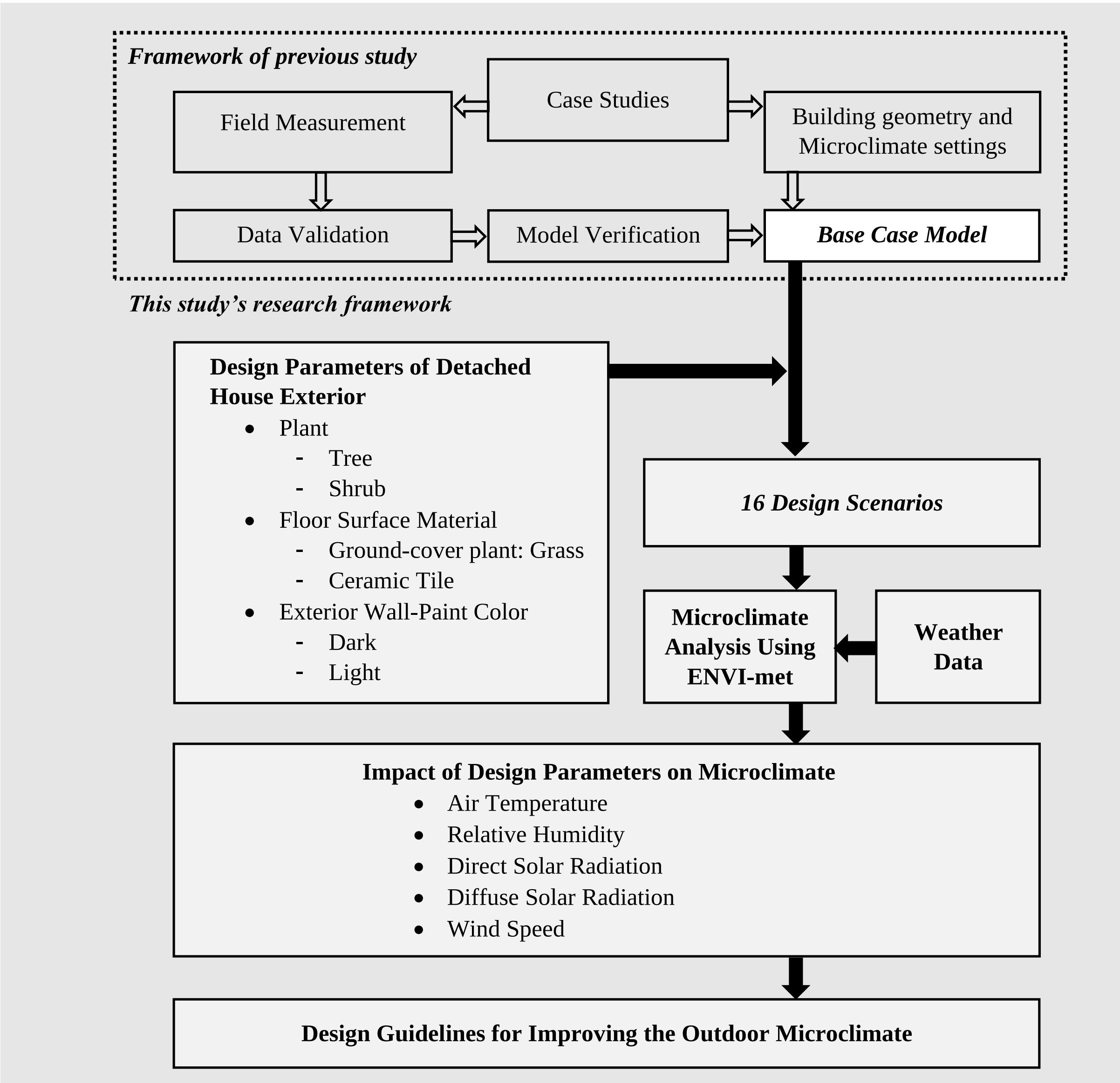


Figure 2

Study Location and the Site Layout Plan of the Selected Housing Estate

Note. From Map of Sai Mai district, Bangkok, by Google Earth, 2022. Copyright 2022 by Google LLC.

Figure 3

Landscape and Surface Pavement Materials for a Representative House (Base Case)

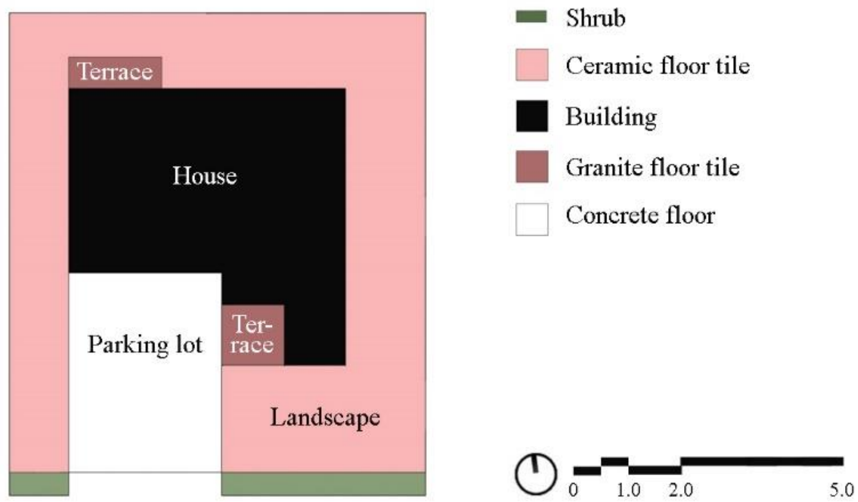


Figure 4

Area of Surface Pavement Material in the Land Plot Layout (a) and the Locations of Tree Plantings and Shrubs Around the House (b)

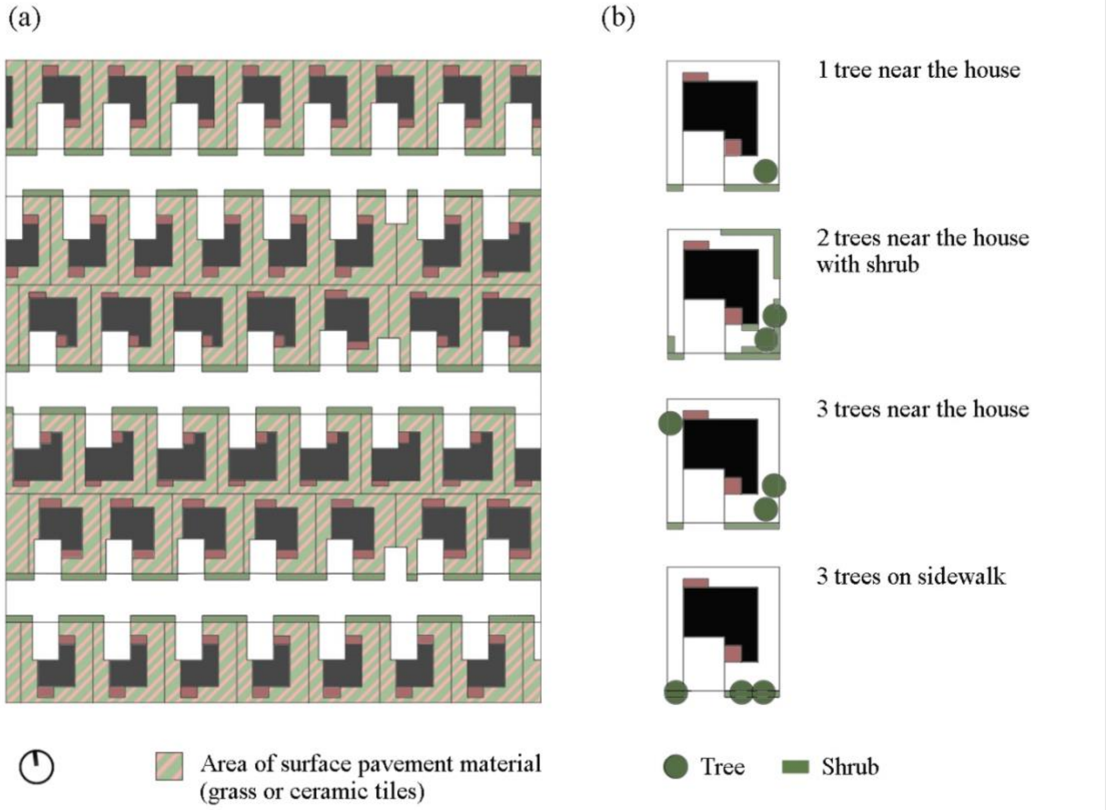


Table 1

Sixteen Combinations of Design Variables

Case	Plants				Exterior surfaces		
	Shrub (h=0.5 m)		Tree (h=6m, d=3 m)		Floor material		Wall-paint color
	House	Sidewalk	House (Number of trees)	Sidewalk	Grass	Ceramic Tiles	
1	/	/	2	-	/	-	Light
2	/	/	2	-	/	-	Dark
3	-	/	0	-	/	-	Light
4	-	/	0	-	/	-	Dark
5	-	/	1	-	/	-	Light
6	-	/	1	-	/	-	Dark
7	-	/	3	-	/	-	Light
8	-	/	3	-	/	-	Dark
9	-	/	0	-	-	/	Light

Table 1 (Continued)

Case	Plants				Exterior surfaces		
	Shrub (h=0.5 m)		Tree (h=6m, d=3 m)		Floor material		Wall-paint color
	House	Sidewalk	House (Number of trees)	Sidewalk	Grass	Ceramic Tiles	
10 (Base case)	-	/	0	-	-	/	Dark
11	-	/	1	-	-	/	Light
12	-	/	1	-	-	/	Dark
13	-	/	3	-	-	/	Light
14	-	/	3	-	-	/	Dark
15	-	/	0	/	/	-	Light
16	-	/	0	/	-	/	Light

Table 2

Thermal Properties of Hard Surface Materials and Natural Features Provided in ENVI-Met Software

Location	Material	Thickness (m)	Absorption	Reflection	Emissivity	Albedo	Specific heat (J/kg*K)	Conductivity (w/m*K)	Density (kg/m^3)	Volumetric heat capacity
Roof tile	Concrete roof	0.05	0.5	0.5	0.90	-	790	0.993	2400	-
Parking area	Concrete	-	-	-	0.90	0.5	-	1.63	-	2.08
Outdoor terrace	Granite tile	-	-	-	0.90	0.4	-	4.61	-	2.35
Wall	Lightweight concrete	0.08	0.7	0.3	0.90	-	840	0.20	620	-
Wall-paint color	Light color	0.01	0.4	0.6	0.84	-	840	0.72	1860	-
	Dark color	0.01	0.9	0.1	0.85	-	840	0.72	1860	-
Landscape-cover material	Ceramic tile	-	-	-	0.85	0.5	1050*	2.04*	2285*	2.40

Location	Type	Diameter (m)	Height (m)	Leaf area index	Leaf density	Reflectivity
Natural features	Natural grass	-	0.05	0.015	0.3	0.2
	Shrub	1	0.50	0.150	0.3	0.2
	Tree	3	6.00	1.200	0.3	0.2

Note. * is the mean value.

Model Description and Set-up Parameters

This study used ENVI-met V4 software to calculate thermal conditions in the outdoor environments, including the Ta, RH, WS, direct solar radiation, and diffuse solar radiation of the 16 design scenarios. Since the study did not assess outdoor thermal comfort conditions, the mean radiant temperature (Tmrt) was not calculated or presented in this paper. The ENVI-met software is a three-dimensional microclimate model. This software is used worldwide to calculate WS and the transient surface energy balance of surface materials by using a 1.5 order turbulence closure k-ε model (Bruse & Fleer, 1998). Previous studies have found that the ENVI-met simulation results were able to provide reliable results in urban microclimate assessment (Aboelata, 2020; Salvati et al., 2022; Srivanit & Jareemit, 2020). The microclimate simulations were performed for Bangkok/Don Muang weather station (13.913° N, 100.607° E). In the model set-up, the hourly ambient Ta and RH in May and June from 2011 to 2016 are shown in Figure 5. The initial Ta was 35.08°C and specific humidity was 7g/kg, which were the default values calculated by the ENVI-met model. The main wind direction during the study period was from the southwest, with an average WS of 3.19 m/s measured at 10 m above the ground, and the roughness length used the default value provided in the model. Table 3 presents the detailed settings of the simulation domain, meteorological data, and simulation period applied in the ENVI-met model. Then, the outdoor thermal conditions of those 16 scenarios were calculated using the microclimate simulation software.

Figure 5

The Hourly Ambient Ta and RH in the Model Set-Up

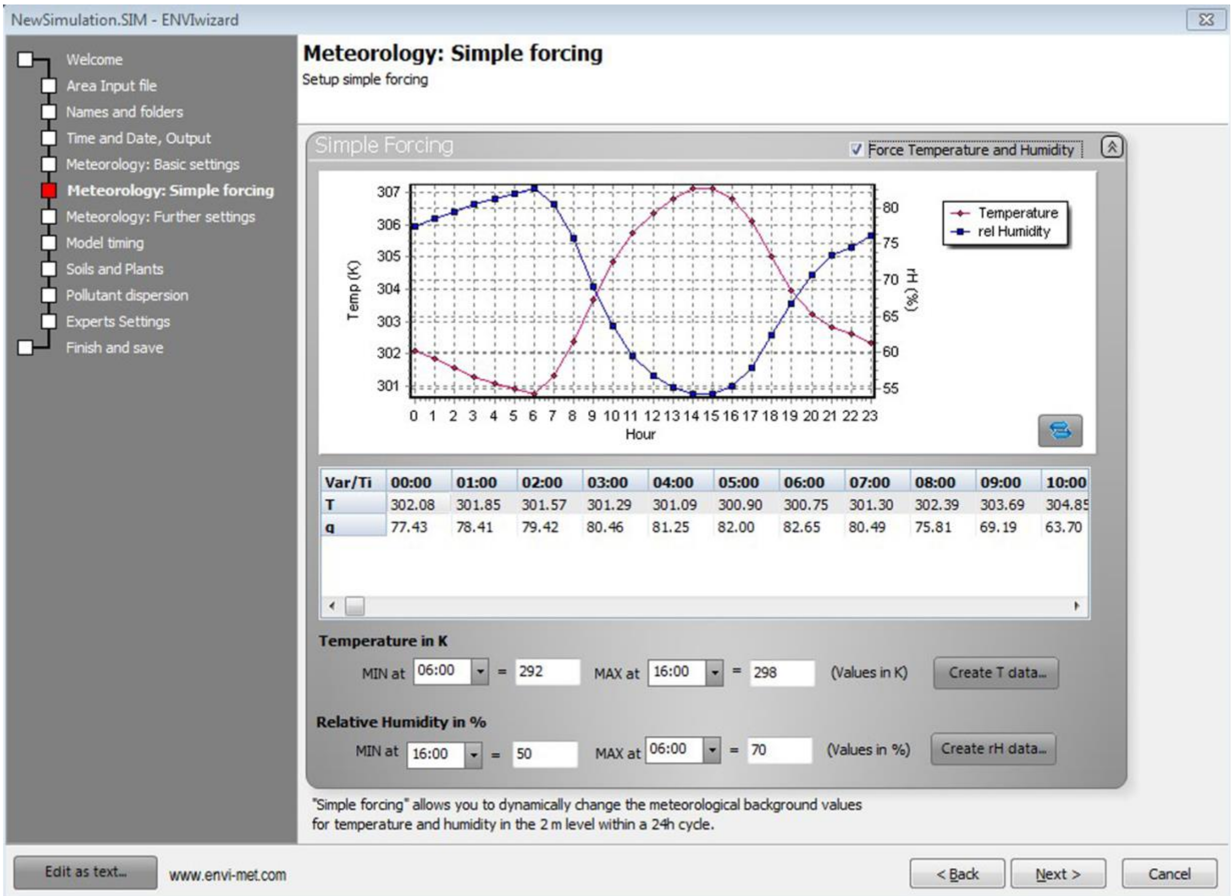


Table 3

Model Settings and Background Meteorological Data in the ENVI-Met Model

Topic	**Parameter**	**Value**
Domain settings	Grid size (x,y,z)	1x1x2 m.
	Number of grid cells	386,000 cells
	Number of cells in nesting grid	1,053,000 cells
	Vertical grid size	Equidistant
	Soil profile in nesting grid	Default unsealed soil
	Roughness length at reference	0.01
	Turbulence model	k-ε model
Meteorological data	Initial temperature	35.08°C (Default)
	Wind speed and direction (0 = from North)	3.19 m/s at H=10 m., 192 degrees
	Specific humidity at 2500 m	7 g/kg (Default)
	Solar adjustment factor	Default
	Cloud cover	Default
Simulation time	Simulation date	28 May 2016
	Simulation period	24 hr

Figure 6

3D Modeling in ENVI-Met (a) Location of the Studied House (b) and the Study Area Boundary

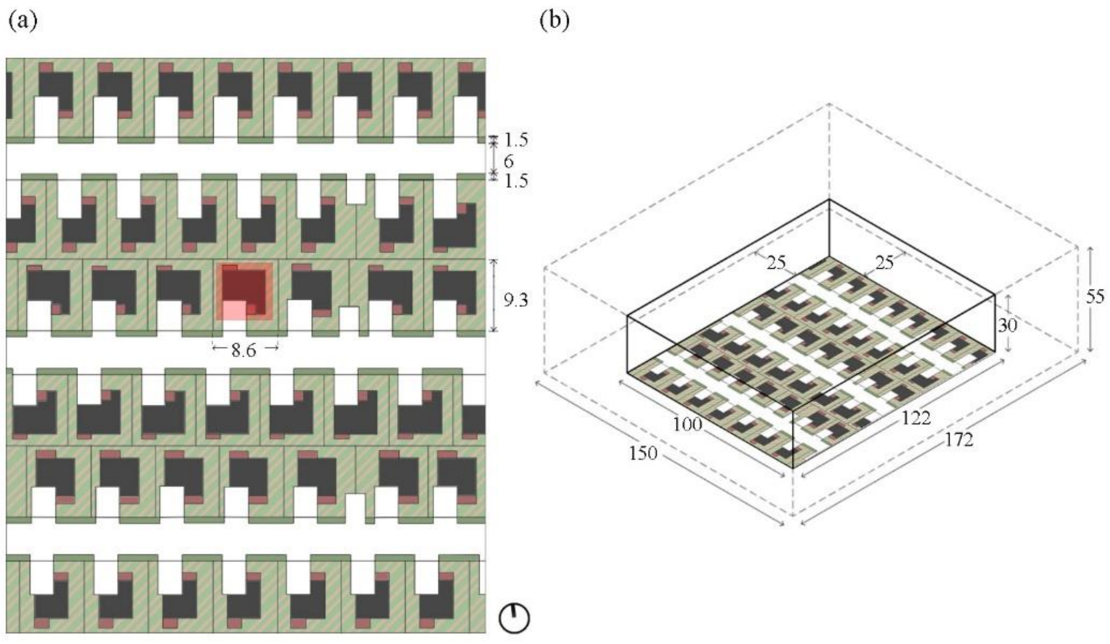


Figure 7

3D Models Representing the Landscape Designs and the House Characteristics of the Base Case (Case 10) and Proposed Design Scenarios

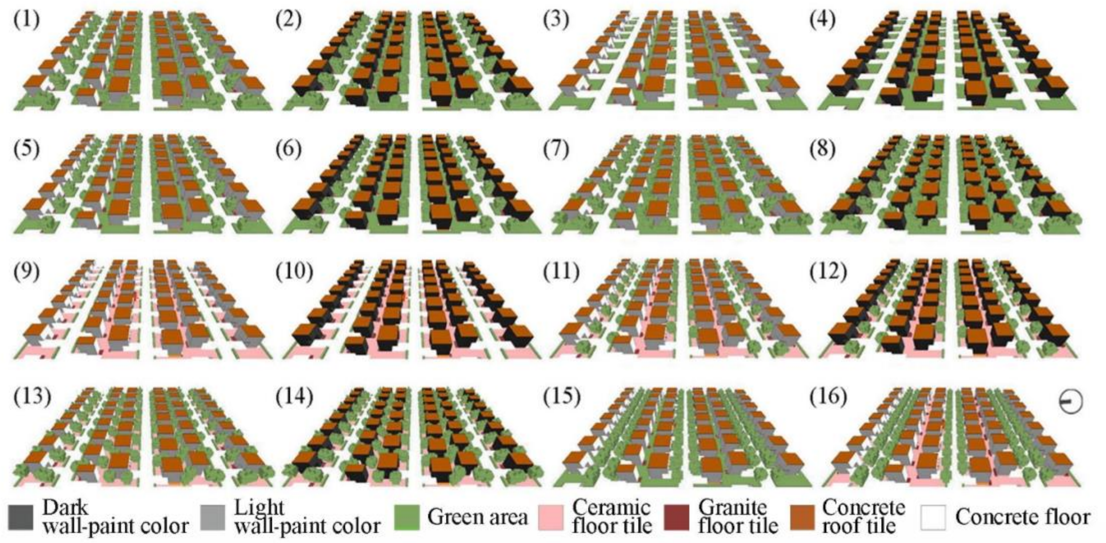


Figure 6(a) presents the plot layout of the housing estate. The location of the study area was at the center, identified by the red area. The land plot size is 8.6 m x 9.3 m. In our analysis, the outdoor thermal conditions surrounding the study house within the land plot were measured. A total of 107 measured data points were averaged and used for analysis. The dimensions of the core simulation domain are 100 m x 122 m x 30 m, and the nesting grid around the core domain (dashed line) is 150 m x 172 m x 55 m, as shown in Figure 6(b), in which the ENVI-met model qualified for this number of grid sizes. In this study, to increase the accuracy of the simulation, the lowest vertical grid cell was divided into 5 cells (Jin et al., 2017). Figure 7 presents the characteristics of the 3D models of the houses and landscape designs generated in the ENVI-met model of the 16 scenarios, including the base case (Case 10).

Validation Method

According to the previous works (Jin et al., 2017; Ng et al., 2012; Salata et al., 2016), the calculation period should be longer than 6 hrs to overcome convergence error. In this study, the simulation started at 12 am and the performance analysis was from 6 am to 5 pm. The grid setting of all models was automatically approved by ENVI-met before the simulation. The simulation results of ENVI-met were compared with the field measurements at the housing cluster estate on 28 May 2016, conducted by Leetongin et al. (2017). In their field measurement, Ta, RH, and globe temperature were measured at 10-minute intervals using a hot-wire anemometer AM-4224SD and LUTRON WBGT-2010SD. All sensors were installed at an elevation of 1.5 m above ground. The validation results proved that Ta simulation provided the best fit, with R^2 =0.45 and a root mean square error (RMSE) of 0.93, which is considered acceptable for urban microclimate assessment. However, more detailed information on the validation process and fine-tuned model can be found in their study. Consequently, this study used the validated model from the previous work (Leetongin et al., 2017) to perform the thermal condition analysis in the outdoor environment.

Performance Comparisons

The simulation results of the outdoor thermal conditions around the studied house were measured at 3 m above the ground. First, the distribution of hourly conditions in each scenario was compared. Then, the comparisons between the average hourly condition of the base case (scenario 10) (X_1) and those of the proposed designs (X_2) were calculated using the percentage changes (ΔX) as shown in Eq. (1).

$$\Delta X = \left(\frac{X_1 - X_2}{X_1}\right) x100 \quad (1)$$

RESULTS

From our study, the simulation results of the outdoor thermal conditions, comprising the Ta, RH, WS, and direct and diffuse solar radiation around the studied house, are presented in Figure 8, and Figure 9 presents the examples of the diurnal range of Ta, RH, and WS, from 6 am to 5 pm. It was found that, for the 16 proposed design scenarios, the hourly Ta around the house differed slightly. The maximum Ta of about 39°C occurred between 3pm and 4pm. The lowest Ta was found in Case 7. Without trees, the ground surface covered with ceramic tiles (Case 10) showed the most extreme heat conditions, with an average value of 35.7°C. In Case 7, the design combination of a light wall-paint color with a natural grass surface and 3 trees planted near the house provided the lowest average Ta of 35.1°C.

Considering the RH of the surrounding air, the hourly RH profile shows contrasting conditions to the Ta profile. The highest RH of 67.5% occurred in the morning at 7 am, while the RH in the afternoon was about 46%. For Case 13, with ceramic paving tiles, the light wall-paint color and 3 trees planted showed the highest RH, while the lowest RH occurred in Case 10, which used ceramic paving tiles with dark wall-paint colors.

Regarding the effect on solar radiation, the maximum direct solar radiation of 936 W/m^2 occurred in Cases 3, 4, 9, and 10, none of which had any trees in the design, showing the effect of the absence of tree shade. Planting trees could prevent solar heat from penetrating the space beneath. In fact, it was found that the cases with 3 trees planted (Cases 7, 8, 13, and 14) significantly reduced the average noon solar radiation to 169 W/m^2, a 22% reduction compared to the base case. However, the factors of the floor pavement material, tree planting, and exterior wall-paint colors hardly affected the diffuse solar intensity.

From our proposed designs, the difference in WS around the studied house, compared to the base case, was clearly seen in all cases. The highest average WS was 0.51 m/s in Cases 13 and 14, where the ground was covered with hard pavement materials. The maximum reduction in WS occurred in Cases 3 and 4, where there were no trees and the ground surface was covered with natural grass.

Table 4-8 summarizes the effect of each design on the maximum, minimum, and average changes in Ta, RH, WS, direct solar radiation, and diffuse solar radiation conducted from 6 am to 5 pm. It was found that the designs, by changing the ground-cover materials, painting exterior walls in a light color, or planting trees, could improve the outdoor thermal conditions, except that these designs did not significantly reduce the diffuse solar radiation. However, planting trees significantly increased the wind speed. In Table 4-8, the shaded colors are used to classify performance achieved from the various designs.

According to the study, the Ta of the scenarios with a light wall-paint color were 0.4–0.7% lower than those with a dark wall-paint color. Greater Ta reductions were found when integrating the planting of 3 trees near the house, which could reduce Ta by up to 1.6%. Ta in Cases 8 and 14 (with 3 trees planted and a dark wall-paint color) performed similarly to those of Cases 1, 5, 11, 15, and 16. Using natural grass instead of ceramic paving tiles had a small effect on the Ta reduction (0.4–0.5%).

Figure 8

24-Hour Distributions of Simulated Outdoor Thermal Conditions: Ta (a), RH (b), Direct Solar Radiation (c), Diffuse Solar Radiation (d), and WS (e)

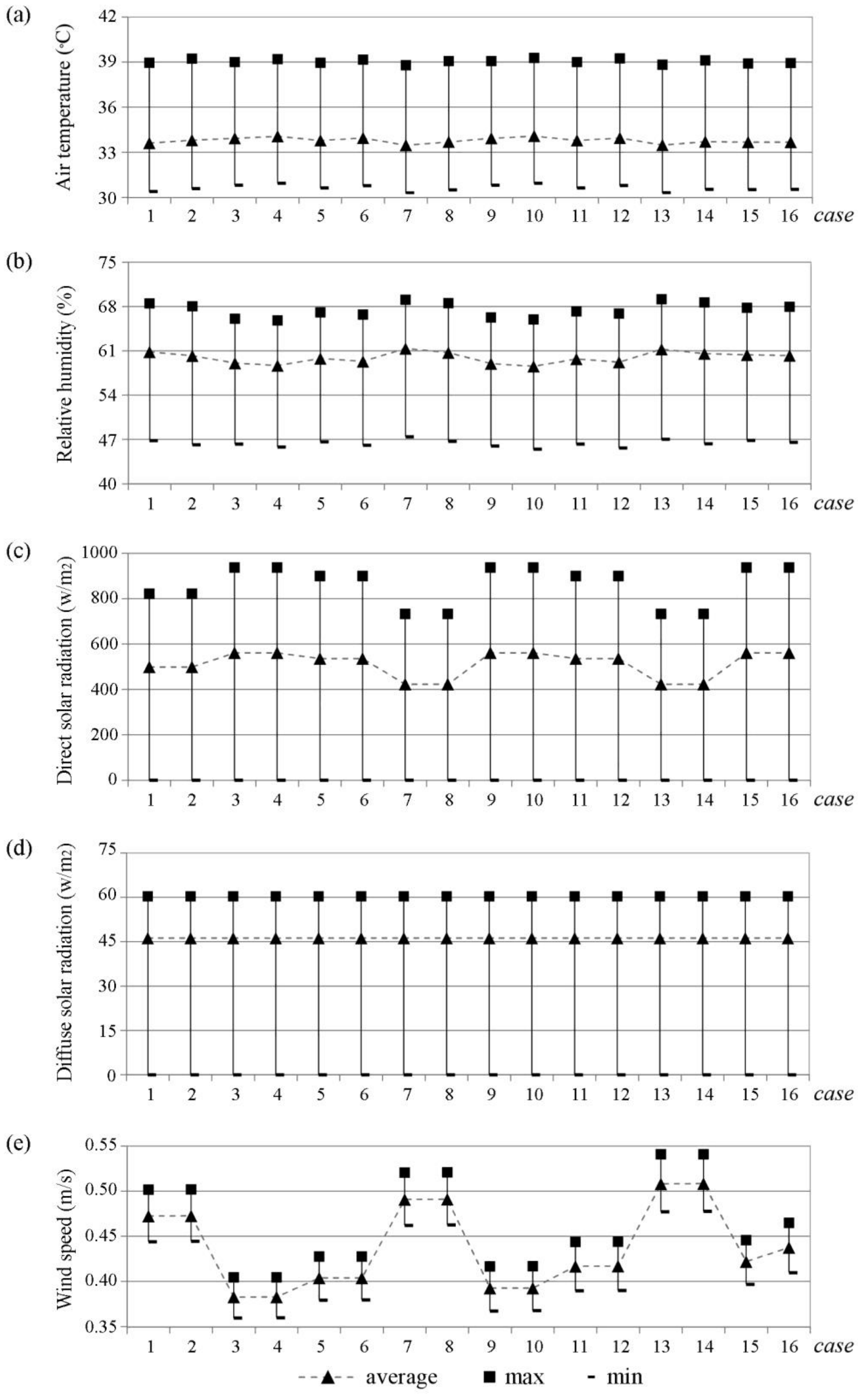
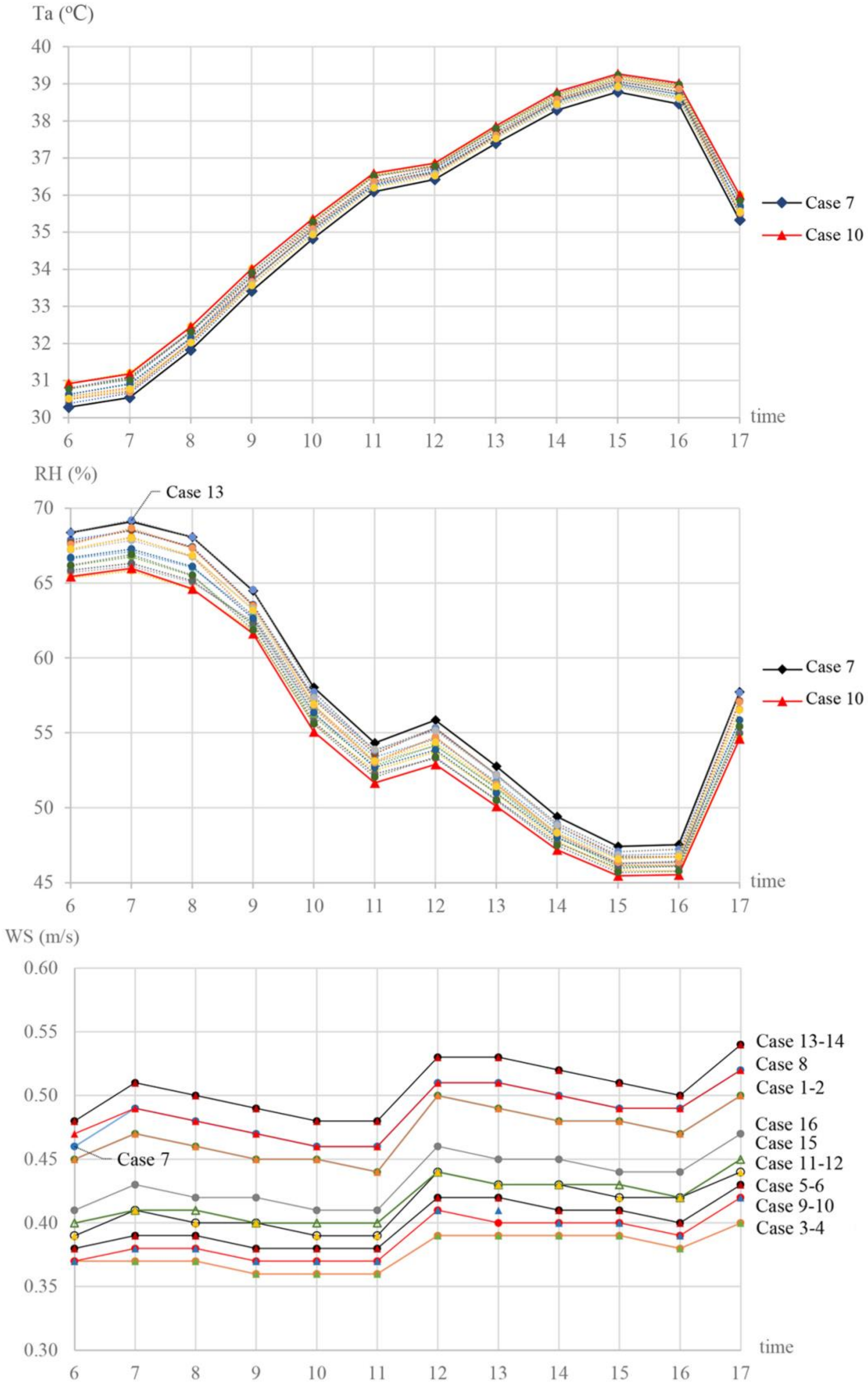


Figure 9

The Examples of the Diurnal Range of Ta, RH, and WS, From 6 am to 5 pm.



Another benefit of planting trees is preventing the space below from being directly exposed to solar heat. Planting more trees near the house is therefore recommended to create a cooler environment. The solar radiation below 3 trees (Cases 7, 8, 13, and 14) dropped by 27.4%, while the cases having 2 trees with shrubs (Cases 1 and 2) reduced the solar radiation by 9.4%. Trees planted on the sidewalk (Cases 15 and 16) did not reduce the solar radiation because the trees did not completely shade the studied area. Moreover, the pavement materials and wall-paint colors slightly decreased the direct solar radiation.

Although it was found that the tree scenarios could significantly reduce the Ta and direct solar heat, planting more trees also had a negative effect on the RH. The RH in cases with 3 trees planted (Cases 7 and 13) increased by 4.5–4.9% compared to the base case. A small incremental increase in the RH was observed in the cases with 3 trees on the sidewalk or with fewer trees (Cases 1, 5, 11, 15, and 16), with a range of 2.0–3.8%. Without trees, the RH of the designs using natural grass was 0.7–1.5% higher than those with ceramic paving tiles (Case 10); however, that effect was negligible compared to the effect of the wall-paint colors.

From our analysis, the highest WS occurred in the cases with 3 trees planted near the house (Cases 7, 8, 13, and 14), and these were 25–30% higher than the base case. On the other hand, trees planted on the sidewalk showed less of an effect, with WS rising from 7.5% to 11.6%.

Table 4

Effect of Environmental Designs on Ta Compared to the Base Case Condition

Ta reduction	Floor paving material	Wall - paint color	Plant type				
			None	1 tree	2 trees with shrub	3 trees near wall	3 trees on sidewalk
Maximum (3 pm)	Grass	Light	0.7%	0.8%	0.8%	1.3%	0.9%
	Ceramic tiles	Light	0.5%	0.7%		1.2%	0.9%
	Grass	Dark	0.2%	0.3%	0.1%	0.5%	
	Ceramic tiles	Dark	0.0%	0.1%		0.4%	
Minimum (6 am)	Grass	Light	0.4%	1.0%	1.8%	2.1%	1.3%
	Ceramic tiles	Light	0.4%	0.9%		2.0%	1.3%
	Grass	Dark	0.0%	0.5%	1.1%	1.4%	
	Ceramic tiles	Dark	0.0%	0.5%		1.3%	
Average (6am-6pm)	Grass	Light	(3) 0.5%	(5) 0.8%	(1) 1.2%	(7) 1.6%	(15) 1.1%
	Ceramic tiles	Light	(9) 0.5%	(11) 0.8%		(13) 1.6%	(16) 1.1%
	Grass	Dark	(4) 0.1%	(6) 0.3%	(2) 0.5%	(8) 0.9%	
	Ceramic tiles	Dark	(10) Base case	(12) 0.3%		(14) 0.9%	

Note: Shaded color classifies the groups having similar performance. ( ) represents the case number.

Table 5

Effect of Environmental Designs on the Incremental Changes in RH Compared to the Base Case Condition

RH increment	Floor paving material	Wall - paint color	Plant type: None	1 tree	2 trees with shrub	3 trees near wall	3 trees on sidewalk
Maximum (7 am)	Grass	Light	0.2%	1.7%	3.8%	4.7%	2.8%
	Ceramic tiles	Light	0.5%	1.9%		4.9%	3.1%
	Grass	Dark	-0.3%	1.2%	3.1%	3.9%	
	Ceramic tiles	Dark	0.0%	1.4%		4.1%	
Minimum (3 pm)	Grass	Light	1.9%	2.6%	3.0%	4.3%	3.1%
	Ceramic tiles	Light	1.1%	1.8%		3.5%	2.4%
	Grass	Dark	0.8%	1.4%	1.5%	2.8%	
	Ceramic tiles	Dark	0.0%	0.5%		1.9%	
Average (6am-6pm)	Grass	Light	(3) 1.5%	(5) 2.6%	(1) 3.8%	(7) 5.0%	(15) 3.5%
	Ceramic tiles	Light	(9) 0.9%	(11) 2.0%		(13) 4.5%	(16) 2.9%
	Grass	Dark	(4) 0.7%	(6) 1.6%	(2) 2.6%	(8) 3.7%	
	Ceramic tiles	Dark	(10) Base case	(12) 0.9%		(14) 3.1%	

Note: Shaded color classifies the groups having similar performance. ( ) represents the case number.

Table 6

Effect of Environmental Designs on Direct Solar Radiation Compared to the Base Case Condition

Direct solar radiation reduction	Floor paving material	Wall - paint color	Plant type: None	1 tree	2 trees with shrub	3 trees near wall	3 trees on sidewalk
Maximum (12 pm)	Grass	Light	0.0%	4.1%	12.3%	21.8%	0.0%
	Ceramic tiles	Light	0.0%	4.1%		21.8%	0.0%
	Grass	Dark	0.0%	4.1%	12.3%	21.8%	
	Ceramic tiles	Dark	0.0%	4.1%		21.8%	
Minimum (7 am)	Grass	Light	0.0%	0.0%	0.0%	39.8%	0.0%
	Ceramic tiles	Light	0.0%	0.0%		39.8%	0.0%
	Grass	Dark	0.0%	0.0%	0.0%	39.8%	
	Ceramic tiles	Dark	0.0%	0.0%		39.8%	
Average (6am-6pm)	Grass	Light	(3) 0.0%	(5) 4.0%	(1) 9.4%	(7) 27.4%	(15) 0.00%
	Ceramic tiles	Light	(9) 0.0%	(11) 4.0%		(13) 27.4%	(16) 0.00%
	Grass	Dark	(4) 0.0%	(6) 4.0%	(2) 9.4%	(8) 27.4%	
	Ceramic tiles	Dark	(10) Base case	(12) 4.0%		(14) 27.4%	

Note: Shaded color classifies the groups having similar performance. ( ) represents the case number.

Table 7

Effect of Environmental Designs on Diffuse Solar Radiation Compared to the Base Case Condition

Diffuse solar radiation reduction	Floor paving material	Wall - paint color	Plant type: None	1 tree	2 trees with shrub	3 trees near wall	3 trees on sidewalk
Maximum (12 pm)	Grass	Light	0.0%	0.0%	0.0%	0.0%	0.0%
	Ceramic tiles	Light	0.0%	0.0%	[redacted]	0.0%	0.0%
	Grass	Dark	0.0%	0.0%	0.0%	0.0%	[redacted]
	Ceramic tiles	Dark	0.0%	0.0%	[redacted]	0.0%	[redacted]
Minimum (7 am)	Grass	Light	-0.1%	0.1%	-0.1%	-0.1%	-0.1%
	Ceramic tiles	Light	-0.1%	0.0%	[redacted]	0.0%	0.0%
	Grass	Dark	0.0%	0.0%	0.0%	0.0%	[redacted]
	Ceramic tiles	Dark	0.0%	0.0%	[redacted]	0.0%	[redacted]
Average (6am-6pm)	Grass	Light	(3) 0.0%	(5) 0.0%	(1) 0.0%	(7) 0.0%	(15) 0.0%
	Ceramic tiles	Light	(9) 0.0%	(11) 0.0%	[redacted]	(13) 0.0%	(16) 0.0%
	Grass	Dark	(4) 0.0%	(6) 0.0%	(2) 0.0%	(8) 0.0%	[redacted]
	Ceramic tiles	Dark	(10) Base case	(12) 0.0%	[redacted]	(14) 0.0%	[redacted]

Note: Shaded color classifies the groups having similar performance. ( ) represents the case number.

Table 8

Effect of Environmental Designs on WS Compared to the Base Case Condition

WS increment	Floor paving material	Wall - paint color	Plant type: None	1 tree	2 trees with shrub	3 trees near wall	3 trees on sidewalk
Maximum (5 pm)	Grass	Light	4.8%	-2.4%	-19.1%	-23.8%	-7.1%
	Ceramic tiles	Light	0.0%	-4.8%	[redacted]	-28.6%	-11.9%
	Grass	Dark	4.8%	-2.4%	-19.1%	-23.8%	[redacted]
	Ceramic tiles	Dark	0.0%	-4.8%	[redacted]	-28.6%	[redacted]
Minimum (6 am)	Grass	Light	0.0%	-2.7%	-21.6%	-24.3%	-8.1%
	Ceramic tiles	Light	0.0%	-5.4%	[redacted]	-29.7%	-10.8%
	Grass	Dark	0.0%	-2.7%	-21.6%	-27.0%	[redacted]
	Ceramic tiles	Dark	0.0%	-5.4%	[redacted]	-29.7%	[redacted]
Average (6am-6pm)	Grass	Light	(3) 3.0%	(5) 2.6%	(1) 20.8%	(7) 25.1%	(15) 7.5%
	Ceramic tiles	Light	(9) 0.2%	(11) 6.2%	[redacted]	(13) 30.0%	(16) 11.6%
	Grass	Dark	(4) 3.0%	(6) 2.6%	(2) 20.8%	(8) 25.3%	[redacted]
	Ceramic tiles	Dark	(10) Base case	(12) 6.2%	[redacted]	(14) 30.0%	[redacted]

Note: Shaded color classifies the groups having similar performance. ( ) represents the case number.

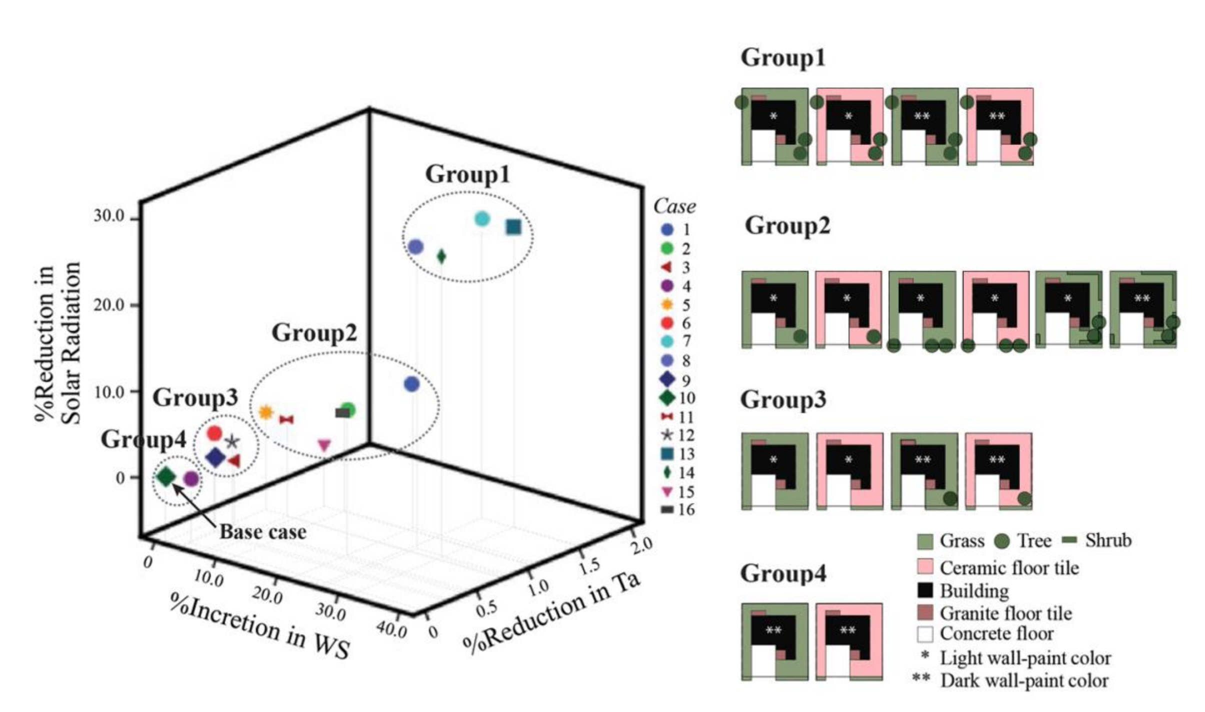
LANDSCAPE DESIGN INTEGRATED WITH WALL-PAINT COLORS TO PROMOTE A COOLING ENVIRONMENT

Besides the Ta and solar radiation, increased WS can increase convective heat loss and evaporative cooling from human skin that makes occupants feel cooler. When examining the ways to mitigate extreme heat conditions, the relationships between Ta, direct solar radiation, and WS were plotted, as seen in Figure 10. RH and diffuse solar radiation were not accounted for in this analysis because these factors had a small effect on cooling the surrounding environment.

From our analysis, the designs of the landscape and wall-paint colors can be classified into 4 groups based on performance. Group 1 provided the highest performance in Ta and solar radiation reductions while accelerating the WS of the surrounding environment. With this group of designs, planting 3 trees near the house significantly contributed to cooling the environment. Various combinations of wall-paint colors and ground-cover materials can be applied to this design. Group 2 provided a lower performance than Group 1. Tree plantings around the house were required to reduce Ta and protect against direct solar radiation. The cases with one tree and 3 trees planted on the sidewalk required the house to be painted in a light color. The conditions of Group 3 were warmer than those of Group 1 and 2. With this group of designs, a building with light wall-paint color provided similar performance to those having one tree planted near the house. Group 4 comprised the designs that resulted in the worst conditions; in this group of designs, there were no trees and the houses were painted in a dark color.

Figure 10

3D Scatter Plot Showing the Percentage of Ta and Solar Radiation Reductions and WS Incremental Changes with the Groups of Design Ccenarios



DISCUSSION

This study applied landscape design strategies integrated with wall-paint colors to mitigate the outdoor heat conditions around a single house in a housing estate. It was expected that the most effective strategy to reduce Ta would be to have trees planted near the house and paint the walls in light colors. This proved correct; the maximum temperature reductions were 0.7°C compared to the base case. This is because tree shade can significantly block direct sunlight and cool down the surrounding air conditions. This investigation showed similar results to previous studies (Elbondira et al., 2021; Farhadi et al., 2019; Shahidan et al., 2012; Srivanit & Jareemit, 2020; Wang & Akbari, 2016). In addition, Elbondira et al., 2021 and Srivanit & Jareemit (2020) investigated the effect of street trees on the thermal conditions in different street canyons. They found that temperature reductions in shallower streets positively correlated with the number of trees and their locations. However, planting trees on the sidewalk had only a small effect because they shaded the studied area only incompletely.

In this study, a high humidity condition was found when planting more trees because the tree leaves release latent heat flux to the surrounding air via the transpiration process. On the other hand, shrubs had a minor influence on the surrounding air conditions because they provided less shade and less evapotranspiration than trees, which concurs with Johansson et al. (2018) and Elbondira et al. (2021). However, in hot and humid conditions, RH levels above 80% could cause Thai people discomfort (Khedari et al., 2000). Consequently, the concept of planting more trees, especially for their effects in the morning and evening, should be studied more fully.

Other studies (Carnielo & Zinzi, 2013; Gartland, 2008; Salvati et al., 2022) have shown that building and surface materials with higher albedos can improve outdoor thermal conditions. In Carnielo and Zinzi (2013)'s work in Athens, Ta was reduced by 1.9°C in an open environment using high-reflectance pavement. This is because high-reflectance materials can reflect the solar heat and reduce the heat stored in the wall materials. Khadraoui and Sriti (2019) reported that the surface temperature of external walls, when painted in a light color, was reduced by approximately 24.5%. Carnielo and Zinzi (2013) showed that the colors of materials used significantly affects outdoor thermal conditions; in fact, the temperature difference between white and black materials was found to be as much as 20°C. However, compared to previous results, our study showed, that, while the high-reflectance wall-paint color led to improved thermal conditions surrounding the house, changing the ground-cover materials was ineffective at reducing Ta. There may be three reasons for this: first, the surface-cover area used in this investigation was small (accounting for only 40% of the total area), resulting in limited temperature reduction. Natural grass might provide greater temperature reductions than ceramic tiles if the area were larger. Secondly, the change in albedo values used in this analysis is small. In this study, the difference between the albedo of natural grass and ceramic tiles is only 0.3. This small change might have only a slight impact on the surrounding air conditions. The temperature reduction might be more significant if higher albedo pavement materials were used. Thirdly, the measurement location was at 3 m height above the ground. At this height, the wind blowing into the space may replace some local hot air. If the measurement locations were nearer ground level, the changes in the ground pavement's albedo might result in larger Ta reductions.

Regarding the wind environment, accelerated WS occurred between the houses due to the Venturi effect, as seen in Figure 11(a). Planting more trees could increase the WS in the space between the houses (see Figure 11(b) and (c)). Previous works have investigated the effect of trees on the wind environment. Aboelata (2020) performed an airflow simulation in street canyons with a 1:1 aspect ratio using the ENVI-met model. That study revealed that street tree scenarios reduced the WS by up to 0.24 m/s.

Meanwhile, Li et al. (2019) used the CFD model to predict the WS in a courtyard with various tree-planting locations and found that some tree scenarios could increase the WS in the courtyard. Our simulations confirmed those of Li that the number of trees and planting locations could increase the pressure difference around the studied house, resulting in higher WS. It is noted that an increase in WS can provide cooling benefits for outdoor living, but an accelerated WS above 5 m/s could cause human discomfort and property damage (Tantasavasdi & Inprom, 2021).

Our results demonstrate that a combination of tree planting designs and wall-paint color can provide better cooling performance. A significant temperature reduction of up to 1.6% occurred when applying a light wall-paint color with 3 trees planted near the house; the next-largest reduction was found with 2 trees planted near the house. These results are consistent with the findings of Zhu et al. (2021).

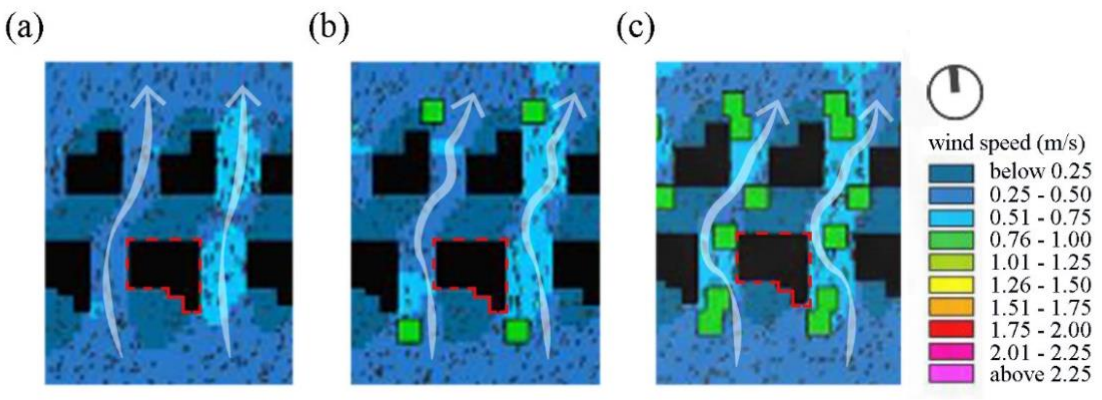
This work selected ground-cover materials and the number of tree plantings by considering the typical landscape design in housing clusters. The locations and number of tree plantings were limited due to the small planting area available in the land plot. Consequently, not all the possible materials and different tree-planting scenarios could be covered. Various other surface materials and tree-planting patterns not considered in this study could provide different performance. Furthermore, variations in orientations of the housing layout and tree-planting locations associated with different sun angles could provide different shading effects. For example, if the houses were mirrors, or if the trees were planted in opposite locations, the tree-shade patterns might be different. As a consequece, such effects could provide different thermal performance. These design variables should be accounted for in future investigations.

Our analysis begins with an assessment how the landscape designs can improve the outdoor thermal environment around the studied house. The results of Ta reductions can be further used to promote energy-saving buildings, especially the decrease in cooling demand. Previous works (Ng et al., 2012; Wang & Akbari, 2016) revealed that a reduction in outdoor Ta of 1-2°C could reduce building energy consumption by 4.5-5%.

Besides the Ta reduction, the outdoor thermal condition is another significant indicator that has been widely studied, incorporating an assessment of UHI mitigation. However, to assess outdoor thermal comfort, as mentioned in previous works, requires a significant dataset of Tmrt, which is a key role in human thermal comfort (Jareemit & Srivanit, 2022; Mayer & Höppe, 1987; Srivanit & Jareemit, 2020). However, the Tmrt was not accounted for in the scope of this research. As a consequence, for outdoor thermal comfort analysis, measurement of Tmrt at 1.1 m height above the ground, corresponding to the average height of the centre of adults (Mayer & Höppe, 1987), is necessary.

Figure 11

Effect of Tree Planting on WS and Airflow Patterns at an Elevation of 3 m Above the Ground in Different Scenarios: Without Trees (a), One Tree Planted on the Sidewalk (b), and 3 Trees Planted Near the House (c)



CONCLUSIONS

More buildings and hard surface materials in city areas lead to more solar heat absorption, increasing urban temperatures. Several strategies, such as natural features and tree shade, high-reflectance materials, and adjacent shading structures, have been used to reduce the heat stored in urban areas. However, suburban areas with low-density buildings are limited to using the shading from adjacent buildings. Furthermore, these areas have greater surface areas that absorb more solar radiation than high-density built-up areas. This study aims to assess design combinations of plants and surface materials, integrating wall-paint colors that might influence outdoor thermal conditions during summer around a single house in a housing estate in a Bangkok suburb. The investigation used the ENVI-met model to perform diurnal profiles of Ta, RH, direct and diffuse solar radiation, and WS in summer conditions. Three design variables, including natural features, ground-cover materials, and wall-paint colors, were analyzed.

It is recommended that trees be planted near the house to mitigate the extreme heat of the outdoor environment. This could reduce Ta and noon solar radiation by a maximum of 0.7°C (1.6%) and 204.3 watt/m^2 (22%), respectively. However, trees planted on the sidewalk and shrubs had a very small impact. The trees also accelerated the WS by 30%, as the trees increased the pressure difference around the house, while the temperature reduction from changing the ground-cover materials had the very small value of 0.5%. There were no significant differences in diffuse solar radiation among the design scenarios.

In this study, the thermal performance simulations were limited to summer observation and only the dominant wind direction. However, seasonal and wind direction variations might present different cooling effects. Furthermore, the study area was limited to the small plot of a single house. Consequently, the proposed landscape designs had a very small impact on Ta reductions. Further studies should assess those effects on heat mitigation across a whole housing estate area in order to examine the cooling effect in a larger area. In addition, future studies could investigate the reduction effect of using more surface materials and combinations. This could provide alternative design solutions for landscape architects and property owners for creating a cooler environment for low-density built-up areas.

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