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A STUDY ON THE COOLING EFFECTS OF GREENING FOR IMPROVING THE OUTDOOR THERMAL ENVIRONMENT IN PENANG, MALAYSIA

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ABSTRACT: Shade tree coverage and reflective pavements are useful mitigation strategies to help cool the air and provide shade. It also helps to lower building energy consumption by providing better outdoor boundary conditions. This study presents a simulation approach to evaluate and determine the cooling effect of greening modification developments of a study area on the surrounding environment. This study presents two approaches, including an on-site measurement and a numerical simulation model that uses ENVI-met V 4.0 BETA. Five scenarios with different types of tree coverage and density canopy by adding reflective pavements at ground surface are used. This study was conducted at the RST Complex of Universiti Sains Malaysia. The simulation results showed significantly lower air temperatures in three greening scenarios compared to the current condition scenario with 10% tree coverage. Increasing 20% of tree coverage with less dense and high dense of canopy in the study area led to a maximum air temperature reduction of up to 0.97 °C and 1.15 °C, respectively. Meanwhile, increasing 20% tree coverage with a highly dense canopy and applying reflective pavements on the ground surface contributed to a maximum air temperature reduction of up to 1.16 °C. The outcome of this study could be used to help urban planners and designers to select strategies for designing outdoor spaces to relieve heat stress with the main aim of improving the outdoor living environment.

Keywords: ENVI-met, Microclimate, Cooling effect, Shade tree, Reflective Pavement

1. INTRODUCTION

Shade trees are actually an ecological solution and one of the strategies that can be used to mitigate heat islands and improve community comfort. It is well-known that plants strategically placed around buildings can bring thermal benefits to the inhabitants. Vegetation not only provides pedestrians with pleasurable visual scenes, but also provides shading, improves air quality and reduces noise levels [1] The cooling effect of vegetation occurs through the process of shading, evapotranspiration and changing wind patterns [2], [3]. Microclimatic benefits of vegetation have been extensively investigated in previous researches [4], [5].

Pavements (roads, pedestrian walkway, parking area, bicycle path, squares, etc.) are one of the main hardscape contributing to the development of a heat island [6], [7]. Several studies have reported that pavements cover almost 29% to 45% of the urban fabric [8], [9]. Heat islands can also be mitigated by using “cool” materials during the summer period [10]–[12]. Cool materials are characterized by high solar reflectance and high thermal emittance. The two properties could reduce the temperature of the surfaces [13]. Solar reflectance is the ability of a material to reflect solar energy from its surface back into the atmosphere. Many studies report the combined effect of increasing solar reflectance of both roofs and pavements which can reduce summertime urban temperature and improve urban air quality [9], [14], [15].

Many methods have been applied to investigate the effect of vegetation and ground pavements on the microclimate, such as numerical modeling, empirical analysis, on-site measurements and satellite images. However, numerical modeling has become more popular during the recent years because researchers have greater control over modeling in regards to time and resources [16]. The ENVI-met model is normally utilized to simulate urban and landscaped environments in terms of potential air and surface temperature, solar radiation, relative humidity, wind speed, and other variables. The ENVI-met model has also been employed to examine the effect of greenery [17], [18] and paved areas [19], [20] on the thermal environment. Most investigations have focused on either the effect of vegetation and pavements on the environment or the differences between thermal stress in the current state and those in various scenarios. Some studies have investigated the effectiveness of modifying configurations of landscape designs [21], [22] and buildings [23] by comparing the thermal performances of before and after a design is implemented.

This study uses a numerical simulation model such as ENVI-met to generate microclimate data for the study area and examine the cooling effect of different greening scenarios in an urban thermal environment in Penang. This study produced different scenarios based on the different leaf densities of shading trees and reflective pavement applications on the ground surface.

2. METHODS

The methods that were used in this study are an on-site measurement program and a simulation model [17], [24], [25]. The on-site measurement program was designed to measure current microclimate conditions in the hostel complex environment at the pedestrian level. These results were used to verify the accuracy of the model. The simulation model was designed to simulate and validate actual conditions and predict the modification effects of the proposed greening scenarios using the ENVI-met V 4.0 BETA.

2.1 Study Area and Climatic Condition

The study site is located in a student accommodation area around the Desasiswa Restu, Saujana and Tekun (RST) Complex (5.356042 ° N, 100.292087 ° E), as shown in Fig. 1. The study area is part of the Universiti Sains Malaysia (USM), Penang campus. Penang is situated in the northern part of peninsular Malaysia. Characteristics of the study area climate are hot and humid. In year 2015, the average annual temperature was recorded at 28.1°C with the maximum and minimum average temperatures of 31.6°C and 24.7°C respectively. The site's area measures at 105,650m². The area is dominated by tall buildings of one to ten levels ranging from dormitory buildings, an administrative building, halls and entrepreneur squares.

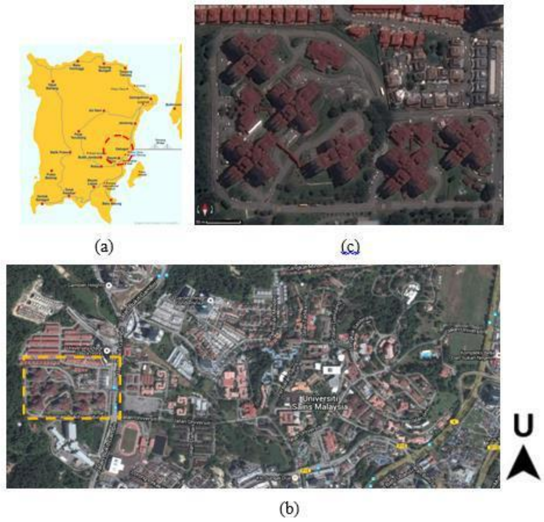

Fig.1 Plans involved for the study area; (a) key plan, (b) location plan, and (c) site plan

2.2 On-site Measurement Program

On-site field measurements were taken between 10.00 and 14.00 local time on December 30th, 2015. This period was used to collect the variables of climatic data during a clear day. There are a total of 12 observation points in the study site. The observation points were selected as they have various landscape features as shown in Fig. 2.

The first instrument that is involved in this measurement is the (Extech 45160) 3-in-1 Humidity, Temperature and Airflow meter that was placed on a camera tripod at a height of 1.5 m above ground level. This instrument has a sensor to measure air temperature and can record between 0°C to 50°C with an accuracy of ±1.2°C. The sensor for wind speed is capable of measuring outdoor convection air speeds of between 0.4 m/s to 30 m/s with reading speeds from wind ≤ 20 m/s with an accuracy of ± 0.9% m/s, while if the reading speeds winds >20 m/s with an accuracy of ±1.2% m/s. In addition, a relative humidity sensor is used to measure the percentage of humidity of between 10% to 95% with an accuracy of ± 4% between 10% to 70% and ± 5.2%> 70%. The second instrument is the (TES-1333) Solar Power Meter which was also placed on a camera tripod at a height of 1.5 m above ground level. This instrument has a sensor to measure solar radiation with a measurement range of up to 2000 W/m² and an accuracy of ±10 W/m². To consider the thermal effects from the pedestrian level, the two instruments were installed at a height of 1.5 m above the ground level and were calibrated before the on- site operation. The time interval for the measurement of each point of observation is 10 minutes.

2.3 ENVI-met Model Parameterization

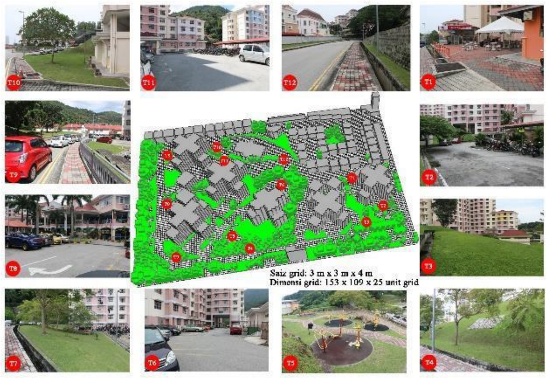

Fig.2 3-dimensional view of initial model geometry

For the ENVI-met model geometry settings in this study, the simulated base model domain was built based on satellite images from Google Maps. The number of floors in each building was manually counted. Each level was assumed to be 3 m high. The total maximum building height in the study area was 30 m (10 levels). The main model domain area represented the current conditions in the area of interest and was built within 153 x 109 x 25 grids with input dimensions of dx, dy and dz = 3 m x 3 m x 4 m, as shown in Fig. 2. Only major elements such as trees and ground surfaces were considered in this simulation. Table 1 presents the initial settings of the model.

Table 1 Input configuration data applied in the ENVI-met simulations

Setting data	value
Initial temp. of atmosphere (°C)	28.10
Relative humidity in 2m (%)	70
Wind speed in 10m height (m/s)	2.0
Wind direction (deg)	33:North

2.3.1 Systematical calibration process for ENVI-met models of outdoor environment

The aim of the systematical calibrated ENVI-met model for outdoor environment is to predict environmental conditions that agree with the on-site measurements. The initial ENVI-met model was created based on the actual site geometry and the on-site field measurements. The boundary conditions for improving the accuracy of the ENVI-met model in this study were called the Lateral Boundary Conditions (LBC) which include the optimal boundary settings by simulating the initial model domain by adding any grids as nesting areas. For this study, the optimum boundary setting is obtained by adding 18 grids (54m) at the x-axis and 66 grids (198m) at the y-axis. In addition, the simulated air temperature (°C), relative humidity (%), wind velocity (m/s) and solar radiation (W/m2) of the outdoor environment were validated at 12 points with on-site measurements as shown in Fig. 3.

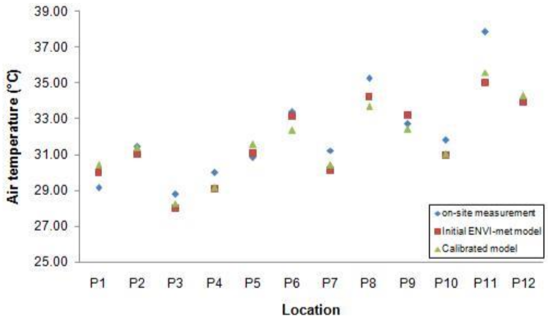

Fig.3 Comparison of calibration stages for improving the accuracy of the ENVI-met model to obtain a better correlation with measured results for air temperature

After the calibration process, a paired t-test was used to determine if a significant difference occurred between the average measured values that were made under different conditions which are between the values measured on-site and the simulated values, as shown in Table 2. The paired t-test results from the four validation criteria display the relationships between the paired differences within a 95% confidence interval. The null hypothesis states that there is no significant difference between the means of the twelve on-site measurement points and the simulated results of the four validation criteria. Table 2 and Table 3 indicate that the significance (Sig.) value is greater than 0.05. Therefore, no significant difference occurred and the null hypothesis was accepted. Thus, the calibrated ENVI-met model predictions agreed with all validation criteria and accurately represents the real environment.

Table 2 Paired samples' test for validation criteria which compares the on-site measurements and initial model data from the ENVI-met simulation model

Criteria	Paired differences				t	Sig.*
	Mean	StD	95% conf. interval of the difference			
			Lower	Upper		
AT	0.551	0.968	-0.064	1.166	1.970	0.074
RH	1.285	3.420	-0.888	3.458	1.301	0.220
WS	0.333	0.276	-0.142	0.209	0.418	0.684
SR	17.404	28.921	-0.971	35.780	2.085	0.061

Notes: * significant at 0.05 level (2-tailed)

Table 3 Paired samples' test for validation criteria which compares the on-site measurements and calibrated model data from the ENVI-met simulation model

Criteria	Paired differences				t	Sig.*
	Mean	StD	95% conf. interval of the difference			
			Lower	Upper		
AT	0.498	0.981	-0.126	1.212	1.756	0.107
RH	2.438	4.583	-0.475	5.350	1.842	0.093
WS	0.058	0.332	-0.152	0.269	0.609	0.555
SR	17.347	28.889	-1.008	35.702	2.080	0.062

Notes: * significant at 0.05 level (2-tailed)

2.4 Development of simulation scenarios

To compare and evaluate the cooling potential of greening modifications on 30 December 2015 and the specific contributions of shade trees and reflective pavements, five different scenarios were simulated, which are (a) case A: current condition, (b) case B: no trees, (c) case C: adding trees with less density, (d) case D: adding trees with high density, and (e) case E: adding trees with high density and reflective pavements, as shown in Table 4 and Fig. 4. The simulation included three greening development strategies that were proposed to improve the outdoor thermal environment through its implementation.

Table 4 Details of the coverage for different scenarios in the simulation domain

Details	Scenarios				
	Case A	Case B	Case C	Case D	Case E
	Current condi-tion	No trees	Add trees with less dense	Add tree with high dense	Add trees with high dense and reflec-tive pave-ment
Building coverage	24.30%	24.30%	24.30%	24.30%	24.30%
Tree coverage	10.43%	-	30.04%	30.04%	30.04%
Grass coverage	16.68%	27.11%	14.24%	14.24%	14.24%
Open area	48.59%	48.59%	31.42%	31.42%	15.30%
Reflective pavement	-	-	-	-	16.12%

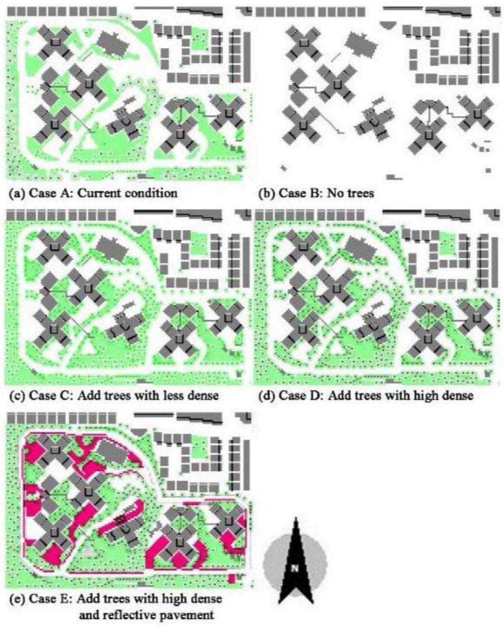

Fig.4 Five different simulation scenarios

The differences between cases C and D could indicate the effect of shade trees with different density canopies, while the differences between cases D and E could show the effect of reflective pavements. The tree species that were used in the ENVI-met simulation was *Dalbergia oliveri* to represent low density canopies (LAI = $2m^2/m^2$), and *Swietenia macrophylla* to represent high density canopies (LAI = $5m^2/m^2$). Use of reflective pavements in the ENVI-met scenario simulation focuses on the walkways by using concrete pavement light, while parking lots and driveways use asphalt with red coating.

3. RESULTS AND DISCUSSSION

3.1 The cooling potentials of the current condition

The ENVI-met simulation under the current conditions were done on a summer day with a temperature between 32.58°C and 22.50°C with an average 27.54°C during the peak of the day, as shown in Fig. 5a. Case A was compared with case B, which is the scenario with no trees in the area to produce Fig. 6a. The air temperature has an average difference of 0.22°C when the quantity of current trees was at 10.43%. The air temperature reduction occurred between these scenarios with a maximum average difference of up to 1.12°C.

Meanwhile, the surface temperature of 49.91°C and 19.85°C with an average 34.88°C, as shown in Fig. 7a. Comparison between Case A and Case B for the surface temperature is produced as in Fig. 8a. The surface temperature has an average difference of 0.07°C. The surface temperature reduction occurred between these scenarios with a maximum average difference of up to 1.12°C. Hot surface area of orange to red spot occurs in the southern part of RST Complex, which is located on roads and buildings in the vicinity. It is getting warmer due to the lack of shade trees that can cool the soil surface around the area.

The relative humidity of between 102.14% and 47.21%, as shown in Fig. 9a. Comparison between Case A and Case B for the relative humidity is produced as in Fig. 10a. The relative humidity has an average difference of 1.14%. The relative humidity increase occurred between these scenarios with a maximum average difference of up to 4.85%. It is found that the relative humidity is low, the spot dark blue to light blue on the buildings around the RST Complex.

This condition was believed to result from the lack of greenery, the ground pavement material and the greater building density within that area. Thus, the cooling effect of the current conditions was not enough to provide optimum cooling for the entire RST Complex, especially along pedestrian walkways and outdoor spaces where most activities occur during the day.

3.2 The cooling potentials of the three greening scenarios

The current conditions were compared with three greening modification strategies. The peak temperature and humidity taken at 15:00 of the five different conditions were compared at the pedestrian level of 1.5m. This comparison was conducted to understand the impact of these greening modifications on reducing air and surface temperature, and increasing relative humidity at the study site. The color gradient in Fig. 6, Fig. 8 and Fig. 10 specifies the air and surface temperature, and relative humidity range to identify the hot and cool spots in the RST Complex.

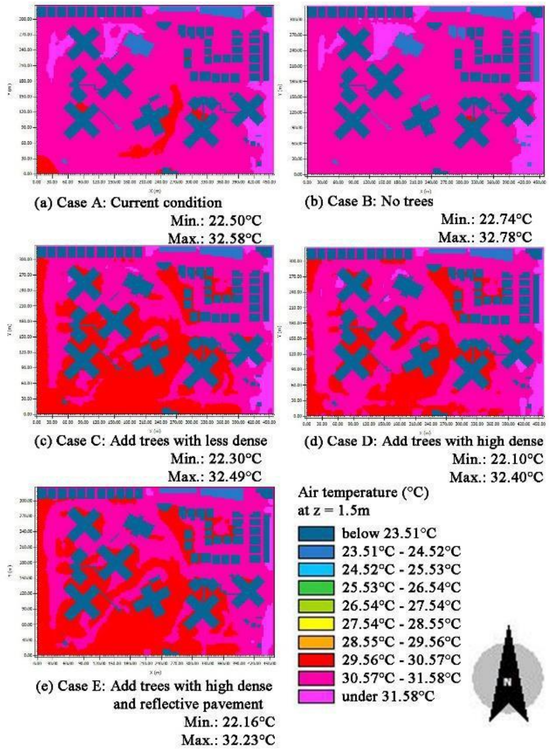

Fig.5 Air temperature under five different scenarios, taken at 15:00 at the pedestrian level

Case C was compared with case A, which is after adding trees with low density canopies and the result is shown in Fig. 6b. The air temperature has an average difference of 0.14°C when the quantity of trees with less density was increased by 19.61%. Air temperature reduction occurred between these scenarios with a maximum average difference of up to 0.97°C. The hot spots which initially occur at the west part of the RST Complex, became much cooler due to the cooling effects of trees with low density canopies.

Case D was compared with case A, which is after adding trees with high density canopies and the result is shown in Fig. 6c. The air temperature has an average difference of 0.29°C. Air temperature reduction occurred between these scenarios with a maximum average difference of up to 1.15°C. These mitigation strategies rely on the density of tree canopies.

Lastly, the combination of both trees with high density canopies and reflective pavement modifications achieved the optimum cooling effects beneath the canopy level as shown in Fig. 6d. Although the results were similar, the yellow color in Fig. 6c becomes greener, while fewer blue spots are shown in Fig. 6d. The air temperature has an average difference of 0.34°C. The largest air temperature reduction occurred between these scenarios with a maximum average difference of up to 1.16°C. The reflective pavements only contributed a small portion of the maximum air temperature reduction by about 0.01°C.

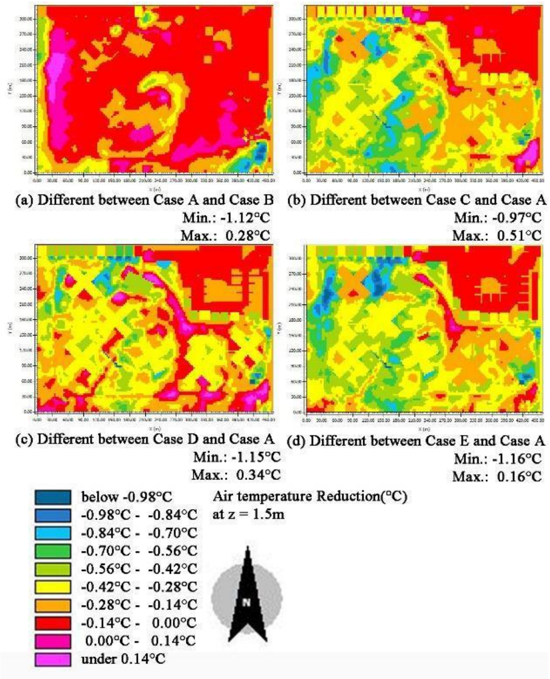

Fig.6 Comparison of the different air temperature reductions from greening modifications, at 15:00 at the pedestrian level

Comparison between Case C and Case A, which is after adding trees with low density and the results is shown in Fig. 8b. The surface temperature has an average difference of 0.21°C. Surface temperature reduction occurred between these scenarios with a maximum average difference of up to 16.48°C. The hot spots which initially occur at the southern part of RST Complex, became cooler due to the cooling effects of trees with low density canopies.

While, Case D as compared with case A, which is after adding trees with high density and the results is shown by Fig. 8c. The surface temperature has an average difference of 0.19°C when the quantity of trees with high density increased by 19.61%. Surface temperature reduction occurred between these scenarios with a maximum average difference of up to 21.40°C. It was found that the effect can be seen on the cooling effect of the decrease in the surface temperature of scenario D is higher than in scenario C.

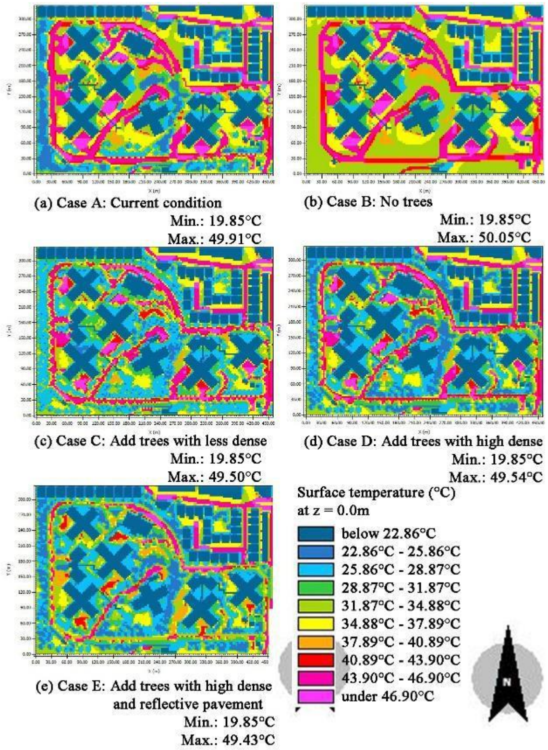

Fig.7 Surface temperature under five different scenarios, taken at 15:00 at the ground level

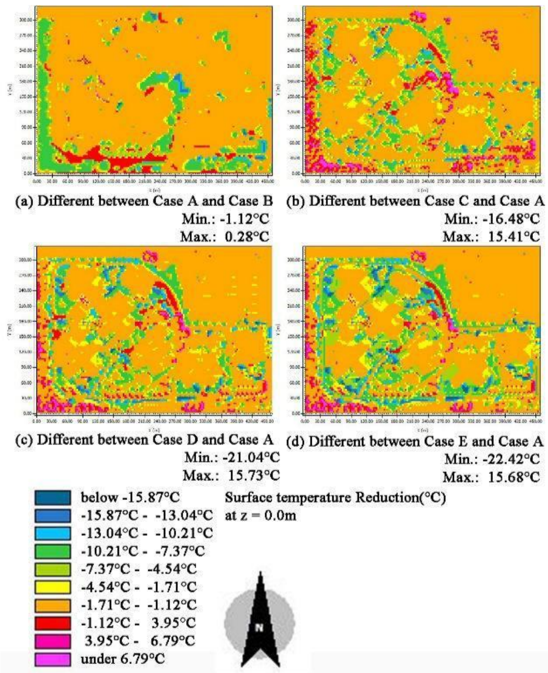

Fig.8 Comparison of the different surface temperature reductions from greening modifications, at 15:00 at the ground level

In addition, the comparison between Case E and Case A is a combination of both between trees with high density canopies and reflective pavement, as shown in Fig. 8d. Figure 8d is found spots of yellow, green and blue are growing and spread to several places. The surface temperature has an average difference of 0.24°C. Surface temperature reduction occurred between these scenarios with a maximum average difference of up to 22.42°C. The reflective pavements only contributed a small portion of the maximum surface temperature reduction by about 1.38°C.

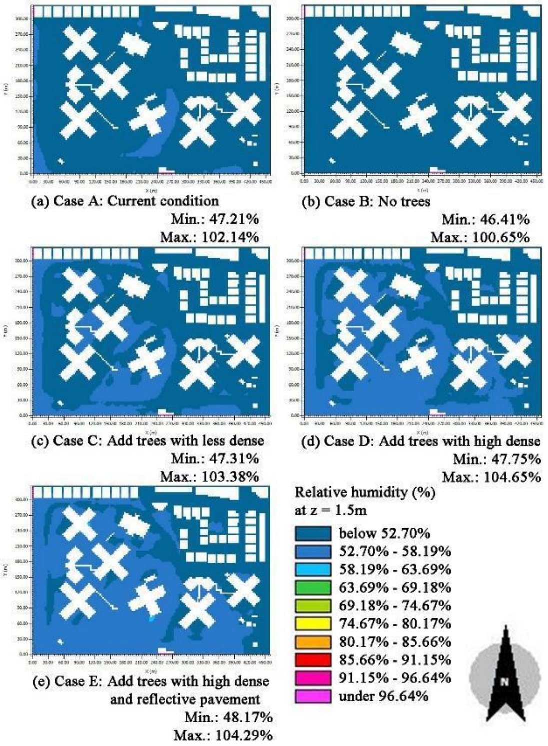

Fig.9 Relative humidity under five different scenarios, taken at 15:00 at the pedestrian level

Case C was compared with case A, which is after adding trees with low density canopies and the results is shown in Fig. 10b. The relative humidity has an average difference of 0.67%. Relative humidity increase occurred between these scenarios with a maximum average difference of up to 4.19%. The hot spots which initially occur at the west part of the RST Complex, became much cooler due to the cooling effects of trees with low density.

While, comparison between Case D and Case A, which is after adding trees with high density and the results are shown in Fig. 10c. The relative humidity has an average difference of 1.53%. Relative humidity increase occurred between these scenarios with a maximum average difference of up to 7.87%. It was found that the effect can be seen on the cooling effect of the increase in the relative humidity of scenario D is higher than in scenario C.

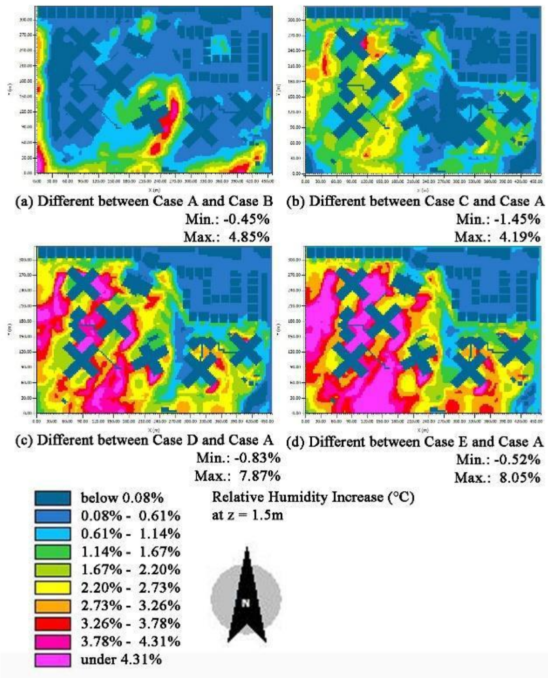

Fig.10 Comparison of the different relative humidity increases from greening modifications, at 15:00 at the pedestrian level

Lastly, the comparison between Case E and Case A is a combination of both between trees with high density canopies and reflective pavement, as shown in Fig. 10d. Fig. 10c have a yellowish-green spots turn reddish-purple in some places, as shown in Fig. 10d. The relative humidity has an average difference of 1.56%. Relative humidity increase occurred between these scenarios with a maximum average difference of up to 8.05%. The reflective pavements only contributed a small portion of the maximum relative humidity increase by about 0.18%.

In this study, the modification by adding trees with high density canopies provides a larger cooling potential than adding tree with low density canopies or applying reflective pavements on ground surfaces. The selection or replacement of tree with high density canopies is recommended in open spaces that have no tree to optimize cooling effect on the outdoor thermal environment at the pedestrian level. Therefore, these strategies are recommended in implementation with outdoor landscape designs.

4. CONCLUSION

The university-in-a-garden concept was conceptualized by Universiti Sains Malaysia (USM), Penang. This study focuses specifically on the RST Complex, USM which is a newly developed area. The study found small quantities of tree coverage in the vicinity. This study developed different scenarios to model the urban thermal impact in order to analyze greening performance following the implementation of feasible green campus policies. The outcome from this study can give solutions and ideas to support the university's planning of improving its thermal environment.

In this study, the ENVI-met computer simulation model was used to understand tree coverage quantities, their canopy densities and reflective pavement on ground surface in an area. These green areas have a pronounced cooling effect and had reduced the ambient outdoor temperature. The calibration and comparison done to improve the accuracy of the ENVI-met model against the initial model, calibrated model and on-site measurements representing the real environment were verified.

Therefore, the use of urban planning and microclimate assessment tools will be useful in assessments of climate which could then feed into decision processes towards providing better living conditions in the future. Designers will be able to assess the impacts of their proposed development on urban climatic conditions.

5. ACKNOWLEDGEMENTS

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