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Impact of small-scale tree planting patterns on outdoor cooling and thermal comfort

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ABSTRACT

The issues of local climate change, urban heat islands and improving outdoor thermal comfort in cities demand special attention in urban planning. This paper examines the effect of various plant arrangements, plant type, and the direction of the rows of trees against the prevailing wind on micrometeorological conditions and thermal comfort. The study area was simulated using the ENVI-met model. It was validated by comparing the values of the output parameters of the model with field measurements. Finally, the proposed scenarios were simulated in the model and identified after analyzing scenarios that displayed better performance in improving outdoor thermal comfort. The results indicated that the rectangular planting of evergreen trees in the outer rows and deciduous trees in the inner rows in a direction perpendicular to the prevailing wind produced the most optimal condition in improving outdoor thermal comfort (1.3 Predicted Mean Vote (PMV) reduction). Also, triangular patterns perpendicular to wind direction with evergreen trees brought out the weakest performance in improving thermal comfort (0.2 PMV reduction). The findings of the research can be used by landscape designers and urban planners to enhance green space designs, develop sustainable cities, and improve thermal comfort in residential areas.

1. Introduction

It is now common knowledge that cities are now more densely populated than villages, with more than half of the world's population living in cities (Salata, Golasi, de Lieto Vollaro, & de Lieto Vollaro, 2016) and the rate of urban population growth being 1.8 % per year (Colunga, Cambrón-sandoval, Suzán-azpiri, Guevara-escobar, & Luna-soria, 2015). With the urbanization process on the increase, the air temperature (T_a) of cities has also increased and extended to rural regions and surrounding areas, a process that is known as the urban heat island phenomenon (Oke, 1982). The urban heat island has a huge negative impact on the people living in cities; some other effects it exercises include cities becoming more vulnerable to other climate change and global warming risks (Morakinyo, Kong, Lau, Yuan, & Ng, 2017). This phenomenon also intensifies heat stress in urban environments, reduces the thermal comfort of public pavements and endangers the overall health of city dwellers (Lu et al., 2017). The consequence of the excessive increase in urban buildings and structures is the urban ecology being damaged and the effects of the urban thermal island being exacerbated (Jin, Bai, Luo, & Zou, 2018). The factors that exacerbate the impact of the urban heat island include the presence of urban surfaces with low albedo, the use of materials with high thermal capacity in buildings, inadequate ventilation and trapping of long-wave radiations, air pollution, lack of vegetation and, consequently, reduced evaporation in the urban environment (Gromke et al., 2015). In urban environments where such surfaces and materials are used to absorb more light, and where the amount of green space and shade in the environment is low, the highest number of thermal stress is observed (Lee, Mayer, & Chen, 2016). Some of the features of planting such as planting density (Unal, Uslu, Cilek, & Altunkasa, 2018), tree arrangement and location (Lee, Mayer, & Kuttler, 2020; Milosevic, Bajsanski, & Savic, 2017), tree planting pattern (Su, Zhang, Yang, & Ye, 2014) and orientation (Sodoudi, Zhang, Chi, Müller, & Li, 2018) are factors influencing the modification of micrometeorological conditions.

Trees are more effective than other plant elements in moderating the climate and reducing T_a (El-Bardisy, Fahmy, & El-Gohary, 2016; Lee et al., 2016). By shading and minimizing short-wave radiation, trees can reduce the air and surface temperature and help improve thermal comfort (Lee, Mayer, & Schindler, 2014; Lee, Holst, & Mayer, 2013, 2020). As the shape and size of leaves affect the amount of shading and evapotranspiration of trees (Perini, Chokhachian, & Auer, 2018), the leaf type in trees also might affect their cooling potential (Hami, Abdi,

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Zarehaghi, & Maulan, 2019). Evergreen trees regulate the climate by reducing wind speed in the environment and preventing the impact of direct sunlight on surfaces (Zhang, Zhan, & Lan, 2018). Deciduous trees also improve thermal comfort by providing shades in warm seasons and allowing sunlight to pass through in cold seasons (Perini et al., 2018). According to El-Bardisy et al. (2016), in spring, coniferous trees are more effective in reducing the predicted mean vote (PMV) index than deciduous trees by 0.5. Thus, leaf type and tree species can be effective in influencing green spaces and local climate modification. As a result, by selecting appropriate trees, the most optimal planting design can be achieved with the aim of improving micrometeorological conditions.

Landscape patterns and different arrangements of green spaces have different effects on T_a and the exchange rate of heat in the environment (Su et al., 2014). With appropriate tree arrangement and planting patterns, the T_a can be reduced in summer and increased in winter (Zhang et al., 2018). The proper arrangement of tree layout leads to climate modification, with the effect being changing direction and wind speed (El-Bardisy et al., 2016). Green spaces with sparse tree planting patterns will reduce wind speed in winter and bring T_a down in summer (Zhang et al., 2018). According to Zhao, Sailor, and Wentz (2018), the two-row planting pattern of trees reduces physiological equivalent temperature (PET) (Mayer & Höppe, 1987) by 1.5 °C in the entire neighborhood of the trees, at a height of 1.5 m in the hottest hours of the day (15:00). As compared to similar studies, this reduction is relatively low; the cluster planting pattern exhibits a better cooling performance in hot and dry climates. When the direction of planting the green belt is parallel to wind direction, it helps reduce T_a and improve thermal comfort due to ventilation and heat dissipation (Sodoudi et al., 2018). Trees affect micrometeorological conditions by controlling air flows, reducing wind speed and changing direction (Perini et al., 2018). They also reduce air and surface temperature through the process of evapotranspiration, shading and prevention of direct sunlight (Morakinyo et al., 2017). The importance of shading and wind patterns in the small surroundings of buildings in improving climatic conditions is greater than in open spaces (Zhang et al., 2017). Due to the characteristics of the environment such as the amount of sun exposure, shading and ventilation conditions, the layout of the trees relative to each other and the surrounding buildings influence thermal comfort (Yang et al., 2018). Ahmadi Venhari, Tenpierik, and Taleghani (2019) and Lee et al. (2020) showed that tree patterns and planting row arrangements are important factors in improving thermal comfort conditions. The cooling potential of the greenery also varies with changes in the location of the trees in the environment (Milosevic et al., 2017). It is in view of these considerations that outdoor thermal comfort can be improved in these types of environments by resorting to appropriate planting designs and using effective planting patterns.

As such, the issues of local climate change, global warming, the urban heat island and improving outdoor thermal comfort in new cities are of undeniable importance and should receive proportionate attention in future urban studies and planning. In their objectives, previous studies have focused on the importance of planting patterns and the effect of tree layout on climate setting. The questions now arising include what the most effective planting pattern is to reduce T_a and provide thermal comfort, which planting compositions include evergreen or deciduous trees with more cooling potential, and which direction to choose in each of these planting patterns, taking into account the fact that the prevailing wind affects outdoor thermal comfort.

As an attempt at answering these questions, 16 scenarios including different planting patterns were simulated with different species and different orientations in the ENVI-met software. Then PMV index and T_a were evaluated in each of the scenarios. The results of this research can help landscape designers and urban planners with introducing optimal planting patterns and improving planting design and landscape planning to enhance climatic conditions, reduce heat stress and provide outdoor thermal comfort.

2. Study area and methods

In this research, the study area was first simulated using the ENVI-met model. Following this, model validation was performed by comparing the values of the output parameters of the model with field measurements. Finally, the proposed scenarios were simulated in the model and were identified after analyzing scenarios that involved better performance in improving climatic conditions and outdoor thermal comfort.

2.1. Thermal comfort index

PMV index represents the average temperature sensed by a group of people and is calculated based on Fanger's heat balance model (Fanger, 1970), which is related to the number of people who are dissatisfied with the amount of ambient heat defined as the predicted percentage of those dissatisfied (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016). Calculating the PMV index based on micrometeorological variables involves T_a, mean radiant temperature (T_{mrt}) (Lee & Mayer, 2016; Thorsson, Lindberg, Eliasson, & Holmer, 2007), relative humidity and wind speed, which evaluates the thermal comfort, taking into account body parameters, clothing parameters and individuals' metabolism (Mayer, 1993). PMV was firstly used to evaluate indoor thermal comfort, but after modification by adding activity and clothing factors, shortwave and longwave radiation fluxes were also used for outdoor environments (Coccolo et al., 2016). Previous studies have also used the PMV index to evaluate outdoor thermal comfort (2016, Barakat, Ayad, & El-Sayed, 2017; El-Bardisy et al., 2016; Karakounos, Dimoudi, & Zoras, 2018; Nasrollahi, Hatami, Khastar, & Taleghani, 2017; Perini & Magliocco, 2014; Salata, Golasi, Vollaro, & Vollaro, 2015). It may be the case that evaluating thermal comfort using the PET index may yield different results that are controversial. Similarly, it was not possible to perform a comprehensive analysis of PET in this study, so future researchers are advised to investigate the effect of planting patterns on thermal comfort using PET and to compare the results with PMV.

2.2. Study site

The site was located at University of Tabriz, East Azerbaijan Province (Fig. 1, northwest Iran. The area of Tabriz is 23,765 square kilometers. The geographical position of the site lies between Eynali and Sahand mountains Fazelpour, Soltani, Soltani, & Rosen, 2015). According to a 2017 census, its population was 1,600,000 (Sharafkhani, Khanjani, Bakhtiari, & Jahani, 2019). Tabriz has a mean annual precipitation of 380 mm and a mean annual T_a of 12 °C (the reference period for both data spans 2013–2014). It is semi-arid, has temperate springs, summers with low humidity and moderate warmth, rainy

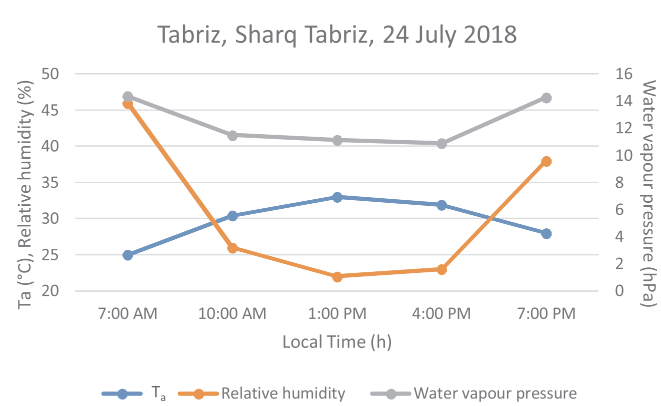

Fig. 1. 3-h measured values of T_a, relative humidity and water vapor pressure at the meteorological station "East Tabriz" on July 24th, 2018, in the period 7:00-19 LST.

Table 1
Input data applied in simulation.

Variable	Value
Longitude, Latitude	46°18′E, 38°04′N
Horizontal grid resolution	3 m × 3 m
Vertical grid resolution	2 m
Model rotation out of grid north	16.6°
Simulation date	24.07.2018
Maximum T_a	33.3 °C
Minimum T_a	18.2 °C
Wind speed at 10 m	4.7 m/s
Wind direction	110°
Name of location	Tabriz, East Azerbaijan Province, Iran

autumns and quite cold winters (Fazelpour et al., 2015). In terms of height, Tabriz (38°04′N, 46°18′E) lies 1361 m above sea level (Sharafkhani et al., 2019). The prevailing wind in the city of Tabriz is usually from the east and west in the summer (Fazelpour et al., 2015). The 24th of July, 2018, which was one of the hottest days of the year, was selected for simulation. Meteorological data including minimum and maximum T_a, minimum and maximum relative humidity, wind speed at height of 10 m and wind direction were collected from East-Tabriz Meteorological Station. Table 1 shows the input data fed into the ENVI-met software. Fig. 1 shows the 3-h measured values of T_a, relative humidity and water vapor pressure at the meteorological station "East of Tabriz" near the University of Tabriz on the simulation day.

2.3. Simulation model

The simulated models in this study were performed by ENVI-met 4.1 software. It is a non-hydrostatic micro-climate model that can simulate a grid resolution of 0.5–10 meters in space and a 10 s temporal resolution climate in urban environments in 3D (Simon, 2016). This model uses the basis of computational fluid dynamics to simulate the processes between plant, surface and atmosphere in urban environments with various physical properties, various materials, and various plants with different layouts (Morakinyo et al., 2017). The simulation of plants in this model is biologically and dynamically oriented such that the evaporation and transpiration of the plants and their energy absorption are also applied in the simulations and the plant is not considered as just a static body with porosity (Morakinyo, Lau, Ren, & Ng, 2018). The model also considers the characteristics of plants, such as height and leaf density distribution, to calculate the shading, absorption, and radiation of short and long waves (Morakinyo et al., 2017). Other factors that could affect thermal comfort, including number of tree rows, inter-row distance, inter-tree distance within a row, tree height, tree crown spread, degree of crown interlocking, foliage density, ground cover, soil moisture supply, and others were considered the same in all scenarios. As such, the effect of these factors in the simulation was ignored, so that a change in these factors could affect the thermal comfort conditions. In the simulations carried out in this study, the spatial resolutions used were 3 m horizontal and 2 m vertical. The sub-model Leonardo V4.4 was used to extract two-dimensional maps and climatic data generated by the ENVI-met V4 software. The sub-model Biomet V1.5 was also used to extract the PMV index.

2.4. Field measurement and validation

In previous studies, field measurements were performed to validate the ENVI-met model, and the validity of this model was determined by comparing the simulated values with field measurements (Forouzandeh, 2018; Lee et al., 2016; López-Cabeza, Galán-Marín, Rivera-Gómez, & Roa-Fernández, 2018; Salata et al., 2016; Taleghani, Tenpierik, van den Dobbelsteen, & Sailor, 2014). In this study, relative humidity was measured and simulated for validation only, as in previous studies (Morakinyo et al., 2017; Zhang et al., 2018; Zhao & Fong, 2017). In this research, due to the importance of the campus and the time spent by the students at the Faculty of Agriculture, University of Tabriz, this place was chosen for simulation. Field measurements of T_a and relative humidity were performed on 24th of October, 2018, from 8:00 to 14:00 at the receptor point R01, and SMART SENSOR Humidity Temperature Meter model AR847 was used with ± 1.5 °C accuracy of T_a and ± 3 % (41 ~ 80 %) ± 5 % (10 % ~ 40 %) accuracy of humidity (Fig. 2). Meteorological data including T_a, relative humidity, wind direction and wind speed at a height of 10 m from the East-Tabriz Meteorological Station located near Tabriz University were collected for simulation in the ENVI-met software. In order to determine the accuracy of the ENVI-met model, the previous studies compared the measured and simulated values, the coefficient of determination (R^2) and the Root Mean Square Error (RMSE); for a reliable model, the R^2 value must tend towards 1, and the (RMSE) towards 0 (Salata et al., 2016). In this study, for T_a, R^2 was 0.96 and the RMSE value was 0.6; for relative humidity, R^2 was 0.89 and the RSME value was 3.83. In previous studies, the value of R2 lay between 0.52 and 0.96 and the amount of RMSE between 0.26 and 4.83 (López-Cabeza et al., 2018), so the model of ENVI-met was found to be valid in this study. In this study, empirical measurement was used to validate the software, but to evaluate the cooling potential of each of the planting patterns that did not exist in this real environment but were designed as scenarios, previous studies (El-Bardisy et al., 2016; Sodoudi et al., 2018) used this method to

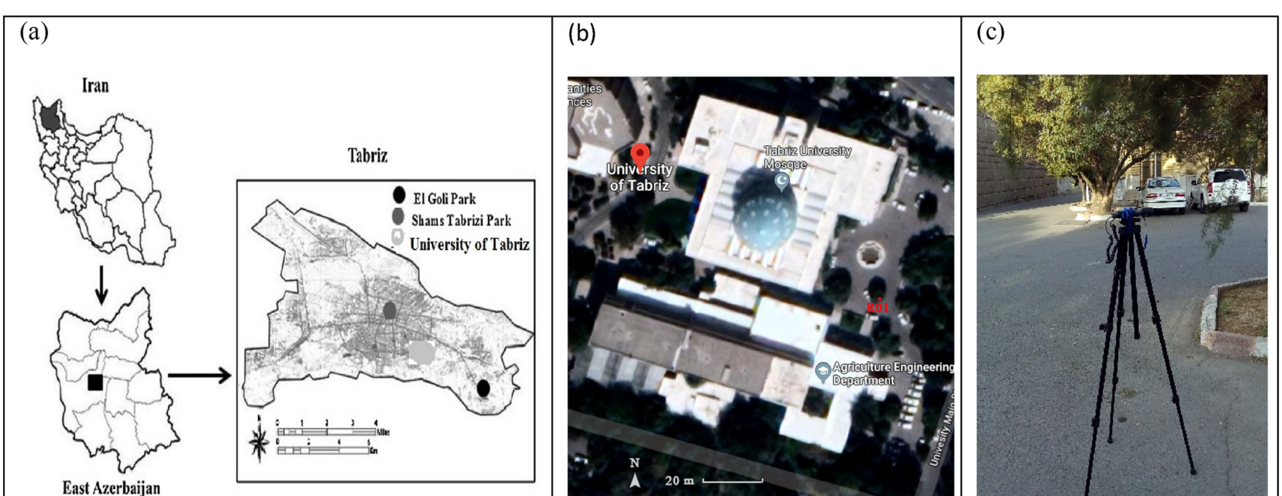

Fig. 2. (a) Tabriz location; (b) Google map of the study area; (c) measuring instrument.

simulate the effects of different tree layouts and arrangements on thermal comfort. Other studies (Duarte, Shinzato, Gusson, dos, & Alves, 2015; Unal et al., 2018; Wang & Akbari, 2016) also evaluated the micrometeorological effects of vegetation using simulations of scenarios with various configurations that were different from the validated environment.

2.5. Scenario design

In general, two types of plant arrangement have been investigated in this study, which include a rectangular pattern (S1, S2, S3, S4, S9, S10, S11, S12) and a triangular alternative pattern (S5, S6, S7, S8, S13, S14, S15, S16). These patterns were designed with four different planting compositions, including deciduous trees (S1, S5, S9, S13), evergreen trees (S2, S6, S10, S14), and two combinations of both evergreen and deciduous trees, involving in one case two outer rows of planting deciduous trees and two inner rows in evergreen ones (S3, S7, S11, S15), and in the other, two outer rows of planting evergreen trees and two inner rows in deciduous ones (S4, S8, S12, S16); all evergreen trees were coniferous in the simulation. In addition, these planting patterns were designed in two different orientations with respect to the prevailing wind, including the direction perpendicular to and parallel to the wind. The first eight scenarios (S1, S2, S3, S4, S5, S6, S7, and S8) were perpendicular to the prevailing wind and another eight scenarios (S9, S10, S11, S12, S13, S14, S15, S16) were in the orientation parallel to it; these were all simulated (Fig. 3). There was a gap in the lower part of the tree rows that is the site entrance. In this study, eight receptor points were determined based on the distance from the rows of trees and buildings. For the analysis of parameters in different scenarios, R05 and R06 had the lowest distance from the building, R07, R08, and R02 were in the rows of trees, with R08 in the first row, R07 in the last row, and R02 in the center of the rows. Also, R03 was within 3 m of the last row of planting trees, R04 was within 12 m and R01 was within 18 m of the last row of trees (Fig. 4). Preparing these scenarios was carried out by the SPACE model in ENVI-met. The evaluation of the cooling effect of each scenario was conducted by comparing the micrometeorological indices in different scenarios with a base scenario that involved no trees. These patterns and planting combinations were selected from existing patterns in urban green space; the different effects of each of these patterns have not been investigated in previous studies.

3. Results

The comparison was made among 16 scenarios of T_a in 12 h, T_{mrt} and PMV in 5 h. The results showed that in all scenarios, the mean T_a and PMV in the R03 receptor were lower than other receptors (Fig. 5). The reason for the high T_a in the R05 and R06 receptors was the distance from the rows of planting; also, in the R08 receptor, the average T_a was higher because of exposure to wind. In addition, the T_a at R03 receptor was lower due to proximity to the rows of planting and the effect of shadows of trees. Wind speed was also reduced behind the four planted rows. Therefore, given that the mean T_a and the PMV in the R03 receptor were lower than other receptors, it was important to study the thermal comfort and climatic conditions behind the rows of planting after the wind transit. Furthermore, the analysis of T_a and PMV was only conducted in the case of receptor R03.

3.1. Air temperature (T_a)

The results of the T_a simulation showed that in all scenarios, the Ta was lower than the base state without trees. In S1 scenario, a rectangular planting pattern with deciduous trees, the highest T_a reduction (2.2 °C) was observed at 1.00 pm (Fig. 6). In addition, in the S13 scenario, a triangular alternative planting with deciduous trees, the T_a decreased by 1.5 °C at that time (Fig. 7). Generally, the T_a was lower in the rows perpendicular to the wind direction at most ours of the day at the height of 1.4 m, which could be due to improved ventilation; for instance, in scenario S1, the mean T_a at the R03 receptor was 27.6 °C. The Ta reduction was 1.8 °C in scenario S2, the rectangular planting pattern with evergreen trees (Fig. 8). In the combination scenario of planting in S3, including deciduous trees on both sides and evergreen trees in the middle rows, the T_a dropped by 2 °C (Fig. 9). The Ta reduction was 1.2 °C at 1 pm with evergreen trees on both sides and deciduous trees in the middle rows in the S8 scenario (Fig. 10). The results showed that at a height of 1.4 m at R03 receptor in rectangular planting patterns, the orientation of the row being perpendicular to the wind (S1 mean T_a 27.6 °C) and in the triangular planting patterns, the alignment of rows parallel with the wind (S13 mean T_a 28 °C) was seen to have a higher cooling effect. However, the T_a was generally lower in rectangular planting patterns (Fig. 11). Also, planting patterns formed by deciduous trees or with deciduous trees on their outer rows had a higher cooling effect than planting patterns consisting of evergreen trees, or with evergreen on their outer rows. Table 2 shows mean values of T_a in different scenarios.

The Bonferroni test was used to check the T_a mean difference between different planting patterns. The mean difference between triangular and rectangular planting patterns was significant in all scenarios. In terms of planting direction, the mean difference between the perpendicular and parallel patterns in triangular patterns was not significant, but in the rectangular pattern, in the planting composition with the deciduous trees and the planting composition of the deciduous trees in the outer rows, the mean differences were significant. Table 3 shows mean differences between planting patterns.

3.2. Thermal comfort

The results showed that in scenario S1, the rectangular pattern perpendicular to wind direction containing deciduous trees, there was a decrease in the PMV index by 1.6 at 12 pm, which was the maximum decrease of the PMV index (Fig. 12). In planting compositions containing deciduous trees, the mean PMV decrease in 4 h of the day (1.1) was observed in the pattern of rectangular planting perpendicular to the wind (S1 (Fig. 13). The average reduction in PMV index (1.1) was observed in two rectangular planting patterns (S2 and S10), which was the highest score (Fig. 14). The pattern with deciduous trees in outer rows and evergreen trees in the inner rows had the highest reduction (0.9) in the mean PMV index for the rectangular planting pattern perpendicular to wind direction (S3) (Fig. 15). In addition, in patterns with evergreen trees in outer rows and deciduous trees in the inner rows, the results were similar to the rectangular planting pattern perpendicular to wind direction (S4), which involved the highest average reduction (1.3) of PMV (Fig. 16). The comparison of the PMV index over 4 h of the day showed that the rectangular pattern perpendicular to the prevailing wind with a mean of 2.9 exhibited the lowest value, while the triangular pattern perpendicular to the prevailing wind with a mean of 3.5 showed the highest. Also, the combination of planting evergreen trees in the outer rows with an average of 2.9 showed the best performance, while planting deciduous trees in the outer row with an average of 3.3 displayed the lowest performance in reducing the PMV index (Fig. 17). Table 4 shows mean values of PMV in different scenarios. According to Fanger (1970), the PMV index ranges between 3 and -3, with values of less than -3 being very cold and values of more than 3 very hot, as well as 1 being slightly warm and 2 being warm. In the base scenario involving no trees, the amount of PMV was very hot at all times of the study period in which many of the scenarios were reduced to the warm range and sometimes to a slightly warm range. On average, scenarios with a rectangular pattern had fewer thermal discomfort hours than those with a triangular pattern. There was less difference between the perpendicular and the parallel directions, but the perpendicular one was better. In this study, it was not possible to perform a comprehensive analysis of PET; its mean, however, was compared in different scenarios at the R03 receptor (Fig. 18). The overall results of the PET were similar

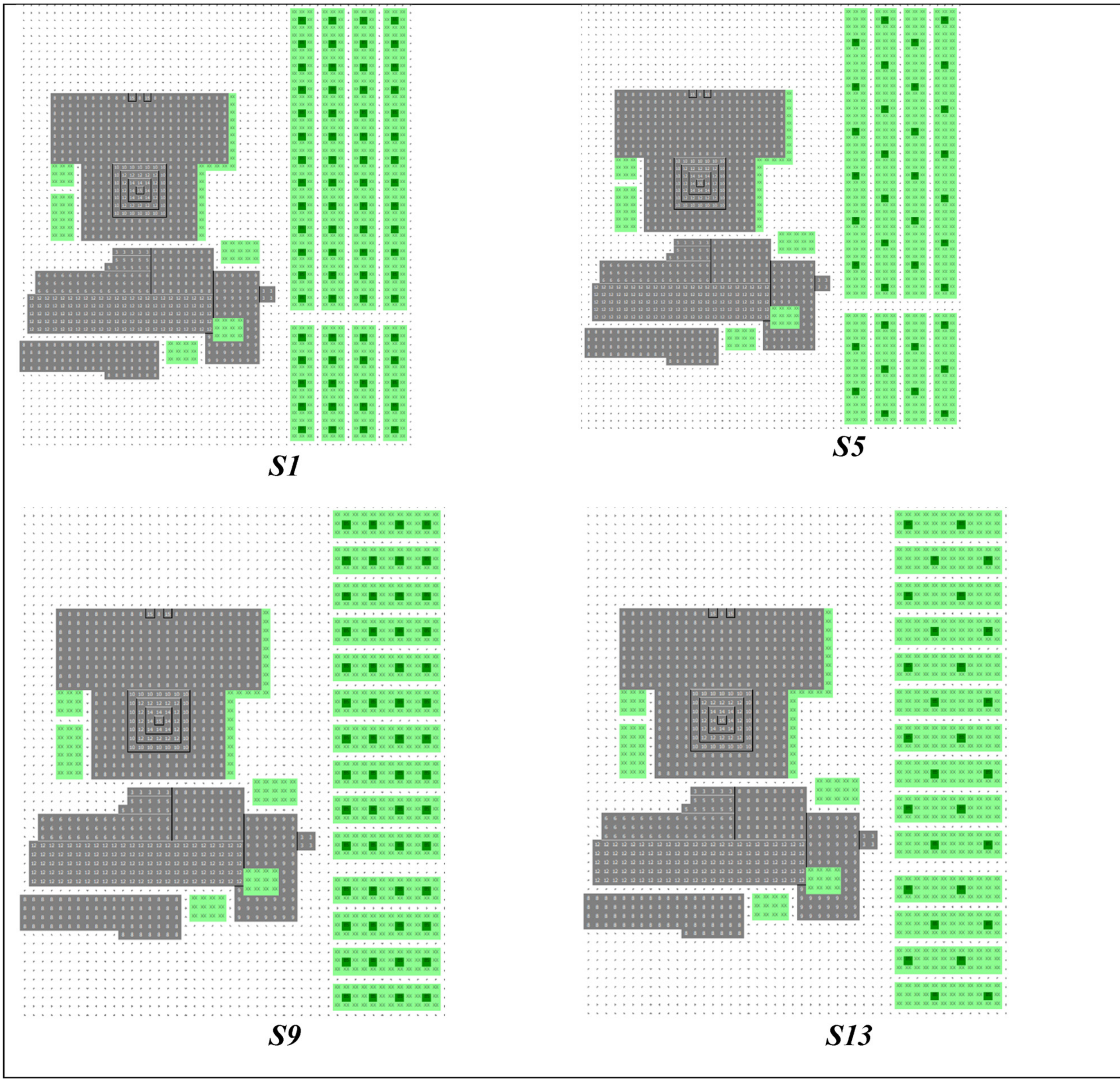

Fig. 3. S1: rectangular pattern with perpendicular direction, S5: alternative triangular pattern with perpendicular direction, S9: rectangular pattern with parallel direction, S13: alternative triangular pattern with parallel direction.

to those of the PMV, so that the rectangular planting pattern, perpendicular to wind direction, and the planting composition of evergreen trees in the outer rows showed better performance in reducing the PET.

The Bonferroni test was used to check the PMV mean difference between different planting patterns. The mean difference between triangular and rectangular planting patterns was significant in all parallel directions, as was the case in the planting composition with evergreens and outer evergreens in a perpendicular direction to the wind. In terms of planting direction, the mean difference between the perpendicular and parallel patterns in triangular patterns was significant in evergreen and outer evergreen scenarios; in the rectangular pattern, in the planting composition with the deciduous trees and the planting composition of the evergreen trees in the outer rows, the mean difference was also significant. Table 5 shows mean differences between planting patterns.

3.3. Mean radiant temperature (T_{mrt})

The overall results of the T_{mrt} were similar to those of the PMV, as the rectangular pattern was seen to demonstrate a better performance in reducing the T_{mrt} than the triangular pattern. The triangular planting pattern had the weakest performance in reducing T_{mrt} and the perpendicular planting pattern was better than the parallel planting one (Fig. 19). At 13:00, the rectangular pattern perpendicular to the wind with evergreen trees and the same pattern with evergreen trees in the outer rows had the lowest T_{mrt} (52.6 °C). Also, the triangular pattern perpendicular to the wind with deciduous trees (66.1 °C) and the same pattern with deciduous trees in the outer rows had the highest T_{mrt} (66.2 °C). Since shading is an important factor in reducing T_{mrt}, the reason for the better performance of evergreen trees was the change in shade pattern during hot hours. Table 6 shows mean values of T_{mrt} in different scenarios.

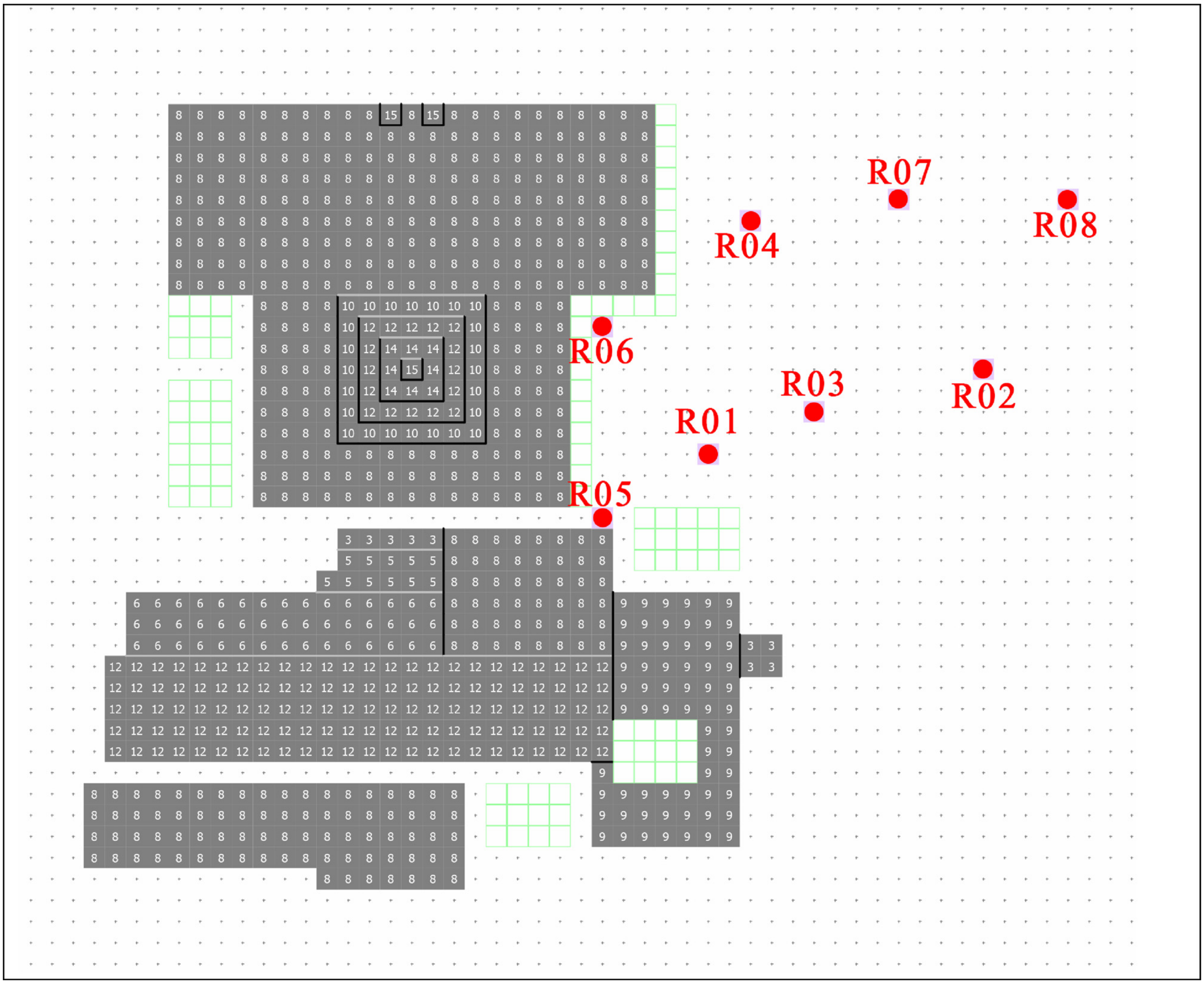

Fig. 4. Base case without trees and the position of receptors.

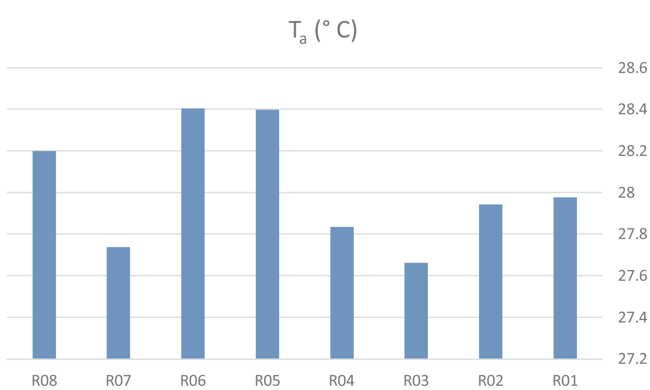

Fig. 5. Mean T_a at receptors points (averaged over 8:00-19:00 LST).

4. Discussion

The results of micrometeorological simulation undertaken in this study showed that planting trees in the outdoor environment would reduce T_a and improve outdoor thermal comfort conditions during the daytime. The findings in a number of previous studies (El-Bardisy et al., 2016; Lee & Mayer, 2018; Morakinyo et al., 2018; Sun et al., 2017; Zhang et al., 2018) support the results here. In all these studies, the results showed that urban green space improves thermal comfort conditions. Lee and Mayer (2018), comparing urban green space in different configurations, showed that green space can reduce outdoor human heat stress in the daytime. The findings of this study revealed that tree planting patterns, direction of rows of trees with respect to the prevailing wind and leaf type affect the reduction of T_a and PMV index, on which the type of planting patterns had the greatest impact. The comparison of T_a and PMV index in the scenarios points to different cooling potentials of different planting patterns with different directions relative to the wind and the type of trees.

4.1. Effect of planting patterns on air temperature (T_a) reduction and thermal comfort improvement

The results revealed that the rectangular planting pattern compared to the triangular alternative planting pattern exercises a stronger cooling effect. According to El-Bardisy et al. (2016), PMV change varies according to the location of the receptors in different plant layouts, but in most situations, the PMV index is lower in the rectangular arrangement of plants than the random one, which is consistent with the results of this research. Between the triangular and rectangular patterns, there is a difference in the type of arrangement of the trees, as the type of arrangement affects the wind flow and changes its velocity and direction as it crosses the planting rows. According to Morakinyo and Lam (2016), when the area of the tree cover is the same, the planting pattern is an important factor in reducing the PET index, so that the double-row

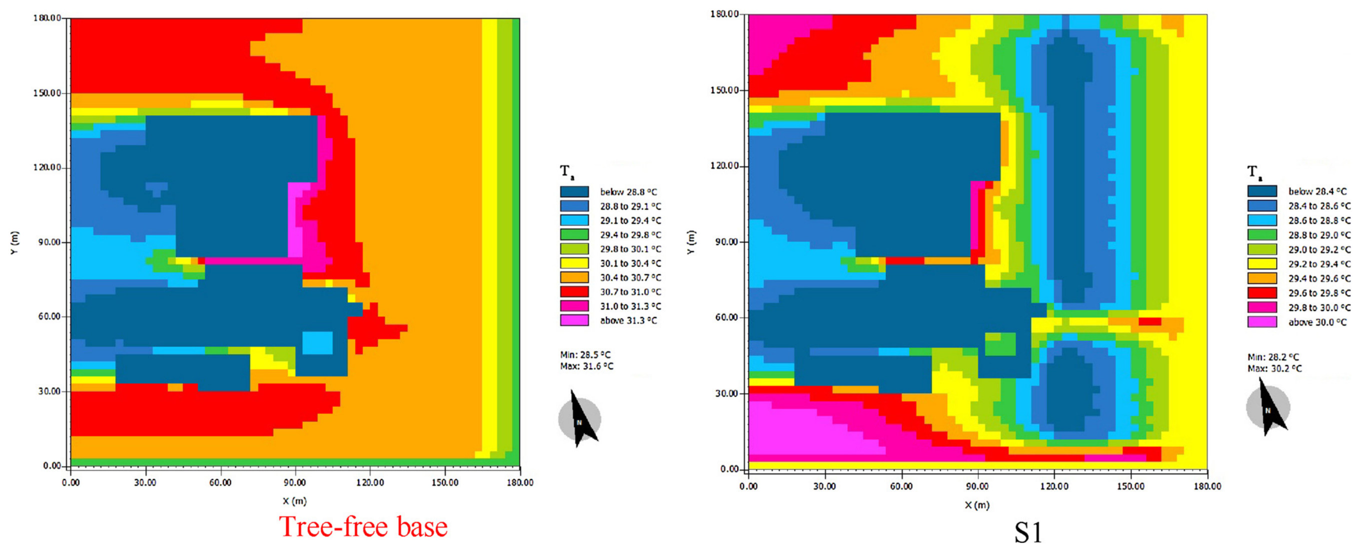

Fig. 6. Comparison of simulated T_a between the tree-free case and S1 at a height of 1.4 m at 13:00 LST (averaged over 1 h).

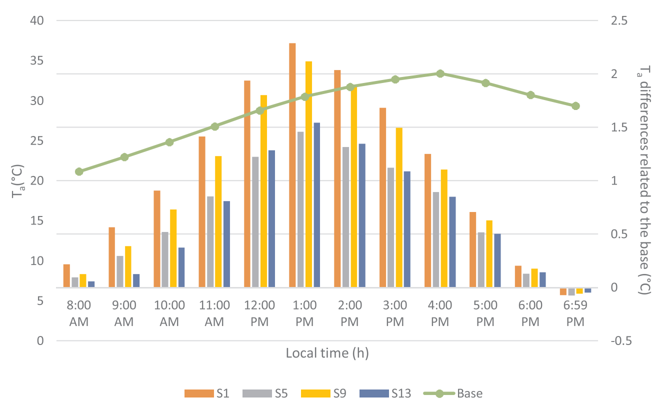

Fig. 7. T_a change in deciduous trees planting composition, Base: tree-free case, S1: rectangular planting pattern with perpendicular direction to wind, S5: triangular planting pattern with perpendicular direction to wind, S9: rectangular planting pattern with parallel direction to wind, S13: triangular planting pattern with parallel direction to wind.

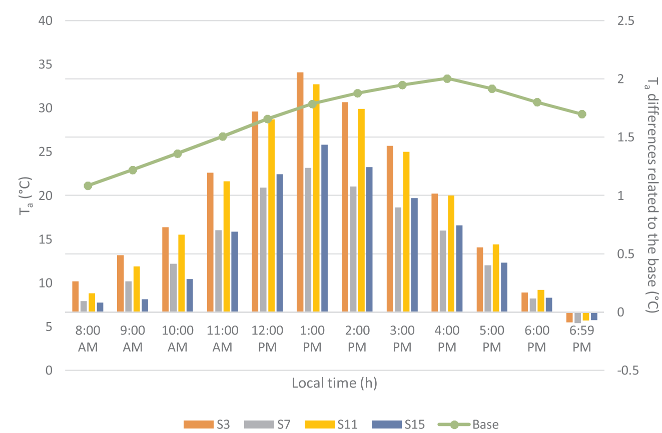

Fig. 9. T_a change in outer deciduous trees planting composition, Base: tree-free case, S3: rectangular planting pattern with perpendicular direction to wind, S7: triangular planting pattern with perpendicular direction to wind, S11: rectangular planting pattern with parallel direction to wind, S15: triangular planting pattern with parallel direction to wind.

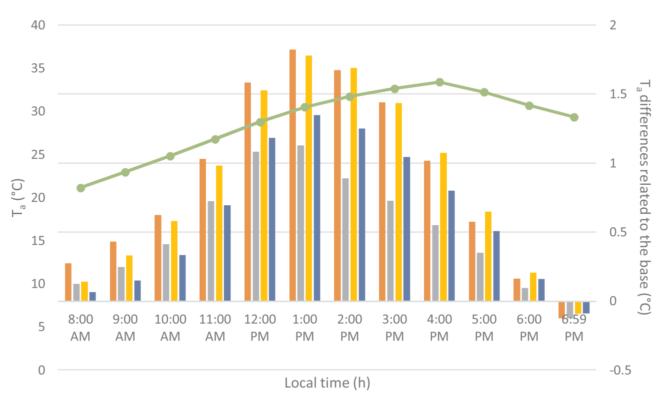

Fig. 8. T_a change in evergreen trees planting composition, Base: tree-free case, S2: rectangular planting pattern with perpendicular direction to wind, S6: triangular planting pattern with perpendicular direction to wind, S10: rectangular planting pattern with parallel direction to wind, S14: triangular planting pattern with parallel direction to wind.

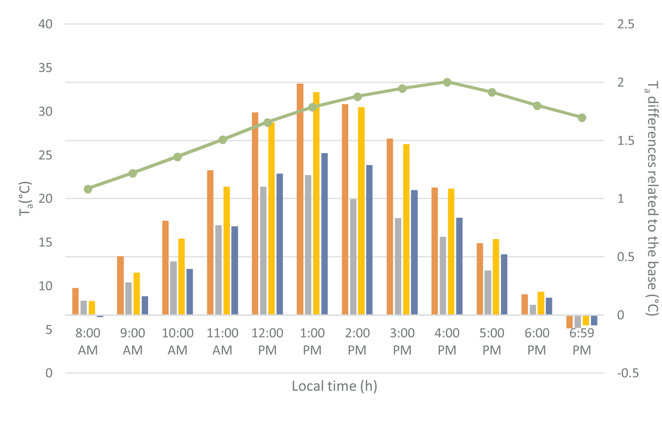

Fig. 10. T_a change in outer evergreen trees planting composition, Base: tree-free case, S4: rectangular planting pattern with perpendicular direction to wind, S8: triangular planting pattern with perpendicular direction to wind, S12: rectangular planting pattern with parallel direction to wind, S16: triangular planting pattern with parallel direction to wind.

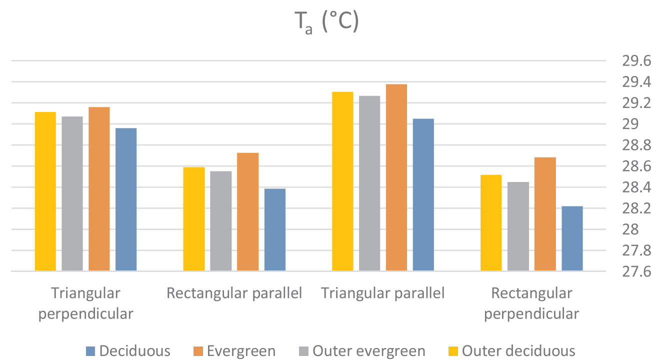

Fig. 11. Comparison of simulated T_a between different planting patterns and directions at a height of 1.4 m at 13:00 (averaged over 1 h at the R03 receptor).

Table 2
Mean T_a values (°C), averaged over 8:00-19:00 LST, at a height of 1.4 m at the R03 receptor (S.D: Standard deviation).

Scenario	Mean	S.D	Scenario	Mean	S.D
S1	27.6	3.7	S9	27.7	3.7
S2	27.8	3.7	S10	27.8	3.7
S3	27.8	3.7	S11	27.8	3.7
S4	27.7	3.7	S12	27.8	3.7
S5	28.0	3.7	S13	28.0	3.7
S6	28.2	3.8	S14	28.1	3.7
S7	28.1	3.8	S15	28.1	3.7
S8	28.1	3.8	S16	28.1	3.7

Table 3
Mean T_a differences (averaged over 8:00-19:00 LST) at a height of 1.4 m in different planting patterns (* shows that the mean difference is significant at the 0.05 level).

Deciduous tree scenarios T_a mean difference (P-Value)					
S1-S5	S1-S9	S1-S13	S5-S9	S5-S13	S9-S13
0.39* (0.002)	0.12* (0.000)	0.42* (0.001)	0.27* (0.011)	0.02 (1.000)	0.29* (0.003)
Evergreen tree scenarios T_a mean difference (P-Value)					
S2-S6	S2-S10	S2-S14	S6-S10	S6-S14	S10-S14
0.35* (0.004)	0.01 (1.000)	0.25* (0.002)	0.34* (0.008)	0.10 (0.276)	0.23* (0.001)
Outer deciduous tree scenarios T_a mean difference (P-Value)					
S3-S7	S3-S11	S3-S15	S7-S11	S7-S15	S11-S15
0.37* (0.003)	0.04* (0.020)	0.34* (0.001)	0.32* (0.005)	0.03 (1.000)	0.29* (0.001)
Outer evergreen tree scenarios T_a mean difference (P-Value)					
S4-S8	S4-S12	S4-S16	S8-S12	S8-S16	S12-S16
0.40* (0.002)	0.06 (0.079)	0.33* (0.001)	0.34* (0.007)	0.07 (0.563)	0.27* (0.001)

pattern is better than the central one. In this study, the number of rows was not examined but in terms of the importance of planting pattern and its effect on shading pattern and thermal comfort in the environment, the results are in line with previous research. Yang et al. (2018) showed that the effect of tree planting pattern on thermal comfort varies under different lighting, ventilation and shade conditions. These results confirm the importance of planting pattern in improving ventilation and shading in the environment. These fluctuations in T_a changes and PMV index can be due to variations in wind direction and different patterns of shadowing of trees in various planting patterns. Although these changes vary with T_a and different planting combinations, rectangularly planted deciduous trees reduced the T_a, while the combination of evergreen trees in the outer rows and deciduous trees in the inner rows yielded better performance in the reduction of the PMV index. Evergreen species affect outdoor thermal comfort by reducing wind speed and blocking direct sunlight (Zhang et al., 2018). Thus, the better performance in reducing the PMV index can be due to the appropriate shadow of this planting pattern, because the low branches of evergreen trees with shades during the hours of the day improve thermal comfort conditions, as do deciduous trees with branches at higher altitudes. Two important factors in reducing T_a and improving thermal comfort are shade and ventilation (Lee et al., 2016); planting patterns and tree layouts affect ventilation in urban spaces (Zhang et al., 2018). The arrangement of the trees also affects the amount of shade in the environment, wind speed and direction (El-Bardisy et al., 2016). Therefore, the best planting pattern to improve thermal comfort is a pattern that improves ventilation and provides a suitable shade in the urban spaces.

4.2. *Effect of the direction of planting rows on air temperature (T_a) reduction and thermal comfort improvement*

The direction of the tree row in front of the prevailing wind in different planting patterns has a different effect on T_a reduction. The results showed that in the triangular planting pattern with a direction parallel to the wind, the T_a decreases, while in the rectangular planting pattern, the rows of trees perpendicular to wind direction, it is increased. In the triangular perpendicular planting pattern, the rows of trees block the wind flow and changes direction, but in the triangular parallel pattern, the airflow passes through the tunnel and the rows as a result of which the difference is due to different ventilation conditions. Conversely, in the rectangular pattern due to the greater interference of the canopy of trees in both directions, it blocks the flow of wind, resulting in less difference in T_a and PMV in these two directions. Sodoudi et al. (2018) found that the pattern of planting with rows parallel to wind direction brought out a stronger cooling effect. The reasons for these differences can vary from the overlap of the crown of the trees and the spacing of the planting that affects ventilation and wind direction change. Morakinyo and Lam (2016) showed that wind conditions are an important factor in improving thermal comfort, so that the most appropriate orientation of the vegetation should be such as to provide favorable ventilation in the environment, confirming the importance of the effects the type of trees and their direction have on ventilation. The effect of planting direction on the PMV index is slightly different, so that there is no difference in the pattern of rectangular planting between the perpendicular and parallel directions; however, in the triangular alternated pattern, the PMV index in the direction parallel to the wind is lower than in the direction perpendicular to it. It should also be noted that the performance of planting combinations containing evergreen trees in the direction parallel to the wind is more desirable than when it is perpendicular to the wind.

4.3. *Effect of tree type on air temperature (T_a) reduction and thermal comfort improvement*

Deciduous trees showed the greatest impact on the reduction of T_a, and evergreen trees pointed to the lowest effect on reducing the T_a. The combined rows of deciduous and evergreen displayed a moderate performance in reducing the T_a. This can be due to the control of the wind speed and direction, as well as the wider shade of deciduous trees. However, in reducing the PMV index, evergreen trees showed better performance than deciduous trees. According to El-Bardisy et al. (2016), coniferous trees reduce the PMV index more than deciduous trees, which is in line with the current findings. The pattern consisting of deciduous trees in the outer rows and evergreen trees in the inner rows reduced the T_a, while this type of planting did not perform well in reducing the PMV index. Evergreen trees in outer rows and deciduous trees in the inner rows reduced the PMV index and improved outdoor thermal comfort. Given that evergreen and deciduous trees had the same size in the simulation, the difference in the cooling effect of these trees was due to their different crown shape and shading pattern. In addition, evergreen and deciduous trees had a different effect on relative humidity in the environment. Thus, the results showed that in

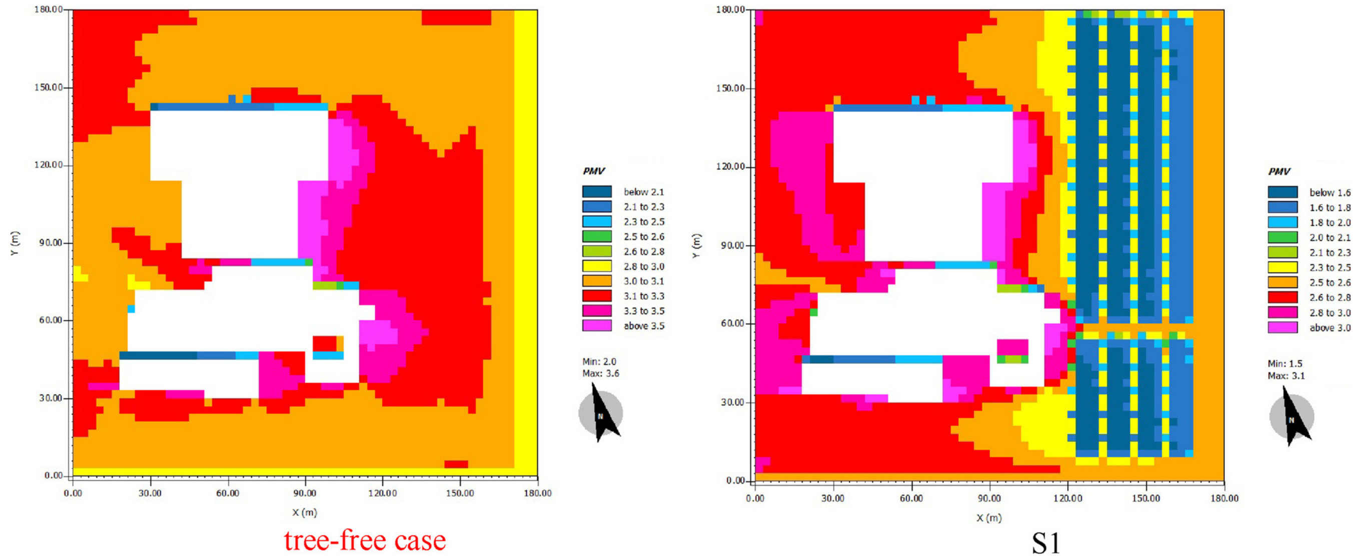

Fig. 12. Comparison of simulated PMV index between tree-free case and S1 at a height of 1.4 m at 12:00 LST (averaged over 1 h).

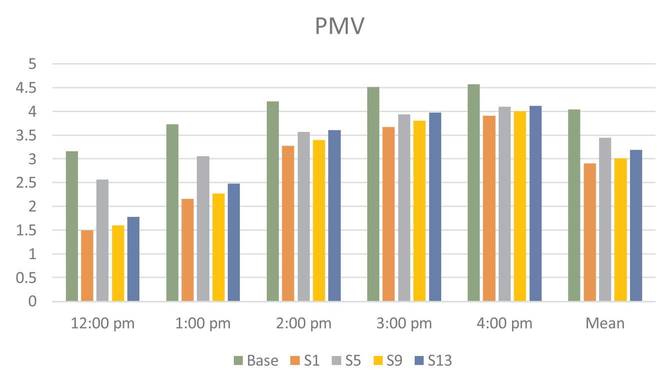

Fig. 13. PMV index at a height of 1.4 m at the R03 receptor in deciduous trees planting composition, Base: tree-free case, S1: rectangular planting pattern with perpendicular direction to wind, S5: triangular planting pattern with perpendicular direction to wind, S9: rectangular planting pattern with parallel direction to wind, S13: triangular planting pattern with parallel direction to wind.

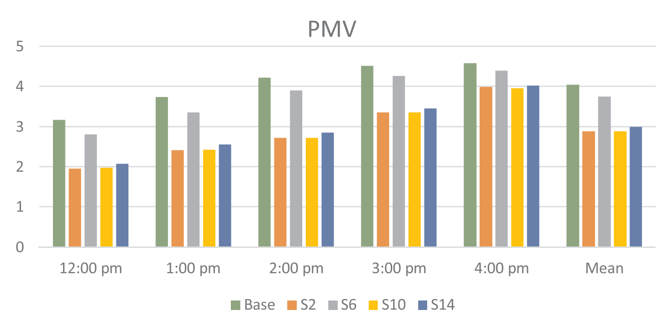

Fig. 14. PMV index at a height of 1.4 m at the R03 receptor in evergreen trees planting composition, Base: tree-free case, S2: rectangular planting pattern with perpendicular direction to wind, S6: triangular planting pattern with perpendicular direction to wind, S10: rectangular planting pattern with parallel direction to wind, S14: triangular planting pattern with parallel direction to wind.

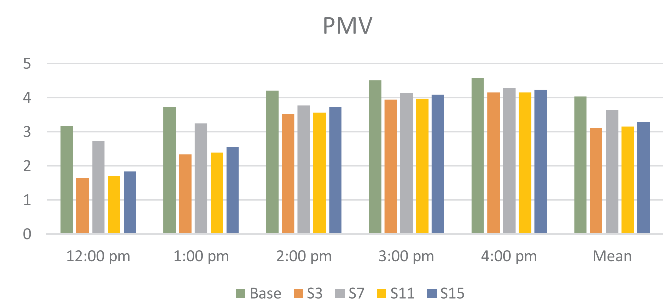

Fig. 15. PMV index at a height of 1.4 m at the R03 receptor in outer deciduous trees planting composition, Base: tree-free case, S3: rectangular planting pattern with perpendicular direction to wind, S7: triangular planting pattern with perpendicular direction to wind, S11: rectangular planting pattern with parallel direction to wind, S15: triangular planting pattern with parallel direction to wind.

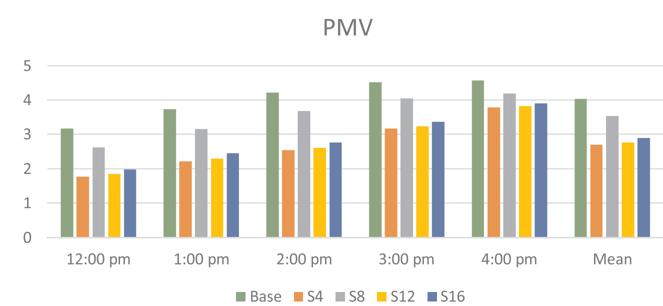

Fig. 16. PMV index at a height of 1.4 m at the R03 receptor in outer evergreen trees planting composition, Base: tree-free case, S4: rectangular planting pattern with perpendicular direction to wind, S8: triangular planting pattern with perpendicular direction to wind, S12: rectangular planting pattern with parallel direction to wind, S16: triangular planting pattern with parallel direction to wind.

different planting patterns with different directions to the prevailing wind, evergreen trees and deciduous trees play different roles and involve different functions, with their cooling performance varying in different rows of trees. It is important to note that in winter, the deciduous trees have a different effect on thermal comfort, but the purpose of this study was to investigate this effect in the warm season.

One of the positive features of the ENVI-met software compared to similar models is considering the plant as an active body and simulating the evapotranspiration process of different plant species, which is a factor affecting micrometeorological conditions. Also, the ability to simulate a variety of plant species with different characteristics such as leaf area index, leaf area density, form, size, leaf type and other features that may influence micrometeorological conditions is one of the other strengths of this model. The disadvantages of this software are its poorer ability to simulate the exact form of plants with various

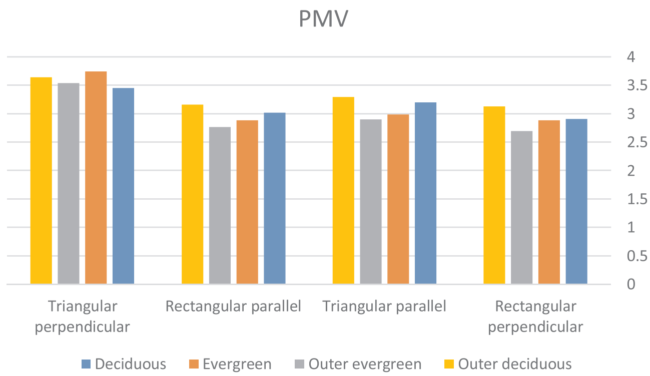

Fig. 17. Comparison of mean simulated PMV index, averaged over 12:00-16:00 LST, between different planting patterns and directions at a height of 1.4 m at the R03 receptor.

Table 4
Mean PMV values, averaged over 12:00-16:00 LST, at a height of 1.4 m at the R03 receptor (S.D: Standard deviation).

Scenario	Mean	S.D	Scenario	Mean	S.D
S1	2.9	1.0	S9	3.0	1.0
S2	2.8	0.8	S10	2.8	0.7
S3	3.1	1.0	S11	3.1	1.0
S4	2.6	0.7	S12	2.7	0.7
S5	3.4	0.6	S13	3.1	1.0
S6	3.7	0.6	S14	2.9	0.7
S7	3.6	0.6	S15	3.2	1.0
S8	3.5	0.6	S16	2.8	0.7

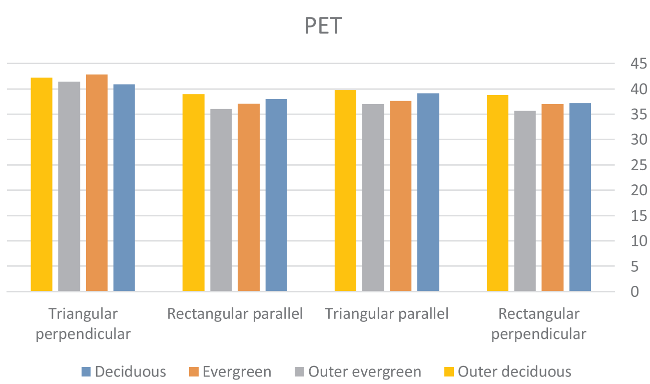

Fig. 18. Comparison of mean simulated PET index, averaged over 12:00-16:00 LST, between different planting patterns and directions at a height of 1.4 m at the R03 receptor.

geometric shapes, as well as buildings and paths that are curved and rounded. If you want macro-scale simulation with a higher number of grids, the model will be very time-consuming, and working with a higher size of grid cells in meter is likely to reduce simulation accuracy, which is also a problem.

5. Conclusion

Trees and green spaces have a great impact on regulating micrometeorological conditions, which means that the study of the key factors and properties of green spaces is of immediate importance and concern. This paper examined the effects of different planting patterns, of the direction of the rows of trees against the prevailing wind and of the types of trees in these different conditions, on the micrometeorological condition and thermal comfort. These patterns were simulated in 16 scenarios using the ENVI-met software. The results indicated that the rectangular planting pattern, with evergreen trees in the outer rows and deciduous trees in the inner rows in the direction perpendicular to prevailing wind, leads to the most optimal improvement in outdoor thermal comfort. The triangular pattern perpendicular to the wind with evergreen trees showed the weakest performance in improving thermal comfort.

The results of this research can be used as another helpful template for landscape designers and urban planners to help boost their landscape plans and designs in order to develop a sustainable city, regulate the local micrometeorological conditions and improve urban residents' thermal comfort. It is suggested that urban planners and designers pay more attention to human thermal comfort in the design of urban environments towards improving micrometeorological conditions. In this regard, a recommended course of action is to consider the prevailing wind in the region in designing urban green spaces. Combinations of deciduous and evergreen trees in a rectangular planting pattern

Table 5
Mean PMV differences (averaged over 12:00-16:00 LST) at a height of 1.4 m in different planting patterns (* shows that the mean difference is significant at the 0.05 level).

Deciduous tree scenarios PMV mean difference (significance)					
S1-S5	S1-S9	S1-S13	S5-S9	S5-S13	S9-S13
0.54 (0.255)	0.11* (0.007)	0.29* (0.001)	0.43 (0.483)	0.25 (1.000)	0.18* (0.003)
Evergreen tree scenarios PMV mean difference (significance)					
S2-S6	S2-S10	S2-S14	S6-S10	S6-S14	S10-S14
0.86* (0.015)	0.00 (1.000)	0.10 (0.057)	0.86* (0.012)	0.75* (0.013)	0.10* (0.008)
Outer deciduous tree scenarios PMV mean difference (significance)					
S3-S7	S3-S11	S3-S15	S7-S11	S7-S15	S11-S15
0.51 (0.363)	0.03 (0.295)	0.16* (0.015)	0.48 (0.382)	0.35 (0.0.765)	0.13* (0.003)
Outer evergreen tree scenarios PMV mean difference (significance)					
S4-S8	S4-S12	S4-S16	S8-S12	S8-S16	S12-S16
0.84* (0.013)	0.06* (0.006)	0.20* (0.005)	0.77* (0.015)	0.64* (0.019)	0.13* (0.005)

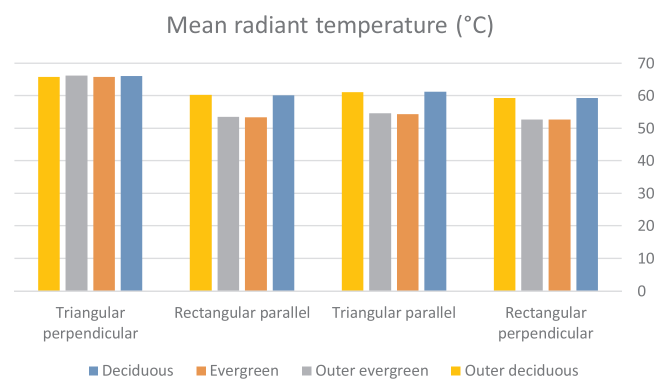

Fig. 19. Comparison of simulated Tmrt values at the R03 receptor between different planting patterns and directions at a height of 1.4 m at 13:00 LST (averaged over 1 h).

Table 6
Mean T_{mrt} values (°C), averaged over 12:00-16:00 LST, at a height of 1.4 m at the R03 receptor (S.D: Standard deviation).

Scenario	Mean	S.D	Scenario	Mean	S.D
S1	59.3	12.0	S9	60.1	11.8
S2	52.6	7.0	S10	53.4	6.8
S3	59.3	12.1	S11	60.2	11.8
S4	52.6	7.1	S12	53.5	6.8
S5	66.1	4.1	S13	61.2	11.6
S6	65.8	4.1	S14	54.4	6.6
S7	65.8	4.1	S15	61.0	11.6
S8	66.2	4.0	S16	54.7	6.5

perpendicular to the wind can be effective. In addition, using a triangular alternative planting pattern involving an alignment parallel to the wind direction can be more beneficial in improving climatic conditions due to the better ventilation it would offer. What is also recommended is to use suitable species for wind control according to the pattern of planting and the direction of planting trees against the dominant wind. Because of the importance of the issue of global warming, climate change and the health threat to citizens as a result of the effects of increases in T_a, future researchers are advised to consider the different patterns of planting with different plant combinations. Assessments of the cooling potential of different plant species such as shrubs, trees and their combinations in different arrangements could also benefit from further research. In addition, it is suggested that future studies examine the effects of different patterns in wind control and outdoor ventilation, as well as more complex patterns.

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