Journal of
Renewable Energy Research and Applications (RERA)

Vol. 4, No. 2, 2023, 209-224 DOI: 10.22044/rera.2022.12254.1169

Impact of Providing Shade on Outdoor Thermal Comfort during Hot Season: a Case Study of a University Campus in Cold Semi-arid Climate

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Received Date 06 September 2022; Revised Date 22 October 2022; Accepted Date 19 December 2022
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Abstract
Thermal comfort is one of the most important factors affecting the quality of outdoor space. This work investigates the effect of shade on outdoor thermal comfort during the hot season. For this purpose, meteorological measurement and questionnaire surveys are conducted simultaneously at four points of the university campus in the cold semi-arid climate of Shahrood, Iran. Then the ENVI-met V4 is validated and implemented to examine the impact of different shading scenarios on outdoor thermal comfort. The neutral physiological equivalent temperature (PET) and the upper boundary of the PET comfort range are obtained at 21.9 °C and 26.9 °C, respectively. The results demonstrate that the plant shade creates the most acceptable thermal environment. Also shading cause a significant reduction in the PET value and thermal stress, while increasing the comfort levels and the comfort hours during the sunny days. Furthermore, the simulation results indicate that creating shade in the open space by trees contribute to lower level of mean radiant temperature up to 24.79 °C and up to 13.7 °C for PET. Moreover, a maximum mitigation effect of an architectural shade is obtained at 32.6 °C for mean radiant temperature and 17 °C for PET. The highest reduction of PET (17.2 °C) is achieved by the combination of trees and the architectural shade. The outcomes of this research work provide useful design recommendations to improve outdoor thermal comfort.

Keywords: *Thermal comfort, Outdoor space, Shade, Physiological equivalent temperature, ENVI-met.*

Highlights
- Field studies and simulation model of ENVI-met V4 were conducted in sunny and shaded locations.
- The neutral PET and upper boundary of PET comfort range were obtained at 21.9 °C and 26.9 °C, respectively.
- Trees contribute to a reduction of 12.62 °C T_{mrt} and 7.6 °C PET, in average.
- A shading structure is capable of reducing 25.3 °C T_{mrt} and 13.2 °C PET, in average.

1. Introduction
Outdoor spaces involve the flow of community life and a variety of activities that bring individual advantages and healthy living. Also urban open spaces will benefit cities in various environmental, economic, and social aspects, and contribute to urban livability and vitality [1-3]. Thermal comfort is one of the most effective parameters in the quality of outdoor space [4, 5]. Therefore, many studies have experimentally investigated the effect of different parameters on the outdoor thermal comfort. Dzyuban *et al*. [6] have examined relationships between the built environment, micro-climate, and subjective thermal judgments across a city neighborhood in Phoenix, USA. Liu *et al*. [7] have compared the impact of sun and wind on outdoor thermal sensation in a cold climate city Tianjin, China. Rossi *et al*. [8] have enhanced pedestrians' thermal comfort under solar awnings through a combination of micro-meteorological monitoring and outdoor thermal comfort survey.

Furthermore, numerous studies examined various mitigating strategies such as urban geometry [9, 10] urban greening [11-16], and surfaces albedo [11, 15, 17] to improve the outdoor thermal comfort by ENVI-met simulation. Lee *et al*. [12] have performed simulations in ENVI-met for a residential district in Freiburg, Germany, to investigate the potential of trees and grasslands to mitigate human heat stress. Jamei and Rajagopalan [14] studied the effect of future structural plans including increased building height, adding tree canopy coverage, and adding green roofs on human thermal comfort in Melbourne. Salata *et al*. [11] have investigated mitigation scenarios of the urban microclimate in Rome. Different configurations, which include increasing the urban greening, implementation of a cool pavement in concrete, cool roofs, and a combination of the previous solutions, were carried out in ENVI-met. Hassan Abdallah *et al*. [18] have applied the ENVI-met model to evaluate the effect of different shading scenarios with increasing tree density and implementing a horizontal shading device on student thermal comfort in Egypt. Tan *et al*. [19] have evaluated the mitigation strategies of building setback from street associated with roadside tree planting by numerical modeling in ENVI-met in Hong Kong. Sanagar Darbani *et al*. [20] have investigated the effects of complex urban form parameters including height to width ratio, canyon orientation, tree canopy cover, and building surface materials on pedestrians' thermal comfort in the arid climate of Mashhad, Iran.

On the other hand, some research aimed to calculate the physiological equivalent temperature[1] index to examine the thermal condition in different climates. Salata *et al*. [21] have examined the outdoor thermal comfort in the Mediterranean area at the university campus in Rome. They calculated the neutral and the preferred PET values and obtained the PET comfort range. Middel *et al*. [22] have investigated the impact of photovoltaic canopy shade and tree shade on thermal comfort at a pedestrian mall at Arizona State University. Also they obtained the acceptable comfort range of PET. Canan et al. [4] have examined the outdoor thermal comfort conditions in Central Anatolia, Turkey, and calculated the PET comfort range.

Despite the knowledge acquired from all these studies, there still seems to be a gap between research and its application to outdoor space design [9]. In Iran, only recently has outdoor thermal comfort begun to be taken into account. Thus the number of research in this field is too limited. In addition, rare studies have attempted to define the PET comfort range in Iran [23]. Thus the comfort range of Western/Middle Europe[24] has been used in the previous outdoor thermal comfort studies [25-27]. Since the measurable variables (objective evaluation) and the human perception (subjective evaluation) of the thermal environment are different according to the local context, it is important to obtain the PET comfort range related to a specific region. To the best of the authors' knowledge, there is no similar study examining the effect of shade on outdoor thermal comfort by providing a specific thermal comfort range based on performing subjective and objective data in the cold semi-arid climate of Iran. Hence, the main purposes of this research work are to deepen our knowledge of to what extent shade can affect outdoor thermal comfort and determine the PET comfort range in the cold semi-arid climate of Iran.

Given the fundamental role of thermal comfort on outdoor space quality, this work contributes to fill the mentioned gaps through three major sections. At first, this paper examined the thermal environment at four locations of the university campus (plants shade, building shade, horizontal shading (canopy), and sunlight) by field studies including measurement of major climatic parameters and the questionnaire survey. Then the PET comfort range for this work has been calculated to evaluate the thermal environment more accurately. At the final step, the three-dimensional microclimatic modelling tool ENVI-met V4 was validated and implemented to investigate the impact of different shading scenarios including an architectural device, the tree canopy, and the combination of both strategies, on the outdoor thermal comfort.

2. Methods

2.1. Studied area

Shahrood city located at latitude 36° 22 'to 36° 26' north and longitude 54° 54 'to 55° 00' east is one of the cities of the Semnan province in northeastern Iran. According to the Köppen-Geiger climate classification, the climate of Shahrood is cold semi-arid (Bsk). Based on the meteorological data, the annual mean value of the air temperature is 15.2 °C. The mean maximum and minimum air temperature in the hottest and coldest months are 33.1 °C and -1.5 °C, respectively [28]. On average, the hottest and coldest months of the year are July and January, respectively. The lowest relative humidity is in August and the highest in January. The months of June to August have the highest wind speed and sun hours [29]. The average air temperature reaches its maximum between late May and early September[28].

In the current study, Shahrood University of Technology (36° 23'N, 54° 56'E) was selected for field studies. According to the focus of this study on the shade, different shaded locations at this

[1] PET

university including plant shade, building shade, and horizontal shading (canopy), as well as sunlight, in order to compare with shaded locations, were investigated. The study points needed to be located at close distances with the same surface albedo. In addition, the position of the sun and shade have not changed at the selected points during the data collection. Figure 1 shows the position of the measurement sites.

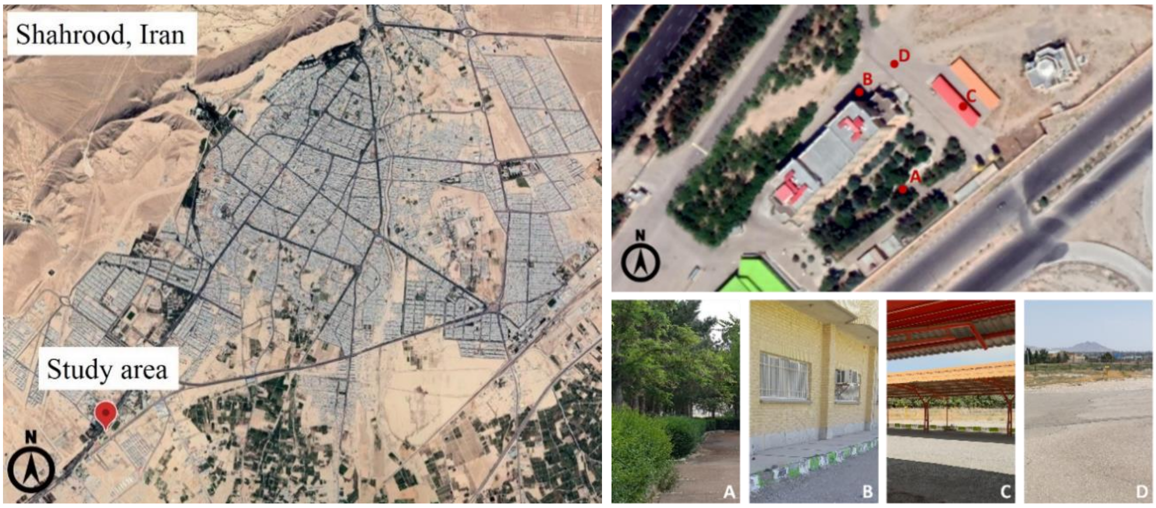

Figure 1. Measurement sites: (A) Plants shade, (B) Building shade, (C) Canopy, (D) Sunlight.

2.2. Field study

This study considered the hot season, and it required the students to participate in the questionnaire survey. The majority of students were present at the university until the late May, then on separate days until the middle of June. Thus the field studies were conducted on May 20-21 and June 17, 2019, in four outdoor spaces of the university campus simultaneously. The time frame was between 10:00 and 17:00 covering the prevailing time of students' presence at the campus.

The meteorological data was recorded on the measurement dates by the meteorological station located at Shahrood University of Technology, near the study area. HOBO RX3000 remote monitoring station data logger recorded the required data at 5-min intervals automatically. Figure 2 shows the Shahrood meteorological data on the measurement dates.

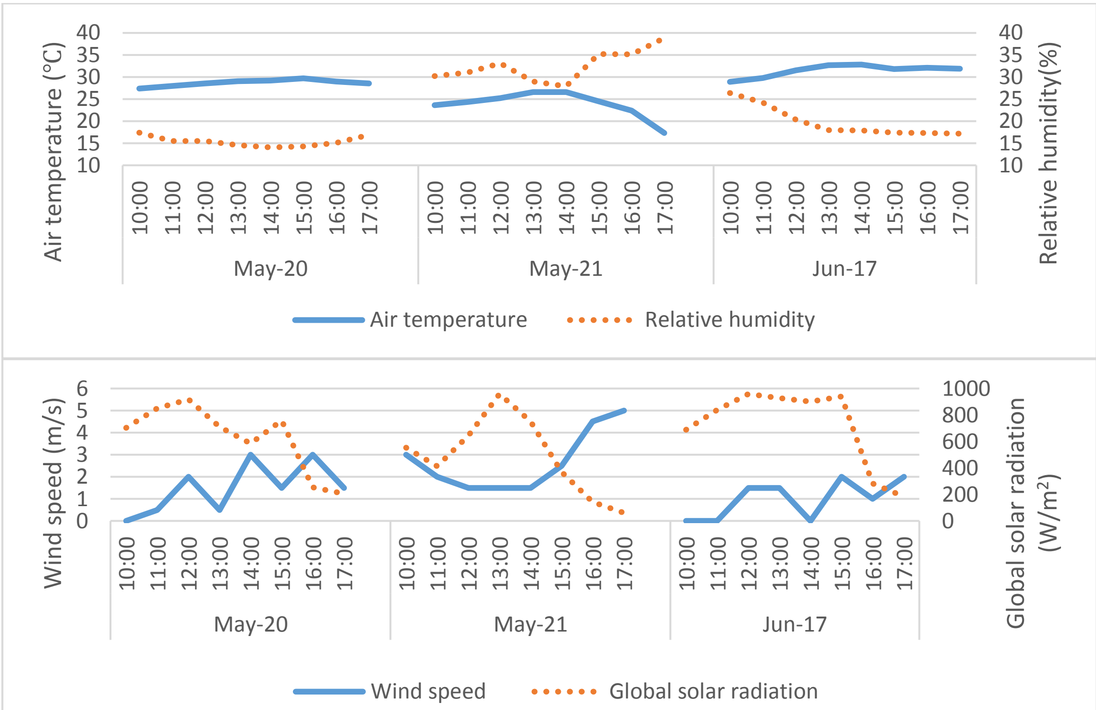

Figure 2. Shahrood meteorological data on the measurement dates.

Field studies were carried out by meteorological variable measurement and evaluating students' thermal sensation using a thermal comfort questionnaire simultaneously. The values of air temperature (Ta), globe temperature (Tg), wind speed (Va), and relative humidity (RH) at 1 min intervals were recorded by the instruments listed in table 1 at each measurement site. All instruments followed the ISO 7726[30], and were pre-tested and calibrated with the date from the meteorological station of the university.

Table 1. Specifications of measurement instruments.

Variables	Instruments	Accuracy	Height (m)
Air temperature (°C)	Onset Hobo, S-THB-M002	±0.21°C (0° to 50 °C)	GL +1.1
Globe temperature (°C)	Onset Hobo, UX100-014M	±0.7 °C ± Thermocouple probe accuracy	GL +0.6 , 1.1
Wind speed (m/s)	Hot Wire Anemometer CEM -3880. ST-3880	±(5%+1d)	GL +1.1
Relative humidity (%)	Onset Hobo, S-THB-M002	±2.5% (10% to 90%)	GL +1.1

Mean radiant temperature[1] is calculated from the observed simultaneous values of the globe temperature, air temperature, and wind speed by equation 1 [30]:

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10 \times 10^8 \times V_a^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273 \qquad (1)$$

where ε is the emissivity of the globe (0.95 for a black globe), and *D* is the globe diameter.

Questionnaires were distributed randomly among the students present in the chosen locations within the selected days. A total of 283 valid questionnaires were completed by the students. The structure of the questionnaire was organized into two parts following the relevant references [31, 32], previous outdoor thermal comfort studies [33-40], and the aim of this study. In the first section, personal characteristics (age and gender), level of activity, and type of clothing, and in the second part, information on the thermal preference, thermal sensation, and overall thermal comfort level were asked according to the climatic parameters. Thermal sensation (hot, slightly warm, neither cool nor warm, slightly cool, cold) and thermal comfort (very uncomfortable, uncomfortable, acceptable, comfortable, very comfortable) were evaluated using a 5-point scale. Also the students reported their thermal preference for each climatic parameter by a 3-point scale (increase, decrease, and no change).

The data from field studies were analyzed by EXCEL and SPSS[2] (version 20) software. The relationship between different variables was determined using the Chi-square test. In addition, the thermal environment was evaluated by the PET index and compared with the findings from human responses. Then the values of neutral PET and the PET comfort range were defined using the statistical methods for this study. Finally, numerical simulations of mitigation strategies were performed in ENVI-met V4.

2.3. Thermal index

Different indices can be used for the thermal evaluation of outdoor spaces. In this study, the PET index, which estimates thermal comfort by integrating thermal environmental factors and heat balance of the human body [41], was implemented. PET is the most widely used model, and it has consequently been found to correlate well with on-site monitoring and questionnaires [42]. Moreover, it is well-suited to the evaluation of the thermal component of different climates[43]. Thus it allows us to compare our results with other thermal comfort studies.

In order to calculate the PET index, the software package RayMan (version 1.2) was used. The climatic parameters including air temperature, relative humidity, wind speed, cloud cover, and mean radiant temperature were considered as the required input data in the software. The PET index for the female and male students was calculated separately for each measurement site and date. Since there are some clothing regulations for universities in Iran, the clothing types of females were mostly similar to each other in all positions, and the clothing types were similar for males too. The clothing insulation value was 0.98 clo for females and 0.57 clo for males according to ISO 7730 [44] and ASHRAE

[1] T_{mrt}
[2] Statistical Package for the Social Sciences

Standard 55[31]. The metabolic rate of students during the data collection procedure was 80 W/m^2, which is based on the authors' observations and the suggested values of ISO 7730 [44] and ASHRAE Standard 55 [31].

2.4. Simulation

ENVI-met, one of the most commonly used tools [11, 45, 46], was applied to simulate the studied area. ENVI-met is a three-dimensional microclimate model, which was designed to simulate the surface-plant-air interaction in an urban environment based on Computational Fluid Dynamics (CFD) model [12, 17]. Different versions of the ENVI-met have been widely employed to assess urban microclimate and thermal comfort conditions [45, 47].

In this study, a simulation domain involving 99 × 99 × 30 grids, which each grid representing 1 m in all axes, has been considered to cover the simulation area. The background meteorological data during the studied time (initial wind speed and direction as well as hourly air temperature and humidity for simple forcing setup) were extracted from the Shahrood University of Technology meteorological station. The ENVI-met default values for roughness length, specific humidity at 2500 m, and soil data were adopted. Table 2 presents the main input parameters for the ENVI-met simulation process.

Table 2. Simulation parameters.

	Variable	Setting
Domain features	Location	Shahrood University of Technology, Iran Latitude: 36° 23'N Longitude: 54° 56'E Altitude: 1330 m
	Climate	BSk
	Time zone	GMT + 3:30
	Domain size	99 × 99 × 30
	Size of grid cell in meter	1 × 1 × 1
	Model rotation out of grid north	320
Simulation timing	Date	17.06.2019
	Duration	10 h, from 8:00 to 18:00
	Output interval (min)	60
Meteorological condition	Wind speed (m/s)	1.14
	Wind direction (deg)	218.89
	Roughness length	0.01
	Initial temperature of atmosphere (k)	295.97
	Specific humidity at model top (2500 m, g/kg)	7.0
	Relative humidity in 2m (%)	35
	Cloud cover	0
Soil data	Initial temperature (K)	293 (0–20 cm), 293 (20–50 cm), 293 (> 50 cm)
	Soil wetness (%)	50 (0–20 cm), 60 (20–50 cm), 60 (> 50 cm)
Building data	Heat transmission of walls (W/m^2 K)	1.6
	Heat transmission of roof (W/m^2 K)	1.4
	Wall albedo	0.3
	Roof albedo	0.35

2.4.1. Validation of ENVI-met simulation

To validate the human-biometeorological performance of the ENVI-met model, numerical simulations on 17 June 2019 were performed for the existing condition of the studied area, where climatic data was measured. The results of the preliminary model were compared with the measured data. For this purpose, the 1-h values of measured and predicted air temperature, relative humidity, mean radiant temperature, and wind speed were examined between 10:00 and 17:00. The validation of each variable was based on 32 pairs of simulated and measurement data collected at four measuring sites. Simulation outputs were investigated at the height of 1.5 m above the ground, which approximates the human-biometeorological reference height of 1.1 m [12].

Figure 3 compares the simulated and experimentally determined values of each climatic parameter.

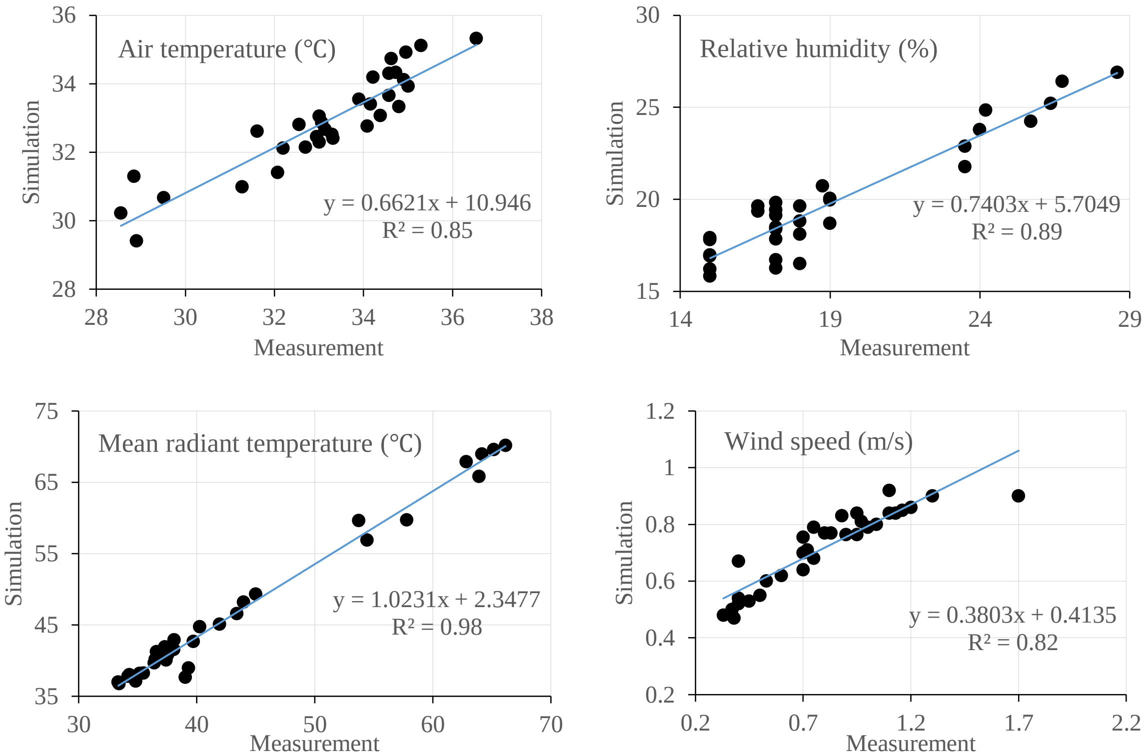

Figure 3. Correlation between values measured experimentally and provided by ENVI-met V4.

The accuracy of the ENVI-met model were determined according to the coefficient of determination (R^2), the root mean square error (RMSE), and Willmott's index of agreement (d). Obtained results have been reported in table 3.

Table 3. Quantitative measures of the performance of the ENVI-met model.

Variable	R^2	RMSE	d
Air temperature	0.85	0.89 (°C)	0.93
Relative humidity	0.89	1.62 (%)	0.94
Mean radiant temperature	0.98	3.65 (°C)	0.97
Wind speed	0.82	0.22 (m/s)	0.95

The simulation results are reliable if their parameters tend to: $R^2 \rightarrow 1$, RMSE $\rightarrow 0$, and d $\rightarrow$ 1[11]. R^2, RMSE, and d values for the studied locations revealed a strong correlation between the simulation and experimental data of all climatic parameters, with R^2 over 0.82 and d over 0.93. Thus it could be concluded that the ENVI-met model V4 can provide reasonable predictions of all climatic parameters.

2.4.2. Simulation scenarios

Once the ENVI-met model, representing the current studied area configuration, has been validated against field measurement data, it has been used to evaluate the impact of different shading scenarios on micro-climate characteristics including air temperature and mean radiant temperature. Then PET values have been calculated with the RayMan model. Figure 4 illustrates ENVI-met simulations, which were used to investigate the effect of three shading scenarios on students' thermal comfort in the entrance area of the faculty that is entirely exposed to the sun (sunlight position).

First scenario: planting deciduous trees (7 m height, 5 m crown width) by a value of Leaf Area Density (LAD) at 0.4, in three rows with a distance of 5 m.

Second scenario: architectural shade structure (35 m length, 11 m width) with a height of 4 m and concrete surfaces which has an albedo of 0.4.

Third scenario: a combination of planting deciduous trees (7 m height, 5 m crown width) by a value of Leaf Area Density (LAD) at 0.4, in two ways with a distance of 9 m, in addition to the architectural shade structure (35 m length, 9 m width) with a height of 4 m and concrete surfaces, which has an albedo of 0.4, placed between the two rows of trees.

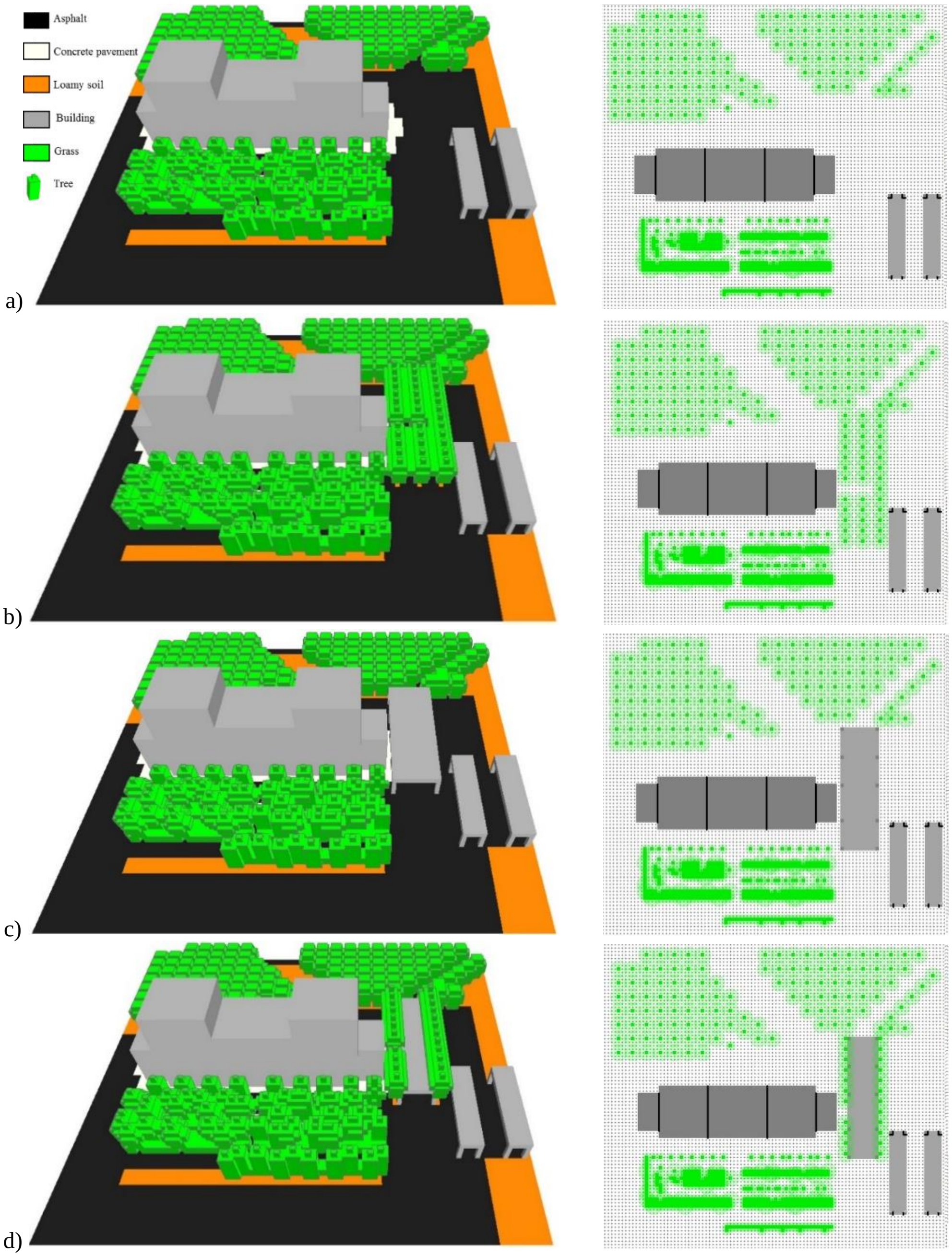

Figure 4. Visualization of the examination scenarios; a) Existing condition, b) First scenario, c) Second scenario, and d) Third scenario.

3. Results and discussion

3.1. Users responses

As mentioned, the data from the questionnaire survey was analyzed to determine the relationship between different variables. Students ranged in age from 18 to 34 years. 59% and 41% of respondents were females and males, respectively. Figure 5a. demonstrates the level of comfort mentioned by the users in each measurement site. It shows that the plants shade and sunlight provide the most comfortable and the most uncomfortable thermal conditions, respectively. According to the ASHRAE standard, an acceptable thermal environment is “a thermal environment that a substantial majority (more than 80%) of the occupants find thermally acceptable” [31]. Therefore, the plants shade with 80.9% satisfaction creates an acceptable thermal environment. Chi-square test showed a significant relationship between location and thermal comfort (p-value = 0.000 ≤ 0.05). Most people in the plants shade, canopy, and building shade (81%, 69%, 65%, respectively) found the thermal environment acceptable, comfortable, and very comfortable. Meanwhile, more than half of the respondents in the sunlight (57%) described the thermal environment as uncomfortable and very uncomfortable.

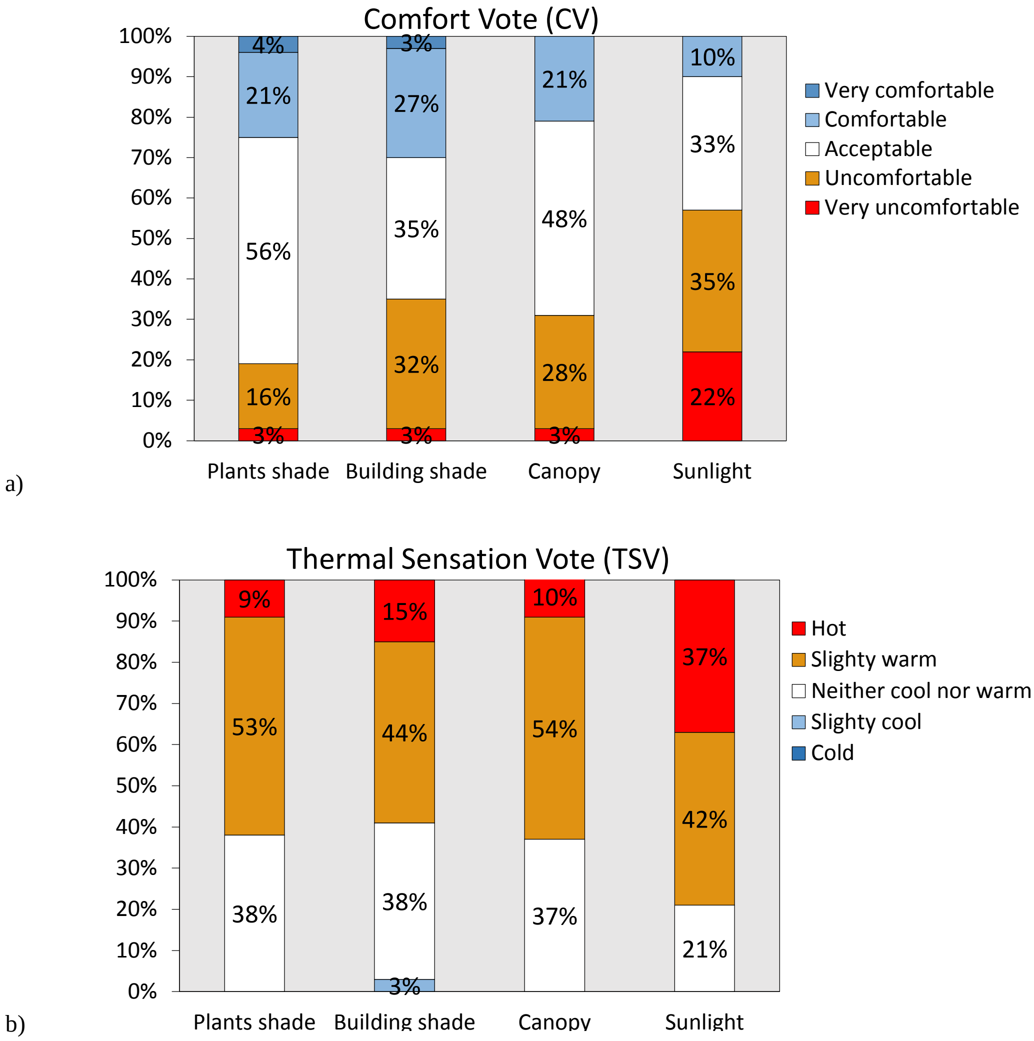

Figure 5. Distribution of (a) Comfort vote and (b) Thermal sensation vote in each measurement site.

Figure 5b shows the distribution of the thermal sensation votes. In all locations, about half of respondents described their current thermal sensation as "slightly warm" and one-third of them described “neither cool nor warm”. A comparison of the four sites showed that most of the heat was experienced by people in the sunlight (37% “hot” and 42% “slightly warm”). The neutral thermal sensation was almost equal in shaded situations, about 38% in each position, while only 21% of people had a neutral thermal sensation in sunlight. These findings show that shading has a significant effect on reducing individual thermal sensation.

-The data analysis shows a significant relationship between gender and thermal comfort level (p-value = 0.03 ≤ 0.05). Men considered the conditions more acceptable than women. 72% of men expressed that the overall thermal comfort is acceptable, comfortable, and very comfortable, while 28% felt uncomfortable and very uncomfortable. However, 61% of women described the thermal comfort as acceptable, comfortable, and very comfortable and 39% described it as uncomfortable and very uncomfortable. This is mainly because of the difference in clothing insulation values, which was significantly higher for women than men, as mentioned in Section 2.3.

-The analysis between the thermal comfort levels and the questionnaire completion time has shown that there is a significant relationship between these two variables (p-value = 0.001 ≤ 0.05). The highest rate of discomfort was at noon and afternoon, while the most amount of comfort or acceptable levels occurred before noon and late afternoon.

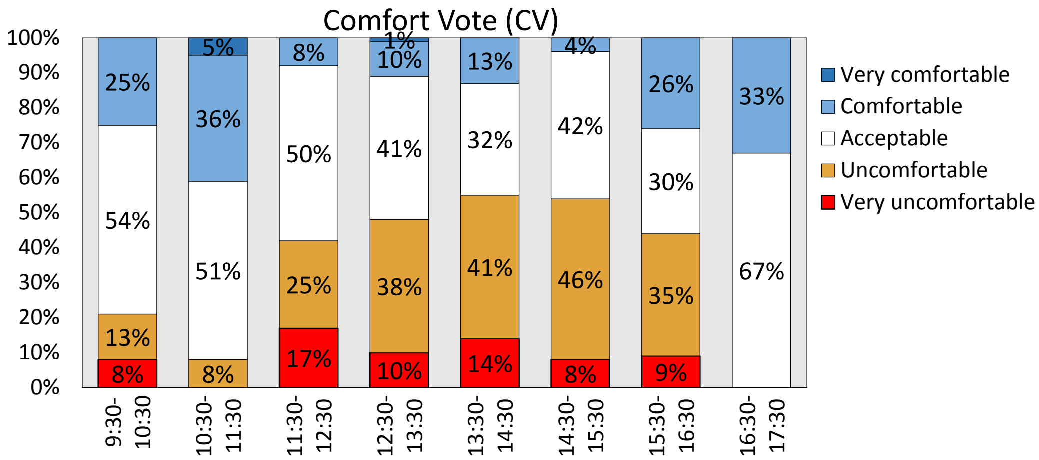

Figure 6. Distribution of the comfort levels in measurement hours.

As shown in figure 6, in the afternoon (13:30-15:30), more than half of the people described their level of thermal comfort as uncomfortable or very uncomfortable. However, in the late afternoon (16:30-17:30), all respondents were in acceptable or comfortable zone. Also before noon (10:30-11:30), the majority of them (92%) described the conditions as acceptable, comfortable, and very comfortable. These findings show that by an increase in radiation, the thermal comfort level would decrease.

3.2. PET

According to descriptions in the methodology, the PET index has been used to evaluate the thermal conditions of the selected areas. Since there is a significant relationship between gender and thermal comfort, the PET index for female and male students was calculated separately. Figure 7 shows the calculated PET in measurement dates and locations.

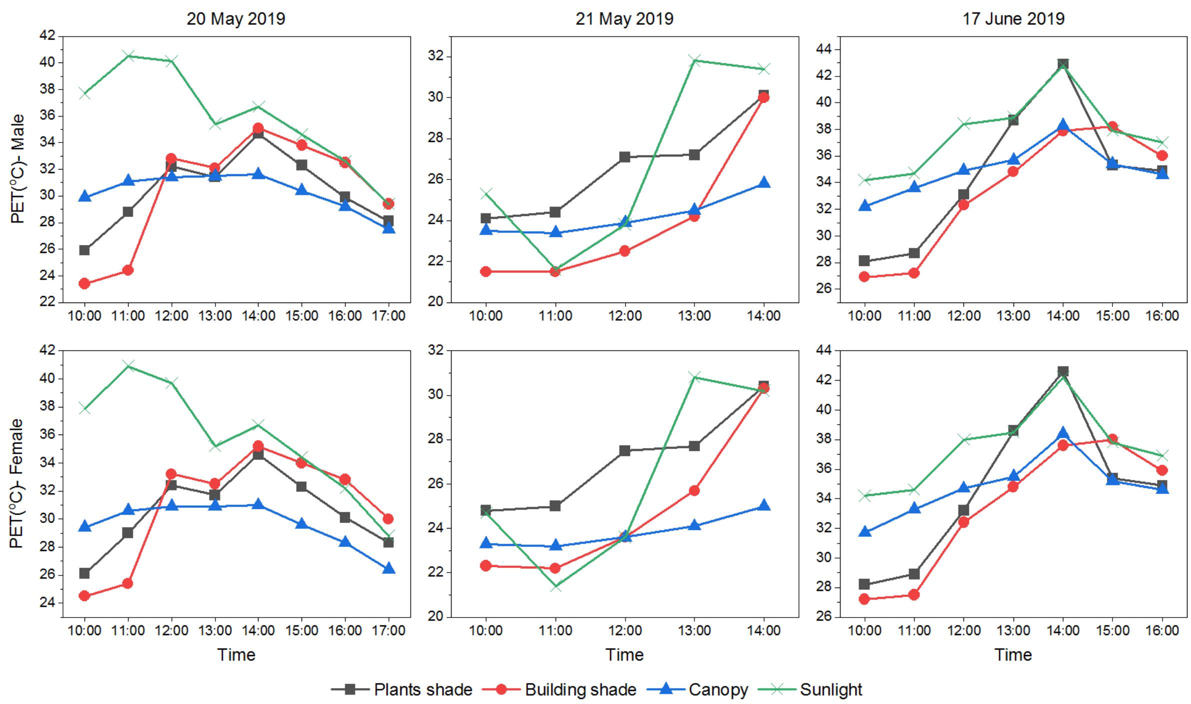

Figure 7. Calculated PET for students in the measurement dates and locations.

Figure 7 shows that the PET value in sunny hours on May 20 and June 17 in sunlight position is higher than the shaded location. This difference reaches its maximum on May 20, at 11:00, between sunlight and building shade, which is 16 ℃ for men and 15.5 ℃ for women. Shaded positions can reduce the PET value up to 16 ℃, and the average of 3.5 ℃ compared to the sunlight.

On the other hand, the most difference between the calculated PET values for men and women was recorded on May 20, at 13:00 in the building shade. In this situation, the PET for women is 1.5 ℃ higher than for men. However, in some hours there is no difference in the PET value calculated for men and women.

Comparison among measurement dates reveals that the lowest value of PET (25.43 ℃) belongs to May 21 when the diurnal air temperature had the minimum amount (20.4 ℃). On June 17, by increasing temperature, the average value of PET had the highest value. As shown in table 4, the maximum difference between the mean PET values on the data collection days is about 10 ℃ between May 21 and June 17.

Table 4. Mean PET values and air temperature on measurement days.

Measurement date	Mean PET values during measurement hours	Mean air temperature during measurement hours
May 20	31.61 ℃	26.92 ℃
May 21	25.43 ℃	20.4 ℃
June 17	35.08 ℃	31.74 ℃

Descriptive analyses show that there is a significant relationship between the PET and peoples' thermal sensation (p-value = 0.000 ≤ 0.05). In the hot season, an increase in the PET value leads to a warmer thermal sensation. Also there is a significant relationship between the PET and thermal comfort level (p-value = 0.000 ≤ 0.05). The thermal comfort level would decrease by an increase in the PET value (reverse correlation).

3.3. Neutral PET and PET comfort range

Comparisons between human responses and the field study results show that there is a significant relationship between the individual thermal sensation and PET values. Several studies determined the value of the neutral PET by regression analysis between TSV and PET [48]. Since thermal sensation varies greatly among subjects even in the same thermal conditions (i.e. at the same PET value), mean thermal sensation votes (MTSVs) were calculated according to 1 ˚C wide PET intervals[4, 48-50]. Figure 8 shows the MTSVs reported by the responses and the corresponding values of PET with considering intervals of 1 ˚C.

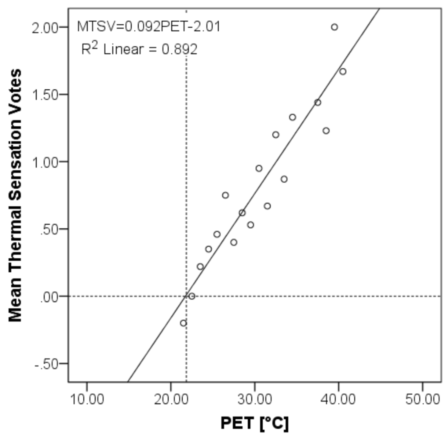

Figure 8. Correlation between the binned MTSVs and PET during the hot season.

The neutral PET value can be determined using figure 8. The neutral PET is the temperature that corresponds to the mean vote of neutral on the thermal sensation scale, i.e. the temperature at which people feel neither cold nor warm [4, 48, 50]. This value was 21.9 ℃ for this study that obtained setting a mean thermal sensation vote (MTSV) of 0 in equation 2:

$$\mathrm{MTSV} = 0.092PET - 2.01 \qquad R^2 = 0.892 \qquad (2)$$

The thermal comfort range with 80% acceptability represents a PET range in which 80% of people feel comfortable (i.e. ≤ 20% of occupants evaluate the thermal environment as unacceptable) [50]. To understand the individual thermal unacceptability under different PETs, the thermal unacceptable rate according to 1 °C wide PET intervals was calculated using logistic regression, and has been shown in figure 9. An unacceptable rate is defined as the proportion of the unacceptable vote accounted for the total votes [49].

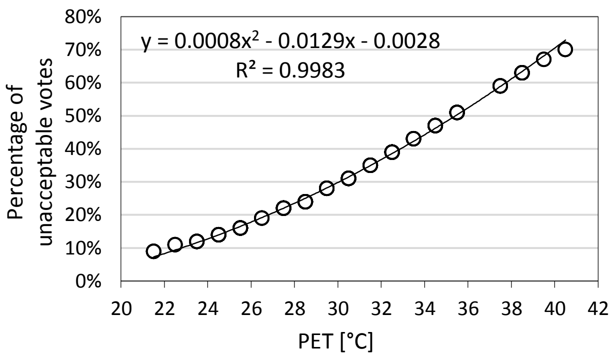

Figure 9. Relationship between the thermal unacceptable rate and PET.

The 80% acceptability limits are the intersections of the fitted curve and the 20% unacceptability line [50]. Since this study was conducted in the hot season, the lower boundary of the PET comfort range is not calculable but the upper boundary of the PET comfort range is 26.9 ℃.

Table 5 shows the PET thermal comfort range calculated in various studies.

Table 5. PET comfort range in other studies.

Location	Season	PET comfort range (℃)	Reference
Western/Middle Europe	Whole year	18-23	Matzarakis and Mayer, 1996 [24]
Guangzhou, China	Whole year	18.1-31.1	Li *et al*. 2016 [49]
Taichung, Taiwan	Whole year	21.3-28.5	Lin, 2009 [51]
Tianjin, China	Whole year	11-24	Lai *et al*., 2014 [36]
Rome, Italy	Whole year	21.1-29.2	Salata *et al*., 2016 [21]
Tempe, USA	Whole year	19.1-38.1	Middel *et al*., 2016 [22]
Cairo, Egypt	Hot month (June) Cold month (December)	22-30 21-29	Mahmoud, 2011 [52]
Konya, Turkey	Summer	21.6-32	Canan *et al*., 2018 [4]

The upper boundary of the PET comfort range of this study (26.9 °C) is close to that of Taichung, Taiwan (28.5 °C) but significantly lower than that in Tempe, USA (38.1 °C). This could be mainly explained according to the highest value in monthly mean air temperature. Shahrood has a monthly mean air temperature of 5-29.9 °C, and Taichungs' monthly mean air temperature ranges from 16.2 °C to 28.5 °C; meanwhile, people in Tempe are exposed to a warmer climate with a monthly mean air temperature of 11-34.9, which led them to have warmer PET comfort range. Also the thermal comfort range in this study is higher than in Western/Middle Europe (18-23 ℃) due to the colder climate (monthly mean air temperature 2–20ºC). These results indicate that people in different areas present different thermal requirements; resulting from climate adaptation. Also clothing insulation value in this study (as described in Section 2.3) was different from other mentioned studies. Thus different clothing types might be effective in the PET comfort range but needs more research to conclude more accurately.

According to the maximum value in the PET comfort range for this study and figure 7, it can be indicated that on May 20, the plants shade and the building shade create the thermal comfort conditions at 10:00 and from 10:00 to 11:00, respectively, for both groups of males and females. Also there is a comfortable condition in the canopy for females in the late afternoon (17:00). On May 21, all locations create the thermal comfort conditions before noon (10:00-11:00) for males and females. The sunlight and the building shade create thermal comfort until 12:00 and 13:00, respectively. The canopy was in the thermal comfort range during the measurement time. According to an increase in the air temperature on June 17, only the shade of the building provides thermal comfort at 10:00 for men. There is no thermal comfort in other locations during the measurement time. These findings indicate that shaded locations reduce the PET value on sunny days that leads to a decrease in the thermal stress during the hot season.

3.4. ENVI-met simulation results

Based on the findings from field studies, it is clear that the sunlight position needs to be shaded to create a more comfortable condition. Thus the impact of shade on microclimate and human thermal comfort has been evaluated by analyzing the consequences on the variation of T_a, T_{mrt}, and PET during the daytime (8:00 to 18:00) for the existing condition and shading scenarios.

The values of T_a during the daytime are reported in figure 10. The diurnal difference in T_a value is reduced by 0.93 °C under the tree canopy, 1.09 °C under the architectural shade, and 1.16 °C under the tree and architectural shade compared to the existing situation, although the highest reduction in all mitigation scenarios was recorded up to 1.6 °C.

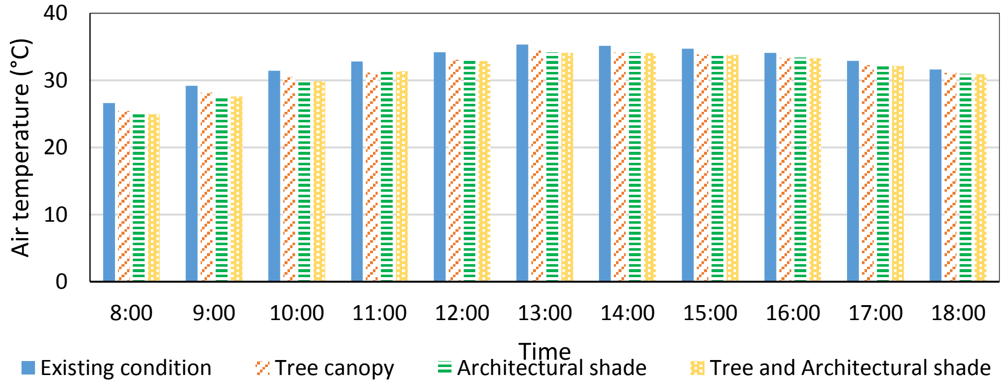

Figure 10. Distribution of air temperature in the existing and mitigation scenarios.

Figure 11 illustrates the distribution of T_{mrt} at 12:00 for the existing and shading scenarios. The values of T_{mrt} in a specific point from 8:00 to 18:00 have been compared in figure 12 to determine the effect of mitigation strategies. The extracted results indicate that trees can provide an environment with a lower T_{mrt} by an average of 12.62 $^{\circ}$C and a maximum of 24.79 $^{\circ}$C at 16:00, whereas an extended cooling effect is created by an architectural shade as well as the combination of tree and architectural shade that decline T_{mrt} by 25.3 $^{\circ}$C on average and a peak of 32.6 $^{\circ}$C at 8:00.

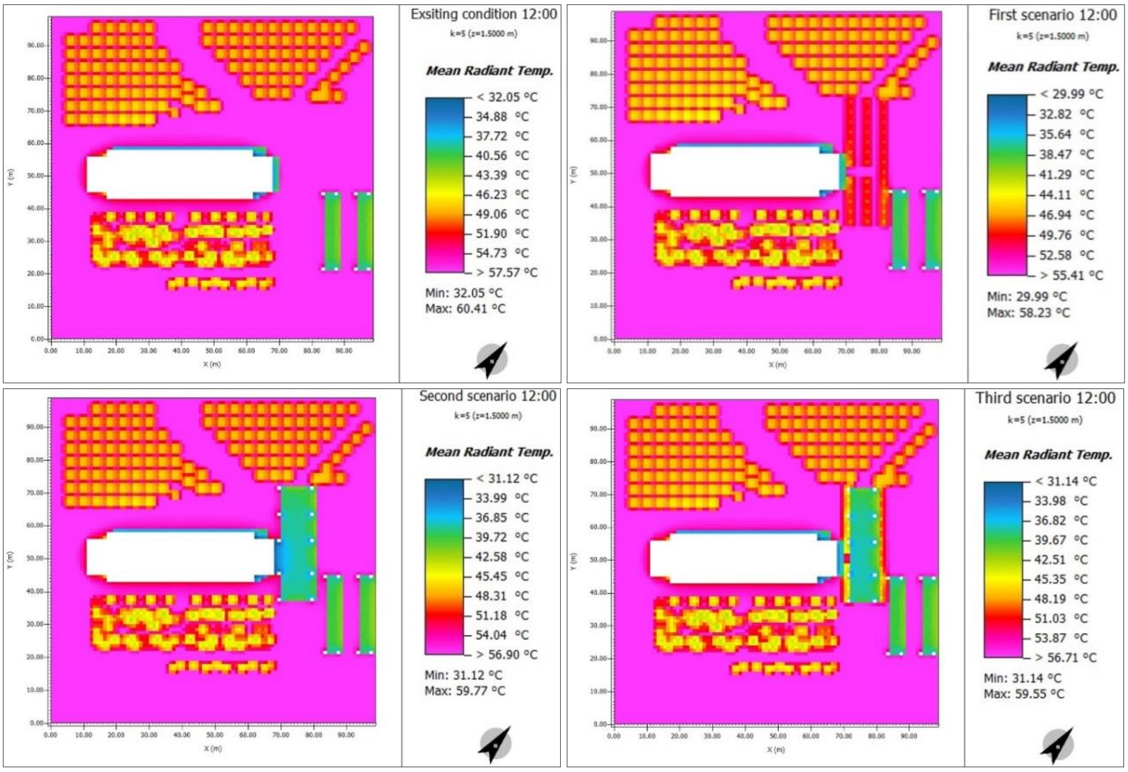

Figure 11. Spatial distribution of T_{mrt} at 12:00 (Z = 1.5 m) for the existing and shading scenarios.

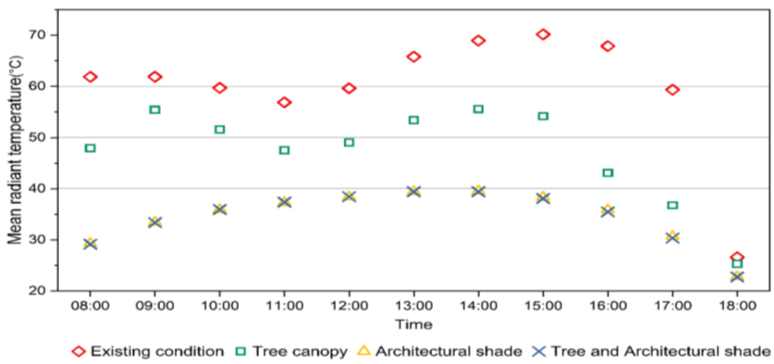

Figure 12. Values of mean radiant temperature for existing and examined scenarios.

PET values of scenarios were determined by the input data for male students (as described in Section 2.3) in the RayMan software. Similar to the reduction in T_{mrt}, PET is also significantly different between existing condition and shading scenarios. The diurnal mean PET value is 45.6 $^{\circ}$C in the current situation, while this value drops to 38 $^{\circ}$C by the first scenario and 32.4 $^{\circ}$C by the second as well as the third scenario. As illustrated in figure 13, the combination of the tree and the architectural shade leads to the largest drop in PET values up to 17.2 °C at 15:00. Also creating the architectural shade has a similar effect which causes the highest reduction of 17 $^{\circ}$C at 15:00. The maximum decrease caused by the trees was recorded at 13.7 $^{\circ}$C. As demonstrated, the variations for T_{mrt} and PET are more noticeable than for T_a.

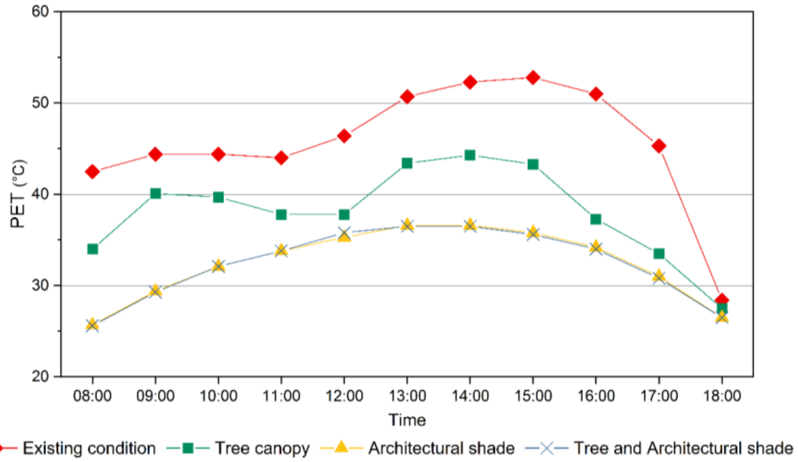

Figure 13. Variation of PET for the existing and shading scenarios.

The findings of this study reveal the impacts of shade on outdoor thermal comfort improvement at the pedestrian level during the hot season that is in good agreement with previous studies[18, 53-57]. Also it is observed that an architectural shade creates a cooler environment than trees. It could be accompanied by trees but there is a negligible difference in improving thermal comfort between these two strategies.

4. Conclusions

This study seeked to find the relation between shade and outdoor thermal comfort during the hot season. Field studies including measurement of major climatic parameters and the questionnaire survey were conducted in sunlight and three different shaded locations at the university campus in Shahrood, Iran. Also the new PET comfort range was calculated for this study. Furthermore, different shading strategies were determined to evaluate the cooling effect of shade in sunlight position using the ENVI-met V4 simulation model. The findings can be summarized as follows:

-It was found that there was a noticeable relationship between location and thermal comfort. The sunlight location with unsatisfactory percentages of over 50% of users causes uncomfortable thermal conditions, while the plants shade provides an acceptable thermal environment with a satisfaction rate of over 80%. Also the canopy and the building shade provide environmental satisfaction for the majority of people who were present in these areas.

-Regression analysis between MTSVs provided by the subjects and the corresponding PET values were implemented to calculate the neutral PET value of 21.9 °C. Moreover, the upper boundary of the PET comfort range has been determined 26.9 °C according to the thermal comfort range with 80% acceptability, higher than that in Western/Middle Europe (18-23 °C) indicating that people in different regions have different thermal requirements.

-The findings show that current shaded locations reduce the thermal sensation, thermal stress, and PET (3.5 °C on average and a maximum of 16 °C for this study) due to preventing direct solar radiation and create a cooler environment than the sunlight. Also during the hot season, with an increase in PET, the thermal comfort level would decrease. Therefore, high levels of shade in the outdoor space lead to an increase in comfort levels and comfort hours during the day.

-The shading scenarios have a significant effect on reducing T_{mrt} values. The tree canopy has contributed to a lower level of the diurnal mean T_{mrt} (47.26 $^{\circ}$C) compared to the existing condition (59.88 $^{\circ}$C). There is a similar trend in decreasing T_{mrt} as a result of creating an architectural shade as well as a combination of trees and architectural shade that could provide a cooler environment by T_{mrt} of 34.6 °C approximately.

-The diurnal average of PET was improved by 7.6 °C and 13.2 °C as a result of cultivating trees and the implementation of the architectural shade, respectively. The identical value to the architectural shade was obtained by the combination of the trees and the architectural shade. It illustrates that creating shade by manmade shading devices has a more noticeable effect in mitigating thermal discomfort than just planting trees.

Future developments of the research will extend the survey to the cold season as well as different climate regions to expand the findings.

5. Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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