International Journal of Architectural Engineering & Urban Planning, Volume 34, Number 2, 2024
DOI: 10.22068/ijaup.833

Research Paper

Impact of Design Composition of Canyon Layout, Greenery, and Cool Surfaces on Outdoor Thermal Comfort in Hot-Dry Climate

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Received: January 2024, **Revised:** June 2024, **Accepted:** June 2024, **Publish Online:** June 2024

Abstract
Urban densities are prone to the urban heat island (UHI) effect, resulting in decreased outdoor thermal comfort for the growing urban populations in hot and dry climates. Canyon layout, surface materials, green cover, and ground moisture can alter the outdoor microclimates of urban canyons at the canopy layer. While the isolated impact of urban cooling strategies is researched extensively, the integration of these UHI mitigation strategies into design compositions for complex projects has yet to be thoroughly examined. This study explores the impact of six different design scenarios for the redevelopment of the entry canyon for the Afifabad garden in Shiraz during the hottest and coldest times of the last decade. The design scenarios include the final proposed and past layouts of the site, along with four interim scenarios introducing feasible compositions of greenery and cool surfaces. The ENVI-met model of the site is validated by field measurement data from 2021, and then used to simulate all six scenarios for the hottest and coldest days of a typical year. The predicted mean vote (PMV) and physiological equivalent temperature (PET) values were calculated from the simulation results and evaluated to identify the most feasible and impactful design compositions. Findings indicate that high albedo pavements were not effective in isolation (scenario 4) and led to an increase in the mean radiant temperature (MRT). Street trees and vegetation were the most influential isolated measures, resulting in a 2.61°C variation in PET. The most impactful results were related to the combined effect of trees, turf, and cool surfaces, which resulted in up to an 11.3°C variation in PET due to the combination of appropriate greenery, shading over surfaces, and cool covers. Understanding the details of the impact of design configurations, when addressing heat stress adaptation in cities, enables the implementation of UHI mitigation strategies into feasible urban retrofit and regeneration projects.

Keywords: *UHI Mitigation, Mean Radiant Temperature, Cool Paving, Urban Greenery, Design Compositions.*

INTRODUCTION

The population of urban areas is predicted to increase to 68% by 2050 (United Nations, Revision of World Urbanization Prospects 2018). This means 6.4 billion people will be living in cities, expecting an increased quality of life and comfort (Fong et al., 2019). However, with global warming progressing faster than initially predicted (Brysse et al., 2013) and the formation of the urban heat island (UHI) effect leading to increased urban temperatures compared to their pre-urban surroundings, such comfort and quality of life in cities are under threat. It is now well-established that the UHI effect is a common phenomenon in cities worldwide, resulting in temperatures up to 12 degrees higher in denser, more developed, and less green urban settings compared to their surrounding rural or even suburban areas (Han et al., 2022; Santamouris and Vasliakopoulou, 2022). Increased demand for indoor cooling, reduction in air quality, and diminished outdoor thermal comfort are common results of the UHI effect (Zhao et al., 2018).

Outdoor thermal comfort is complex due to the impact of physical, physiological, and psychological

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parameters of open spaces and their participants (Nikolopoulou, 2004). Physically, outdoor thermal comfort may be affected by local climate, microclimates, surface covers, landscape, greenery, and shading. Different areas in cities, suburbs, and even public spaces in close proximity may experience significant variations in microclimate parameters of air, surface, and mean radiant temperatures, consequently impacting the outdoor thermal comfort of participants (Errel et al., 2010; Gartland, 2008; Haddad, Paolini et al., 2018).

Meanwhile, outdoor thermal comfort is more subjective to individuals with different climate expectations, perceived control over the environment, past experiences, physiological states, and psychological specifications compared to indoor environments (Nikolopoulou and Steemers, 2003). There is more limited exposure time outdoors compared to indoor environments, and dynamic changes in microclimate parameters such as mean radiant temperature (MRT) and wind speed result in variations in perceived thermal comfort over relatively short periods (Szűcs, 2013; Abdollahzadeh and Biloria, 2021). Individual expectations of outdoor spaces, relative to seasonal and daily cycles and cultural norms (Taleb and Taleb, 2014), only add to the complexity of outdoor thermal comfort, resulting in an extended outdoor thermal comfort range compared to indoors (Sharifi and Boland, 2018). Outdoor thermal comfort can enhance the user experience when attending public spaces (Lenzholzer, 2012), especially for outdoor activities that are optional, such as exercise, dining, and meeting others (Gehl, 2011; Gehl and Svarre, 2013).

In outdoor environments, building mass, heat-trapping geometries, and a lack of natural landscapes can contribute to an additional form of heat load in urban heat islands. Such outdoor spaces tend to absorb more solar energy than pre-urban settings, causing a delay in the heat exchange between the urban space and its surrounding atmosphere (Oke, 2006). During the hot summer months, this alteration of heat exchange may cause extended heat stress during consecutive days (i.e., summer heatwaves), posing a threat to human health and the stability of urban infrastructures (Santamouris, Cartalis et al., 2015).

In this paper, six different cooling intervention scenarios, including a range of feasible combinations of UHI mitigation strategies, are evaluated for the entry parade of Afifabad Garden.

Historical towns and vernacular settlements in hot and dry climates are known for their use of local building materials, greenery, and water to provide cool retreats in harsh environments. Increased human interventions in urban settings, such as the introduction of impervious pavements and roads, reduction of vegetation, and increased building mass, have resulted in changes to urban microclimates (Santamouris, 2015), affecting urban ecosystem services (Padmanaban et al., 2019). Therefore, mitigating the UHI effect in cities with high density, hard impervious layers, and dense building materials is crucial for the sustainability and livability of urban settings (Faragallah and Ragheb, 2022; Liao et al., 2021).

A high percentage of urban areas are covered by impervious and unreflective dark surfaces such as asphalt and paving. This is known to cause increased urban surface temperatures, especially on hot summer days (Madhumathi et al., 2018; Elmarakby et al., 2021). Cool surfaces and urban greenery are highlighted as the main design countermeasures to mitigate the urban heat island effect in cities (Akbari and Muscio, 2015; Santamouris, Ban-Weiss et al., 2018).

Advances in cool and permeable surface covers

Urban space surface materials have been shown to impact the microclimate around them (Akbari et al., 2001; Atwa et al., 2020). Cool paving materials have high albedo to reflect solar radiation, high emissivity to emit stored energy in their mass more efficiently (Faragallah and Ragheb, 2022), or increased permeability to allow evaporative cooling through the surface (Anupam et al., 2021).

The properties of cool paving materials have been modified to achieve low thermal conductivity and heat capacity, higher solar reflectance from the surface, and higher heat emittance. These modifications reduce the stored energy in the materials' mass and enable them to emit stored heat faster than conventional surfaces (Anupam et al., 2021; Yenneti, 2020; Hendel, 2016). Cool surfaces come in various types and colors and can be achieved by applying cool coatings on existing surfaces or incorporating reflective aggregates into new paving materials (Faragallah and Ragheb, 2022; Anupam et al., 2021). Cool paving can be achieved through the application of:

- High-reflective coats on existing surfaces
- Infrared (IR) reflective coat on existing surfaces
- Spectral (selective) reflective coat on existing surfaces
- Thermochromic coat on existing surfaces
- Near-infrared nanoparticle coating on existing surfaces
- Any of the above heat-reflective aggregates in the mix for new surface materials

Thermochromic cool red coating has been shown to reduce the surface temperature of asphalt by 13°C

(Anupam et al., 2021) and parks by 12°C (Santamouris et al., 2012). However, issues such as visual glare and ultraviolet reflection need to be addressed when applying high-reflective coatings in public spaces (Cheela et al., 2021).

Relying on evaporative cooling, permeable surfaces allow infiltration of surface water into the ground and evaporation of moisture, which cools down surfaces exposed to solar radiation (Drake et al., 2013). The dual impact of permeable surfaces facilitates better stormwater management during wet seasons while providing cooler urban environments during hot and dry seasons (Li, 2012). Permeable urban surfaces can be achieved using permeable (pervious or porous) materials such as permeable asphalt or incorporating open joints and voids in the construction details of conventional pavements (Anupam et al., 2021; USEPA, 2008). The presence of moisture in or below permeable surfaces, and the facilitation of evaporation from the surface, contributes to surface cooling as temperatures increase (Santamouris, 2014; Aletba et al., 2021). However, the cooling effect of permeable surfaces is highly dependent on the availability of surface moisture and the local climate. Their cooling capability, up to 15°C (Li et al., 2013), can be compromised by a lack of moisture supply or blockage of permeability over time (Osmond and Sharifi, 2017).

Urban greening and cooling

The literature highlights multiple benefits of trees and vegetation, including reducing noise levels (Van Renterghem et al., 2012), improving air quality (Jim and Chen, 2008), increasing social interaction (Elings, 2006), and enhancing outdoor thermal comfort (Wang and Akbari, 2016). Urban greenery has been shown to reduce the UHI effect (Gunawardena et al., 2017; Li et al., 2020) and improve thermal comfort in hot and dry climates (Jamei and Rajagopalan, 2016; Lachir et al., 2017). The cooling effect of vegetation mainly results from shading and evapotranspiration:

- Shading: The shade provided by trees can limit the exposure of open space surface covers to solar radiation, resulting in a reduction of surface, mean radiant, and ambient temperatures (Afshari, 2017; Tan et al., 2017; Taleghani, 2018; Shahidan et al., 2012).
- Evapotranspiration: The process of evapotranspiration in trees and other urban vegetation effectively reduces urban temperatures by utilizing solar energy for photosynthesis. By increasing the latent heat flux, trees use this energy to cool the environment (Susca et al., 2011; Bachir et al., 2021; Wong and Yu, 2005; Coutts et al., 2016).

The biological and physical characteristics of tree species, including their geometric parameters, evapotranspiration rate, leaf area, leaf density, color, and soil moisture, can impact the cooling effect of urban greenery, resulting in temperature reductions ranging from 5°C to 25°C on the surfaces below tree canopies (Cheela et al., 2021; Greene and Kedron, 2018).

Application of microclimate simulation tools

The use of microclimate simulation tools is economically viable for saving resources and time compared to the traditional practice of speculation, trial, and measurement (Sailor and Dietsch, 2007). These tools help to better understand the impact of spatial configurations on outdoor thermal comfort in existing and proposed urban settings (Liu, Hu, and Liu, 2020). Their ability to handle the non-linearity and complexity of microclimate systems makes simulation increasingly popular for testing spatial and landscape scenarios for urban development and infill projects before the construction phase (Jamei et al., 2019).

Rayman, ENVI-met, the ANSYS package, CitySim Pro, and Grasshopper’s Ladybug/Honeybee plug-in have been used in recent years to perform urban microclimate simulations. ENVI-met, SOLWEIG, RayMan, and their combinations have been widely applied to project outdoor microclimates (Kleerekoper et al., 2017; Lee and Mayer, 2016; Yin et al., 2019). Among them, ENVI-met offers the most comprehensive list of outputs, including air, surface, and mean radiant temperature, relative humidity, air speed and direction, surfaces' energy flux, soil, and greenery measures (Thorsson et al., 2014; Paramita and Fukuda, 2018; Liu et al., 2021; Ouyang et al., 2022). It is capable of simulating the impacts of changes in the albedo and emissivity of various surfaces and plants (Jänicke et al., 2015), as well as the effects of building density and arrangement, street canyon design, and urban greening (Lam et al., 2021).

Accuracy of the findings and deviation from site measurements

ENVI-met is extensively validated in the literature (Lam et al., 2021; Yao and Fricker, 2021; Pignatta et al., 2018; Lopez-Cabeza et al., 2022). However, like any other simulation tool, ENVI-met can produce outputs that deviate from site measurements. Differences between modeled and measured data tend to be higher when airflow directions change rapidly, when global radiation varies during the diurnal cycle, and during extreme hot environments exposed to intense solar radiation (Acero and Arrizabalaga, 2018; Tsoka et al., 2018; Jamei et al., 2019). New features in façade and rooftop greening still require systematic evaluation (Ouyang et al., 2022), similar to the impact of grass under tree canopies and green walls on façades (Tsoka et al., 2018). Additionally, ENVI-met performance has been evaluated mostly in warm conditions (Tsoka et al., 2018).

Despite existing knowledge on urban cooling strategies and the capability of urban microclimate simulation tools in predicting the impact of proposed design measures, complex design proposals for real-world projects involving combinations of urban cooling strategies are scarcely explored. Some cooling measures may enhance or compromise the impact of other strategies when applied together (Peluso et al., 2022). This is crucial for architects, landscape, and urban designers to better understand the combined impact of feasible cooling strategies for real-world projects. In this study, we explore to what extent complex spatial and landscape configurations can affect the cooling effect of greenery and cool surfaces in hot and dry climates.

METHODOLOGY

Case study of Afifabad entry plaza

In this paper, we focus on studying the entry plaza of Afifabad Garden in Shiraz. Afifabad Garden was chosen as a case study due to its upcoming development plans for the entry plaza using cooling strategies, and its reputation in the local community for having cooler microclimates compared to its surrounding medium density residential and mixed-use developments.

Shiraz is situated at an altitude of 1500 meters above sea level, spanning approximately 340 km², located at 29°53′N, 52°58′E, and surrounded by the Zagros mountain range in Iran. The city experiences a balanced climate characterized by four distinct seasons (Sarvestani et al., 2011). Afifabad Garden is positioned in the Central North of Shiraz, with its entry plaza covering an area of 6000 m². Previously, the plaza was entirely covered with dark asphalt up until 2015. In 2018, changes were made, converting the footpath area into stone paving with the addition of a central pool, while maintaining the existing greenery. The Afifabad entry plaza is frequently utilized for social events and is encircled by private gardens. The recent and proposed redesigns of this site make it particularly insightful for our study (see Figure 1).

Firstly, design scenarios for the Afifabad plaza site were developed and simulated using appropriate tools. Following simulation, (PMV) and (PET) scores were calculated at selected receptors within the plaza. Finally, the overall performance of these design scenarios was analyzed, compared, and discussed.

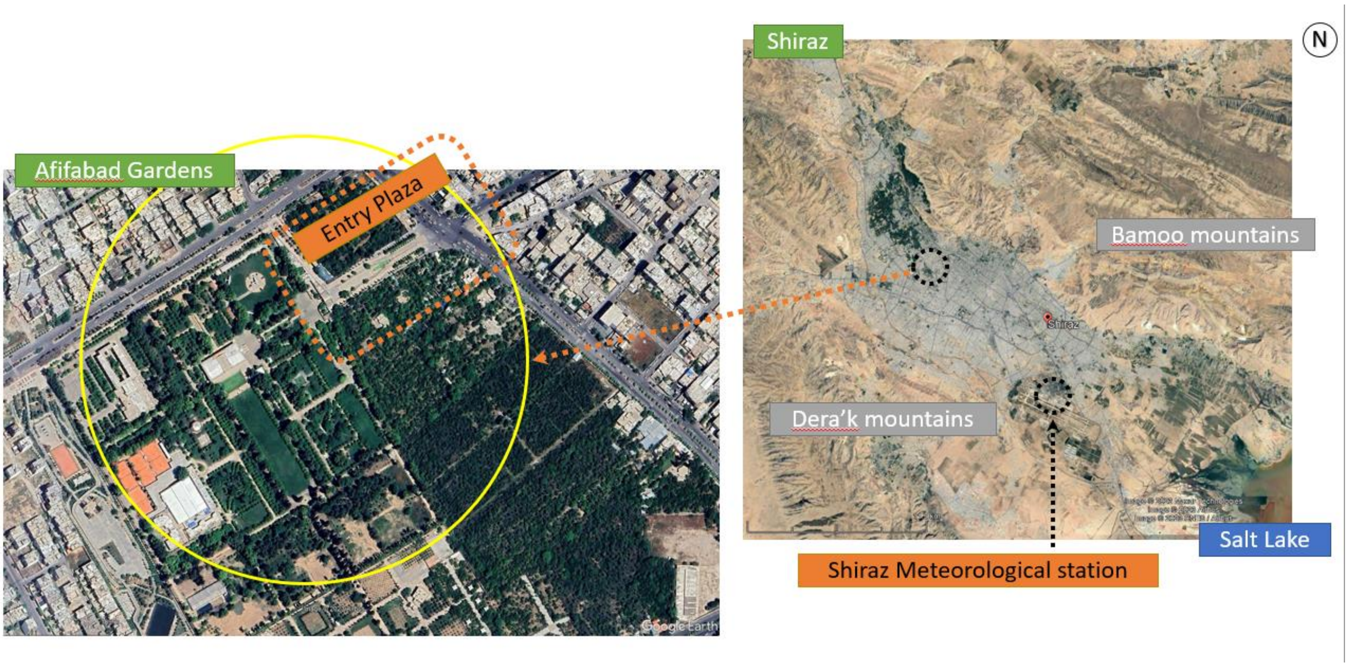


Fig 1. Afifabad Gardens in Shiraz and airport meteorological station (Google Earth Pro, 2023)

Simulation in ENVI-met and `Rayman

In this study, ENVI-met version 5.0.1 was employed to simulate design scenarios for the Afifabad plaza on the hottest day of 2020 (13/07/2020) and the coldest day of 2020 (04/02/2020). ENVI-met was used to calculate the Predicted Mean Vote (PMV) values, while Rayman software, developed by Matzarakis et al. (2007), was utilized to calculate the Physiological Equivalent Temperature (PET).

The entries in the ENVI-met Biomet tool were configured based on ISO 7730 standards, which define the thermal comfort conditions for humans (ISO 7730, 2005). The Biomet tool calculates the energy balance of the human body and assesses the thermal sensation experienced by individuals exposed to specific environmental conditions.

Tables 1 and 2 (a-c) present the input data used for summer and winter simulations. Specifically, Tables 1-a and 2-a detail the meteorological and geographic data input into ENVI-met, sourced from Shahid Dastgheib International Airport (Shiraz International Airport) on the hottest and coldest days of 2020.

For PET calculations using Rayman software (Table 4-c and 2-c), parameters such as clothing insulation values (0.9 for summer and 2 for winter) and metabolic activity levels (80 W for walking in summer) were considered, adhering to ISO 7730 guidelines (ISO 7730, 2005). PET is based on the Munich Model of Energy Balance for Individuals (MEMI), which models the physiological thermodynamic balance of humans (Ali-Toudert and Mayer, 2006).

Table 1. Input data for summer simulation

(a)- ENVI-met input data for simulations	
Simulation days	12-13 July 2020
Starting time	22:00 pm
Simulation Period	26 hours
Wind speed at 10m	2.4 m/s
Wind direction	255.29 °
Air temperature	Min. at 01:00 AM 22.5° C
	Max. at 11:00 AM 41.34° C
Relative humidity	Min. at 11:00 AM 4.21%
	Max. at 02:00 AM 31.54° C
Number of grids (x, y, z)	(50, 20, 15)
Size of x, y & z grid cells	3, 3, 2

(b)- Personal Human Parameters			
Body Parameters			
Age of person (y):	35	Gender:	male
Weight (kg):	75.00	Height (m):	1.75
Surface Area (DuBois-Area):	1.91 m2		
Clothing Parameters			
Static Clothing Insulation (clo):	0.90		
Persons Metabolism			
Total Metabolic rate (W):	164.49 (=82.21 W/m2)		
(met):	1.48		

(c) - Rayman input data for calculating thermal comfort		
Clothing insulation		0.9 (Iso 7730)
Activity		80 W (walking)
	Height (m)	1.75
	Weight (kg)	75.00
	Age(y)	35
	Sex	male

Table 2. Input data for winter simulation

(a)- ENVI-met input data for simulations	
Simulation days	03-04 February 2020
Starting time	22:00 pm
Simulation Period	26 hours
Wind speed at 10m	0.87 m/s
Wind direction	176.96 °
Air temperature	Min. at 00:00 AM -5.74° C
	Max. at 12:00 AM 10.19° C
Relative humidity	Min. at 10:00 & 13:00 AM 19.70%
	Max. at 11:00 PM 73.64 %
Number of grids (x, y, z)	(50, 20, 15)
Size of x, y & z grid cells	3, 3, 2

(b)- Personal Human Parameters			
Body Parameters			
Age of person (y):	35	Gender:	male
Weight (kg):	75.00	Height (m):	1.75
Surface Area (DuBois-Area):	1.91 m2		
Clothing Parameters			
Static Clothing Insulation (clo):	2		
Person Metabolism			
Total Metabolic rate (W):	164.49 (=82.21 W/m2)		
(met):	1.48		

(c)- Rayman input data for calculating thermal comfort		
Clothing insulation		2 (Iso 7730)
Activity		80 W (walking)
	Height (m)	1.75
	Weight (kg)	75.00
	Age(y)	35
	Sex	male

Tables 4a-4c provide detailed information on the surface cover materials and vegetation used in the simulations. The vegetation at the Afifabad garden site consists entirely of deciduous trees, each with varying heights. The Leaf Area Density (LAD) value for all trees is set at 2. Receptors within the plaza were designated based on the specific characteristics and locations of vegetation and surface cover materials, which were meticulously defined. For each scenario analyzed, 6 receptors were identified and specified for comparison and analysis (Table 1-f). Scenario 6 includes a combination of paving with 50 cm tall grass alongside the existing plane trees of varying heights. Surrounding gardens feature trees with a consistent height of 4.5 meters. Simulation outputs include parameters such as air temperature, surface temperature, mean radiant temperature, relative humidity, and wind speed. These measurements were taken at a height of 1.8 meters using the LEONARDO tool within ENVI-met.

Instrumentation and validation

In this study, the ENVI-met model was validated using field measurements, as recommended by Atwa et al. (2020) and Karimi et al. (2020). Air temperature data from meteorological records on April 20, 2020, were utilized to validate the ENVI-met model before further simulations were conducted. The current state

of the plaza at Afifabad Garden was simulated and compared against the field measurements. Surface temperature was measured using a Testo-905 T2 thermometer, which has an accuracy of ±1°C and a resolution of 0.1°C. Figure 2 illustrates the comparison between the actual recorded temperature data at the site and the simulated outputs from ENVI-met. The root mean square error (RMSE) between the recorded and simulated data was calculated to be 2.98. Given that the average recorded temperature was 38.93°C, the error in simulation was determined to be 7.66%. This indicates that the ENVI-met model performed reliably with less than 10% RMSE variation compared to the measured data, validating its accuracy for further simulations in this study.
The slight difference in the diagram is due to the difference in the distance between the meteorological station and the site and the lack of accurate simulation of ENVI-met software in soil and plants.

Scenario development

Six scenarios have been developed and are detailed in Tables 3 and 4 to investigate the effects of different cooling strategies at the Afifabad Garden Plaza.

Scenario 1, described in Table 2, represents the past state of the Afifabad Garden Plaza when it served as a local throughway. Scenario 2 depicts the current state of the plaza, which functions as a pedestrian area and hosts social gatherings and events. One significant advantage of converting the plaza into a pedestrian-only area is the elimination of cars, which can positively impact air quality and reduce noise levels. The current state of the site has been extensively analyzed using field measurements and satellite images to assess air temperature, surface temperature, relative humidity, wind speed, mean radiant temperature, Predicted Mean Vote (PMV), and Physiological Equivalent Temperature (PET). Scenarios 1 and 2 serve as foundational baselines upon which the other scenarios are built. Each subsequent scenario is designed to explore different combinations of cooling strategies aimed at enhancing the thermal comfort and environmental quality of the Afifabad Garden Plaza. These scenarios are crucial for evaluating and recommending optimal design interventions to improve the overall comfort and usability of the site.

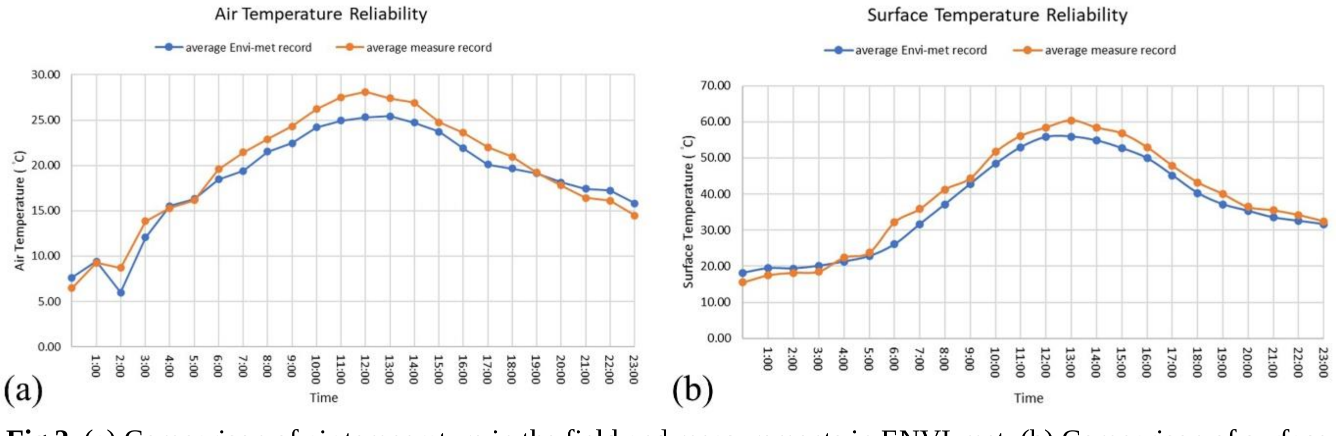


Fig 2. (a) Comparison of air temperature in the field and measurements in ENVI-met, (b) Comparison of surface temperature as field studies and illustrating measurements in ENVI-met.

Table 3. Site design scenarios

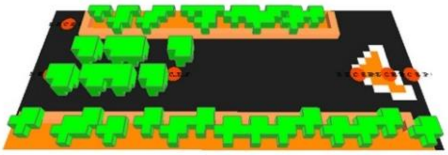
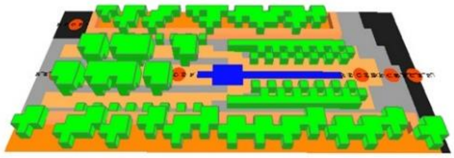
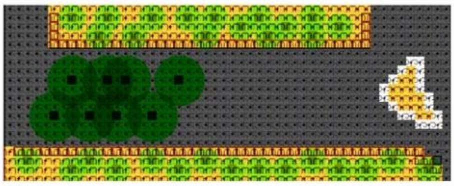
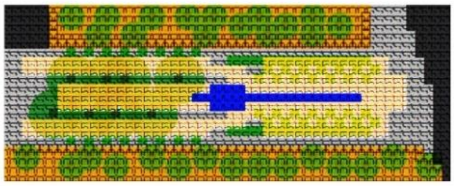
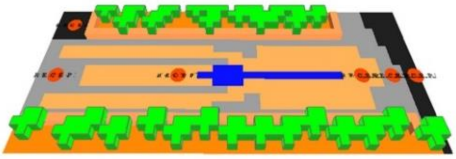
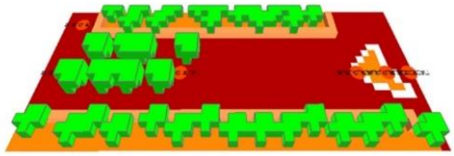
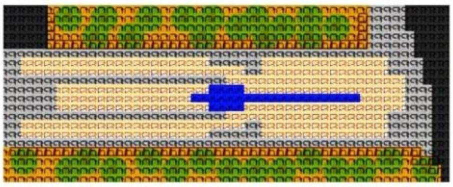
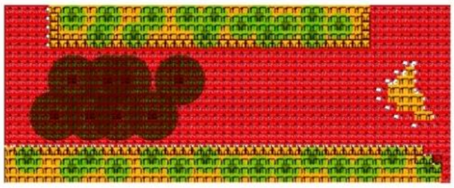
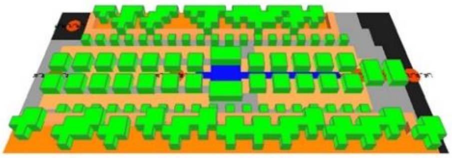
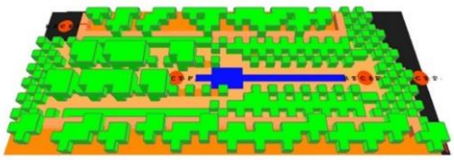
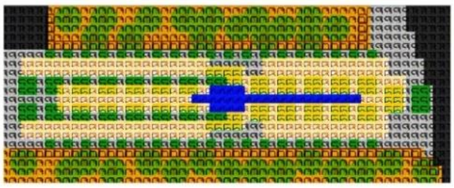
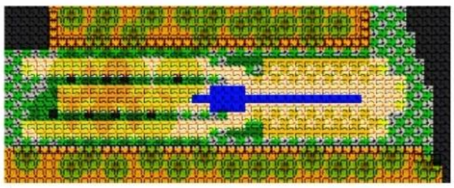
Scenarios of Afifabad Jelokhan	Scenario	Scenario 1	Scenario 2
	Code	SC1	SC2
	Description	Previous condition (street)	Current condition of walkway
	Map 3D		
	Plan		
	Scenario	Scenario 3	Scenario 4
	Code	SC3	SC4
	Description	Current condition of walkway but seprating additional trees	Previous condition (street) but with cool paving instead of asphalt
	Map 3D		
	Plan		
	Scenario	Scenario 5	Scenario 6
	Code	SC5	SC6
	Description	Current condition of walkway but single trees on the both sides of walkway and cluster trees in the middle of the walkway	Current condition of walkway (cool pavement-mixture of travertane and grass)
	Map 3D		
	Plan		

Table 4. Model inputs for 6 design scenarios

(a)- Details of park pavement surfaces

Scenario	Material	Albedo	Emissivity	Thermal Capacity	Thermal Conductivity
Scenario 1	Asphalt	0.2	0.9	2.251	0.9
Scenario 2	Travertine	0.6	0.9	2.954	2.17
	Granite	0.4	0.9	2.345	4.61
Scenario 4	High albedo asphalt	0.7	0.9	2.251	0.90
Scenario 1, 4	Gray concrete pavement	0.5	0.9	2.083	1.63

(b)- Details of different vegetation species

Scenario	Number	Height (m)
scenario 1, 4	8	2
scenario 2, 6*	8	2
	76	7
scenario 5*	162	2

(c)- ENVI-met receptor's location

Scenario	Receptor	Material
scenario 1, 4	1, 2, 3 & 4	Asphalt
	5	Loamy Soil
	6	Concrete
scenario 2, 3,5 & 6	1 & 6	Asphalt
	2 & 5	Granite
	3 & 4	Travertine

RESULTS

Based on the provided information, the simulation results for the entry plaza of Afifabad Garden have been visualized in Figure 2 for summer and Figure 3 for winter. Additionally, PMV and PET values were calculated at specific hours—10:00, 12:00, and 16:00—using Rayman software, positioned at a height of 1.8 meters above the ground. These results are presented in Figure 3 and Figure 4, respectively.

Air temperature variations

The results for the average air temperature for the entire site are shown in Figure 2a. In Scenario 1 (previous condition), the air temperature reaches its peak at 40.63°C (10:00 am), 42.10°C (12:00 pm), and 38.84°C (4:00 pm), which is 0.6°C to 1.49°C higher than Scenario 2 (current condition). Scenario 6, featuring travertine and greenery on the floor, shows the lowest air temperature of 39°C at 10:00 am, which is 1.63°C lower than Scenario 1. By 12:00 pm and 4:00 pm, the air temperatures are 40.31°C and 37.49°C respectively (Figure 7).

Scenario 1 (previous site conditions with only asphalt) exhibits the highest air temperature, differing by 1.79°C compared to Scenario 4 (cool paving but no new trees). Scenario 3 shows a temperature 1.49°C lower than Scenario 1 at 10:00 am. Scenario 2 has an average air temperature 1.17°C lower than Scenario 1 at 12:00 pm, while Scenario 6 shows a temperature 0.99°C lower than Scenario 1 at the same hour. At 12:00 pm, both Scenario 3 (cool materials without additional trees) and Scenario 5 (additional trees on both sides and clusters in the middle) demonstrate similar cooling effects. Therefore, increasing albedo or vegetation individually reduces air temperature nearly equally at noon. By 4:00 pm, Scenario 3 shows a decrease of 0.7°C compared to Scenario 1.

Figure 5-a depicts the air temperature variations on the coldest day of 2020. It shows that the air temperature differences between scenarios are all less than 1°C under cold conditions. The largest variation occurs between Scenario 1 (previous conditions) and Scenario 4 (cool paving) at 12:00 pm, with a difference of 0.88°C. Scenarios 2 and 3 exhibit nearly identical air temperatures, differing by only 0.01°C. Similarly, Scenarios 5 and 6 (with the most trees) show a maximum variation of 0.56°C (Figure 6).

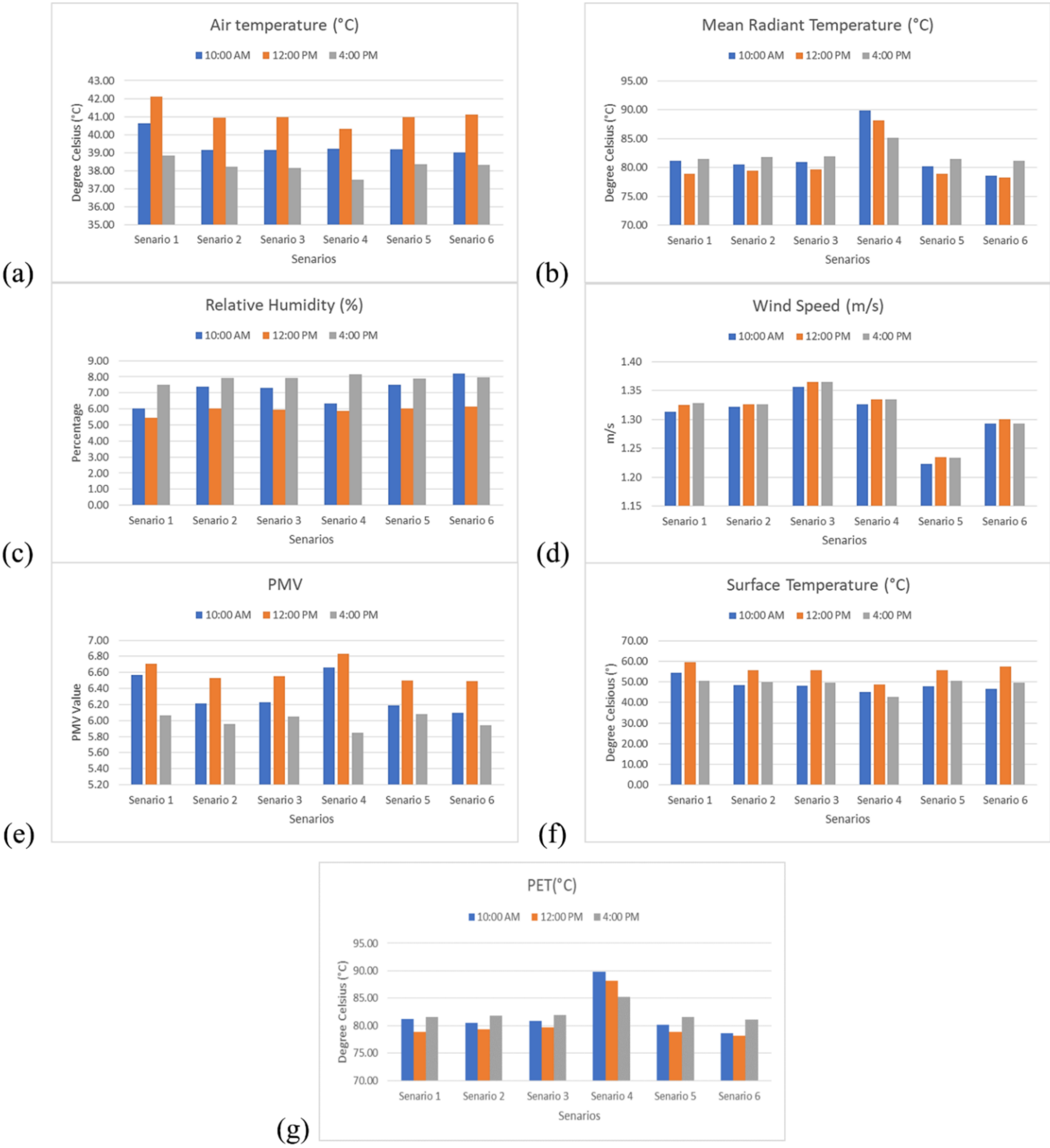


Fig 3. Comparison of average air temperature, average radiation temperature, relative humidity, wind speed, PMV, and surface temperature in six scenarios at 10:00, 12:00, and 16:00 in summer

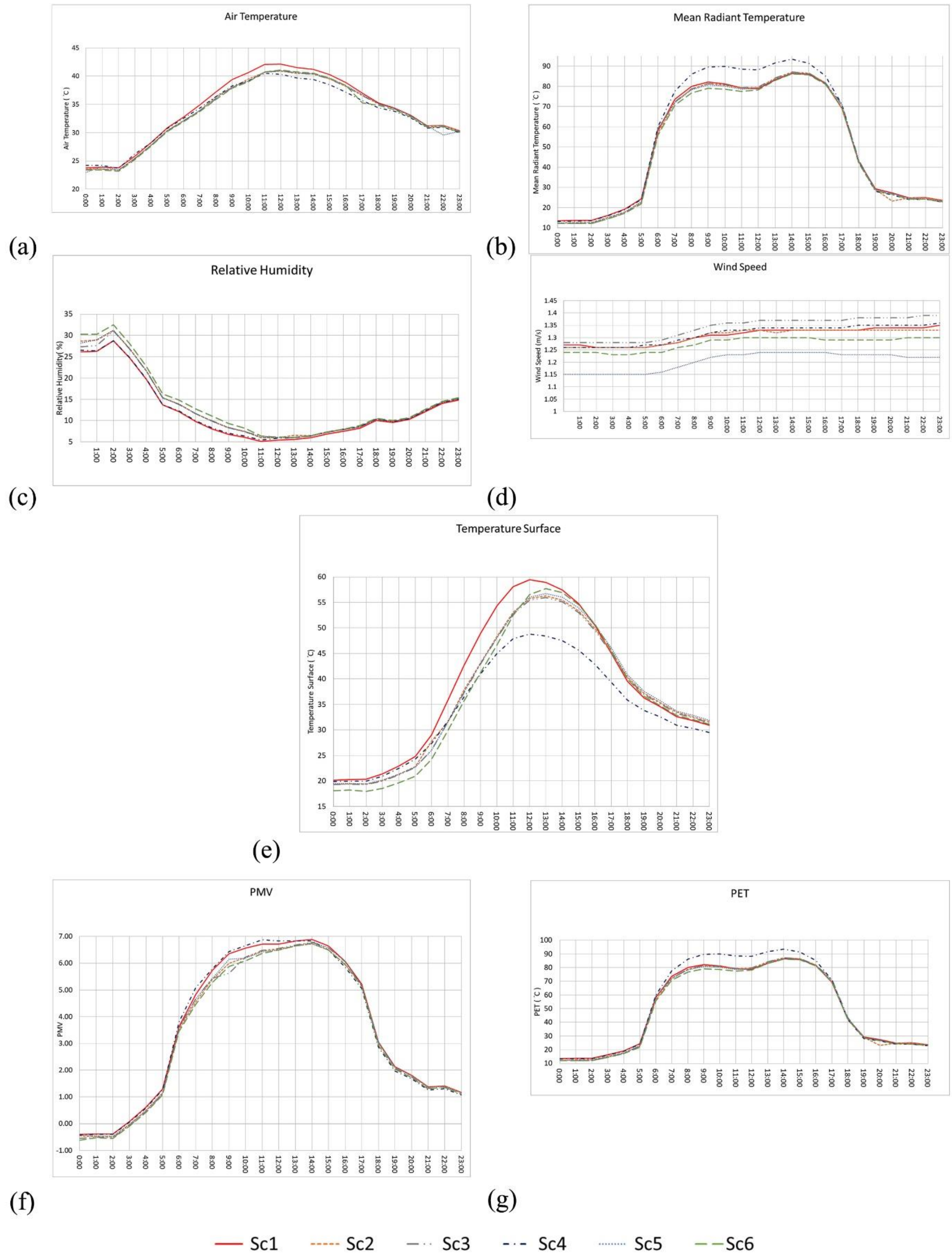


Fig 4. Average changes of Ta, MRT, RH, WS, Ts, PMV, and PET at a height of 1.8 m from the ground in summer

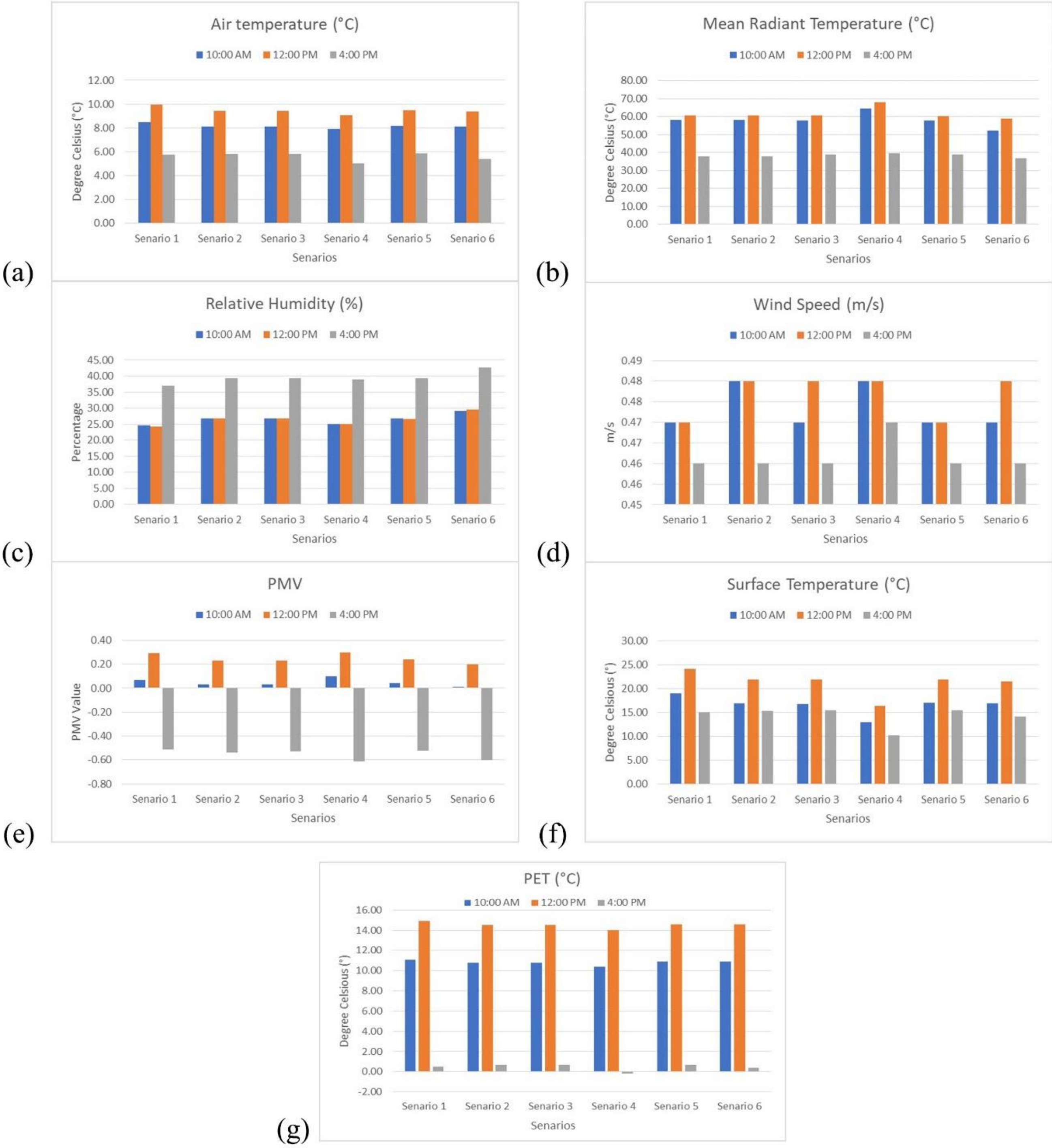


Fig 5. Comparison of average air temperature, average radiation temperature, relative humidity, wind speed, PMV, and surface temperature in six scenarios at 10:00, 12:00, and 16:00 in winter

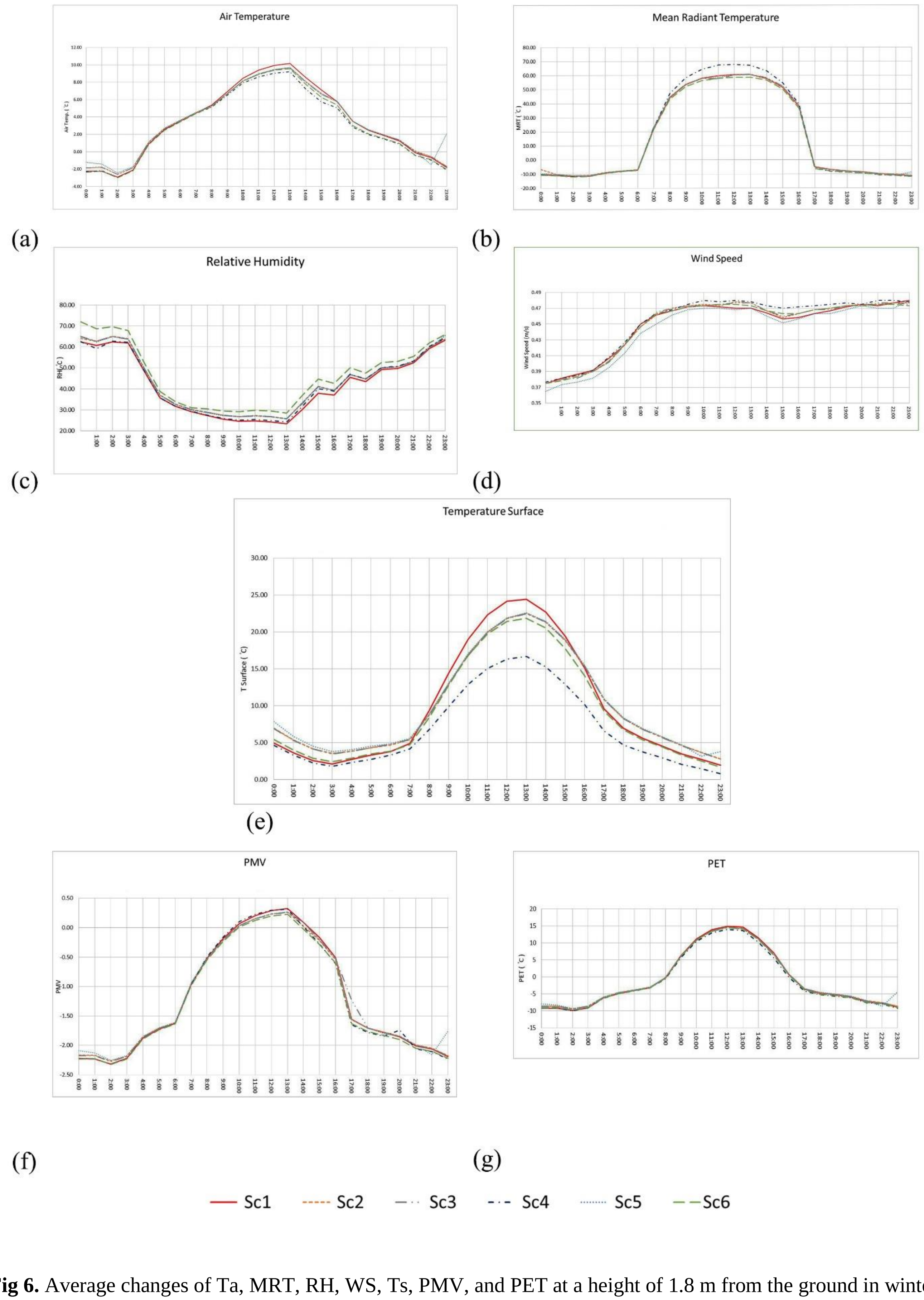


Fig 6. Average changes of Ta, MRT, RH, WS, Ts, PMV, and PET at a height of 1.8 m from the ground in winter

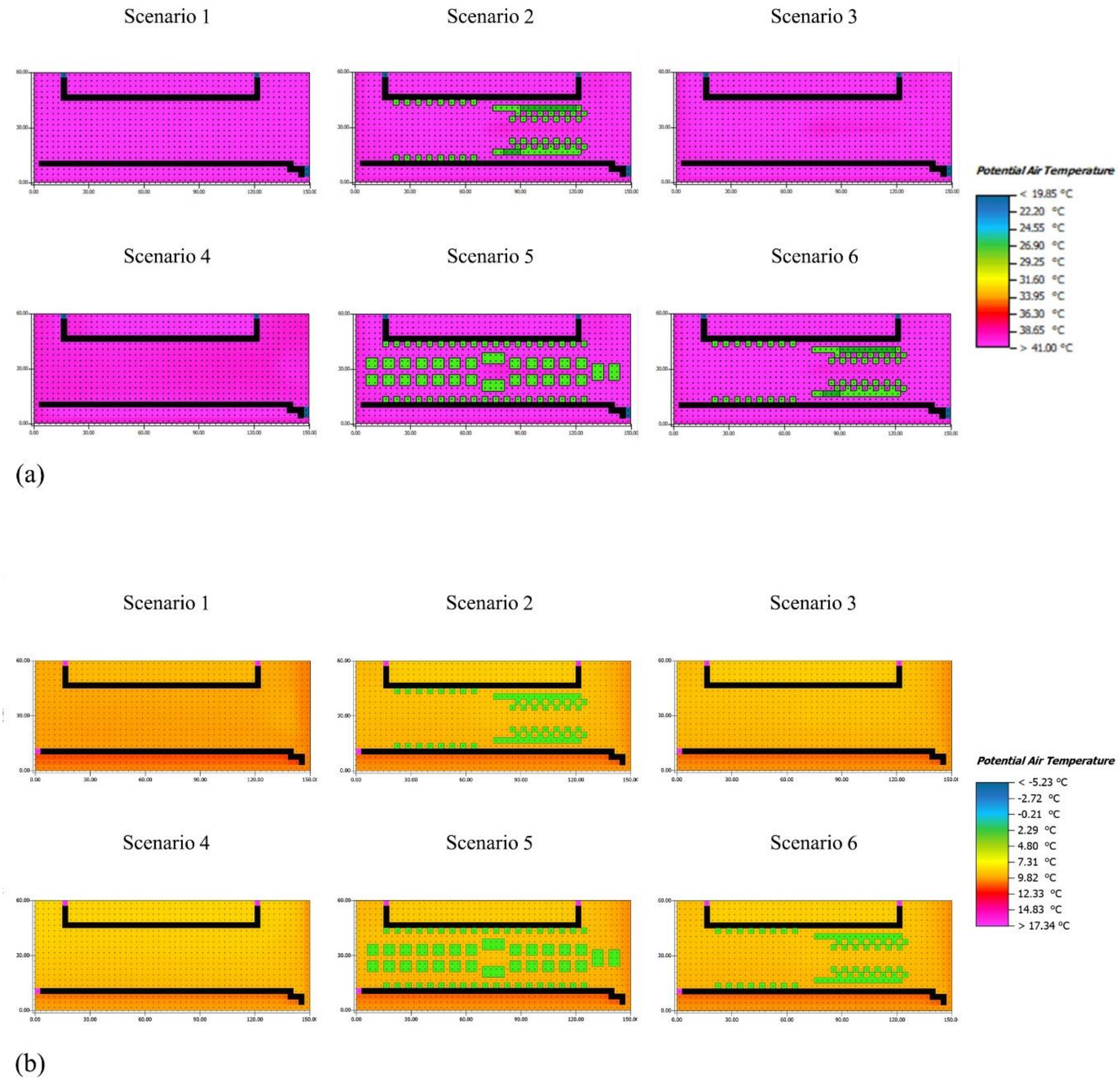


Fig 7. (a) Scenarios' maps of air temperature on the hottest day of 2020- (b) Scenarios' maps of air temperature on the coldest day of 2020

Mean radiant temperature variations

Figure 3-b illustrates the differences in Mean Radiant Temperature (MRT) among different scenarios throughout the day. Scenario 6 exhibits the lowest MRT values at 10:00 am, 12:00 pm, and 16:00, measuring 78.59°C, 78.21°C, and 81.18°C respectively. This is 1.97°C, 1.18°C, and 0.6°C lower than Scenario 2 (current site conditions) (Figure 8). The reduction in MRT in Scenario 6 can be attributed to the presence of floor vegetation and reduced solar reflection. The plants provide shade over the surface materials, thereby lowering MRT, while high albedo materials have a negative impact on the MRT. Scenario 4, which features high albedo paving, shows the highest MRT at 16:00, reaching 89.84°C, 88.19°C, and 85.19°C respectively. This is 9.28°C, 8.8°C, and 3.33°C higher than Scenario 2. In Scenario 4, the high MRT values at 10:00, 12:00, and 16:00 are 11.25°C, 9.98°C, and 4.01°C respectively. The use of high albedo paving in this scenario increases MRT by altering the diffusion and reflection of solar radiation. Comparatively, Scenario 6 maintains a lower MRT than Scenario 5 due to the higher presence of vegetation on the ground (grass cover). At 10:00, 12:00, and 16:00, Scenario 5 exhibits MRT values that are 0.39°C, 0.51°C, and 0.33°C lower than Scenario 2.

The difference between Scenarios 2 and 3 highlights that the current condition (Scenario 2) exhibits a lower MRT compared to Scenario 3 (without trees), emphasizing the significant impact of tree shading on MRT. Scenario 4, characterized by high surface albedo, shows higher mean radiant temperature due to increased reflection of solar radiation from the surface. Figure 4-b indicates that, except for Scenario 4, MRT remains relatively stable across all scenarios, with variations of less than 1 ℃ throughout the day. In Scenario 4, the incorporation of cool paving and minimal tree canopy results in MRT being up to 5.8 ℃ higher compared to Scenario 1, which represents nearly half of the maximum impact observed during summer at noon (Figure 8).

Relative humidity variations

Figures 3-c and 5-c illustrate the significant impact of trees and permeable paving materials on the relative humidity (RH) of adjacent open spaces. Scenario 1, representing the previous condition with asphalt cover and no trees, shows the lowest RH values of 6.05%, 5.53%, and 7.48% at 10:00, 12:00, and 16:00, respectively. These values are 1.36%, 0.58%, and 0.43% lower than Scenario 2 (current condition). The highest RH of 8.14% is observed in Scenario 4 at 16:00 on the hottest day of 2020. Scenario 3 exhibits marginally higher RH compared to Scenario 1, likely due to the presence of various floor materials and the incorporation of lighter-colored Travertine pavers. Increased vegetation, as seen in Scenario 5, results in a notable rise in RH during the afternoon and evening hours.

At 16:00 in Scenario 6, the relative humidity is measured at 7.95%, which is only 0.4% higher than in Scenario 2, indicating that Scenario 6 (cool pavement) had minimal impact on RH. In contrast, Scenario 5 exhibits higher relative humidity, primarily attributed to increased tree cover. According to Figure 5-c, the highest RH occurs in Scenario 6 (highest tree cover), reaching 11.30% at 16:00 on the coolest day of 2020. This peak RH increase is nearly double the maximum RH difference observed during summer on the hottest day of 2020 (1.36%). The presence of trees in Scenarios 5 and 6 contributes to their respective higher RH levels. Scenarios 2 and 3 have similar RH levels, differing by only 0.01% at 16:00.

Wind speed variations

The variation in wind speed (WS) primarily stems from differences in tree configuration and density, influencing local air movement by either obstructing or accelerating it on site. Average speeds are depicted in Figures 3-d and 4-d, showing consistent values across all scenarios. Figure 3-d highlights Scenario 3 as the baseline condition without trees, exhibiting the highest wind speeds of 1.36 m/s, 1.37 m/s, and 1.37 m/s at 10:00, 12:00, and 16:00, respectively.

The lowest speeds are found in Scenario 5 (with the highest tree density), measuring 1.22 m/s, 1.24 m/s, and 1.23 m/s at 10:00, 12:00, and 16:00, respectively. Scenarios 1 and 2 exhibit nearly identical wind speeds, while Scenarios 1 and 4 record the highest wind speeds. Areas with sparse or linear tree coverage generally experience higher wind speeds compared to those with dense tree canopies. On the coldest day of the year, wind speeds are nearly identical across all scenarios, with a maximum variation of 0.01 m/s observed between Scenarios 2 and 4 at 10:00 and 12:00.

DISCUSSION

Surface materials combinations, solar exposure, and temperature

Surface cover materials and tree shading significantly influence surface temperatures, with higher albedo paving reducing temperatures independently. According to Figure 3-f, average surface temperatures are lowest in Scenario 4 at 44.97°C (10:00), 48.82°C (12:00), and 42.56°C (16:00), showing a maximum variation of 7.33°C compared to Scenario 2.

Despite having fewer trees, Scenario 3 consistently exhibits lower surface temperatures than Scenario 2 across all three time points. Generally, shading has the most pronounced impact on surface temperatures, followed by the use of cool surfaces.

On the coldest day of the year, Scenario 4 shows a maximum temperature variation of 5.55°C compared to Scenario 2, whereas Scenarios 5 and 6, with increased tree canopy cover, are up to 2.31°C cooler than the current conditions modeled in Scenario 2.

Predicted mean vote of different design scenarios

Variations in Predicted Mean Vote (PMV) can be observed in Figure 2-e for hot conditions and Figure 5-e for cold conditions. The PMV index integrates air temperature (T), mean radiant temperature (MRT), relative humidity (RH), and wind speed (WS) from simulations, along with activity rate and clothing insulation (averaged based on summer and winter conventions at the site).

Scenario 5 exhibits the lowest PMV values at 10:00 and 12:00, measuring 6.09 and 6.49 respectively, which are 0.12 and 0.04 lower than Scenario 2. (The standard PMV range recommended by ASHRAE is between -3 and +3, although simulation tools may calculate values outside this range for comparative purposes—these values are rounded to the nearest standard range value when compared with thermal sensation votes.) Scenario 4 records the highest PMV values at 10:00 and 12:00, reaching 6.66 and 6.83, which are 0.45 and 0.3 higher than Scenario 2. At 16:00, Scenario 4 also shows the lowest PMV at 5.85, which is 0.11 lower than Scenario 2, while Scenario 5 exhibits the highest PMV of 6.08, which is 0.12 higher than Scenario 2.

On the coldest day of the year, Scenario 4 records the highest PMV of 0.3 at 16:00, with a minimal 0.02 variation compared to Scenario 2. Scenario 6 shows the lowest PMV at -0.61, with only a 0.07 variation from Scenario 4. Scenarios 2 and 3 have very similar PMVs throughout the day, differing by only 0.01. Thus, in cold conditions, the cooler Scenarios 5 and 6 (with more trees and cooler paving) are marginally cooler than the warmer Scenarios 1 and 2 (with conventional covers and fewer trees).

In summer, increased albedo at noon leads to higher PMV values, as observed in Scenario 4. Therefore, the isolated use of high-albedo paving can negatively impact the thermal comfort of outdoor participants at the site. Scenario 1, fully covered by asphalt, has the second highest PMV after Scenario 4. Average PMVs in Figure 3-f indicate that Scenarios 5 and 6 (with more vegetation) have the lowest PMV in the morning, while Scenarios 4 and 2 have lower PMVs in the afternoon during summer. Conversely, Figure 5-f shows these differences are less significant in winter.

Scenario 3, with new paving but without trees, exhibits higher PMV compared to Scenario 2, emphasizing that solar radiation exposure increases PMV even when cool materials are used.

Physiological equivalent temperature of different design scenarios

Figure 3-g indicates the highest Physiological Equivalent Temperature (PET) at 10:00, corresponding to Scenario 4 (with the highest overall albedo) in summer, which is 9.28°C higher than Scenario 2. Once again, isolated increases in albedo did not improve outdoor thermal comfort at the site but rather exacerbated it. The lowest PET is associated with Scenario 6 (cool pavement under dense tree canopy) at 12:00, which is 1.14°C lower than Scenario 2.

Scenario 1 at 10:00, and Scenario 3 at 12:00 and 16:00, consistently exhibit the highest PET. Due to increased tree cover in Scenario 6 and ground vegetation in Scenario 5, they experience the lowest PET during the hottest day of summer. Scenario 6 is up to 1.96°C cooler than Scenario 2 under the most extreme conditions. During the coldest conditions, PET varies by only up to 0.9°C between Scenario 4 and Scenario 2, with other scenarios showing variations in the range of 0.3-0.4°C at 10:00 and 12:00, and 0.7°C at 16:00.

Combinations for maximum thermal comfort benefit in hot and dry climate

Figures 4 and 6 demonstrate that changes in surface materials and tree canopy cover lead to significant variations in air, surface, and radiant temperatures, while relative humidity (RH) and wind speed are minimally affected. These impacts are most pronounced during midday in both summer and winter. However, the cooling effect in winter is marginal compared to the pronounced cooling observed in summer, especially when dense tree canopies are combined with cool surface materials.

Scenarios lacking tree cover exhibit lower RH, which can pose challenges during hot and dry conditions at the site. In Scenario 6 (featuring a combination of tree canopy and cool surface covers), RH was higher than in all other scenarios, attributed to the presence of green surface coverage (turf). Additionally, this scenario displayed the lowest overall surface temperature, air temperature, and mean radiant temperature (MRT) during the early hours of the day. Between scenarios with high vegetation cover, air temperature, surface temperature, and MRT were lower in Scenario 6 compared to Scenario 5 before 12:00 and after 16:00, primarily due to increased shading. The best cooling performance among the six modeled scenarios was observed in Scenario 6, followed by Scenario 5.

These findings underscore the importance of increasing vegetation cover alongside enhancing surface albedo in urban environments to improve outdoor thermal comfort. During hours without direct sunlight (01:00 to 05:00 and 18:00 to 23:00), natural decreases in air, surface, and radiant temperatures occur, while RH typically increases. Careful consideration is necessary to avoid using very dense tree canopies in open spaces with limited exposure to the sky (sky view factor) to prevent the long-wave radiation of stored heat from materials' thermal mass during the night.

CONCLUSIONS

This research monitored outdoor thermal comfort parameters to assess the influence of various combinations of surface materials and vegetation on microclimates in the entry plaza of Afifabad Garden in Shiraz, a city characterized by hot and dry summers and cool winters.

The results highlight that cool pavements with higher albedo, complemented by appropriate tree canopy and ground vegetation, significantly enhance outdoor thermal comfort. Conversely, isolated high-albedo surfaces exacerbate thermal discomfort during hot and dry conditions. Ground vegetation coverage also reduces surface and radiant temperatures while increasing relative humidity, which is crucial for hot and dry climates. The cooling effect is more pronounced in summer compared to winter, with reductions in Physiological Equivalent Temperature (PET) reaching up to 1.9°C in summer and limited to 0.9°C on the coldest winter day. Proper arrangement of trees and surfaces can effectively enhance outdoor thermal comfort, especially when using materials with higher albedo and emissivity. Spaces covered with cool surfaces and minimal vegetation may experience more rapid decreases in Predicted Mean Vote (PMV) at night.

The study demonstrates that combining trees with cool surfaces magnifies cooling effects without the drawbacks of very high-albedo surfaces, such as glare and increased UV exposure in urban settings. Furthermore, without adequate shading, high-albedo surfaces may counteract efforts to improve thermal comfort during hot conditions, leading to increased Mean Radiant Temperature (MRT), and consequently, higher PMV and PET in exposed open spaces. The scenarios analyzed underscore the effectiveness of integrating high-albedo materials with appropriate vegetation to enhance thermal comfort significantly.

The study's findings emphasize the critical role of tree and surface configurations in improving outdoor thermal comfort and advocate for contextual simulations in urban design processes before implementation. Understanding these impacts is crucial for integrating Urban Heat Island (UHI) mitigation strategies into practical urban retrofit and regeneration projects.

However, this study is constrained by the specific linear NE-SW orientation of the case study site within a hot and dry climate. Similar configurations may yield different results in other orientations and climates. Additionally, current simulation software limitations restrict simulations to up to 5 days, underscoring the need for future software developments to enable longer-term simulations. Lastly, the study used deciduous trees based on local council practices in Shiraz; future research could explore the use of evergreen species for further insights.

AUTHOR CONTRIBUTIONS

Conceptualization, A.H. and E.SH.; methodology, A.H.; software, R.T.; validation, A.H., R.T., and E.SH.; formal analysis, R.T.; investigation, A.H, and R.T.; resources, A.H and M.N and R.T.; data curation, X.X.; writing—original draft preparation, A.H, and R.T.; writing—review and editing, E.SH and A.H.; visualization, M.N, and R.T.; supervision, A.H, and M.N. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

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HOW TO CITE THIS ARTICLE

Habibi, A,. Tafvizi, R,. Nikkar, M,. Sharifi, E. (2024). Impact of Design Composition of Canyon Layout, Greenery, and Cool Surfaces on Outdoor Thermal Comfort in Hot-Dry Climate. *Int. J. Architect. Eng. Urban Plan,* 34(2): 1-21, https://dx.doi.org/ijaup.833.

URL: http://ijaup.iust.ac.ir