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Greenery Impact on Physiological Equivalent Temperature for Pedestrians in Residential Zones in Hot and Arid Climates

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Abstract: The study of street geometry has gained significant attention in recent years, with researchers investigating the effects of design factors on pedestrian thermal comfort in hot and arid climates. This research investigates how introducing vegetation to pedestrian path design influences thermal comfort on a street section in residential neighborhoods in Riyadh, Saudi Arabia. The case studies explore location-specific investigations to understand pedestrian path design scenarios with variations of vegetation and their placement while focusing on their impact on outdoor thermal comfort, furthermore, using Envi-met 5.6.1 to analyze and compare existing case studies and offer optimized outdoor samples supporting thermal conditions. By examining the influence of vegetation on outdoor thermal comfort, identifying environmental parameters that affect thermal comfort, and comparing their impact on physiological equivalent temperature (PET) recommendations to improve pedestrians' physical health and impact their well-being. This study emphasizes the significance of vegetation in shaping pedestrians' outdoor thermal comfort in hot and arid climates, with design factors such as type, height, width, and distance. Understanding these factors and their crucial roles in determining thermal conditions and their immediate impact on pedestrian thermal comfort can inform urban design strategies aimed at enhancing pedestrian comfort and promoting sustainable and livable urban environments

Keywords: Outdoor Thermal Comfort; Physiological Equivalent Temperature; Pedestrian Path; Vegetation; Simulation; Solar Radiation; Urban Heat Island; Residential Neighborhood.

1. Introduction

Urban environments in hot and arid climates, such as Riyadh, Saudi Arabia, pose significant challenges to pedestrian comfort due to extreme temperatures and the urban heat island effect. Outdoor thermal comfort has become an essential factor in urban design as it directly affects pedestrians' health, mobility, and overall well-being. Creating pedestrian-friendly environments is crucial for encouraging active mobility and reducing reliance on vehicular transportation, thereby improving the livability and sustainability of urban spaces. Additionally, in hot climates, the design of pedestrian paths and streets can either exacerbate or mitigate heat stress. Various design strategies, such as introducing vegetation, have been explored to enhance outdoor thermal comfort. Trees, in particular, play a critical role in shading, reducing solar radiation, and enhancing microclimates.

Despite the known benefits of urban greenery, there is limited research in the city of Riyadh on how specific configurations of vegetation—such as tree height, density, and spacing, affect thermal comfort and Physiological Equivalent Temperature (PET) in residential areas. Riyadh's residential streets are often characterized by the lack of functioning sidewalks and harsh thermal conditions that reduce walkability. Yet, practical design recommendations tailored to the local climate and urban fabric remain underdeveloped. The problem this study addresses is how to optimize vegetation design in these streets to improve pedestrian thermal comfort. However, improving outdoor thermal comfort through vegetation is critical in hot and arid cities, where high temperatures significantly impact pedestrian well-being, safety, and the overall urban experience. Urban planners and designers can enhance walkability and reduce heat stress by understanding how vegetation can be strategically deployed, contributing to more sustainable and livable urban environments. This research but addresses local needs with site-specific simulation in Riyadh and also addresses local needs with site-specific simulation in Riyadh and provides insights applicable to other cities with similar climatic conditions.

The primary goal of this study is to investigate the impact of tree height, density, and spacing on outdoor thermal comfort, particularly on the Physiological Equivalent Temperature (PET) within the residential streets of Riyadh. The study will also provide site-specific urban greenery recommendations by using ENVI-met simulations for optimizing pedestrian comfort in 20m wide streets. Moreover, the research aims to answer how tree height affects pedestrian thermal comfort in Riyadh's residential streets and how the density and spacing of trees influence the reduction of PET in different local urban configurations. Also, what are the optimal tree configurations for improving outdoor thermal comfort on 20m wide streets in Riyadh? Furthermore, the hypothesis guiding this study is that taller and denser trees planted at narrower intervals will lead to a more significant reduction in PET, thus improving pedestrian thermal comfort in Riyadh's residential streets. Optimized tree configurations are expected to mitigate heat stress more effectively, particularly during peak daytime temperatures, and create more comfortable outdoor environments. Finally, simulations were conducted using ENVI-met software to test this hypothesis, comparing different tree configurations to assess their impact on outdoor thermal comfort in terms of PET.

2.Literature Review

This section highlights the importance of pedestrian sidewalks in urban environments. Moreover, it discusses the advantages of active mobility, such as walking, and emphasizes the need for pedestrian-friendly cities. It also mentions the impact of pedestrians on urban spaces' overall livability and quality. At the same time, linking outdoor thermal comfort for pedestrians in street configurations. It discusses the factors that influence thermal comfort, such as solar radiation, wind speed, and the presence of vegetation. It also mentions shading structures, cool materials, and urban vegetation as strategies to improve outdoor thermal comfort. Finally, it introduces the Physiological Equivalent Temperature (PET) as a comprehensive index for assessing outdoor thermal comfort.

2.1. Importance of Pedestrian

Pedestrians play a crucial role in the urban environment, and their importance cannot be overstated. The presence of pedestrians in cities has been a topic of interest for designers, as it significantly impacts the overall mobility and livability of urban areas that reduce reliance on vehicular movement (Choudhury, 2021). This shift in focus is driven by the numerous advantages that active mobility, such as walking, provides regarding health, social, and environmental aspects (Manzolli et al., 2021). Moreover, walkability refers to the degree to which the environment is pedestrian-friendly. It is a concept that has gained traction in sustainable design, as it emphasizes the creation of cities with high walkability values (Sofwan & Tanjung, 2020). Additionally, the design of pedestrian paths and the provision of facilities for pedestrians are essential. The impact of pedestrians on urban areas contributes to the overall livability and quality of urban cities city spaces (Seminar & Kusumaningrum, 2022). The design of streets and public spaces should prioritize pedestrian friendliness to create a of more livable city that represents its character and promotes a better quality of life (Ja'afar & Harun, 2018). Moreover, the walkability of residential areas is also important in promoting the development of urban green transportation systems in residential neighborhoods (Qian et al., 2018). Pedestrian-friendly streets and urban configurations can enhance pedestrian mobility and contribute to a more sustainable and environmentally friendly transportation system (Delso et al., 2018).

Furthermore, walkability and pedestrian-friendly environments have been found to have a positive influence on the social environment of neighborhoods (Heejung & Hur, 2015). Pedestrianization schemes, which prioritize pedestrians over vehicles, have been shown to have numerous benefits, including increased economic activity and improved quality of life (Soni & Soni, 2016). Pedestrian-friendly streets and urban spaces can also contribute to cities' overall attractiveness and desirability, attracting residents, visitors, and businesses (Basak et al., 2023). Overall, pedestrians play a vital role in the urban environment. Their presence and mobility significantly impact the overall livability and sustainability of cities. Walkability and pedestrian-friendly environments are essential for creating cities prioritizing pedestrians' well-being and needs. The design of streets should prioritize pedestrian comfort, and accessibility. By prioritizing pedestrians, cities can create more livable and sustainable urban environments.

Pedestrians in the scope of this research are within residential neighborhoods and refer to individuals who walk on the streets within residential areas. These individuals may include neighborhood residents, visitors, or people passing through the area. The presence of pedestrians in residential neighborhoods is influenced by various factors related to the built environment, neighborhood characteristics, and individual preferences. However, the representativeness of street sampling protocols can vary in residential neighborhoods (McMillan et al., 2010). Different types of streets, including residential and arterial ones, may be included within a certain radius when sampling pedestrian activity. This suggests that pedestrians in residential neighborhoods can be found on various types of streets, not just exclusively residential streets. Moreover, the characteristics of pedestrians in residential neighborhoods can also vary based on the location. For example, suburban pedestrians may exhibit different needs and behaviors than their urban counterparts (Hess et al., 1999). Moreover, the layout and design of streets in residential neighborhoods can also impact pedestrian use and behavior. Changes in street layout, such as increasing density and connectivity, can reduce barriers to walking and promote pedestrian activity (Anciaes & Jones, 2016). Also, there may be disparities in pedestrian amenities and infrastructure within residential neighborhoods, such as sidewalks, crosswalks, and intersections (Thornton et al., 2016). Other factors that can shape pedestrian movement within residential neighborhoods, such as the presence of points of interest and proximity to public transportation, also play a role in pedestrian distribution (Sheng et al., 2021).

Street geometries refer to the physical layout and arrangement of streets in an urban or rural area. It includes streets' shape, size, and configuration (Khalfi et al., 2021). However street elements, on the other hand, are the various components and features that make up a street. These elements can include road segments, sidewalks, crosswalks, traffic signals, streetlights, trees, buildings, and other infrastructure (Jia et al., 2020; Tanner et al., 2008; Demková et al., 2019; Long & Liu, 2017; Ja'afar et al., 2012). The geometry of streets plays a crucial role in shaping the overall urban environment and influencing pedestrians and the overall walkability (Li et al., 2021; Heldens et al., 2020; Cuo et al., 2008; Williams & Burkle, 2017). The orientation and arrangement of streets and elements can also impact the microclimate and air quality within a city and the distribution of sunlight and shade (Liu et al., 2022; Wei et al., 2021; Park et al., 2019). Additionally, street geometries can influence the visual aesthetics and sense of place in a neighborhood or city (Al-Obeidy & Shamsuddin, 2017; Ng & Chan, 2022; Askari & Soltani, 2018; Lou, 2007).

Moreover street elements, on the other hand, are the physical components that make up a street and contribute to its functionality and character. Road segments are the main elements of a street, providing the space for vehicular traffic. Sidewalks and crosswalks are important for pedestrian movement and safety. Trees and other greenery along streets can provide shade, improve air quality, and mitigate the urban heat island effect to enhance the overall quality of the urban environment (Lindal & Hartig, 2015; Mishra & Kolay, 2019; Johnson et al., 1991; Li et al., 2010). Additionally, the arrangement and design of street elements can significantly impact an area's functionality and livability. For example, well-designed sidewalks and crosswalks can encourage walking and active transportation (Chen et al., 2020; S. et al., 2022; Porter et al., 2020). Overall, street elements like sidewalks are essential to urban and rural environments, especially for pedestrians. They play crucial roles in shaping the functionality, comfort, connectivity, and overall quality of urban spaces for neighborhoods. Moreover, pedestrians play a vital role in the urban residential environment. Their presence and mobility significantly impact the overall livability, safety, and sustainability of cities. Walkability and pedestrian-friendly environments are essential for creating cities prioritizing pedestrians' well-being and needs. By prioritizing pedestrians, cities can create more livable, sustainable, and attractive urban environments.

2.2. Outdoor Thermal Comfort for Pedestrians

Outdoor thermal comfort in pedestrian sidewalks refer to individuals' subjective perception of thermal conditions in urban street environments. Street canyons are formed by buildings on either side of a street, creating a narrow and confined space. However, the thermal conditions in a street configuration are influenced by various factors, including solar radiation, wind speed, air temperature, humidity, and the geometry of the canyon itself. Research has shown that the solar reflectance of walls and roads in street canyons can significantly impact outdoor thermal comfort (S et al., 2019). The reflectance of these surfaces affects the amount of solar radiation absorbed and reflected, affecting the air temperature and thermal sensation within the canyon. Higher solar reflectance can help reduce the heat absorbed by the canyon and improve thermal comfort. Moreover, the configuration and geometry of the street also play a crucial role in thermal comfort. Additionally, the aspect ratio (height-to-width ratio) and orientation of the canyon can affect the distribution of solar radiation, wind flow, and air temperature within the canyon (Wu et al., 2022; Ali-Toudert & Mayer, 2006).

Research has shown that higher aspect ratios can improve pedestrian-level thermal comfort by increasing wind speed and providing more shading (Dissanayake et al., 2021). Additionally, the canyon's orientation can influence the amount of solar radiation received and the airflow patterns within the canyon (Achour-Younsi & Kharrat, 2016). However, vegetation, such as trees, can also significantly impact thermal comfort in street configuration. Trees provide shade and evaporative cooling, which can help reduce air temperature and improve thermal comfort (Huang et al., 2020). The amount and distribution of tree canopy cover in street canyons can affect the microclimate and thermal conditions within the canyon (Ratnayake et al., 2022). Research has shown that higher tree canopy cover can lead to lower air temperatures and improved thermal comfort (Pothiphan et al., 2019).

Outdoor thermal comfort is the focus of this study and is a crucial aspect in urban environments as it directly impacts the well-being and walkability of pedestrians (Nasrollahi et al., 2020). Numerous studies have been conducted to assess and enhance pedestrian thermal comfort in various contexts. A survey conducted in Kuala Lumpur, a tropical city, found that the presence of shading structures significantly improved the thermal comfort of pedestrians in outdoor spaces (Ishak et al., 2023). Shading structures can effectively reduce direct exposure to solar radiation and create a cooler microclimate, thereby enhancing pedestrian comfort. Mechanical ventilation also plays a role in improving outdoor pedestrian comfort. Moreover, several heat-mitigation strategies have been thoroughly evaluated and compared to enhance pedestrian thermal comfort in urban environments (Nasrollahi et al., 2020). These strategies include the implementation of green roofs, cool materials, and urban vegetation. Green roofs have been recognized as an effective tool for mitigating the urban heat island effect and improving thermal comfort (Peng & Jim, 2013). They can reduce surface temperatures and provide a cooling effect in the surrounding area. Cool materials, on the other hand, can minimize heat transfer to the air and improve thermal comfort (Kim et al., 2018). Urban vegetation, such as trees and grass, has also been found to positively impact outdoor thermal comfort (Shashua-Bar et al., 2010). Vegetation provides shade, reduces air temperature, and enhances the thermal environment.

The design of urban streets and neighborhoods significantly influences pedestrian thermal comfort. Street configuration, including sidewalks and shading, can affect thermal comfort (Zheng et al., 2018). Proper street design can enhance wind flow and block solar radiation, creating a more comfortable pedestrian environment. Overall, pedestrian thermal comfort in the street is influenced by various factors, including solar radiation, wind speed, air temperature, humidity, and the geometry of the canyon. Also, the solar reflectance of walls and roads, the aspect ratio and orientation of the street, the presence of vegetation, and the airflow patterns within the canyon all play a crucial role in determining street canyons' thermal conditions and comfort levels. Understanding and optimizing these factors can help improve thermal comfort and create more usable and livable urban environments.

2.3. Physiological Equivalent Temperature

The Physiological Equivalent Temperature (PET) indexing for assessing outdoor thermal comfort. It is derived from the human energy balance and considers various meteorological parameters such as air temperature, humidity, wind speed, and solar radiation (Matzarakis et al., 1999). PET provides a comprehensive measure of thermal comfort by considering the heat exchange between the human body and the surrounding environment (Höppe, 1999). Moreover, PET has been utilized in several studies to assess outdoor thermal comfort in different contexts. For example, a study in three hot-humid climate theme parks in Jakarta, Indonesia, employed PET as a thermal index to investigate the impact of climate on thermal comfort (Koerniawan & Gao, 2015). The study found that PET can capture the influence of climate on thermal comfort and provide insights for improving outdoor thermal conditions in theme parks. The study found that urban shading can significantly reduce PET and improve thermal comfort in tropical climates. Similarly, a study in Erbil, Iraq, determined thermal comfort zones for outdoor recreation planning using PET and meteorological data (Hamad & Oğuz, 2020). The spatial distribution of PET was analyzed to identify areas with optimal thermal conditions for outdoor activities.

PET has also been employed to evaluate thermal comfort in specific outdoor spaces. A study in a summer urban park in Mianyang, China, used PET to assess the thermal comfort level of park visitors and analyze the thermal environment of diverse landscape elements (Cheng et al., 2020). Another study conducted in Colombo, Sri Lanka, used PET as a thermal comfort index to investigate the impact of urban shading on outdoor thermal conditions (Emmanuel et al., 2007). PET has also been compared to other thermal comfort indices to assess its effectiveness. A study by Zafarmandi et al. (2022) in Tehran, Iran, compared PET with the Predicted Mean Vote (PMV) and Universal Thermal Climate Index (UTCI) for evaluating semi-outdoor thermal comfort. The results showed that PET was a better predictor of thermal comfort in summer and winter than UTCI. Moreover, the perception of thermal comfort has also been studied. Research has shown that there is a correlation between the physiological equivalent temperature (PET) and subjective thermal sensation, with PET values influencing the outdoor thermal comfort experienced (Manteghi et al., 2020). Factors such as wind speed, solar radiation, and air temperature have been found to affect thermal sensation and comfort (Cheng et al., 2011). Gender differences have also been observed in outdoor thermal comfort, with women generally having higher thermal comfort requirements than men (Tung et al., 2014).

Furthermore, several studies have been conducted to investigate the effects of various factors on pedestrian thermal comfort and to propose strategies for improving it. For example, the creation of street greenery in urban pedestrian streets has been found to positively affect microclimates and particulate matter concentrations, which can contribute to improving the pedestrian environment (Jung & Yoon, 2022). Shading strategies and configurations designed in traditional neighborhoods have also been shown to impact pedestrian-level thermal comfort, with different shading strategies leading to different thermal environments (Yin et al., 2019). The presence of mature trees in urban canyons has been found to provide sufficient shading and contribute to thermal comfort for pedestrians (Wong & Jusuf, 2010). However, the impact of different urban design parameters on outdoor thermal comfort has also been investigated. Studies have shown that the compactness of urban forms and the presence of vegetation can significantly affect thermal environments and pedestrian comfort (Taleghani et al., 2015; Ma et al., 2020). Additionally, using cool pavements and the design of elevated walkways have been proposed as strategies to improve thermal comfort conditions for pedestrians (Taleghani & Sailor, 2016; Yang et al., 2016).

Various strategies have been proposed to improve pedestrian thermal comfort in urban environments. These include using shading strategies, greenery, and cool pavements to mitigate the effects of solar radiation and reduce mean radiant temperature (Ridha et al., 2018; Nasrollahi et al., 2020). Urban design parameters such as building porosity and the arrangement of buildings can also be optimized to enhance outdoor ventilation and improve thermal comfort (Yuan & Ng, 2012). Additionally, of selecting and placing trees in urban areas can provide optimal shade benefits to pedestrians and contribute to their thermal comfort (Langenheim et al., 2020). Overall, physiological equivalent temperature (PET) is a widely used thermal index for assessing thermal comfort in outdoor environments. However, this research gears toward obtaining site-specific information within the hot-arid climate zone by proposing a variation of nature-based solutions to gain insights into the thermal comfort of outdoor environments and make informed decisions to improve thermal conditions.

3. Methodology

This research took an experimental approach using a computer simulation with ENVI-met 5.6.1 software of existing sites. They were studied against eleven scenarios to understand their impact on the physiologically equivalent temperature (PET), which affects pedestrians' outdoor thermal comfort within the residential zones of the city of Riyadh. The methodology depicted in the flowchart in Figure 1, begins by collecting input data using various tools. Forcing Manager 5.6.1 inputs weather data, while field measurements provide real-world environmental information. Albero 5.6.1 inputs vegetation parameters, which are crucial for understanding the impact of greenery on the environment. Next, the base model and scenarios are constructed using Spaces 5.6.1. This model is then validated using temperature and relative humidity data (Ta-RH) to ensure accuracy. The study is set up with specific durations and dates using ENVI-guide 5.6.1, and the simulation of parameters at specified study points is conducted with ENVI-core 5.6.1. Moreover, BIO-met 5.6.1 is used to calculate the Physiologically Equivalent Temperature (PET), an indicator of thermal comfort. The data generated from these simulations is visualized and extracted using Leonardo 5.6.1. The study examines various points A and B, represented at BM and S1-S11, to assess the impact of other scenarios. The methodology further includes evaluating the effects of greenery on PET, analyzing critical scenarios where pedestrian comfort might be compromised, and comparing outdoor thermal comfort across different study points. The final goal is to identify optimal solutions to improve outdoor thermal comfort for pedestrians based on the analysis's findings.

PET is a thermal comfort indicator that utilizes a predictive model of the human energy balance to calculate the skin temperature, body core temperature, perspiration rate, and garment temperature as an additional variable. The model is mainly derived from the 2-node model introduced by Gagge et al. (1971) and then refined and expanded by Höppe (1999) into the Munich Energy Balance Model for Individuals (MEMI). Moreover, PET, as defined by Höppe, is the air temperature at which, in a standard indoor environment, the heat balance of the human body is equal to that of the body under the varied outside circumstances being evaluated, with the same core and skin temperature. Starting with the Winter 22/23 release version 5.1.1 and above, the PET module has been thoroughly reviewed to address several accumulated faults and inconsistencies. This incorporates several recommendations from Walther and Goestchel (2018) and many enhancements and modifications. These alterations led to the creation of a PET* (PET Reviewed) presented as PET in this study.

The primary modifications are setting the metabolic rate to the basal rate (about 80 W) and the workload for walking at a speed of 0.1 m/s, irrespective of the chosen outdoor activity.

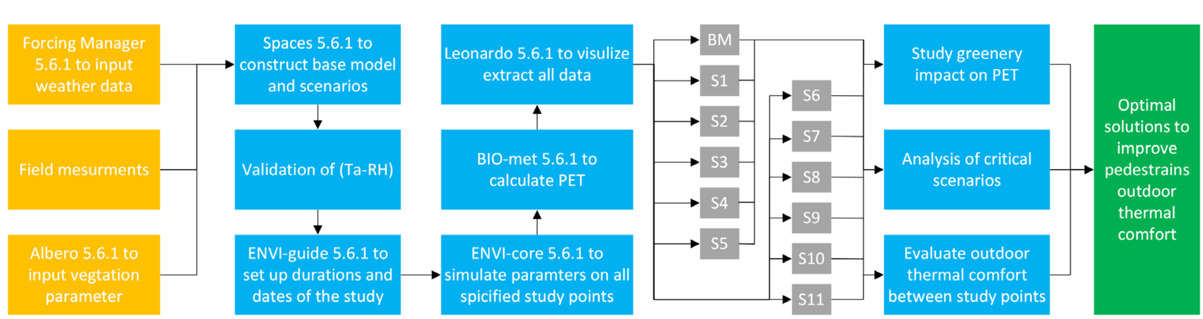

Figure (1). Methodology Steps

The revised metabolic rate affects the breathing settings and energy fluxes, which are not modified throughout the iterations. Furthermore, the proportion of moist skin is reset to zero before computing the inside environment (although it may subsequently grow dependent on the perspiration rate and humidity). Furthermore, the energy balance equation of the skin node was revised to include the alterations. Moreover, the skin energy balance is now comprised solely of radiation and convection between the basal skin sections and conduction flux between the clothing layers. There are no further elements involved. The number of output variables has been expanded to include T Skin static (°C), T Core static (°C), T Cloths static (°C), Fraction Wet Skin, Sweat Rate (g/h), Radiative Budget Skin (W), and Convective Flux Skin (W). Overall, PET is calculated using BIO-met 5.6.1 in this research from the input of the weather data specific to the city of Riyadh with the setting used for calculating as, Male (35 y), outdoor: 0.90 clo, pref. Speed: 1.34 m/s.

Additionally, the following is a list of the abilities of the methodology: a) The methodology's flexibility to be used in different places with the same design is a good example for streets 20m wide in hot and arid regions. b) Providing diverse techniques that include different types of greenery in urban street design—conducting a study on the effects of different kinds of greenery on outdoor thermal comfort in a specific area. This will include examining two specific study points and two frequently observed orientations. c) The selected study area facilitates its application to the length of any roadway with comparable circumstances. The methodology's efficacy in forecasting outdoor thermal comfort directly influences thermal performance at the initial design phase, facilitating its resolution. However, the author does acknowledge some limitations in the methodology: a) The research focused only on fences to exclude the influence of buildings' self-shading. In the designated research zone, during periods of increased heat, it is possible that the structure does not throw any shadows directly on point A or B. b) The Base Model was simplified for modeling, and the floorings were standardized to make the model suitable for a broader range of comparable places. c) The study did not evaluate other features of passive cooling strategies, such as materials, since they were not within the scope of this research.

3.1. Case Studies Description

According to Riyadh Municipality data shared on the Saudi open data portal for 2023, the total road network area is 259,357,843 m2. Out of that, 173,351,552 m2, or 66.83%, are non-main streets, totaling 61,024, as opposed to 2,212 main streets in Riyadh. The street selected for the study is 20m, is within 66.84% of non-main roads, and resembles a standard width that exists in almost every residential neighborhood in the city. Five locations were nominated for this study, all with 20m widths from different residential neighborhoods in Riyadh. All represent the current situation in residential neighborhoods, where

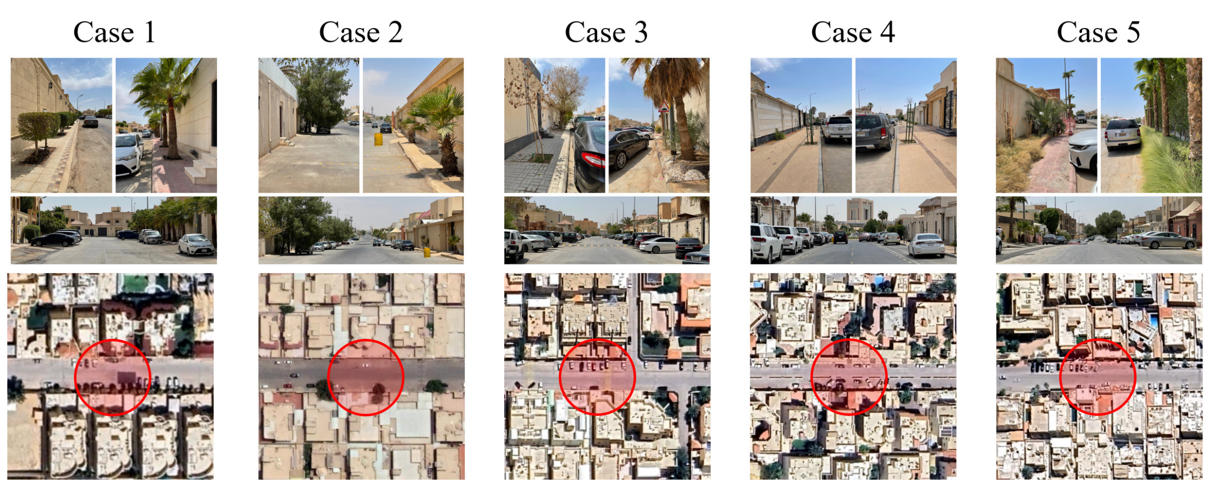

Figure (2). All five case studies' locations, street elevation, and orientation

pedestrians exist even without sidewalks. Some shared similar street orientation but varied in street elements with different greening strategies and sidewalk dimensions. Case 1 had 2m sidewalks on both sides, and case 2 had 1.4m on some parts.

Moreover, case 3 had 1.7 sidewalks, whereas case 4 was one of the few new sample streets, and the sidewalk here was 4m. Case 5 had sidewalks with various dimensions, with the right side 1.6m and the left 2m. Moreover, cases 1,2,3, and 5 had mainly palms and some trees primarily decorative, and very few were used for shading, with case 5 showing ground cover greenery. However, case 4, with the newly added sidewalks in 2024, is the widest with newly planted trees. Nevertheless, it resembles most residential streets in Riyadh, which have a fence around properties. In this case, it was 3m high. Figure 2 shows all five case studies, the targeted area for the survey, and views of the existing streetscape. Cases 1 and 4 had streets that were 115° off the north, and cases 2,3 and 5 had streets that were 25° off the north.

3.2. Numerical Simulation and Validation

The base model (BM) construction resembling the existing case had two orientations, 25° and 115° of the north, to represent all the case studies selected for this study with streets 20m wide and 40 m long, where each unit is 2m by 2m with a height of 1m. In this case, the residential neighborhood streets that contain pedestrians are usually surrounded by residential fences up to three meters high, which were modeled with a default wall setting and the road with asphalt. However, the chosen two points in the study zones covered each side of the street. The two points, A (11,9) and B (11,2), resemble both possible pedestrian sidewalks being studied at 25° and again at 115° street orientations off the north, with k=5 (height at 1.5m), as shown in Figure 3, through data logged hourly from 7 am to 7 pm over twelve months of study from January to December, for each sample day that is the 15th representing a month of the year.

The numerical ENVI-met model was validated by comparing it to field measurements of air temperature (Ta) and relative humidity (RH). These parameters were chosen since they are indicators of outdoor thermal comfort. The fourth case study area, illustrated in Figure 3, was monitored for temperature and relative humidity at point A. Monitoring was conducted on the 15th of May 2024, for hourly logged data between 7 am and 7 pm. The Wintact digital monitor, specifically the WT83 model, was used and mounted on a tripod to conduct measurements. This device can measure temperatures within the range of -20 to 70 °C and relative humidity within the range of 0% to 100%. Featuring a precision of ± 0.5 and ± 2% accuracy and a resolution of 0.1%. The Coefficient of Determination (R^2) . The coefficients for air temperature (Ta) and relative humidity (RH) were calculated and reported as 0.97 and 0.95, respectively, as seen in Figure 4. Moreover, the results closely aligned with the realactual conditions in this research due to the thorough calculation of coefficients. In addition, the Envi-met model was successfully verified.

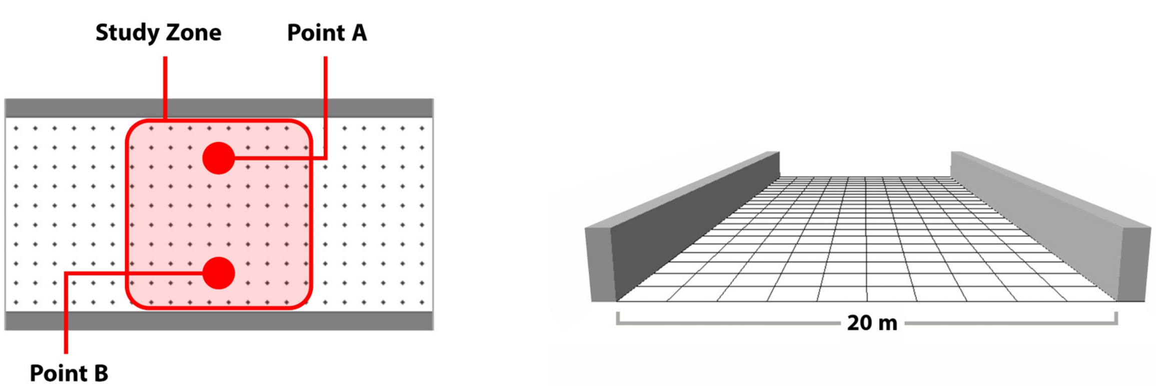

Figure (3). Displaying the BM perspective and plan with highlighted study zone and points A and B

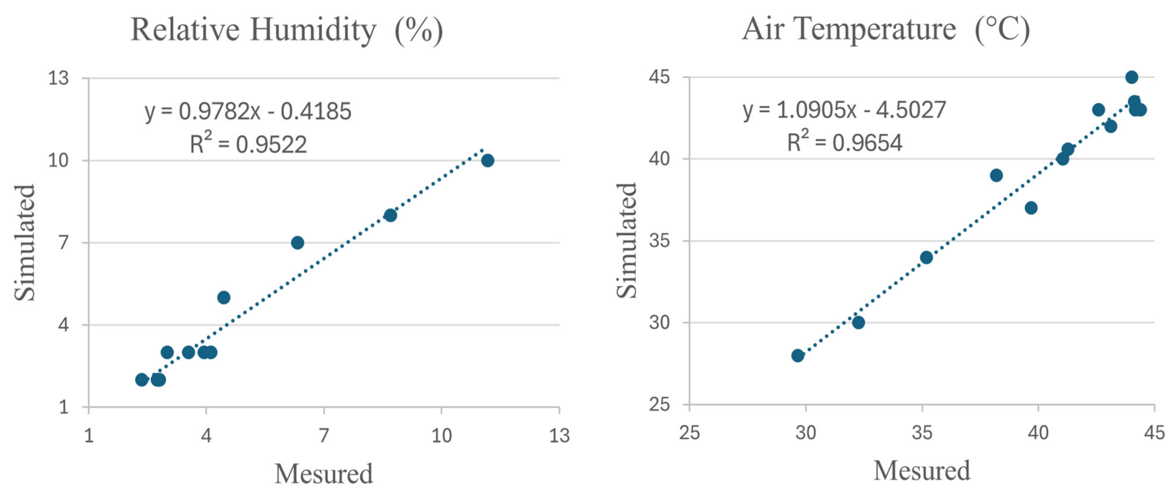

Figure (4). Shows Linear regression of air temperature to the left, and relative humidity to the right

3.3. Scenarios and Their Properties

The base model and scenarios were constructed using Spaces 5.6.1 from S1 to S11, as shown in Figure 5. This research proposed the scenarios as strategies to improve PET by reducing the temperature for outdoor thermal comfort and implied them on both orientations at 25° and again at 115°. Moreover, to simulate, the following details were selected: scenario 1 (S1) adds living wall-only plants on the fences on the street side, and scenario 2 (S2) adds trees 3m high, 4m spacing, single row. Scenario 3 (S3) adds trees 3m high, 8m spacing, single row, and scenario 4 (S4) adds trees 3m high, 4m and 8m spacing, double rows. Also, scenario 5 (S5) adds trees 3m high, 4m spacing, double rows, and scenario 6 (S6) adds trees 3m high, 4m and 8m spacing, and triple rows.

Scenario 7 (S7) adds trees 5m high, 4m spacing, and a single row, and scenario 8 (S8) adds trees 5m high, 8m spacing, and a single row. Additionally, scenario 9 (S9) – adds trees 5m high, 4m and 8m spacing, double rows, and scenario 10 (S10) adds trees 5m high, 4m spacing, double row. Lastly, scenario 11 (S11) – adding trees 5m high, 4m and 8m spacing, triple rows. Furthermore, to

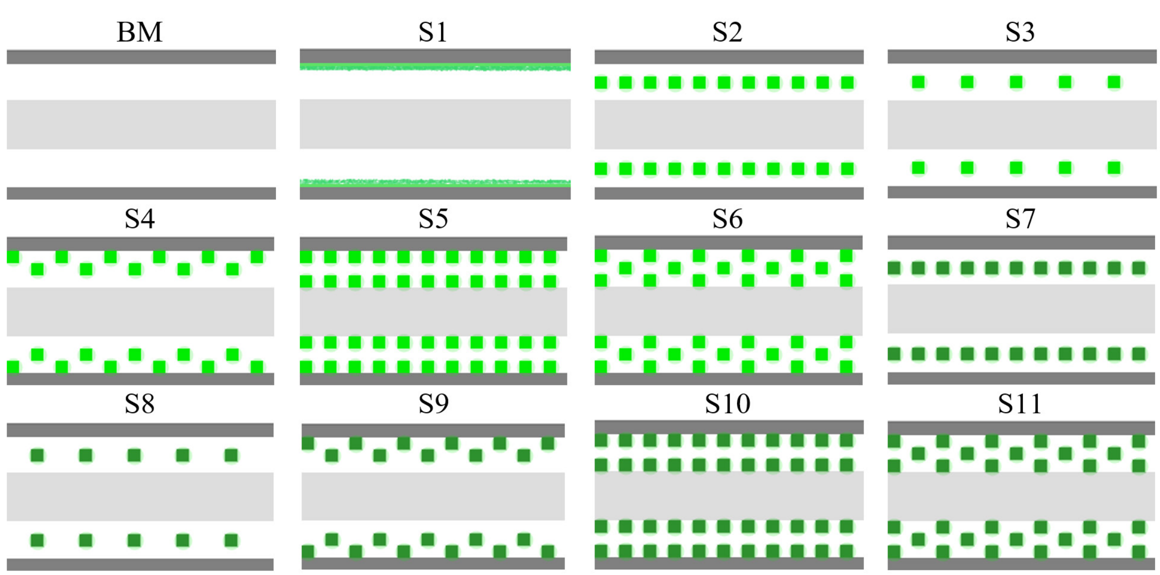

Figure (5). Top views of the base model and all proposed scenarios

Table (1). Vegetation parameters used in the study.

Properties	LW Plant	Tree #1	Tree #2
Description	Climber plant	Spherical, medium trunk, dense	Very dense, leafless base
Leaf type	Evergreen	Evergreen	Evergreen
Height	3m	3m	5m
Width	Covers as needed	3m	3m
Foliage Albedo	0.15	0.18	0.20
Foliage Transmittance	0.25	0.30	0.28
Emissivity of Leaves	0.95	0.96	0.97
leaf factor	1.0 (full leaf)	1.0 (full leaf)	1.0 (full leaf)

simulate the greenery, the parameters were derived from the two prevalent species, namely Hedra Helix (living wall plant), Delonix Regia (tree#1), and Ficus (tree#2). The tree descriptions were aligned with the corresponding characteristics from Albero 5.6.1, with modifications made to each tree's height and leaf type. The characteristics considered were height, breadth, leaf type, foliage (albedo, transmittance, emissivity), and leaves factor, as shown in Table 1. Furthermore, all scenarios maintained a 2m wide sidewalk minimum or more, ensuring sufficient space for comfortable and safe pedestrian movement under Universal accessibility guidelines issued by King Salman Center for Disability Research. Also, comply with international standards such as the ADA Accessibility Guidelines and the UK Department for Transport recommendations. This ensured the sidewalks could accommodate all users, including two-way movement for individuals with wheelchairs.

4. Results & Discussions

4.1 Base Model and Outdoor Thermal Comfort

This section examines outdoor air temperature and PET for the two study points on both street orientations 25° and 115° of the case study base model. All data was listed hourly from 7 am to 7 pm and displayed as °C. However, the highest degree averages were in June and August across points and street orientations. The maximum increase in temperature was reached with the street orientation of 115° at point A, while PET peak temperature was recorded on the street orientation

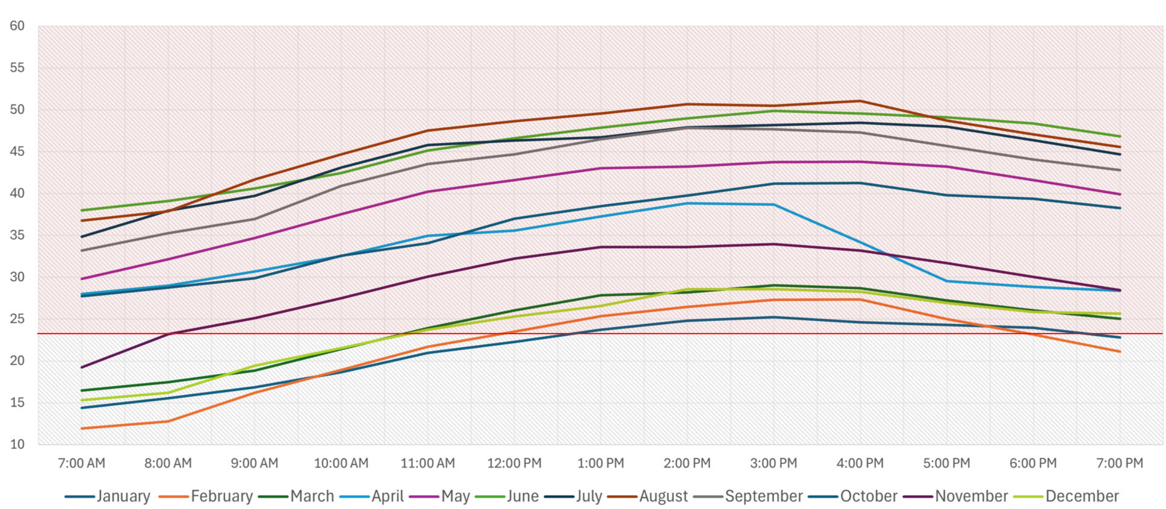

Figure (6). Displaying hourly air temperature in °C from 7 am to 7 pm for January to December.

of 25° at point B. Since PET is the comprehensive outdoor thermal index chosen for this research, the street orientation 25 with point B was selected to apply the scenarios and analyze the attempted solutions. Figure 6 displays air temperature at point B's 25° street orientation from January to December. Additionally, the maximum temperature of 51.066°C for August at 4 pm and a minimum of 11.928°C in February at 7 am. Figure 6 shows a steady increase and a decrease that is higher around noon as solar radiation impacts temperature are evident. Also, it shows that mainly from April to November, the temperatures are above 30°C, and from May to September, they are above 40°C, with June and August experiencing record temperatures. From 7 am to 10:00 am in December till March, the temperatures are below the comfort threshold of 23°C, and January is the only month with acceptable temperatures.

However, PET is displayed in Figure 6 for the street orientation 25° and point B from January to December, where seasonal variations are evident, with the highest temperatures observed during the summer months of June, July, and August. Striking the maximum in June with 57.71°C at 2 pm. Conversely, the winter months of December, January, and February display the lowest temperatures of 12.77°C at 7 am. Spring and autumn months, including March, April, May, September, October, and November, show intermediate temperature values, transitioning gradually between the extremes of summer and winter. The graph highlights a rapid increase in temperature from around 7:00 am, reaching a peak between 12:00 pm and 3:00 pm, followed by a gradual decline towards the late evening at 7:00 pm. Notably, solar radiation and the shade cast by the concrete fences impact the temperature depending on sun's angle with the time of day and month. Only 17.30% of the temperatures are within what is considered slightly warm, which falls under 29°C, indicating 82.2% of the study hours experiencing warm to very hot temperatures.

From comparing air temperature and PET, it is noticed that PET had a higher range with a more substantial peak around noon hours and a drop in late afternoon. The physiological Equivalent Temperature (PET) index can significantly impact the assessment process. Air temperature is a crucial factor affecting outdoor thermal comfort (Zhang et al., 2020). However, the PET index considers various factors such as air temperature, relative humidity, wind speed, mean radiant temperature, and personal factors like clothing and metabolic rate. It is a holistic assessment index of human thermal comfort in outdoor settings (Luo, 2024).

4.2 Scenarios Impact on Physiological Equivalent Temperature

This research simulated eleven vegetation scenarios to investigate their impact on PET for pedestrians' outdoor thermal comfort at two points, A and B, with two street orientations, 25° and 115°. However, an initial comparison of the monthly average reduction of all proposed scenarios between 7 am and 7 pm, between points A, B for 25° and A, B for 115° street orientation. Clearly, point B on

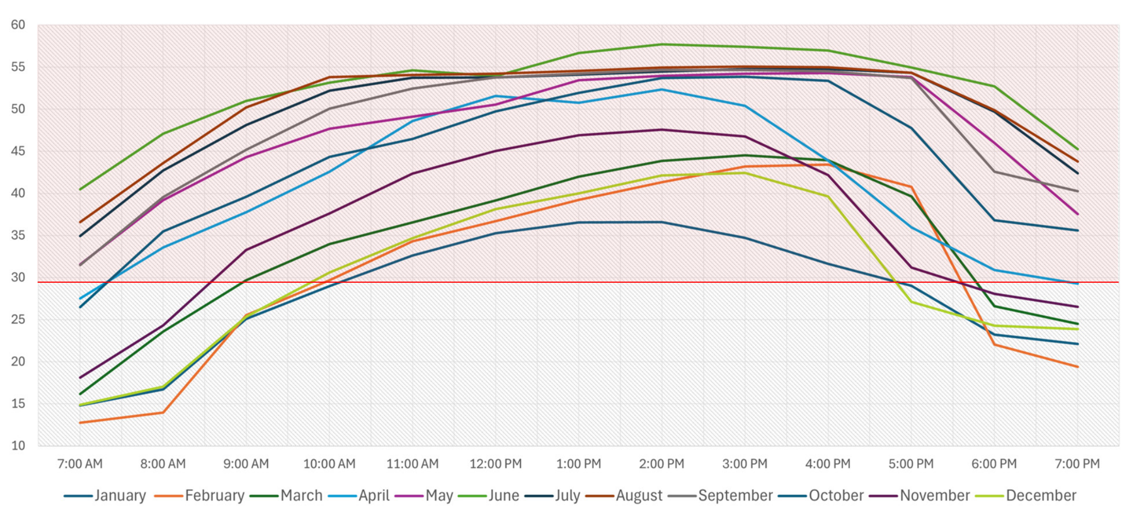

Figure (7). Displaying hourly PET in °C from 7 am to 7 pm, covering all months of the year

street orientation 25° made the most decisivemost substantial impact by reduction, as shown in Figure 8. This made it the point of reference for extreme conditions and the best reduction; therefore, it was chosen to be further explored monthly.

In Figure 9, the base model BM in January showed that PET values ranged from 14.825°C at 7:00 am to 36.597°C at 2:00 pm. Among the scenarios S1 to S11, Scenario 1 (living wall) generally resulted in lower PET values in the morning hours compared to BM. In contrast, scenarios involving more extensive tree plantings showed higher PET values during the afternoon, indicating a lesser impact on reducing temperatures during peak heat hours. The best scenario was S10 (trees 5m high, 4m spacing, double rows), which demonstrated the

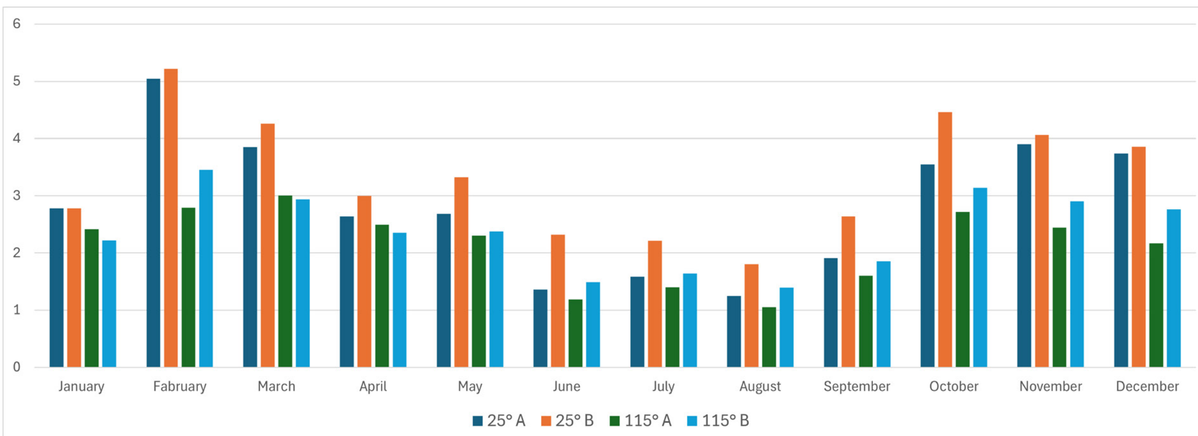

Figure (8). Displaying the monthly average reduction of all proposed scenarios between all points

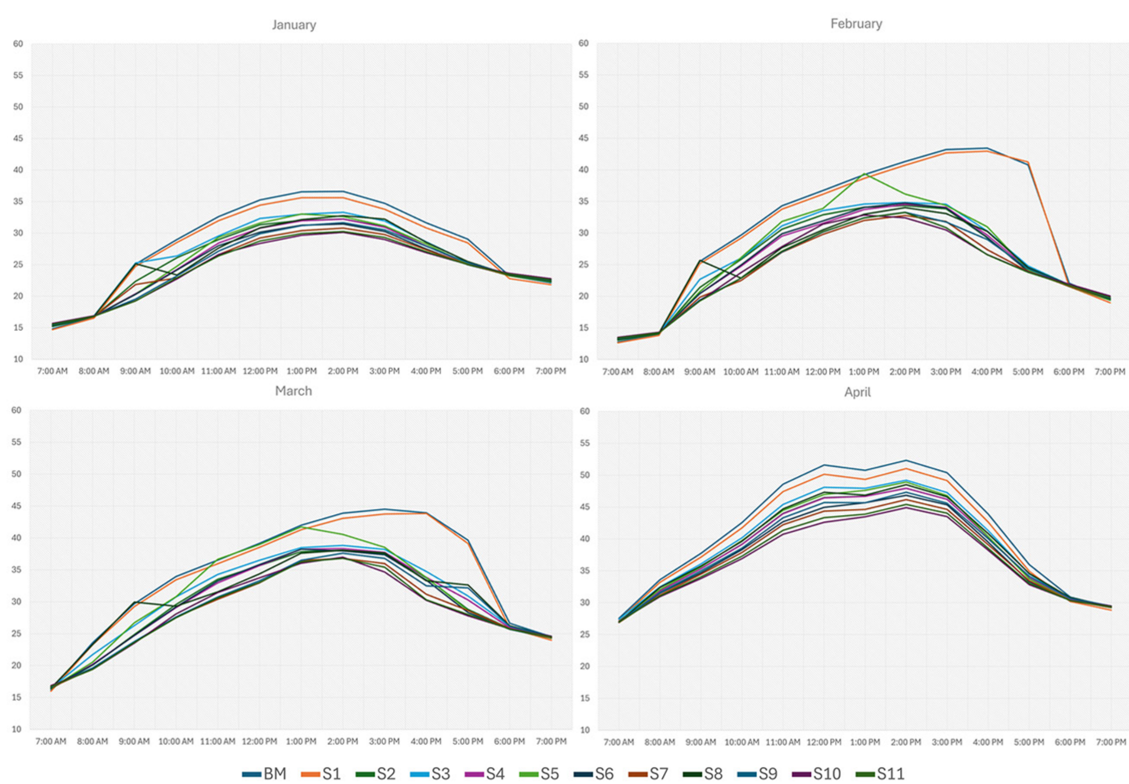

Figure (9). PET in °C from 7 am to 7 pm for January, February, March and April

most significant reduction in PET, particularly in the late afternoon. At 3:00 pm, the PET value was reduced from 34.73°C BM to 28.976°C. The worst scenario was S5 (trees 3m high, 4m spacing, double rows), which showed less effectiveness, with PET values close to the BM. At 1:00 pm, the PET value was 33.013°C, slightly reduced from 36.56°C BM. However, In February, PET values for BM ranged from 12.773°C at 7:00 am to 43.412°C at 4:00 pm. Scenarios with dense tree plantings S6, S7, and S9 consistently showed reduced PET values compared to BM, particularly in the late morning to early afternoon, as displayed in Figure 9. For instance, at 3:00 pm, S10 reduced the PET from 43.199°C BM to 30.481°C. The best scenario was S11 (trees 5m high, 4m and 8m spacing with triple rows), showing the best performance by reducing the PET at 5:00 pm from 40.77°C BM to 23.802°C. The worst scenario was Scenario 5, which had less impact, with PET at 3:00 pm reduced to 36.152°C compared to 41.309°C BM.

In March, Figure 9 illustrates the BM PET values ranged from 16.172°C at 7:00 am to 44.519°C at 3:00 pm. The most significant reductions in PET were observed in scenarios involving high-density tree planting. For example, at noonnoon, S7 (single row trees at 5m high and 4m spacing) reduced the PET from 39.153°C BM to 32.956°C. The best scenario was S10, significantly reducing PET values, with the PET at 4:00 pm dropping from 43.933°C BM to 30.218°C. The worst scenario was Scenario 3, showing the least reduction in PET, with the PET at 2:00 pm reduced to 38.828°C compared to 43.874°C BM. Moreover, as seen in Figure 9, April's PET values for BM ranged from 27.54°C at 7:00 am to 52.33°C at 2:00 pm. S1 (living wall) showed a noticeable reduction in PET during early hours, while S11 showed considerable reductions during peak hours. At 12:00 pm, S11 (trees 5m high, 4m, and 8, spacing with triple rows) reduced PET from 51.59°C BM to 43.326°C. The best scenario was S10, demonstrating the most significant reduction by reducing PET at 12:00 pm from 51.59°C BM to 42.604°C. The worst scenario was S3, showing the least reduction, with PET at 2:00 pm reduced to 49.202°C compared to 52.33°C BM.

In the second group, in May, as shown in Figure 10, the BM PET values ranged from 31.557°C at 7:00 am to 54.276°C at 4:00 pm. S7 showed

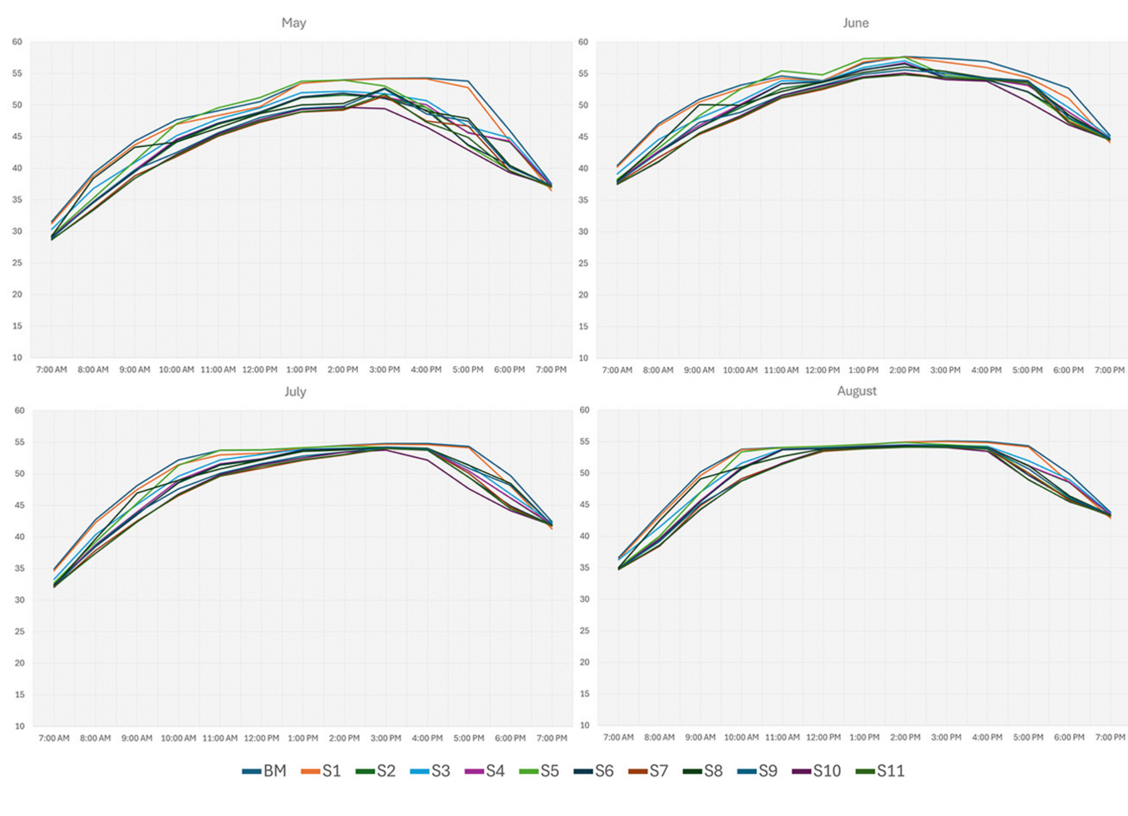

Figure (10). PET in °C from 7 am to 7 pm for May, June, July and August.

significant PET reductions, dropping PET values from 53.976°C BM to 49.2°C at 2:00 pm. Scenarios with triple rows of trees S11 also demonstrated similar effective temperature reductions at 2:00 pm, where it was reduced to 49.415°C. However, the best scenario was S10, the most effective in lowering PET at 5:00 pm from 53.795°C BM to 42.894°C. One of the least effective was S2 (Trees 3m high, 4m spacing, single row), having the least impact with PET at 2:00 pm reduced to 52.182°C compared to 53.976°C BM. Additionally, June's BM PET displayed in Figure 10, values ranged from 40.47°C at 7:00 am to 57.717°C at 2:00 pm. S7, S10, and S11 demonstrated the most effective PET reductions, particularly around peak temperature. At 3:00 pm, the PET for S7 and 11 was reduced to 54.336°C and 54.328°C compared to 57.411°C for BM. Yet, the best scenario was Scenario 10, showing significant PET reduction with values at 8:00 am and 6:00 pm dropping from 57.079°C and 52.692°C BM to 41.021°C and 46.914°C. The worst scenario was S3, showing the least reduction with PET at 2:00 pm reduced to 57.049°C compared to 57.717°C BM.

In July, as illustrated in Figure 10, PET values for BM ranged from 34.933°C at 7:00 am to 54.785°C at 4:00 pm. The scenarios with denser tree plantings showed reduced PET values during the hottest parts of the day. At 2:00 pm, S7 and S11 reduced PET from 54.485°C BM to 52.991°C and 53.081°C. The best scenario was S10, effectively reducing PET values with a reduction at 5:00 pm from 54.344°C BM to 47.599°C. The worst scenario was S3, which had the least impact with PET at 2:00 pm, which was reduced to 54.05°C compared to 54.485°C BM. Similarly, August's PET values ranged from 36.606°C at 7:00 am to 55.079°C at 3:00 pm for BM, as demonstrated in Figure 10. Scenarios involving taller trees S9 and S10 showed effective reductions, with PET at 9:00 am dropping from 50. 195°C BM to 45.122°C and 44.241°C. The best scenario was Scenario 11, with tall trees and triple rows showing the best reduction by decreasing PET at 5:00 pm from 54.319°C BM to 48.918°C. The worst scenario was S3, less effective with PET at 4:00 pm reduced to 54.998°C compared to 54.283°C BM.

Moreover, in the third group, September, as shown in Figure 11, BM PET values ranged from 31.472°C at 7:00 am to 54.672°C at 3:00 pm. The

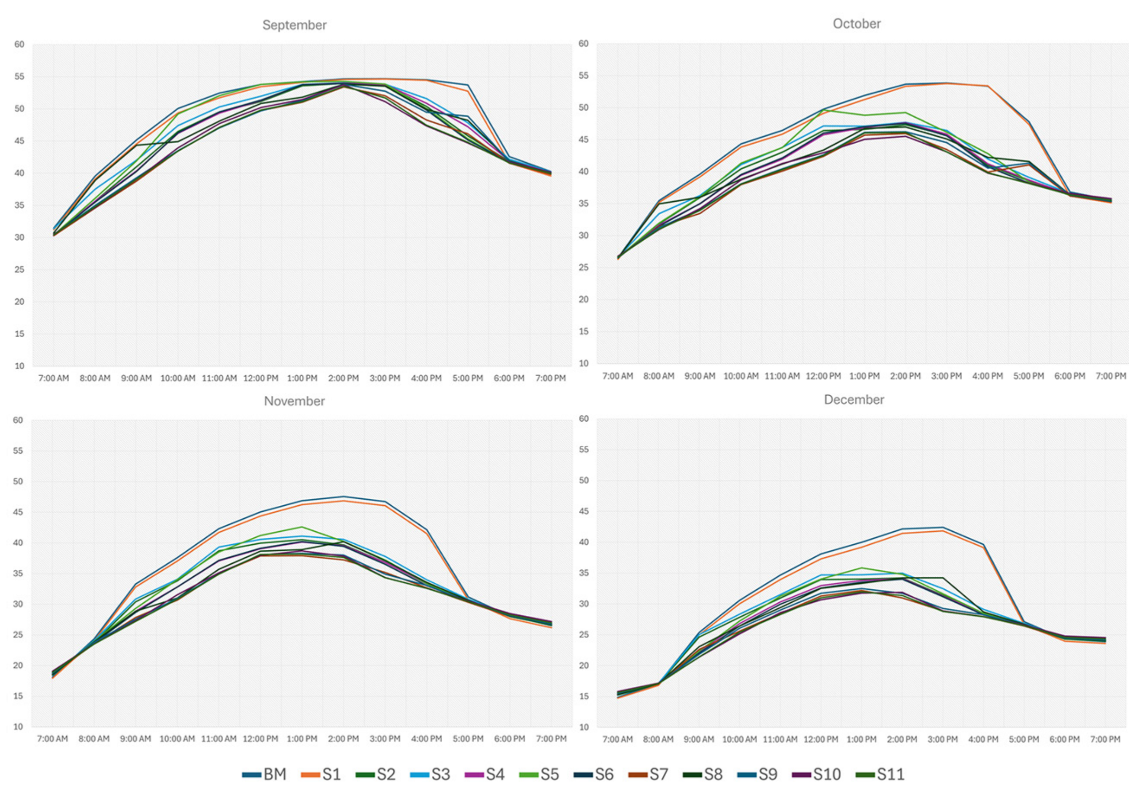

Figure (11). PET in °C from 7 am to 7 pm for September, October, November and December.

most significant reductions around the highest PET were seen in scenarios with extensive tree coverage, especially with the taller trees as S7, S10, and S11. At 3:00 pm, S10 reduced PET from 54.672°C (BM) to 51.012°C. The best scenario overall was Scenario 6, significantly decreasing PET values with values at 5:00 pm dropping from 53.7°C BM to 44.687°C. The worst scenario was S5, showing the least reduction with PET at 12:00 pm reduced to 53.797°C compared to 53.784°C BM. In addition,, PET values for BM in October ranged from 26.511°C at 7:00 am to 53.847°C at 3:00 pm, as in Figure 11. The scenarios with high-density plantings, taller trees, and smaller distances between them, such as S7, S10, and S11, showed noticeable reductions; also, they were close with more spacing and shorter trees than S9 (trees 5m high, 4m, and 8m spacing with double rows) and S6 (trees at 3m high, 4m spacing and double rows). The PET at 4:00 pm decreased from 53.375°C BM to 39.821°C S11, 40.557°C S9, 40.75°C S6. The best scenario was S11, being the most effective in reducing PET at 5:00 pm from 47.769°C BM to 38.134°C. The worst scenario was S5, which had the least impact with PET at 2:00 pm, reduced to 49.228°C compared to 53.687°C (BM).

November's BM PET values ranged from 18.139°C at 7:00 am to 47.566°C at 2:00 pm as presented in Figure 11. Scenarios with denser tree configurations reduced PET effectively, with values at 2:00 pm dropping from 47.566°C BM to 37.838°C by S10. The best scenario was Scenario 11, effectively reducing PET values with a reduction at 3:00 pm from 46.749°C BM to 34.324°C. The least effective scenario was S3, having the least impact with PET at 9:00 am reduced to 30.847°C compared to 33.287°C BM. Furthermore, PET values for BM in December ranged from 14.885°C at 7:00 am to 42.419°C at 3:00 pm, as revealed in Figure 11. Some scenarios consistently showed effective PET reductions, particularly during midday. At 2:00 pm, S7 reduced PET from 42.146°C BM to 30.978°C and 31.726°C S9, 31.89°C S10, 31.379°C S11. Additionally, the best scenario was S11, significantly reducing PET at 4:00 pm from 39.648°C BM to 27.924°C. The minimum impact was from S3 and S8, being less effective with PET at 10:00 am reduced to 28.345°C compared to 30.599°C BM for S3 and at 9:00 am at 23.09°C from 25.365°C for S8.

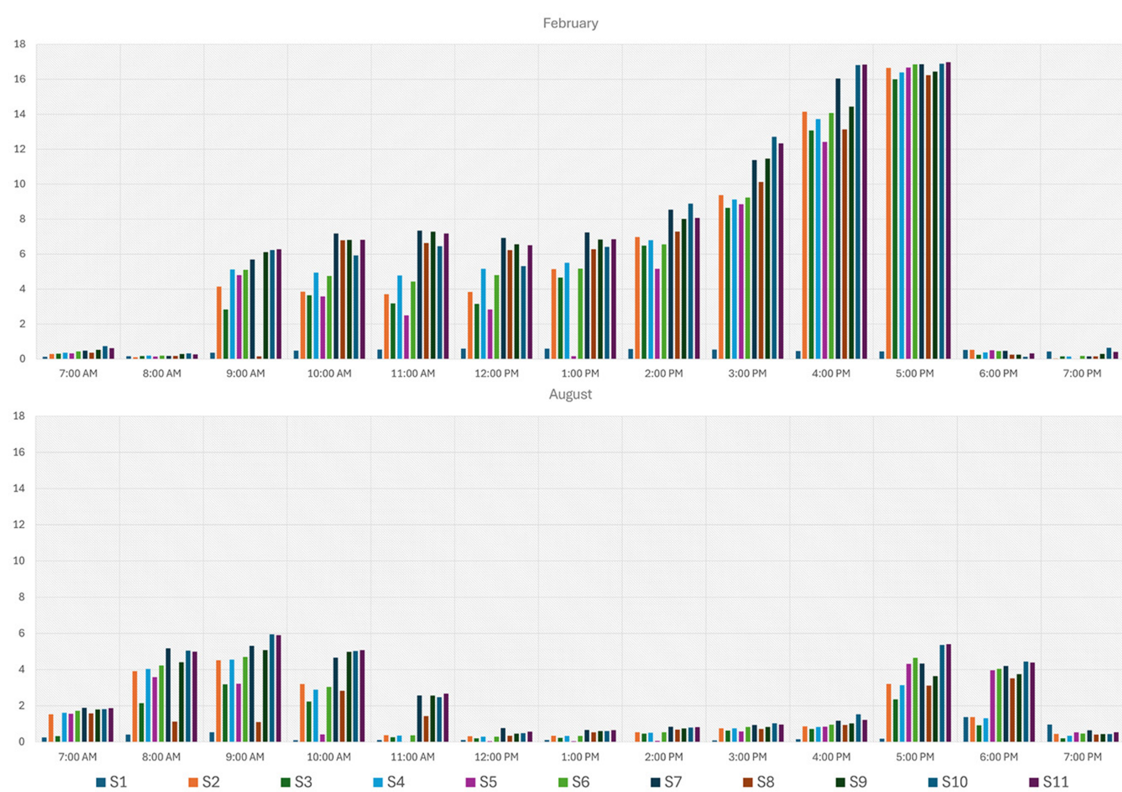

Figure (12). PET reduction is shown in °C from 7 am till 7 pm for S1-S11.

In general, S1, with living walls on the sides of the fences overlooking the pedestrian path, resulted in the least reduction throughout the year. Scenarios involving extensive tree planting, especially those with taller trees and higher density (less spacing and multiple rows), such as S7, S10, and S11, consistently demonstrated the most significant PET reductions across most months but were less efficient in the hottest extremes. Moreover, in some cases, more mixed spacing and shorter trees came close to reducing PET as S6 and S9 during specific times of the day, making them viable choices for reduction. However, after analyzing all year-long data for all scenarios, throughout all time slots from 7 am to 7 pm, it was found that February was the most effective PET reduction and August was the least effective, as shown in Figure 12. Where S7, S10, and S11 shared the highest levels of PET reduction, S7 from 16.866°C to 0.005°C, S10 from 16.9°C to 0.89°C, S11 from 16.978°C to 0.027°C.

4.3 Assessment of Optimal Case Temperature Distribution

In this section, the street orientation of 25° was further investigated all year long. Temperature distribution maps are examined at 5 pm across scenarios 7, 10, and 11 using Leonardo 5.6.1 to obtain visual temperature distribution for all study areas. Where S7 implemented trees 5m high, 4m spacing, single row, S10 added trees 5m high, 4m spacing, double row, and S11 used trees 5m high, 4m and 8m spacing, triple rows. However, upon preliminary examination of data and while comparing the average reduction between S7, S10, and S11, the maximum reduction and minimum for the year-long data were S7 16.866°C – 0.005°C, S10 16.9°C – 0.089°C, and S11 16.978°C – 0.027°C. The differences between the averages were marginal. However, Figure 13 shows the amount of reduction from 7 am to 7 pm hourly for February and August for study point B, and the differences vary depending on the month and the time of the day (1-3°C in August) and (1-10°C in February). Furthermore, the scale used in this study in Figure 13 shows stress categories adapted and adjusted from the original PET thermal scale introduced by Matzarakis et al. (1999). The modified scale caters to the temperatures within the limits of this research by eliminating the substantial,intense cold temperatures. It also adopts similar stress categories as Binabid and Anteet (2024) with different degree ranges, starting at 12°C and reaching 43°C +. Additionally, the heat distribution maps in Figure 14 use the same PET stress categories color coding shown in Figure 13 for the base model and all scenarios throughout the year at 8 am and 4 pm. The figure visually demonstrates the effectiveness of these scenarios in reducing temperatures across different times of the day and throughout the year. The maps highlight the temperature distribution

Figure (13). To the left shows PET reduction from S7, S10, and S11 for February and August, and to the right PET stress categories

across the study area, showing how each scenario affects outdoor thermal comfort. The findings suggest that higher-density tree configurations and taller trees (such as those in S10 and S11) tend to have a more significant impact on reducing PET, especially during the hottest parts of the day.

Furthermore, at 4 p.m., it was observed that in May, June, July, August, and September, while scenario reductions happened, they were minimal and did not lower the PET temperature from extreme heat stress. Additionally, between S10 and S11, the effect of 4m distancing, as S10 made higher density, gave better-sounding impact, and covered more space. However, in S11, where two distancing is used, 4m and 8m with more trees, but the density is lowered, and that reduced parameter of PET temperature reduction as shown in Figure 14 at 4 pm for April to October and at 8 pm for the months January to April and October to December.

Overall, the results indicate that configurations with taller, denser trees and narrower spacing significantly lower PET, creating more comfortable outdoor environments for pedestrians. This effect is due to the extensive shading by taller trees, which reduces direct solar radiation. Denser tree placement further amplifies this cooling effect by minimizing the exposure of surfaces to sunlight, thus lowering ground temperature and air temperature in the immediate area. Scenarios with 5m high trees planted in double or triple rows reduced PET by up to 15% compared to less dense configurations. Consequently, the reduction in PET directly enhances outdoor thermal comfort, particularly during peak midday temperatures.

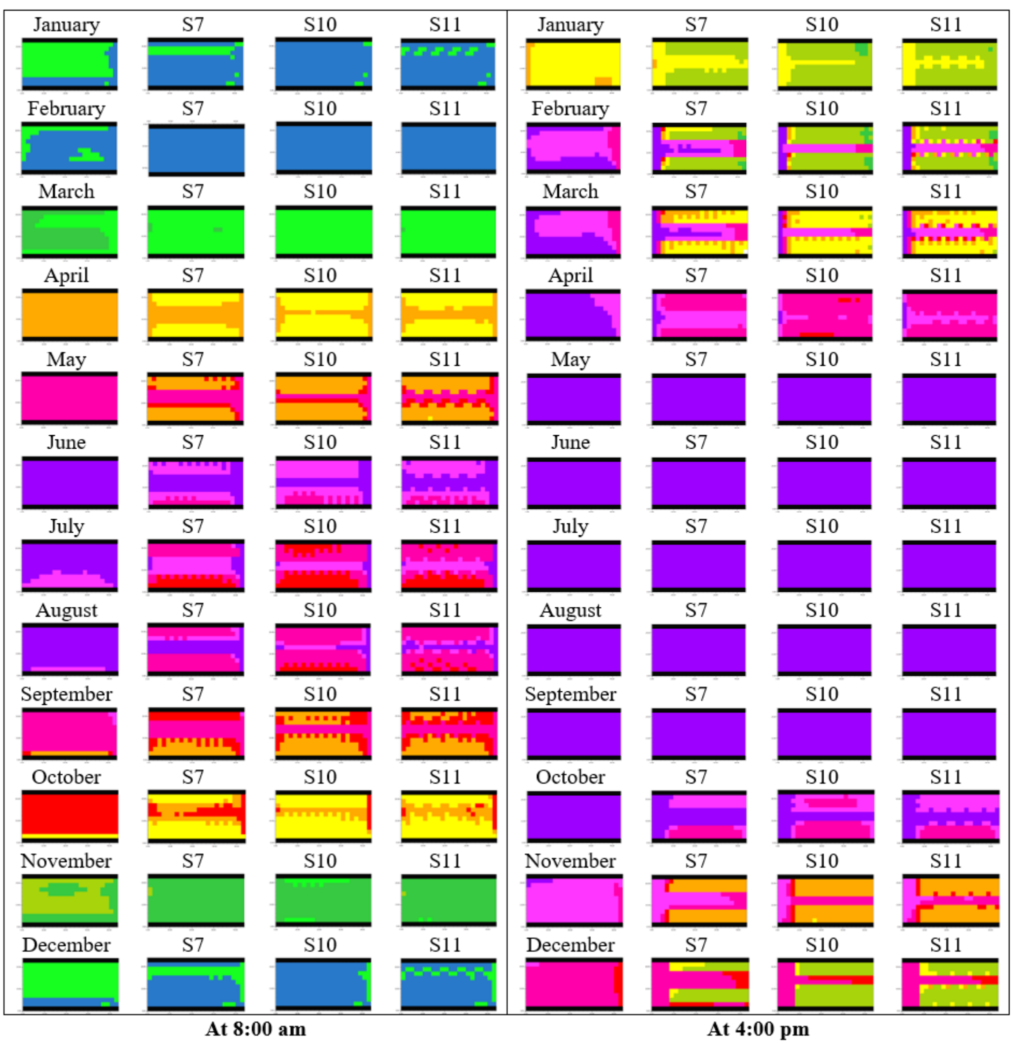

Figure (14). Showing heat distribution map at 8 am and 4 pm for BM and S1 to S11.

5. Conclusion & Recommendations

The study conducted on the impact of greenery on outdoor thermal comfort for pedestrians in residential zones of Riyadh, Saudi Arabia, has provided site-specific insights into the effectiveness of different vegetation configurations in mitigating the harsh thermal conditions characteristic of hot and arid climates. Utilizing ENVI-met 5.6.1 simulation software using a reviewed calculation model thoroughly and examined to address several accumulated faults and inconsistencies. Moreover, various scenarios were modeled to assess the physiologically equivalent temperature (PET) hourly from 7 am to 7 pm and from January to December. The results indicate that of incorporating greenery, especially for street orientations of 25° off north, particularly trees 5m in height and spacing 4m between them, can significantly reduce PET, thus enhancing outdoor thermal comfort. Living walks have the least impact as their shading effect is minimal, although covering the surface area of fences.

However, scenarios with taller trees and higher planting densities (such as S10 and S11) consistently demonstrated the most significant PET reductions, ranging from 16.978°C to 0.027°C for S11. Also, with smaller distances between trees and higher density, the reduction impact reaches more area covering parts of the street, not just the pedestrians, which in return lowers the heat island effect, eventually impacting the microclimate of the neighborhood. This reduction is critical in improving the livability and walkability of urban spaces, which is essential for promoting sustainable urban development.

This will encourage residential pedestrians to walk to public transportation in the early morning or later in the evening when returning from work. The best strategies here are S10 or S11, which can reduce heat stress in a few categories for months of the year. While being less effective with extreme heat, such as at 4 pm during warmer months, May to September. In conclusion, the findings emphasize the importance of strategic urban planning that incorporates nature-based solutions to address the challenges of thermal comfort in hot climates. The study suggests that urban designers should prioritize including green infrastructure, particularly in the design of pedestrian paths and residential streets, to create more comfortable and livable urban environments. In this case, scenario 11 has the best impact on reducing PET at a specific point under the shade of the trees, such as point B in this study with three rows of planting and using distances of 4m and 8m between the trees. However, having closer distances only at 4m gives a more significant overall impact on the surrounding area.

Several design recommendations can be made based on the results of this research to improve pedestrian thermal comfort on Riyadh's 20 m residential streets. First, the optimal tree height for maximizing thermal comfort is 5m, with a recommended spacing of 4m between trees arranged in double or triple rows, depending on the available space. This configuration provides ample shade while maintaining pedestrian visibility and accessibility. Additionally, tree species should be selected locally based on their ability to withstand Riyadh's arid climate, with a focus on those that provide dense foliage to maximize shading. Where possible, integrating green walls or vertical greenery along property fences can further enhance shading and reduce the urban heat island effect. Finally, these design recommendations could be implemented nonuniformly to some sections in variations throughout residential streets to tailor to the unique requirements of each neighborhood, area, and region while considering pedestrian outdoor thermal comfort.

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تأثير استخدام النباتات على درجات الحرارة الفسيولوجية المكافئة للمشاة في المناطق السكنية ذات المناخ الحار والجاف

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قدم للنشر في ٩/ ٢/ ١٤٤٦ هـ؛ وقبل للنشر في ١٧/ ٤/ ١٤٤٦ هـ.

ملخص البحث. يهدف البحث إلى دراسة تأثير استخدام النباتات في تصميم مسارات المشاة على الراحة الحرارية ضمن حي سكني في مدينة الرياض، في المملكة العربية السعودية. تُركز الدراسة على نمذجة استراتيجيات باستخدام النباتات من خلال موقع جغرافي قائم، بهدف فهم سيناريوهات تصميم مسارات المشاة مع تباين توزيع النباتات، والتركيز على تأثير ذلك على الراحة الحرارية. كما تم استخدام برنامج Envi-met 5.6.1 لتحليل ومقارنة دراسات الوضع الراهن وتقديم نماذج محسّنة تدعم الظروف الحرارية المناسبة من خلال دراسة تأثير النباتات على الراحة الحرارية الخارجية، وتحديد المعايير البيئية التي تؤثر على هذه الراحة، ومقارنة تأثيرها على درجة الحرارة الفسيولوجية المكافئة (PET) ، بهدف تقديم توصيات للمحافظة على الصحة الجسدية للمشاة وتعزيز رفاهيتهم. يركز هذا البحث على أهمية استخدام النباتات في تحسين الراحة الحرارية للمشاة في المناطق الخارجية ضمن المناخ الحار والجاف، مع مراعاة عوامل تصميمية مثل: موقع النبات، وارتفاعه، وعرضه، والمسافات الفاصلة بين النباتات. يُساهم فهم هذه العوامل وأدوارها الحيوية في تحديد الظروف الحرارية وراحة المشاة وهو ما يساهم في رفع عدد ساعات استخدام ممرات المشاة في فترة النهار وإيجاد استراتيجيات تصميم حضري تعزز من الراحة الحرارية للمشاة وتدعم بيئات حضرية مستدامة.

الكلمات المفتاحية: الراحة الحرارية، درجة الحرارة الفسيولوجية المكافئة، مسار المشاة، النباتات، المحاكاة، الإشعاع الشمسي، المناطق السكنية