Bagh-e Nazar
DOI:10.22034/bagh.2026.507504.5769

Bagh-e Nazar, *23*(158), 21-28 / 2026
Persian translation of this paper entitled:
بررسی تأثیر پوشش‌گیاهی بر آسایش حرارتی در اقلیم گرم و خشک
(در مقیاس خرد-محله مسکونی خلدبرین- شیراز)
is also published in this issue of journal.

Original Research Article

Investigating the Impact of Vegetation on Thermal Comfort in a Hot and Arid Climate
(A Micro-Scale Study of Kholdebarin Residential Neighborhood, Shiraz, Iran)

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Received: 20/02/2025 Accepted: 13/04/2026 Available online:23/07/2026

Abstract
Problem statement: Urbanization and uncontrolled physical expansion of cities, without consideration of climatic consequences, have led to rising ambient temperatures and a subsequent decline in thermal comfort and quality of life for residents in outdoor spaces within hot and arid climates. Although vegetation can enhance thermal comfort through shading and radiation mitigation, the effectiveness of this strategy at the microscale, such as in residential alleys, remains uncertain and warrants further investigation.

Research objective: This study evaluates the role of vegetation in moderating thermal comfort at the microscale in urban spaces within a hot and arid climate.

Research method: Two alleys with similar physical characteristics but different vegetation conditions in the Kholdebarin neighborhood of Shiraz, Iran, were selected. Field data, including air temperature and relative humidity, were collected during peak heat hours. Following the simulation of the study environment in ENVI-met, the data were analyzed using the PMV index in Bio-MET.

Conclusion: Results showed that the maximum temperature difference was approximately 2°C, while the PMV index remained in the "very hot" range. Despite the relative effect of vegetation, this degree of change is insufficient to provide thermal comfort. The findings demonstrate that tree species and canopy form play a significant role in improving thermal conditions. This study emphasizes that effective green space design incorporating trees with wide canopies is more impactful than simply planting trees with limited canopy cover.

Keywords: *Thermal comfort, Hot and arid climate, Vegetation, Microclimate simulation.*

Introduction
Global climate change and urbanization are two fundamental factors contributing to the decline in the quality of urban life, particularly in hot and arid climates. These phenomena create unfavorable thermal conditions, such as urban heat islands (UHI), leading to increased ambient temperatures and reduced thermal comfort. For instance, the 2003 heatwave in Europe resulted in the death of more than 70,000 people (Robine et al., 2008). More than half of the world's population lives in cities and suffers from unfavorable thermal conditions and urban heat islands. This situation leads to increased energy consumption, fire risk, and thermal discomfort (Wang et al., 2021).

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In urban areas, the use of nature-based and human-made solutions can address this issue to some extent (Sabrin et al., 2021). More precisely, these strategies can help designers create safe and comfortable urban environments that improve the level of thermal comfort in outdoor spaces (Narimani et al., 2022). Research on how outdoor spaces should be designed to achieve better thermal comfort helps landscape and urban designers optimize open urban environments for more active public engagement and a more pleasant experience. Accordingly, the role of street trees in enhancing thermal comfort in urban areas has become increasingly important, as they can provide more comfortable conditions for people in these spaces (Liu et al., 2022).

Aim of the Study

This study specifically aims to examine the role of trees in heat mitigation and the provision of thermal comfort in urban corridors within hot and arid climates. If their contribution at the microclimate scale is significant, they can be considered effective strategies for improving ambient temperature; otherwise, the hypothesis that trees contribute to environmental comfort will be called into question.

Research Questions

Is vegetation effective in providing thermal comfort in urban spaces? Is the mere presence of vegetation in a location sufficient to expect improved comfort conditions?

Literature Review

Several studies have investigated the role of vegetation on thermal comfort in hot and arid climates. In these studies, the use of simulation software alongside precise measuring tools and field surveys has yielded confirmatory results on this subject. Some of these studies demonstrate that trees play a fundamental role in improving thermal comfort in urban outdoor spaces (ibid., 2022).

Most of the studies conducted over the past decade, using ENVI-met software, cover topics such as achieving architectural design criteria and thermal comfort (Lenzholzer, 2012); simulation of built architectural forms and their landscapes (Middel et al., 2014); and simulation of various design alternatives, examining the influence of architectural factors such as height-to-width ratios, building placement, and shading on reducing the urban heat island effect and improving pedestrian comfort, as well as proposing suitable vegetation cover (Al-Kurdi & Awadallah, 2015). Abdollahzadeh and Biloria (2021) also found that the use of green space and tree planting can increase specific humidity and improve street-level thermal comfort (Abdollahzadeh & Biloria, 2021). Regarding tree dimensions and species, Ananyeva and Emmanuel (2023) found that vegetation is a key factor in reducing surface temperature in 75% of urban areas, with trees having the greatest impact (Ananyeva & Emmanuel, 2023).

Sabrin et al. (2021) also argue that a tree's potential for temperature reduction depends on environmental characteristics, including building density and height, surface materials, and local climate conditions. Park et al. (2024), in a study on urban heat islands and the impact of vegetation cover, concluded that a temperature reduction of 1–2°C is achievable through tree planting (Park et al., 2024).

Terrani et al. (2024) found that the impact of trees on pedestrian walkways is more perceptual and psychological than physical, meaning that while the actual temperature reduction is modest, users perceive greater comfort than the physical measurements would suggest (Terrani et al., 2024). Another study reported that adding more trees can reduce air temperature by an average of 0.2°C (Cortes et al., 2022). Lai et al. (2024) identify the crown diameter of trees that provide wider shade as the primary factor in improving thermal comfort conditions. Their findings also indicate that, perceptually, pedestrians under tree shade — at the same temperature as unshaded areas — experienced greater perceived comfort (Lai et al., 2024). The cooling effect of vegetation appears to be primarily attributable to shading, which reduces radiation reflection (Li et al., 2019). Heat perception depends more on radiation and the temperature of surrounding objects (mean radiant temperature) than on air temperature itself; therefore, the more ambient radiation is controlled, the greater the sense of comfort. Terrani et al. (2024) found that trees can intercept up to 85% of long-wave solar radiation, preventing its reflection from paved surfaces and ultimately reducing radiant temperature (Terrani et al., 2024). Although higher leaf density in tree canopies is preferable for creating shade, it is considered a negative factor due to reduced airflow (Nicholson et al., 2024). Chu et al. (2024) propose adopting a more dispersed green design for open spaces to maximize the shading effect on paved surfaces and reduce solar radiation within the space, reporting temperature reductions of 1–2°C (Chu et al., 2024).

This section reviews and critically analyzes international and domestic studies, respectively. Elwy et al. (2018), in the hot and arid climate of Cairo, Egypt, demonstrated through ENVI-met simulation and field data that vegetation reduces air temperature and mean radiant temperature (MRT). While the study benefits from high credibility due to the combination of field measurements and numerical simulation, it does not address differences between plant species (Elwy et al., 2018). Zhao et al. (2018), in Phoenix, USA, investigated the effect of different tree species and their placement on airflow and thermal comfort. By emphasizing street orientation and tree canopy form, they demonstrated that trees with wide canopies and appropriate orientation can improve thermal comfort conditions. However, this study relied solely on simulation and lacks field validation (Zhao et al., 2018). Al-Kurdi & Awadallah (2015), in Amman, Jordan, used numerical simulation to show that street design incorporating vegetation can reduce urban heat island effects and enhance thermal comfort, though the study lacks field data (Al-Kurdi & Awadallah, 2015). Coutts et al. (2015) highlight the role of vegetation in environmental cooling and improving human thermal comfort through shading and transpiration, emphasizing the importance of adequate water availability for tree health, as well as sufficient canopy cover for shading, transpiration, and soil moisture retention (Coutts et al., 2015). Narimani et al. (2022) in Iran, focusing on tree form and street orientation, demonstrated that different tree species have varied effects on users' thermal comfort, with taller trees featuring wider canopies creating better conditions through improved airflow and more effective shading. The study employs ENVI-met simulation but does not address user comfort perception (Narimani et al., 2022). Mentioned researches are camparisoned in Table 1.

Previous studies generally confirm that vegetation is effective in improving thermal comfort in hot and arid climates. However, two key gaps remain. First, the extent to which this effect is tangible to humans and sufficient to transform an uncomfortable urban space into a comfortable one has not been adequately addressed. For instance, it remains unclear whether a temperature reduction of 1–2°C due to vegetation actually leads to environmental comfort. Second, if vegetation plays a fundamental role in environmental comfort, what is the underlying mechanism? Does the mere presence of greenery ensure comfort? This study addresses these gaps by modeling two residential alleys in the urban context of Shiraz — one with and one without vegetation — using a combination of ENVI-met numerical simulation and field data to better understand the role of trees in improving thermal conditions.

Table 1. Summary of previous studies in hot and arid climates. Source: Authors.

Study	Location	Tools	Method	Strengths	Limitations
Elwy et al. (2018)	Cairo, Egypt	ENVI-met + field measurement	Numerical simulation + field	High credibility due to the combined approach	Limited analysis of plant species
Zhao et al. (2018)	Phoenix, USA	ENVI-met	Numerical simulation	Emphasis on species and tree orientation	Lacks field validation
Narimani et al. (2022)	Iran	ENVI-met	Numerical simulation	Analysis of species and street orientation effects	Does not address user experience
Al-Kurdi & Awadallah (2015)	Amman, Jordan	—	Numerical simulation	Emphasis on urban design and vegetation	Lacks precise measurement tools

Theoretical Foundations

Considering the purpose of the research, it is necessary to provide complete definitions of thermal comfort and its measurement indicators, as well as to review theories regarding the impact of vegetation on thermal comfort.

In urban areas, urban heat islands are formed due to impervious surfaces (such as asphalt and concrete), reduced vegetation cover, heat generated by human activities, and the emission of pollutants. These conditions cause urban areas to be warmer than surrounding rural areas (Sabrin et al., 2021). Thermal comfort is defined as a subjective state in which individuals are satisfied with the ambient temperature. This concept has gained particular importance, especially in urban open spaces, due to rapid urbanization and climate change (Liu et al., 2022). Solar radiation is the most important factor affecting thermal comfort in outdoor spaces (Yang et al., 2013). One of the most common strategies for reducing the impact of solar radiation is the use of vegetation (Liu et al., 2022). Vegetation, particularly trees, improves thermal comfort conditions by creating shade and reducing direct solar radiation. Trees with wide canopies can create favorable conditions for users through shading and surface temperature reduction (Picot, 2004). Liu et al. (2022), examining different climates, show that the effect of tree shade is influenced by factors such as planting design and tree morphology (Liu et al., 2022).

Research Methodology

This study employs a mixed methodology (quantitative simulation with field data) to investigate the impact of vegetation on thermal comfort in the hot and arid climate of Shiraz, Iran. The research was conducted in four main stages.

- **Site selection**

Shiraz is located in southwestern Iran, characterized by a hot and arid climate, at approximately 29°N latitude and 52°E longitude, at an elevation of 1,486 meters above sea level. Two alleys with similar physical characteristics in the Kholdebarin residential neighborhood (Fig.1) were selected. Alley A contains two Citrus x aurantium trees, while Alley B contains 25 Citrus x aurantium trees and one Acer Pseudoplatanus tree (Fig. 2). Both alleys are similar in terms of building density (2– 4 stories), construction materials (brick and stone), width (8. 3 m), and orientation (54° southwest).

- **Field data collection**

Field measurements were carried out on July 22, 2022, one of the hottest days of the year in Shiraz, between 6: 00 a.m. and 6: 00 p.m. Data were recorded at three time intervals: 10:00 a.m., 2: 00 p.m., and 6: 00 p.m. Measurements were taken at five points along each alley, spaced 20 meters apart. At each point, air temperature, relative humidity, and wind speed were measured at human height using a Thermo-hygro- barometer (TES 1161 model) and a Pen Type Thermo-hygro-anemometer. In addition, the length and width of each alley and the dimensions and height of the residential buildings within the study area were recorded through field surveys (Table2).

- **Simulation with envi-met**

Envi-met is used as a dynamic 3d model for simulating the impact of vegetation on thermal comfort in urban

Fig. 1. Study area. Source: Google Earth.

Fig. 2. From left to right: Alley A and Alley B, respectively. Source: Authors' archive.

spaces (Lenzholzer, 2012). The simulation process in this study was conducted using ENVI-met version 5.0. 3 in two main stages: environmental modeling and thermal comfort analysis, covering the period from 6: 00 a.m. to 6: 00 p.m. on July 22, 2022. In the initial model settings, the geographic coordinates of Shiraz were defined: latitude 29.62°N, longitude 52.51°E, and an elevation of 1,486 meters above sea level. Based on the physical characteristics of the study area, the model grid was defined as x-grids = 135, y-grids = 135, and z-grids = 14, with a horizontal resolution of 1 meter in the x and y directions and 3 meters in the z direction. Furthermore, to improve modeling accuracy in accordance with the orientation of the studied alleys, the model was rotated 54° from north. The number of nesting grids was considered 4. Then, the area with 119,115,118, and 106-meter length in respective north, east, south, and west with buildings with 2- 4 flats (6-12m) was modeled. Next stage Citrus x aurantium trees in both allays, and one Acer Pseudoplatanus in B, were located in the model based on Google Earth photos and field measurements (Fig.3). The meteorological data for the study area were converted from EPW format to FOX format for use in the Full Forcing method in ENVI-met. Due to model complexity and the software's limitation in simulating varying wind conditions, wind speed and direction were kept constant throughout the simulation. Based on data obtained from the Shiraz Meteorological Organization, the average wind speed on July 22, 2022, was 1. 87 m/s, with a prevailing wind direction of 300°, both of which were entered manually into the software.

To analyze the thermal conditions, initial outputs, including potential air temperature and relative humidity, both key parameters influencing thermal comfort, were extracted using the Leonardo tool in ENVI-met. These parameters were examined at 12: 00 p.m., 2: 00 p.m., and 4: 00 p.m., representing the peak heat hours in Shiraz.

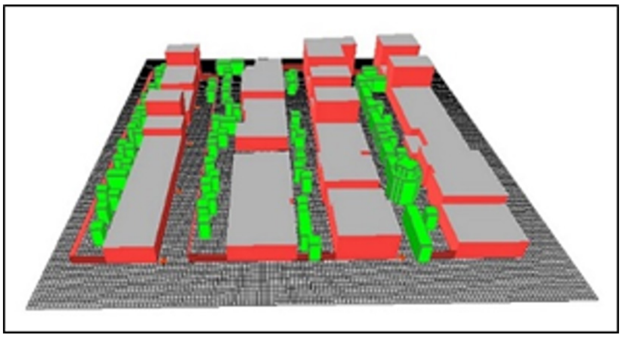

Fig. 3. Modeling of the study area in ENVI-met version 5.0.3. Source: Authors.

Findings

- **Potential air temperature**

The simulation results indicate that the mean air temperature in Alley B, which has extensive vegetation cover, is lower than that of Alley A, which lacks effective vegetation. The maximum temperature difference between the two alleys was recorded at 14:00, reaching 2.13°C, confirming that during peak solar radiation hours, Alley B consistently recorded lower temperatures than Alley A.

Furthermore, a notable thermal difference was observed within Alley B itself, particularly in the vicinity of the Acer Pseudoplatanus tree, where the surrounding temperature was on average 0.61°C cooler than other parts of the alley containing Citrus x aurantium trees. This highlights the significant role of tree species and canopy form in moderating local temperatures.

- **Relative humidity**

The relative humidity maps generated by the software indicate no meaningful difference between the two alleys in terms of relative humidity.

- **Predicted mean vote (PMV)**

In this study, the PMV index was used to evaluate the thermal comfort of users, as it is recognized as one of the most reliable indicators for assessing thermal comfort in both indoor and outdoor environments (Yilmaz et al., 2018). The PMV model is based on the regulation of body temperature and the theory of thermal equilibrium. According to this theory, the human body employs physiological processes such as sweating, shivering, and regulation of blood flow to the skin in order to balance heat generated by metabolism with heat loss. In practice, PMV is commonly interpreted alongside the Predicted Percentage of Dissatisfied (PPD) index, which estimates the percentage of individuals experiencing thermal discomfort at any given PMV value (Javadi & Nasrollahi, 2021). The thermal perception scale and the degree of physiological stress corresponding to

PMV values are presented in the Table 3. The simulation outputs (air temperature and relative humidity) were imported into Bio-MET to calculate the PMV index. The index was calculated and compared based on conditions at 2:00 p.m., representing the peak heat hour. Since the PMV values in both alleys exceeded 7.25, both are classified as very hot and thermally uncomfortable. However, Alley B, with a PMV range of 7.25–9.3, represents more favorable conditions compared to Alley A, where the PMV reaches a peak of 10.67, indicating extremely unfavorable thermal conditions (Fig. 4).

Discussion

An examination of the field data and modeling results challenges the research questions regarding the effectiveness of vegetation in improving thermal comfort at the microscale. Both indicate that the degree of improvement in comfort conditions is minimal. In fact, even limited vegetation on one side of the alley can locally improve the thermal comfort index, reduce air temperature, and increase relative humidity in the vicinity of the tree canopies. However, these effects are localized, and the entire width of the alley remains largely unprotected from hot and dry conditions (Table 4).

Conclusion

This study evaluates the impact of vegetation on thermal comfort in urban environments within hot and arid climates. Through field data collected using precise measuring instruments and comparison with simulation results, thermal indices such as potential air temperature, mean radiant temperature, and relative humidity were assessed using the PMV index. The use of the combined PMV index enabled the simultaneous measurement of air temperature, relative humidity, and mean radiant temperature, providing a comprehensive analysis of micro-scale thermal comfort conditions.

Table 3. Range of the thermal index predicted mean vote (PMV). Source: Yilmaz et al., 2018.

PMV (°C)	Thermal perception	Grade of physiological stress
< -3.5	Very cold	Extreme cold stress
-3.5 / -2.5	cold	Strong cold stress
-2.5 / -1.5	Cool	Moderate cold stress
-1.5 / -0.5	Slightly cool	Slight cold stress
-0.5 / 0.5	Comfortable	No thermal stress
0.5 / 1.5	Slightly warm	Slight heat stress
1.5 / 2.5	warm	Moderate heat stress
2.5 / 3.5	hot	Strong heat stress
3.5<	Very hot	Extreme heat stress

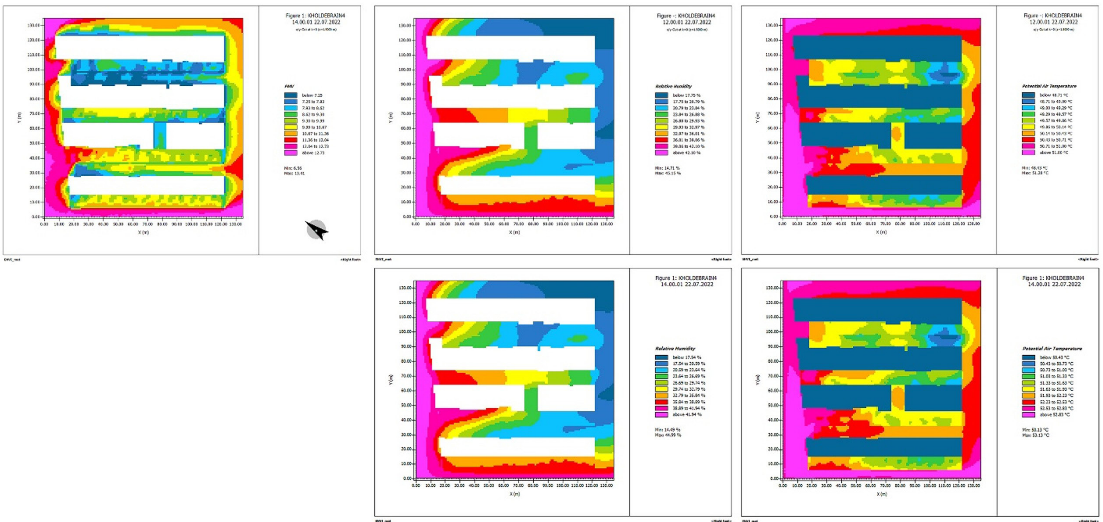

Fig. 4. The first, second, and third columns represent the simulation outputs of potential air temperature, relative humidity, and PMV index conditions, respectively, at 12:00 p.m. and 2:00 p.m. (from top to bottom) on July 22 in the study area. Source: Authors.

Table 4. Analysis of ENVI-met outputs at stations at 12:00 p.m. and 2:00 p.m., Source: Authors.

	Time	A	B
PMV	2:00 p.m.,	Very hot and incompatible with thermal comfort	PMV values in areas close to trees range between 6.5 and 8.5, within the limit of tolerable heat, representing better comfort conditions compared to other points.
Air Temperature	12:00 p.m.,	Uniform and hot temperature due to direct solar radiation	Shaded areas are cooler than other points
	2:00 p.m.,	Very hot and critical	Shaded areas remain cooler than unshaded points. During peak heat hours, the cooling effect of trees is more pronounced, with approximately 2°C temperature reduction recorded only in the immediate vicinity of the trees, though still insufficient to achieve thermal comfort.
Relative Humidity	12:00 p.m.,	Dry, low humidity	Humidity in shaded areas is higher than in unshaded points.
	2:00 p.m.,	Dry, low humidity	Humidity in the shade of trees is significantly higher.

According to the results, although vegetation has a measurable effect on environmental comfort, the PMV index in both alleys remained within the very hot range. Furthermore, the extent of this effect is limited to the immediate vicinity of the trees and is insufficient to provide adequate thermal comfort.

Trees with sparse canopies or limited shade, such as Citrus x aurantium, are unable to significantly reduce mean radiant temperature. In contrast, the Acer Pseudoplatanus tree, with its wider canopy, produced greater localized temperature reduction. The findings demonstrate that air temperature reduction alone is insufficient; unless solar radiation and other PMV-related parameters are controlled, achieving genuine thermal comfort will not be possible. This challenges the common assumption that the mere presence of trees in an urban environment improves thermal comfort.

This study suggests that to achieve broader and more sustainable thermal comfort, it may be necessary to increase the number of trees along the alley, raise planting density, and select species with wider canopies.

A comparative review of related studies further confirms that the effect of vegetation is only significant when trees are strategically designed with wide canopies and appropriate heights.

The critical findings of this research can be summarized as follows: temperature reduction alone is insufficient to create comfortable conditions; the mere presence of trees does not guarantee thermal comfort improvement; and the absence of empirical evaluation of users' thermal perception represents a limitation that can be addressed in future research.

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HOW TO CITE THIS ARTICLE

Minabian, F., Fakhfoori, N., & Mehrabanigolzar, M. R. (2026). Investigating the Impact of Vegetation on Thermal Comfort in a Hot and Arid Climate (A Micro-Scale Study of Kholdebarin Residential Neighborhood, Shiraz, Iran). *Bagh-e Nazar, 23*(158), 21-28.

DOI: 10.22034/bagh.2026.507504.5769
URL: https://www.bagh-sj.com/article_243397.html?lang=en