

Article

Understanding the Role of Urban Fabric in Shaping Comfort Microclimate: A Morphological Analysis of Urban Development

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Abstract

Rapid urbanization has led to substantial changes in land use, resulting in challenges related to the urban microclimate across multiple scales. Given the strong relationship between urban morphology and microclimatic conditions, designing appropriate urban fabric models plays a key role in supporting sustainable urban development. The spatial form and geometry of buildings influence external environmental conditions and affect the performance of urban architecture. This study investigates how morphological and geometric characteristics of urban form influence microclimate, using a case study approach. Data were obtained through a literature review and existing urban development plans. ENVI-met software was used to simulate microclimatic variables, which were treated as dependent factors. In parallel, morphological components—treated as independent variables—were analyzed using GIS Pro software. Findings reveal that the configuration of urban fabric has a notable impact on microclimate. Specifically, higher building density is associated with greater heat accumulation around structures. Urban areas with fragmented and highly granular layouts tend to trap more heat, thereby intensifying the urban heat island effect. Conversely, when buildings are spaced apart, increased wind flow helps reduce temperatures in central urban zones of urban development in District 9, Mashhad, Iran. The results also emphasize the importance of vegetation placement. While greenery can mitigate heat in ventilated areas, dense vegetation in wind-restricted zones may raise ambient temperatures. Overall, the study offers a simulation-based understanding of how urban form influences microclimate. These insights can assist urban planners and designers in creating environments that promote more favorable local climatic conditions.

Keywords: urban microclimate; residential building; sustainable urban development; thermal environment; cold semi-arid climate; Mashhad



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1. Introduction

Urbanization is a defining trend of the 21st century, responsible for nearly 70% of global greenhouse gas emissions. These emissions stem largely from the built environment, transport systems, and waste production [1]. With the global urban population expected to rise from 55% to 68% by 2050, especially in developing countries, the demand for housing continues to drive rapid urban expansion [2]. This growth has reshaped land use patterns, leading to significant changes in urban microclimatic conditions [3].

The physical structure of cities, referred to as the urban fabric, includes elements such as building height, street layout, vegetation, and water features. These components critically influence local environmental conditions, including temperature, humidity, wind behavior, and solar radiation [4]. In particular, they contribute to urban heat island (UHI) phenomena, where dense and impermeable built areas experience elevated temperatures due to limited vegetation and airflow [5,6].

Microclimatic dynamics are shaped by complex interactions between urban form and environmental factors. Building geometry, land cover types, and human activities all influence urban temperature regimes [7]. The orientation, height, and spacing of buildings affect how solar energy is absorbed and dispersed. These parameters also influence wind flow and shading patterns, which can either mitigate or worsen localized heat accumulation [8–10].

Urban morphology plays a key role in determining local microclimatic conditions, especially in hot and arid regions where thermal stress can negatively affect outdoor comfort and increase energy consumption. Various studies have shown that specific aspects of urban form, such as street orientation, aspect ratio, and surface characteristics, significantly influence thermal conditions experienced by pedestrians [11]. In hot and dry climates, the geometric configuration of urban canyons, including their height-to-width ratios and alignment with respect to solar paths, affects shading, wind flow, and temperature distribution [12]. Research has shown that east–west oriented streets often experience higher levels of heat stress during summer months due to extended periods of direct solar exposure [13].

This highlights the need for climate-responsive design strategies that can moderate outdoor thermal conditions. Planning-based approaches have further emphasized that modifying urban form, especially street layout and building orientation, can serve as an effective passive solution for improving thermal comfort in arid urban areas [14]. In response to these challenges, urban design must integrate microclimatic considerations into planning practices. Design interventions that optimize building configuration, street geometry, and the use of green infrastructure can lead to more thermally balanced and resilient urban environments [15,16]. For example, properly oriented urban canyons can help reduce daytime heat accumulation, while excessively dense or high-rise structures may block airflow and intensify heat retention [17,18].

Moreover, retrofitting urban spaces through material changes and shading enhancements is gaining traction as a practical response to increasing thermal stress, particularly under projected climate change scenarios [19].

These insights form the foundation for the current study, which examines the influence of urban morphology on microclimate in Mashhad, Iran. As one of the country's largest and fastest-growing cities, Mashhad lies in a semi-arid climatic zone and exhibits complex urban growth patterns. Understanding the influence of urban morphology on microclimatic conditions is essential for designing sustainable and thermally comfortable urban spaces, particularly in rapidly expanding cities [20], in their study of informal settlements in Dar es Salaam, demonstrate that variations in microclimate and outdoor thermal comfort are significantly affected by urban form, including building density and surface materials. Their research underscores the need for context-specific morphological analyses to mitigate thermal discomfort in warm climates. Similarly, studies by [11,13,14] reveal that the geometry, orientation, and aspect ratio of street canyons play a critical role in shaping microclimatic conditions. These studies, while foundational, primarily rely on idealized simulations or case studies from European settings such as Freiburg. They do not fully capture the morphological diversity or socio-cultural complexity of cities like Mashhad. Moreover, although simulation-based approaches have contributed to under-

standing thermal conditions in simplified urban forms [12], they fall short when applied to heterogeneous and organically developed fabrics typical of Middle Eastern cities.

This study addresses that gap by analyzing real-world urban configurations in Mashhad through detailed morphological tools. Rather than isolating specific street canyons, it evaluates a range of urban patterns at a district scale. The research integrates regional planning norms, local development patterns, and climate data to generate a more holistic, climate-responsive understanding of urban form.

A specific focus is placed on District 9 of Mashhad, located in the southwestern part of the city. Covering roughly 4010 hectares, this district has experienced significant demographic and physical transformation over the past two decades. Rapid population growth and vertical development have altered its urban fabric, reducing open space and affecting natural ventilation. These changes have contributed to intensified local heat stress. The area’s diverse urban typologies, including fragmented and block-based forms, make it an ideal context for examining how morphological variation impacts microclimate [15].

The primary goal of this study is to identify the key morphological factors that influence local microclimatic behavior and to propose spatial strategies for more thermally adaptive urban environments. By offering empirical insights specific to Mashhad’s evolving fabric, this research contributes to both local planning practices and broader discussions on urban resilience. It emphasizes the importance of tailoring climate-responsive design to the social and environmental realities of fast-growing cities in semi-arid regions.

2. Literature Review

A review of recent studies—both international and within the Iranian context—shows a growing emphasis on the influence of urban form on microclimatic conditions. This shift reflects increasing concern over the effects of rapid urbanization and rising global temperatures. Researchers are focusing on how spatial geometry contributes to localized heating and are seeking design-based approaches to reduce adverse climatic impacts. The analysis of the existing literature provides valuable insight for developing environmentally responsive and context-specific planning strategies. A summary of key contributions in this area is presented in Table 1.

Table 1. Comparative summary of urban morphology and microclimatic strategies in case studies.

References	Image
• This study investigates the link between urban thermal conditions and microclimate in historic Tlemcen. • It uses perceptual analysis and ENVI-met simulations to examine microclimatic influences. • Key urban factors include building materials, vegetation, green spaces, and land use patterns. • Seasonal temperature, humidity, and precipitation are critical environmental parameters. • A mixed-methods approach is adopted, combining simulations with qualitative assessments. Results show that vegetation and green design reduce urban heat, while densely built areas increase thermal discomfort [21].	

Table 1. Cont.

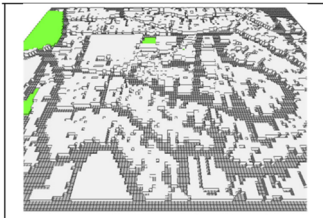
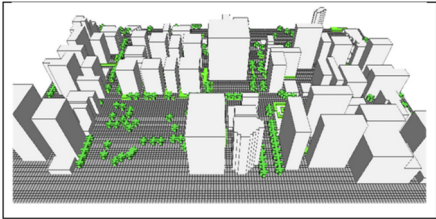
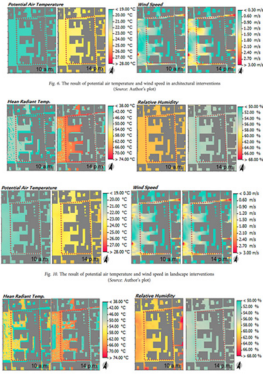
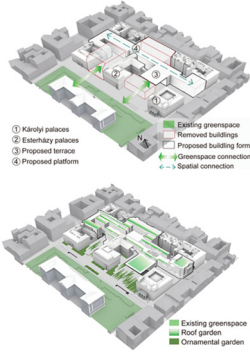
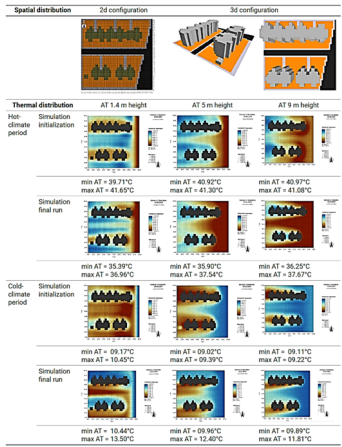
References	Image
• This study explores the impact of building density on the urban microclimate using simulation tools. • Key urban parameters include population density, building typology, land use, height, and materials. • Environmental factors such as background climate and heat-generating conditions are also considered. • The methodology involves field data and ENVI-met V4 simulations in two urban areas. Results show that air temperature varies with building density, with differences of up to 3.3 °C in Brazil and 3.2 °C in São Paulo [22].	
• This study aims to guide urban designers in improving outdoor thermal comfort through microclimate-based design. • Urban parameters include vegetation, materials, building form, water features, and spatial layout. • Environmental factors such as temperature, humidity, wind, radiation, and air quality are considered. • ENVI-met simulations were used to analyze conditions at 10 AM and 2 PM. • Results show that green infrastructure plays a key role in mitigating heat and enhancing comfort. Integrating green spaces is essential for sustainable and climate-resilient urban development [23].	
• This study investigates how optimizing urban morphology can improve outdoor thermal comfort. • Urban parameters include building height, density, spatial layout, vegetation, and materials. • Environmental factors such as climate (temperature, humidity, solar radiation) and topography affect microclimate. • ENVI-met simulations evaluate different urban forms during warm and cold seasons. • Results show that integrated design approaches significantly improve microclimate. Optimizing urban form is essential for creating sustainable, climate-responsive urban spaces [24].	

Table 1. Cont.

References

- This study assesses how floor coverings and urban geometry affect microclimate.
- Key urban parameters include building blocks, open spaces, materials, compactness, and historic areas.
- Vegetation is the primary environmental factor influencing the urban microclimate.
- The LCZ Generator and ENVI-met are used for simulation and spatial analysis.
- Results show open urban forms improve thermal comfort through better airflow and less heat accumulation.

The LCZ4/LCZ6 combination enhances comfort and supports social and environmental benefits [25].

Image

Figure showing urban morphology and microclimate simulation results. (a) Top-down views of compact and open urban zones. (b) 3D perspective views of compact and open urban zones.

- This study examines how urban street geometry influences thermal comfort in arid regions, highlighting the role of urban form in reducing thermal stress and enhancing outdoor livability.
- Key urban parameters include street orientation, aspect ratio (height-to-width), and canyon geometry.
- Environmental factors include solar radiation, air temperature, wind speed, and mean radiant temperature.
- ENVI-met was used to simulate microclimate conditions, and thermal comfort was evaluated using the PET (Physiological Equivalent Temperature) index.

The results show that optimized street geometry—particularly higher aspect ratios and east–west orientation—enhances shading and microclimate, with mean radiant temperature as a key factor, underscoring the critical role of street design in climate-responsive planning for arid regions [14].

Figure showing street geometry and orientation diagrams, and a PET index map. The diagrams show street geometry (W=8m, H=4m and W=8m, H=16m) and street orientation (E-W, N-S, NE-SW, NW-SE). The PET index map shows temperature contours (32°C to 68°C) for a street width of 8m and a height-to-width ratio of 0.5, East-West.

An analysis of the theoretical literature on urban morphology and microclimate was conducted, through which key theoretical perspectives and constituent elements were identified and summarized in Table 2.

Table 2. Theorists’ perspectives on the nature of morphology and microclimate.

Source	Nature	Theorists
[26]	Thermal comfort is defined as a person’s subjective perception of the thermal environment, existing along a continuum from satisfaction and well-being to discomfort and distress.	Gagge et al. (1971)
[27]	The publication contains a comprehensive inventory and explanation of morphological indicators for cities, neighborhoods and buildings. However, it does not contain suitable methods for calculating these indicators.	Alexander (1977)
[27]	Quantitative research has explored the relationships among variables such as open space, floor area, and building height.	Lynch (1984)
[27]	Urban morphology, in this context, is concerned with the spatial and temporal processes that shape the evolution of human settlements.	Moudon (1977)

Table 2. *Cont.*

Source	Nature	Theorists
[28]	Cold semi-arid climates are characterized by sharp temperature variations and unique humidity conditions, which strongly influence microclimatic experiences and human adaptation. In such regions, outdoor microclimate becomes a key factor in urban planning, as it directly affects residents' daily comfort and overall quality of life.	Canan et al. (2019)
[26]	In his influential book, <i>Living Between Buildings: Using Public Space</i> , he demonstrated that people's choices for outdoor activities can have a significant impact on local conditions of sun or shade.	Jan Gehl (1981)
[29]	The PMV (Predicted Mean Vote) model, developed by Fanger, is considered one of the pioneering models for thermal comfort. This model is the result of extensive testing with a large number of people. The parameters studied indoors were determined by two key variables, namely clothing insulation (Clo) and activity level (Met).	Fanger (1982)
[30]	The research findings were presented to demonstrate the intertwining of road layouts and the effectiveness of the district cooling system in Singapore's densely populated urban areas.	Shi et al. (1983)
[31]	Urban configurations with built-up ratios between 0.37 and 0.5 show a decrease in average wind speed, while those with ratios above 0.43 experience reduced wind flow. High-rise compact configurations can lower temperatures by 1.12 °C per hour compared to open layouts.	Heshmat Mohajer et al. (2023)

Urban morphology refers to the study of the physical layout and structure of urban areas, focusing on the evolution, form, and spatial relationships of built environments and open spaces [32]. Within this broader framework, urban form describes the specific physical characteristics and configuration of cities, such as layout, density, and building patterns. Typology, in turn, relates to the classification of urban elements—such as building forms or street patterns—based on shared morphological features. Establishing a clear hierarchy among these concepts helps to differentiate the overarching analytical framework (urban morphology) from its more specific applications in spatial form and typological categorization [27].

The relationship between urban morphology and microclimate has garnered significant attention due to rapid urbanization and rising global temperatures, which exacerbate urban heat island (UHI) effects and impact outdoor environmental quality [33]. Microclimate, defined by air temperature, humidity, wind speed, and solar radiation, significantly influences how individuals perceive outdoor environmental conditions and contributes to the overall quality of life in urban areas [26,34]. In cold semi-arid climates, such as Mashhad, Iran, considerable temperature fluctuations and distinct humidity patterns highlight the need for climate-responsive urban design strategies to improve microclimatic conditions and enhance urban livability [28].

This literature review synthesizes key studies to explore how urban geometry and environmental factors interact to shape microclimates, with a focus on identifying effective solutions to mitigate heat-related challenges in urban settings.

Theoretical perspectives on urban morphology highlight its role in shaping human settlements and environmental conditions. Typological approaches categorize urban forms based on building layouts, street geometry, and green spaces, revealing how these elements influence social, demographic, and environmental dynamics [35,36]. For example, Srivanit and Jar-eemit (2020) found that the aspect ratio, defined as the relationship between street width and building height, plays a key role in shaping microclimate. It influences both the amount of solar radiation received and the level of airflow within urban

canyons [37]. Similarly, building orientation, density, and materials significantly affect wind conditions, surface temperatures, and solar radiation absorption [38]. Early models, such as Fanger's Predicted Mean Vote (PMV), introduced key parameters like clothing insulation and metabolic rate. Later studies expanded this framework by incorporating outdoor microclimatic variables such as wind speed and solar radiation distribution [30]. Studies also highlight the psychological and health-related effects of microclimate. Access to shaded areas and well-designed open spaces supports social interaction and contributes to overall well-being [26,29]. These theories provide a robust framework for understanding how urban morphology influences microclimatic conditions and human experiences.

Empirical studies across diverse geographical contexts further illustrate the impact of urban morphology on microclimate. In subtropical São Paulo, Brazil, ENVI-met simulations revealed that variations in building density resulted in air temperature differences of up to 3.3 °C, highlighting the role of urban geometry in modulating microclimates (Table 2). In Singapore, compact urban configurations with built-up ratios of 0.37 to 0.5 reduced wind speeds, while high-rise layouts lowered temperatures by 1.12 °C per hour compared to open designs, demonstrating the cooling potential of dense urban forms when combined with effective infrastructure like district cooling systems [31]. In Rabat, Morocco, mixed Local Climate Zones (LCZ4/LCZ6) improved microclimatic conditions by enhancing wind circulation and reducing heat accumulation. The strategic location of services near residential zones also limited heat emissions from transportation (Section: Assessment of Mixed Local Climate Zones). Similarly, a study in Tlemcen, Algeria, showed that areas with higher vegetation density and well-planned green spaces experienced lower urban temperatures. In contrast, compact urban forms with minimal greenery led to intensified heat exposure (Section: Understanding Urban Thermal Environments).

These case studies highlight the importance of urban form, vegetation cover, and spatial layout in regulating microclimate. The deliberate integration of green infrastructure proves to be a critical approach in improving outdoor environmental conditions. Numerous studies confirm that vegetation, water bodies, and open public spaces reduce surface and air temperatures, thereby mitigating urban heat island effects and supporting sustainable urban development [26]. For instance, simulations using ENVI-met in various urban contexts have shown that green spaces not only lower temperatures but also improve residents' quality of life by fostering comfortable outdoor environments (Section: A Study on the Impact of Green Infrastructure). Moreover, urban design that optimizes building orientation, height, and materials can enhance airflow and reduce solar radiation absorption, further improving thermal conditions [39]. However, challenges such as pollution from CO₂ emissions and noise, driven by urban density and traffic, exacerbate thermal discomfort and undermine urban livability [33]. These findings highlight the need for a holistic approach that integrates morphological considerations with climatic responsiveness to create resilient urban habitats.

Despite these insights, a research gap persists in integrating phenomenological and ecological perspectives to fully understand how urban morphology shapes microclimates while fostering meaningful, thermally comfortable places. While quantitative studies using tools like ENVI-met provide robust analyses of microclimatic conditions, they often overlook the socio-cultural and experiential dimensions of place-making [40]. Moreover, limited research has examined cold semi-arid climates, such as Mashhad, where sharp temperature fluctuations create distinct urban design challenges. This study addresses that gap by adopting a bricolage approach to explore how urban form shapes microclimatic conditions. It investigates how spatial configurations transform generic "sites" into meaningful "places" that support human well-being, offering practical guidance for climate-responsive and sustainable urban design.

Based on the documents reviewed, the indicators of each morphological and microclimate component were identified, as shown in Figure 1.

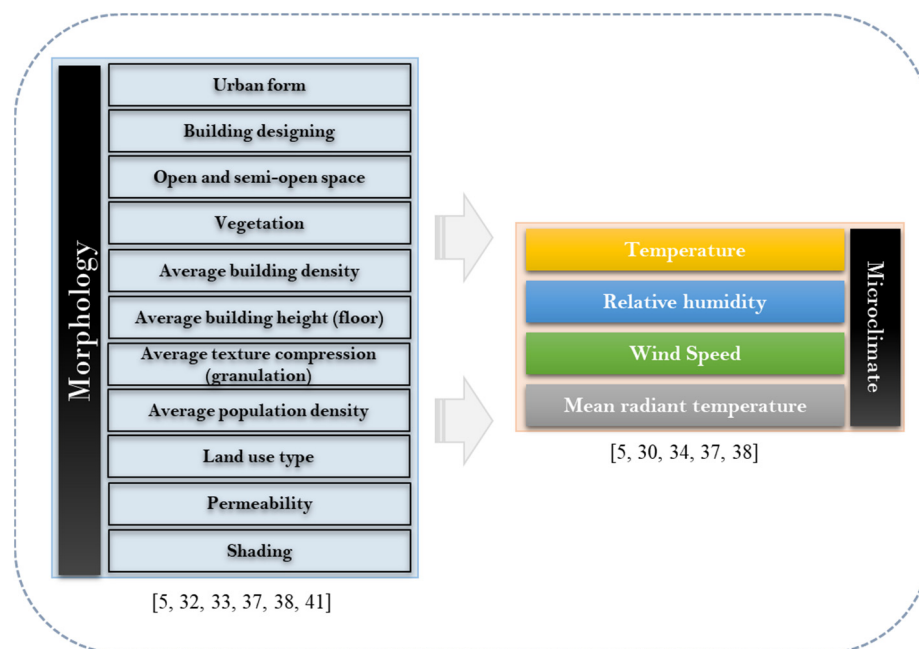


Figure 1. Impact of morphological components on microclimate [5,30,32–34,37,38,41].

3. Case Study

Mashhad, located in northeastern Iran at 36.2972° N and 59.6067° E, spans approximately 351 km^2 . The city lies in the Kashfroud watershed, between the Binalood and Hazarmasjid mountain ranges, at elevations ranging from 950 to 1150 m. Its climate is temperate yet variable, with hot, dry summers and cold, wet winters. Temperature extremes range from 43°C in summer to -22°C in winter (Figure 2).

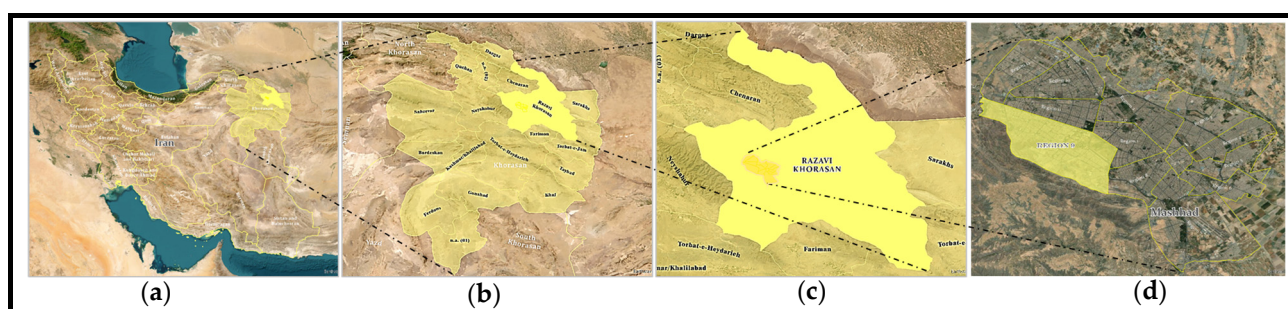


Figure 2. Studying the zoning position of Mashhad metropolis and District 9: (a) the location of Khorasan Province on the territory of Iran; (b) the location of Khorasan Razavi Province on the territory of Khorasan (c) Geographical position of Mashhad in the Khorasan Razavi Province; (d) District 9's location in Mashhad metropolis.

Before the 1950s, high-rise construction in Mashhad began with residential and hotel buildings, including notable projects such as the 611 and 511 residential complexes. After the 1979 revolution, development slowed, with scattered high-rise estates mostly on the city's outskirts. However, by the early 2010s (1390s AH), high-rise residential construction increased, especially in District 9 of the Mashhad Municipality. Located in the southwest, between Vakil Abad, Pirouzi, and Fekoori Avenues, this district became a key area in the city's detailed development plan [41].

District 9 has since become a major investment zone, hosting large-scale urban development projects. For the purpose of this study, three types of urban fabric in this district were identified. Although all are residential in use, they differ in form, including granularity, permeability, building and population density, and vegetation coverage. These are categorized by age:

1. Urban Fabric Case One: Features semicircular housing complexes centered on internal green spaces for communal use.
2. Urban Fabric Case Two: Comprises a semi-organic layout with high vegetation density and a flexible structure.
3. Urban Fabric Case Three: Adopts a quasi-grid pattern, integrating residential, commercial, and service functions in a mixed-use form.

This study adopts Yin's (2014) case study method, which is suited to analyzing complex phenomena in real-life contexts. As the research examines three different urban morphologies within one district, it qualifies as a multiple case study [42]. According to Yin (2014), such an approach is effective in exploring the complex interplay between urban form and environmental behavior—particularly microclimatic conditions [42].

This relationship is central to advancing sustainable urban development, which directly influences human comfort, health, and overall well-being. Key morphological elements—such as building orientation, density, and architectural design—significantly shape the thermal performance of urban environments.

The integration of shaded areas, whether provided through architectural design or vegetation, plays a critical role in moderating microclimatic conditions in urban spaces. At the same time, sustainable urban planning must encompass broader environmental objectives, including the conservation of natural resources, climate-sensitive design practices, and the development of efficient transportation systems. These components are fundamental not only to environmental sustainability but also to the creation of livable, adaptable, and resilient urban communities. As emphasized by [33], effective planning strategies should prioritize human well-being while enhancing the city's capacity to respond to environmental challenges.

4. Research Methodology

This study employs a descriptive-analytical approach to investigate the relationship between urban morphology and microclimatic conditions, structured into three distinct phases: theoretical framework development, data collection and analysis, and model simulation and validation. This organization ensures a clear and logical progression of the research process, aligning with the objective of understanding how urban fabric influences microclimate in District 9 of Mashhad.

4.1. Theoretical Framework Development

The first phase involves developing a theoretical framework based on a comprehensive literature review. Sources include academic books, peer-reviewed articles, and theses, analyzed using documentary analysis.

4.2. Data Collection and Analysis

The second phase adopts a quantitative approach to examine urban texture as a complex system. Urban form was analyzed through Geographic Information Systems (GIS), while microclimatic conditions were simulated using ENVI-met software (version 5.1.2). Three representative types of urban fabric were selected for comparative analysis.

Two key datasets support this investigation:

- Urban Density Data: These include indicators such as building density and spatial configuration, analyzed in GIS as independent variables describing the urban form.
- Microclimate Data: Meteorological data from 22 July 2023 (recorded at 12:00, 14:00, and 16:00), were used as dependent variables in ENVI-met simulations. These were modeled using simple forcing inputs.

4.3. Model Simulation and Analysis

The ENVI-met (version 4) simulation was conducted from 06:00 to 18:00 to capture the daytime thermal dynamics of the study area. This timeframe was selected to correspond with the period of peak solar radiation, pedestrian activity, and outdoor space usage. Since the main focus of this study is to evaluate the impact of urban morphology on outdoor thermal conditions during high-stress hours, the simulation was limited to the daytime period. While it is acknowledged that structures continue to store and release heat after sunset, the thermal perception during daytime hours has a more immediate effect on human comfort and urban livability, especially in warm and semi-arid climates.

In the case study analysis, GIS tools were used to extract morphological indicators—including building density, spatial layout, and vegetation cover—for each of the three urban fabric types. ENVI-met was then employed to simulate air temperature and relative humidity, allowing for a comparative assessment of microclimatic variations.

Climatic input data for Tables 3 and 4 were obtained from standard meteorological stations and ENVI-met default settings. Due to the lack of localized solar radiation data, ENVI-met’s regional defaults for Mashhad (36.2972° N, 59.6067° E) were applied. Soil characteristics were defined using both ENVI-met defaults and field observations specific to the study area. To assess the accuracy of ENVI-met simulations, field-measured data were compared against simulated outputs. The absolute percentage error was calculated using Equation (1). Detailed results of model validation are presented in Section 5.1.

Table 3. Model settings and climate and thermal conditions in ENVI-met.

Model Location	Mashhad		Source
Simulation days	22 July 2023	6:00 am–6:00 pm	
Sizes of grid cells (x, y, z)	2 × 2 × 2		ENVI-met Standard Settings
Number of grid cells	30 × 30 × 30		
The primary and final air temperature (6:00 am to 6:00 pm)	20–34 °C		Mashhad weather station
The primary and final relative humidity (6:00 am to 6:00 pm)	16–22%		
Wind speed	2–10 km/h		
Cloud cover medium level (octas)	0% octas		
Atmospheric pressure	1005–1012 hPa		Simulation software outputs
Solar radiation	800–1000 W/m ²		
Soil moisture	Very low (dry topsoil)		Field surveys
Materials	Table 4		

Table 4. Physical properties of the materials used in the simulations.

Materials	Urban Fabric Case One	Urban Fabric Case Two	Urban Fabric Case Three
Façade material	Normal brick	Normal brick	Normal brick
Ground material	Asphalt and soil	Asphalt and soil	Asphalt and soil
Roof materials	Concrete	Concrete	Concrete

Meteorological data—including initial and final air temperature, relative humidity, wind speed, and mid-level cloud cover (measured in octas)—were obtained from the Mashhad weather station, the nearest available source. Atmospheric pressure and solar radiation were derived from simulation software outputs, while soil moisture and material data were collected through field surveys.

The selected urban fabrics of Mashhad's 9th district were modeled using Envi-met software, incorporating weather data. The morphological indicators in GIS Pro were then compared with thermal indices generated by ENVI-met.

Data mining of morphological indicators in GIS Pro reveals variations in geometric patterns across the selected urban fabrics, which can inform the identification of optimal patterns for urban development. GIS analysis aids in understanding urban structure, particularly in high-rise areas. This system promotes the creation of more efficient and livable environments by preventing urban elements from obstructing traffic flow [43]

ENVI-met is a software tool used to evaluate the impact of urban design and architecture on microclimates and environmental variables. It simulates atmospheric conditions by integrating factors such as vegetation, buildings, weather, and surface properties. The software provides high spatial resolution (0.5 to 10 m) and temporal resolution (up to 10 s) [44]. In urban microclimate modeling, particularly, using tools like ENVI-met, leaf area index (LAI) and leaf area density (LAD) is essential for accurately representing vegetation. These parameters significantly influence solar radiation absorption and air temperature regulation in urban environments. Areas with higher LAI and LAD values typically experience lower surface and air temperatures [45].

Vegetation reduces solar heat gain by intercepting radiation and promoting evapotranspiration, which decreases sensible heat flux and contributes to localized cooling—most notably during the afternoon heat peak (12:00–16:00).

LAI increases horizontal shading, protecting ground surfaces and building façades from direct solar exposure. LAD, in turn, describes the vertical distribution of leaves, allowing models to simulate how different canopy layers affect airflow, radiation transfer, and shading patterns.

The effectiveness of LAI and LAD varies according to urban morphology. In dense, compact urban fabrics with limited vegetation, even minor increases in greenery significantly enhance microclimatic performance. In open or semi-open layouts, vegetation impacts broader areas, offering more extensive cooling effects.

In the case study of District 9 in Mashhad, LAI and LAD values were integrated into ENVI-met simulations across three distinct urban fabric types (Table 5). The obtained information indicates that areas with denser and more vertically structured vegetation consistently showed the following:

- Lower ambient temperatures, particularly in vegetated courtyards and open plots;
- Reduction of environmental heat, resulting from enhanced shading and reduced radiative heat load;
- Greater microclimatic variation, shaped by the density and height of vegetation canopies.

LAI and LAD values were derived from field observations, ENVI-met standard datasets, and comparable peer-reviewed studies. Field observations included visual assessments of canopy cover and sample measurements conducted in District 9 of Mashhad.

Table 5. Physical properties of the materials used in the simulations.

Data Source	LAD	LAI	Height (m)	Tree Species	Urban Structure
Field observations and ENVI-met assumptions	5.68	7.53	15	Plane tree	Semi-circular
Standard ENVI-met data	3.97	4.73	10	Pine tree	Semi-organic
Similar studies in temperate climates	4.50	6.20	12	Acacia tree	Quasi-chessboard

District 9 in Mashhad has become a prime area for developers and wealthy residents due to its favorable socio-economic and environmental qualities. The district’s urban fabric is diverse, combining historic buildings—mostly single-unit structures dating back almost four decades—with modern high-rise developments. Additionally, the presence of major institutions like Ferdowsi University, alongside commercial, service, and recreational centers, drives significant daytime activity, influencing local thermal conditions. The district’s distinct appeal arises from the combination of varied urban textures, mixed land uses, and abundant greenery (Figure 3).

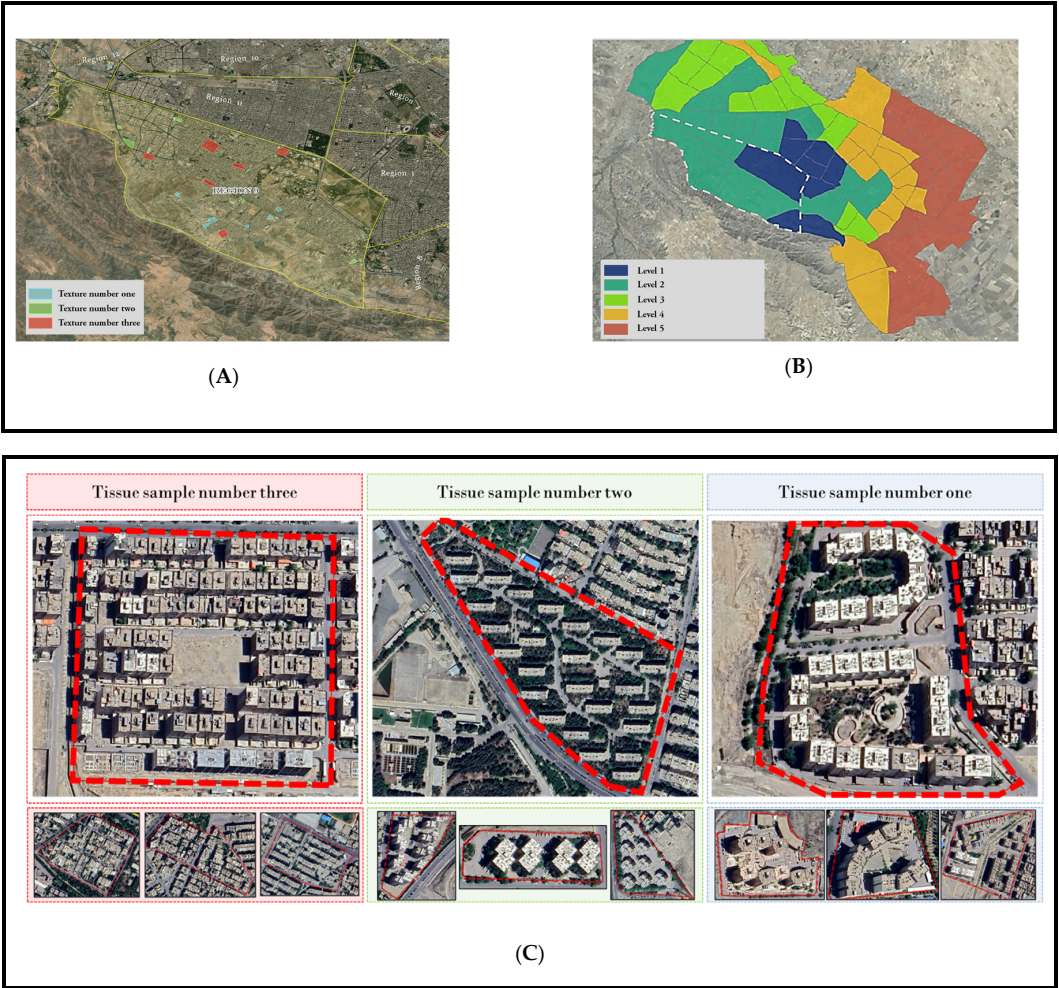


Figure 3. Selection of three samples from the new fabric in District 9 of Mashhad Municipality. (A) Top priority for building high-rises in Mashhad (district 9 at level one) [41]. (B) Classification of three fabric types in District 9 Mashhad metropolis. (C) Selection of three samples from the new fabric in District 9 of Mashhad Municipality.

Figure 4 presents a three-stage research process designed to examine the impact of urban morphology on microclimatic conditions. In the first stage, a theoretical framework is developed, and representative case study samples are selected. The second stage involves

the use of analytical tools such as ENVI-met and GIS Pro to assess both morphological and environmental indicators. The final stage centers on evaluating the effects of these indicators on microclimatic patterns through a combination of quantitative and qualitative analysis, leading to the study's findings and conclusions.

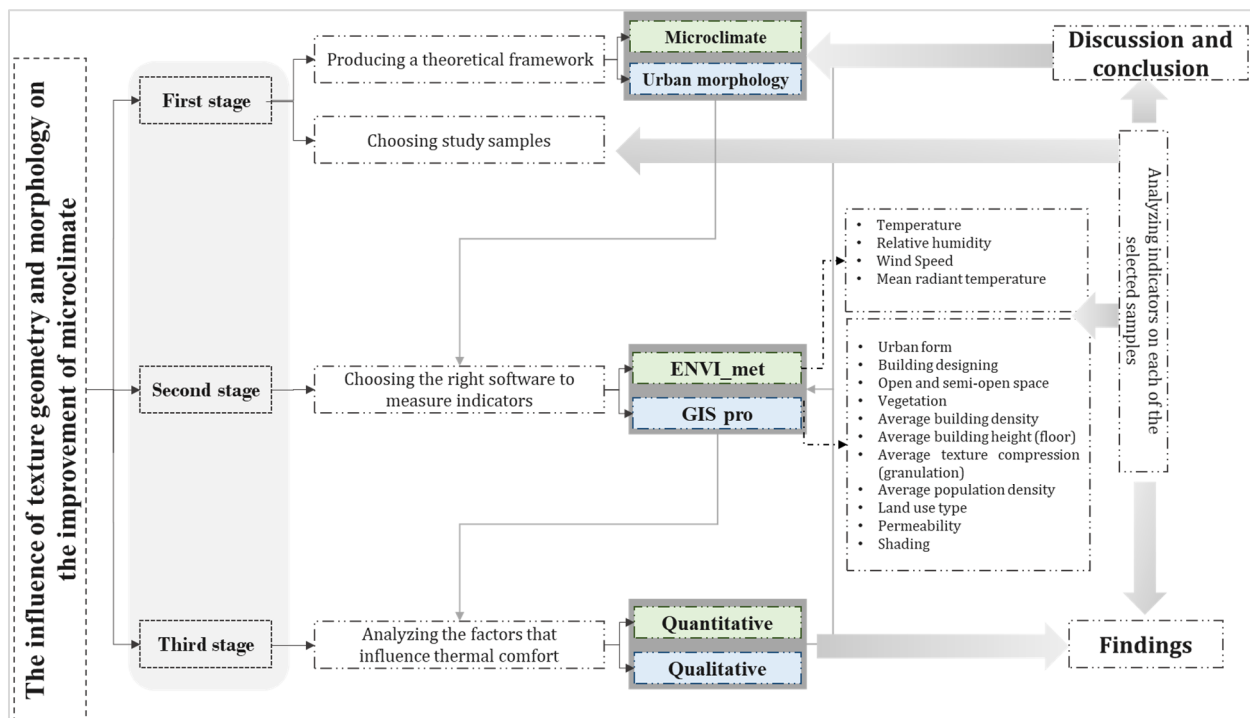


Figure 4. Research process.

5. Findings

5.1. Model Validation

Solar irradiance is nearly uniform across the city, allowing for the use of radiation data from the Mashhad synoptic station. Weather data was collected over a 12-h period (6:00 a.m. to 6:00 p.m.) from a weather website. Figure 5 shows the temporal changes in both measured and simulated air temperatures (T_a) for Urban Fabric Case zones one, two, and three. The comparison reveals that, in the morning to mid-afternoon, measured temperatures are slightly higher than simulated ones, while later in the day simulated temperatures are generally higher.

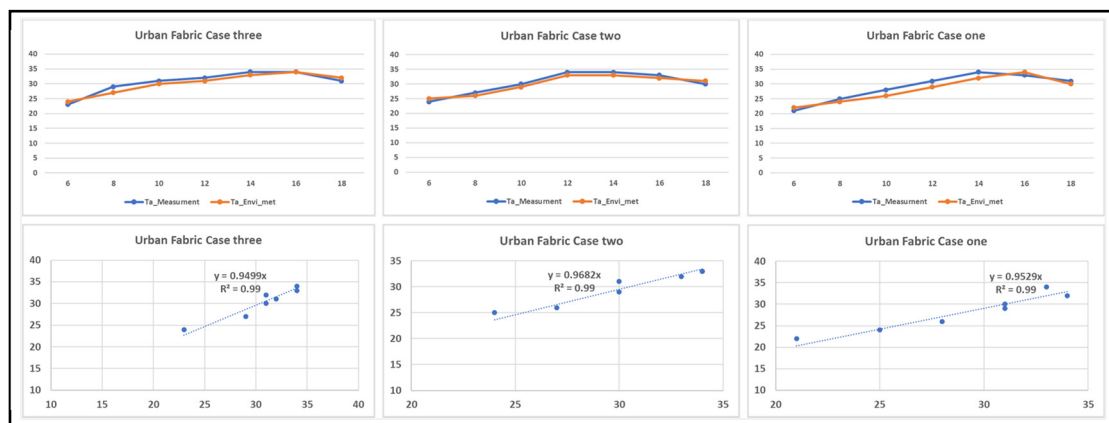


Figure 5. Temporal patterns of simulated and measured T_a .

To assess the accuracy of the ENVI-met simulations in analyzing the impact of building density on the microclimate in Mashhad District 9, the percentage error between observed and simulated air temperature data was calculated. In this analysis, the measured value refers to field-recorded air temperature, while the simulated value corresponds to results generated by the ENVI-met model. Equation (1) was used to calculate the error percentage.

$$\text{Percentage Error} = \frac{| \text{Measured Value} - \text{Simulated Value} | \times 100}{\text{Measured Value}} \quad (1)$$

This calculation provides a quantitative evaluation of the model's reliability in replicating real-world microclimatic conditions [46–48]

The mean absolute percentage error (MAPE) was determined to be 2.39% for Urban Fabric Case One, 1.65% for Urban Fabric Case Three, and 1.60% for Urban Fabric Case Two. Additionally, regression analysis of the measured versus simulated values yielded R^2 values of 0.99 for all zones (see Table 6), highlighting the high accuracy of the ENVI-met model in replicating actual temperature patterns.

Table 6. Model Validation Metrics for Urban Fabric Cases.

Urban Fabric	RMSE	R^2
Case one	The calculated RMSE for this dataset is approximately 2.39, indicating an average deviation of 2.39 units from observed values.	0.99
Case two	The calculated RMSE for this dataset is approximately 1.60, indicating an average deviation of 1.60 units from observed values.	0.99
Case three	The computed RMSE for this dataset is approximately 1.65, indicating an average deviation of 1.65 units from observed values.	0.99

The analysis of Root Mean Square Error (RMSE) values offers critical insight into the predictive performance of the simulation model. As RMSE quantifies the average deviation between predicted and observed values, lower RMSE values denote higher model accuracy. Among the datasets evaluated, the first dataset yielded the most accurate results, with an RMSE of 1.60, indicating a strong correlation with empirical temperature measurements. In contrast, the third dataset, which recorded an RMSE of 2.39, exhibited the weakest performance, suggesting greater deviation from actual temperature values.

This trend is further supported by the mean absolute error (MAE) results presented in Table 3 and illustrated in Figure 5, which show an average deviation of 2.1% between simulated and observed air temperatures. However, the model's accuracy was not spatially uniform. It achieved its highest precision in shaded urban areas, likely due to the thermal buffering effect of reduced solar radiation and increased surface reflectivity in those zones. Conversely, predictive errors were notably higher over exposed asphalt surfaces.

Simulations were conducted for all three urban fabrics, and the resulting microclimate indices were presented for each. The following section discusses each fabric in terms of both its morphological and microclimate aspects.

The simulation results were validated based on the methodologies, described in Table 7, of earlier studies. This validation was conducted to assess the accuracy and consistency of the microclimate model used in this research. By following well-established validation procedures, the study aimed to confirm the model's ability to represent Mashhad's specific climatic conditions. Ensuring the reliability of the model was a necessary step before analyzing the selected urban development patterns. This process helped establish a solid foundation for the case studies and ensured that the findings could be meaningfully compared with previous research.

Table 7. A review of studies related to air temperature validation in Mashhad.

Study	Methodology	Temperature Validation	Description
[49]	Land-use and remote sensing	Satellite LST cross-checked with meteorological data	In their MDPI Atmosphere article, they detail LST changes and validate correlations with air temperature data from ground stations and remote-sensing imagery.
[50]	GIS temporal UHI mapping	Satellite + station air temperature	Spatial-temporal analysis of urban heat island intensity in Mashhad due to land-use changes. Air temperature validated through satellite data and GIS modeling, with multi-year trends documented.
[51]	PET analysis with climate change lens	2007–2017 station temperature data	Explored climate change impacts on outdoor comfort in Mashhad using Physiological Equivalent Temperature (PET) index, analyzing meteorological station data from 2007 to 2017 and assessing air temperature trends.
[52]	Multi-temporal satellite LST mapping	Calibration via local weather station records	Modeled Mashhad's urban heat island using ENVI-met simulations, comparing simulated ground temperatures (surrogates for air-surface conditions) with observed urban thermal patterns.
[46]	ENVI-met V4 simulations of historical, contemporary, and modern neighborhoods; PET via RayMan	Compared ENVI-met outputs with 2018 Mashhad meteorological station air temperature data	The study simulated summer and winter microclimates in three urban districts of Mashhad using ENVI-met and RayMan models. Air temperature outputs were validated using 2018 meteorological station data from Mashhad.

5.2. Urban Fabric Case One

As shown in Figure 3, this urban fabric is a recent development in Mashhad's 9th district, built over the past 10 years. The buildings typically range from 1 to 10 stories, with an average of 3.5 stories. This area has the highest average building and population density, which is consistent with its residential zoning (Table 8). Consequently, the observed density aligns with expected values.

Table 8. Investigation of the morphology components in fabric case one.

Land Use Type	Average Population Density	Average Fabric Compression (Granulation)	Average Building Height (Floor)	Average Building Density
Residential	285.70	162.100	3.50	302.90

The buildings are designed with a central courtyard, which records the lowest temperature (32.21 °C), the lowest average radiant temperature (39.24 °C), and the highest humidity (22.77%). These favorable conditions are likely due to the vegetation and shading from the surrounding buildings. Additionally, the tall structures around the courtyard block wind, resulting in the highest wind speed (0.92 m/s) in this area.

Figure 6 presents the spatial distribution of key microclimatic variables—air temperature, relative humidity, mean radiant temperature (MRT), and wind speed—at three different times (12 PM, 2 PM, and 4 PM) for Texture Number 1. The findings underscore the significant impact of urban morphology on local environmental conditions.

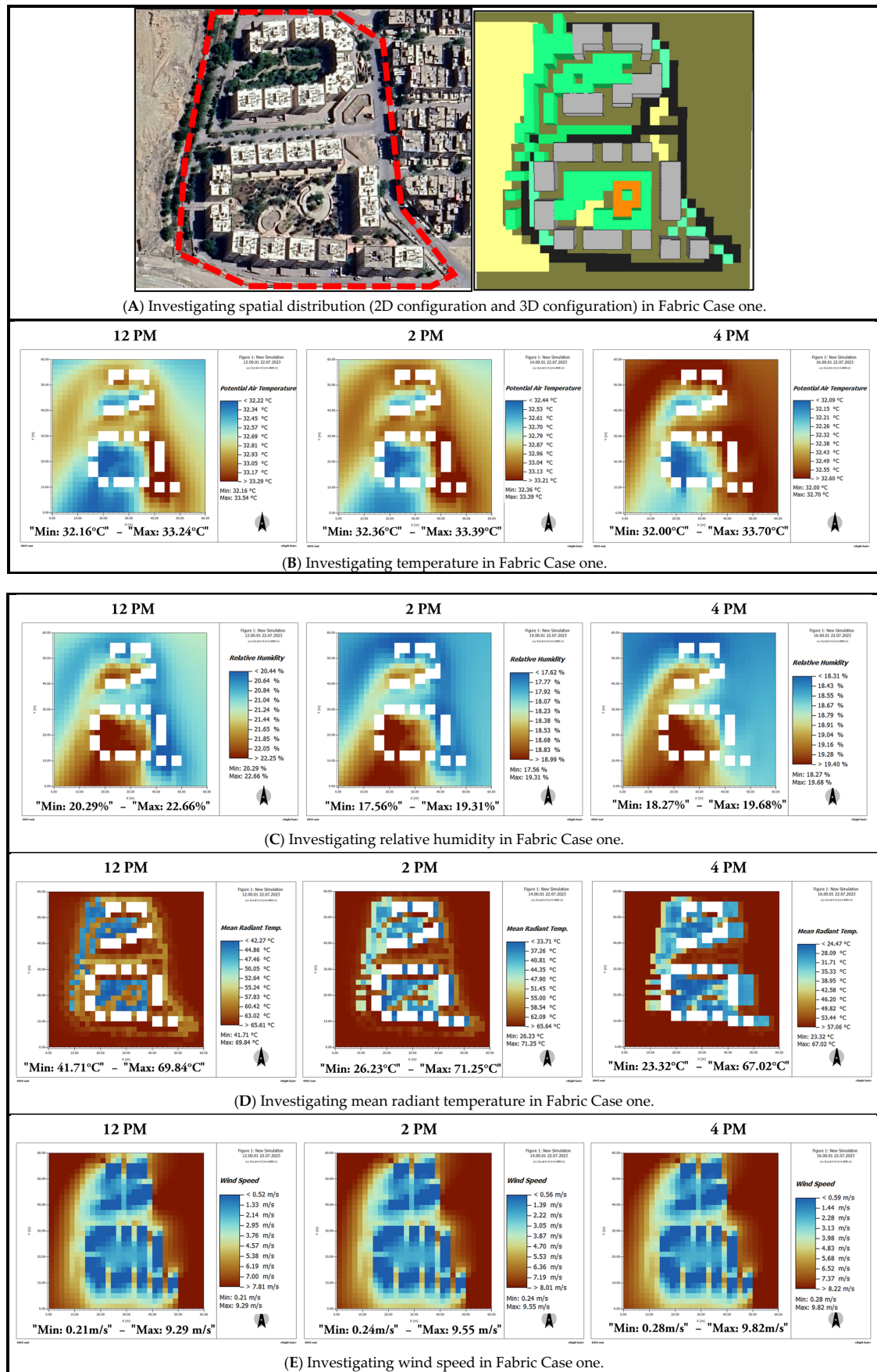


Figure 6. Investigating microclimate components in Fabric Case one.

Air Temperature: Throughout the day, air temperature fluctuates, with midday values ranging from 33 °C to 34 °C, influenced by partial solar exposure and shading. By 2 PM, direct solar radiation increases temperatures above 35 °C in exposed areas, while shaded regions remain around 33 °C, highlighting the cooling effect of building-induced shade. At 4 PM, temperatures slightly decrease to around 34 °C, though densely built areas retain residual heat due to their higher thermal inertia (Figure 6B).

Relative Humidity: Humidity follows an inverse pattern to temperature changes. At 12 PM, moisture levels are relatively stable. By 2 PM, increased solar radiation intensifies evaporation, lowering humidity in sunlit areas, while shaded zones retain more moisture. At 4 PM, humidity levels stabilize or slightly rise as solar intensity decreases, reflecting how urban structures modulate local moisture dynamics (Figure 6C).

Mean Radiant Temperature (MRT): MRT shows a clear temporal increase, ranging from about 31 °C (lighter hues) to nearly 40 °C (darker hues). At midday, MRT typically falls between 31 °C and 35 °C. By 2 PM, values increase to 35–38 °C, aligning with peak solar exposure. By 4 PM, large portions of the urban fabric experience MRTs exceeding 38 °C, with some areas nearing 40 °C (Figure 6D).

Wind Speed: Wind patterns also highlight the role of urban morphology. At 12 PM, wind speeds range from 1.8 m/s to 2.6 m/s, with a prevailing direction around 130°. By 2 PM, wind speeds increase, particularly in the northern sector, surpassing 3.0 m/s, and shifting to a dominant direction of 145°. At 4 PM, wind speeds exceed 3.5 m/s in certain areas, stabilizing at a prevailing direction of 150° (Figure 6E).

5.3. Urban Fabric Case Two

As shown in Figure 2, this urban fabric is spread across different parts of District 9 and cannot be considered entirely new or innovative. The buildings in this area are scattered and primarily designated for residential use, with an average of 2.84 stories per building (Table 9).

Table 9. Investigation of the morphology components in Fabric Case Two.

Land Use Type	Average Population Density	Average Fabric Compression (Granulation)	Average Building Height (Floor)	Average Building Density
Residential	243.00	16.80	2.84	235.00

The spaces between these buildings are densely planted with vegetation, particularly trees.

Dense vegetation inhibits wind flow, leading to the accumulation of hot and humid air, which is evident in the northern part of this fabric, where the temperature reaches 33.86 °C and wind speed is low (0.87 m/s) (Table 7). The vegetation, which often matches the height of the buildings, also provides shade and prevents direct solar radiation in open and semi-open areas, resulting in the lowest average radiant temperature in most parts of this area.

The presence of open spaces in the southern part of the district (outside the studied area) facilitates the penetration of cooler air, leading to the lowest temperature (32.62 °C) in this section. As a result, the southern part of the fabric has a more comfortable temperature (33.17 °C), with high humidity (20.21%) and a higher wind speed (2.38 m/s).

Figure 7 provides an integrated overview of the microclimatic variations for Texture Number 2, highlighting how urban morphology impacts temperature, humidity, mean radiant temperature (MRT), and wind speed throughout the day.

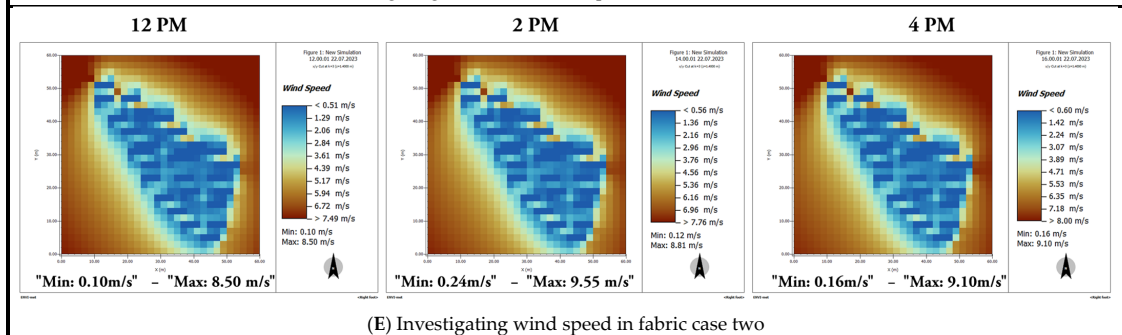
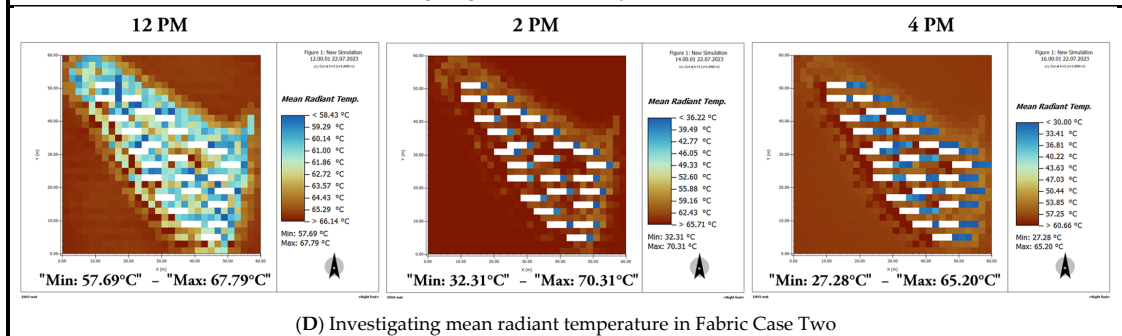
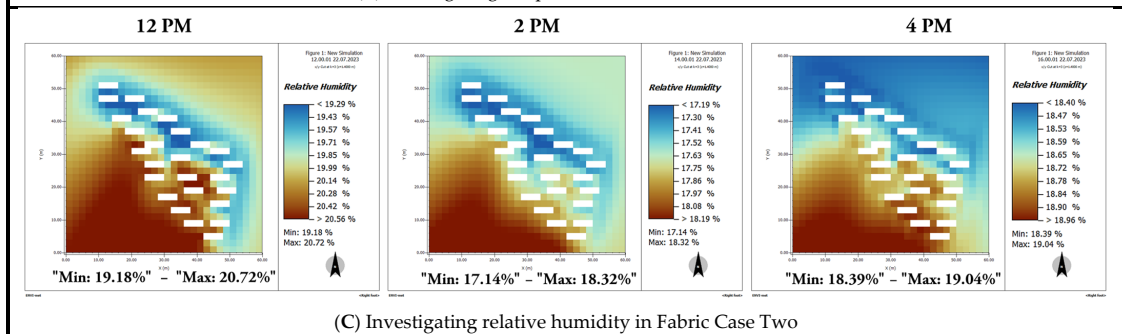
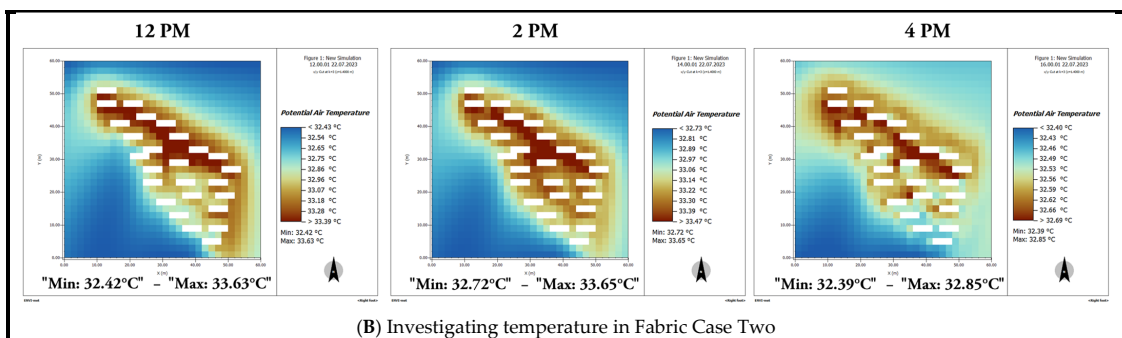
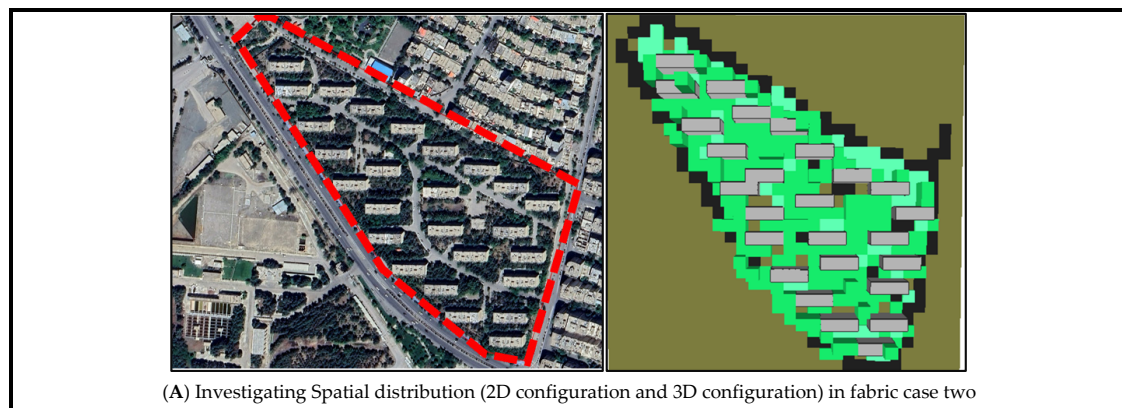


Figure 7. Investigating microclimate components in Fabric Case Two.

Air Temperature: At midday (12:00 PM), surface temperatures range from 31 °C to 34 °C, with higher temperatures in densely built areas due to restricted airflow and reduced shading, which amplify solar heating. Relative humidity is between 45% and 55%, with lower values in compact urban zones, where increased thermal mass and limited ventilation contribute to higher temperatures (Figure 7B).

Relative Humidity: By 2:00 PM, when solar altitude reaches its peak, temperatures exceed 34 °C in sun-exposed areas, particularly in tightly clustered urban zones that retain heat due to poor ventilation. Relative humidity decreases to 40–45% in these regions, while shaded and vegetated areas maintain higher humidity levels, around 50% (Figure 7C).

Mean Radiant Temperature (MRT): MRT values follow the same thermal pattern, with readings at 12:00 PM ranging from 40 °C to 50 °C, rising to 45–55 °C by 2:00 PM as heat accumulates, especially in canyon-like street configurations. By 4:00 PM, a slight cooling effect occurs, but dense areas remain above 32 °C, while MRT decreases to around 42–52 °C. Open and green spaces cool more rapidly (Figure 7D).

Wind Speed: Wind speeds at 12:00 PM range from 1.0 to 2.0 m/s, with a prevailing wind direction around 220°, leading to localized variations based on the urban structure. By 2:00 PM, wind speeds increase to 1.5–2.5 m/s due to enhanced convection, particularly in areas aligned with the wind. By 4:00 PM, wind speeds stabilize or decrease back to 1.0–2.0 m/s as the cooling process takes effect (Figure 7E).

5.4. Urban Fabric Case Three

The most prevalent urban fabric in District 9 of Mashhad is Fabric Case three, characterized by mixed land uses, including services, facilities, and housing. This fabric exhibits the highest degree of densification (granulation), with an average density of 407.1 and an average of three building classes (Table 10). One notable aspect of this fabric is the lack of vegetation used to mitigate air temperature. As shown in the images in Figure 8, the average radiant temperature across most of the area exceeds 60 °C, which could be reduced by incorporating vegetation. The presence of buildings with solid concrete walls restricts wind flow between structures. To address this issue, buildings should avoid continuous walls and incorporate gaps. In areas like the central and southern parts of the fabric, where barren land and separate buildings are present, wind speeds have increased, relative humidity is higher, and air temperature has decreased.

Table 10. Investigation of the morphology components in Fabric Case Three.

Land Use Type	Average Population Density	Average Fabric Compression (Granulation)	Average Building Height (Floor)	Average Building Density
Residential	177.30	407.10	3.00	211.9

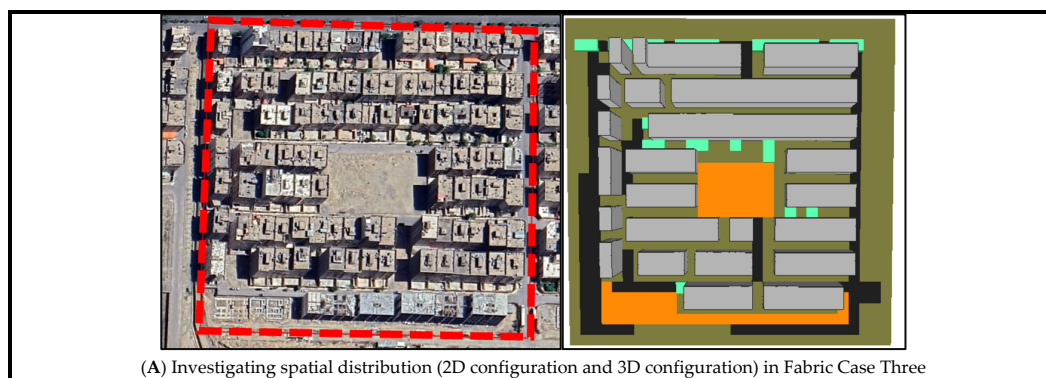


Figure 8. Cont.

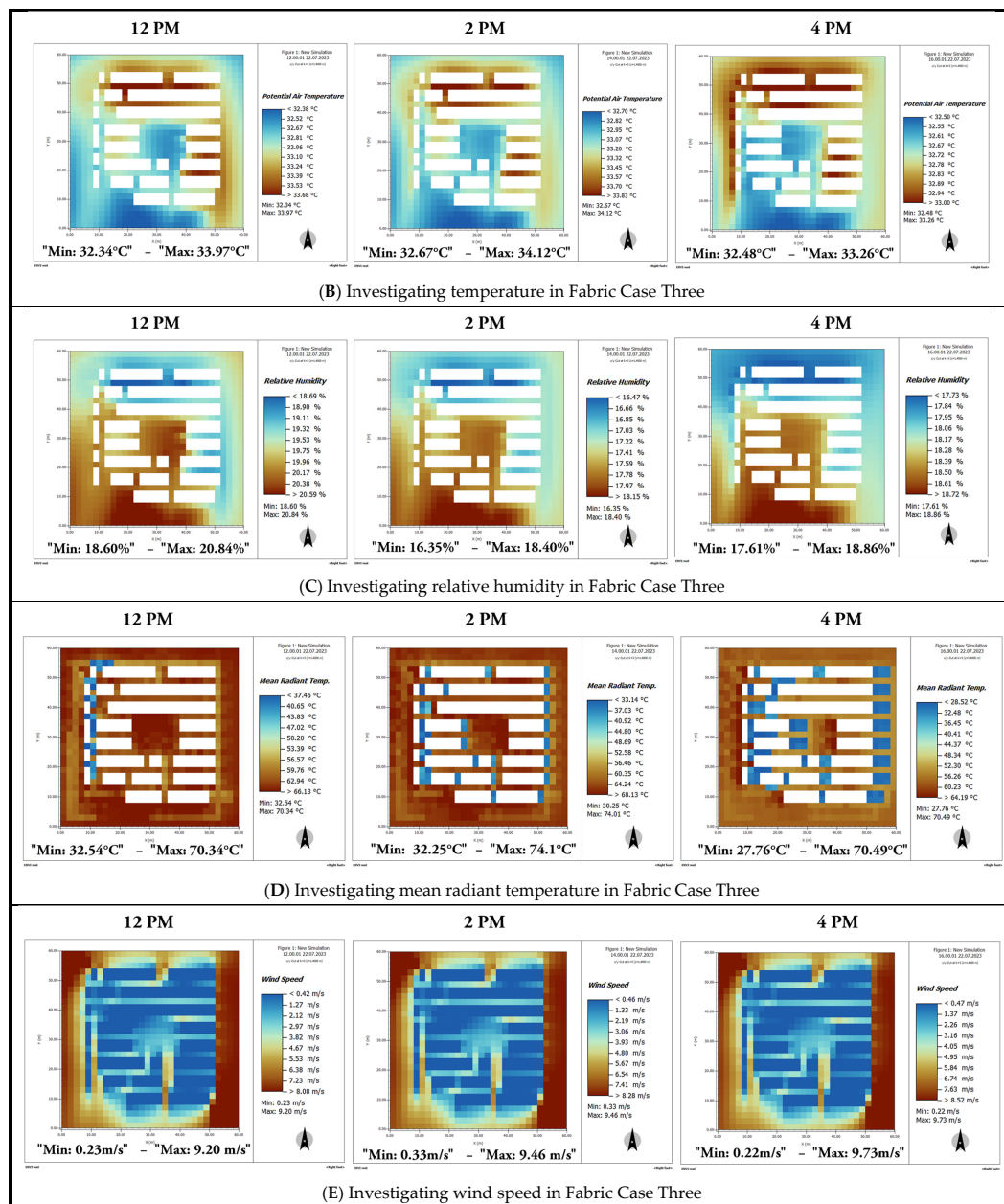


Figure 8. Investigating microclimate components in Fabric Case Three.

Air Temperature: The diurnal microclimatic analysis of Texture Number 3 highlights the strong impact of urban form on local climate behavior. At noon, open spaces exhibit moderate air temperatures ranging from 31.5 °C to 33.5 °C, while densely built areas record higher temperatures due to limited ventilation and increased heat absorption. By 2:00 PM, solar radiation intensifies, pushing temperatures in exposed zones above 34 °C. Although a slight cooling occurs by 4:00 PM, high-density areas maintain elevated temperatures due to thermal inertia (Figure 8B).

Relative Humidity: Relative humidity remains stable at 45–50% around midday but declines to 40–45% in compact urban clusters during the early afternoon when temperatures exceed 30 °C. In contrast, shaded spaces, such as courtyards and tree-lined streets, retain higher moisture levels. Humidity gradually recovers later in the day, especially in vegetated areas with lower thermal mass (Figure 8C).

Mean Radiant Temperature (MRT): Mean radiant temperature (MRT) peaks at 45–50 °C in open plazas and wide streets around midday and can surpass 50 °C by 2:00 PM

in unshaded locations. MRT decreases later, although surfaces with high thermal mass retain heat (Figure 8D).

Wind Speed: Wind speed varies across the urban fabric: open spaces and broad streets maintain higher velocities (1.5–2.0 m/s), whereas narrow alleys and urban canyons experience lower speeds (0.5–1.0 m/s). By 2:00 PM, enhanced solar heating increases airflow in well-ventilated corridors. At 4:00 PM, cooling reduces wind speeds slightly, except where favorable street orientations sustain effective ventilation (Figure 8E).

5.5. Comparison of Three Fabric Samples in Terms of Morphological Components

The study presents a detailed comparative analysis of urban microclimates, focusing on three distinct urban textures, each defined by unique building morphology, vegetation cover, and thermal dynamics (Table 11).

Table 11. Comparison of microclimate parameters in three urban structures.

	Temperature (°C)		Relative Humidity (%)		Wind Speed (m/s)		Mean Radiant Temperature (°C)	
Urban Fabric Case One	34.03	32.21	22.77	19.75	8.46	0.08	69.84	39.24
Urban Fabric Case Two	34	32.62	20.9	18.59	7.66	0.12	67.69	57.09
Urban Fabric Case Three	34.28	32.52	20.64	18.22	8.56	0.07	70.76	33.84

In Texture 1, midday temperatures range from 33 °C to 34 °C, peaking above 35 °C in exposed areas by mid-afternoon before slightly decreasing by 4:00 PM. Densely built sections show a delayed cooling effect due to thermal inertia. Relative humidity remains stable at midday, drops in the early afternoon due to increased evaporation, and then stabilizes or rebounds as temperatures decrease later in the day.

Texture 2 exhibits a similar pattern, with midday temperatures ranging from 31 °C to 34 °C, which rise further in exposed zones by 2:00 PM. Relative humidity drops from 45–55% at noon to 40–45% during peak solar exposure. Mean radiant temperature (MRT) increases from 40–50 °C to 45–55 °C, before slightly declining in the afternoon. Wind speeds are relatively low at midday (1.0–2.0 m/s), with a prevailing wind direction of about 220°. Winds increase slightly by 2:00 PM before stabilizing or decreasing as cooling begins.

Texture 3 clearly demonstrates the influence of urban form on microclimatic conditions. Open spaces register moderate temperatures (31.5–33.5 °C) at midday, while densely built areas experience higher temperatures due to limited ventilation and higher heat absorption. By 2:00 PM, temperatures exceed 34 °C in exposed regions, and despite slight cooling by 4:00 PM, high-density zones retain elevated temperatures. Relative humidity drops during peak heat and gradually recovers, particularly in areas with vegetation. MRT reaches its peak in open plazas and broad streets at midday (45–50 °C) and can exceed 50 °C in unshaded areas by mid-afternoon. Wind speeds vary significantly: open areas support higher airflow, while narrow alleys and urban canyons impede wind movement.

As shown in Figure 9, the comparative analysis of the three urban fabrics reveals distinct differences in their microclimatic performance.

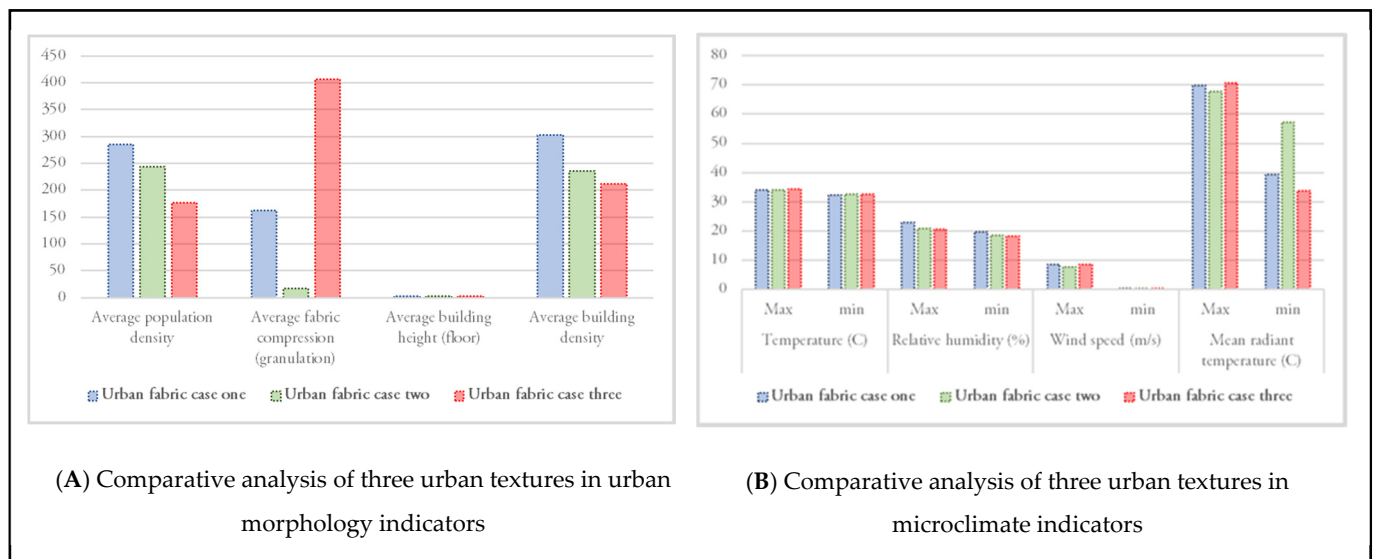


Figure 9. Comparison of morphological and microclimate indices in all three urban fabrics.

Texture 1 exhibits the lowest average air temperature (approximately 32 °C) and the highest relative humidity (around 22.66%). This suggests that a more open urban form, coupled with moderate vegetation, effectively mitigates thermal stress. The balance between moderate temperatures and higher humidity offers a more comfortable environment, especially in hot and arid climates. However, its limited ventilation (indicated by low wind speed) may hinder airflow, though it compensates by retaining moisture and reducing diurnal heat fluctuations. This makes it ideal for climates where shade, density, and moisture retention are crucial for comfort.

Texture 3 recorded the highest average air temperature, approximately 34.12 °C, along with the lowest relative humidity at around 16.35%. This texture exhibits marked spatial variability. In the northern part, densely packed buildings restrict natural airflow, contributing to increased heat retention. Conversely, the more open southern zones allow for greater wind penetration, with wind speeds reaching up to 8.52 m/s, which facilitates localized cooling. Despite favorable conditions for ventilation and nighttime cooling evident in its high maximum wind speed and reduced mean radiant temperature, the compact built form leads to significant heat accumulation during daytime hours. This pattern intensifies microclimatic stress in the denser sections of the texture.

Texture 2 is the least favorable in terms of microclimatic performance. Although it records the lowest maximum temperature, it performs poorly in key factors such as relative humidity, wind speed, and mean radiant temperature. Its low urban fabric compression and modest building density reduce its capacity to provide adequate shading or regulate temperatures, making it more vulnerable to heat stress and thermal discomfort.

A comparative analysis of the three selected urban sites, as summarized in Table 12, indicates that Urban Fabric Case one offers the most favorable performance in terms of morphological impact on microclimatic conditions. Its compact structure, higher building density, and well-balanced vertical profile contribute to improved environmental outcomes, particularly with regard to air temperature regulation and relative humidity levels. These findings underscore the significance of urban morphological parameters in influencing local climatic behavior.

Table 12. Final evaluation and ranking for each of the three studied tissues.

Rank	Case	Reason	Index
Best	Urban Fabric Case One	The urban texture provides optimal overall microclimatic performance. Despite limited ventilation, it demonstrates strengths in humidity retention, urban compactness, and population efficiency. These characteristics make it well-suited for hot-arid climates that require dense development and effective shading.	Average Air Temperature: 32 °C, the lowest among the three. Relative Humidity: 22.66%, the highest, suggesting better moisture retention.
Acceptable	Urban Fabric Case Three	Good ventilation and nighttime cooling due to MRT swing, but extreme compactness and high radiant heat during the day make it less comfortable overall.	Average Air Temperature: 34.12 °C, the highest among the three. Relative Humidity: 16.35%, the lowest, indicating drier conditions.
Most Inappropriate	Urban Fabric Case Two	Underperforms across almost all indicators: low fabric cohesion, poor airflow, high radiant heat, and inadequate shading. Most vulnerable to heat stress and poor thermal regulation.	Performs poorly across most parameters.

The identification of Urban Fabric Case One as the most effective configuration represents a key contribution of this study. It highlights how specific spatial characteristics, such as density and building height, can be purposefully applied to mitigate microclimatic stress in high-density urban areas, especially within hot and arid climates. This insight provides a valuable foundation for future urban planning and design strategies aimed at enhancing climate responsiveness and promoting environmental resilience in rapidly urbanizing cities.

Analysis of vegetation cover, permeability, and shading using GIS Pro (Figure 10) revealed that Urban Fabric Case Two had the highest surface permeability. However, its dense vegetation limited airflow, resulting in higher air temperatures. In contrast, Urban Fabric Case One allowed better wind circulation due to less obstructive vegetation.

When both permeability and vegetation were considered, Case One exhibited more favorable microclimatic conditions than the other cases. This suggests that while vegetation improves environmental quality, excessive density can hinder cooling by reducing wind speed.

In District 9 of Mashhad, the orientation of shadows shifts steadily throughout the day, reflecting the sun's east-to-west path across the sky at this latitude. In the early morning, shadows are long and directed toward the southwest. As the sun rises, they gradually shorten and shift northward. Around noon, shadows reach their minimum length and point almost directly north. In the afternoon, they lengthen again, turning progressively toward the northeast and then east.

Shading analysis conducted at 12:00, 14:00, and 16:00 confirmed this directional shift from southwest to northeast over time. In Case One, open spaces remained shaded for longer durations, leading to reduced solar exposure. These findings underscore the critical role of urban design in managing heat gain and supporting microclimatic balance in semi-arid urban environments.

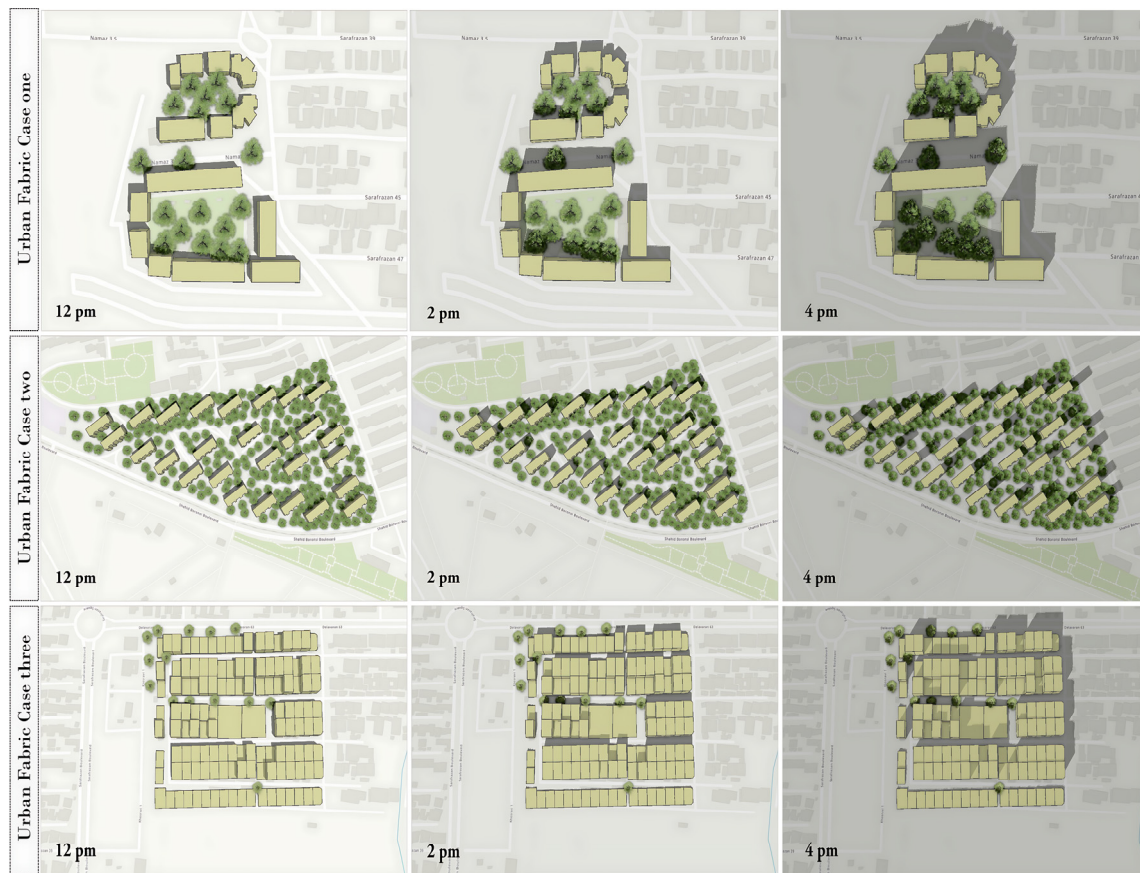


Figure 10. Investigating vegetation, permeability, and shading indicators in the urban fabric cases.

6. Discussions

This study supports and builds upon previous research [53–55] by highlighting rapid urbanization as a key driver of deteriorating outdoor microclimatic conditions. The morphological characteristics of urban environments, such as building density, spatial configuration, land use, and built form, exert a significant influence on local climate dynamics. This conclusion aligns with findings by [56], who also highlight the critical role of urban morphology in shaping thermal conditions. These insights underscore the need for integrated urban planning strategies that consider the thermal implications of built form.

The arrangement of buildings and open spaces directly influences temperature distribution and airflow. Dense urban layouts tend to retain heat due to larger thermal masses, raising ambient temperatures.

The incorporation of green infrastructure, particularly vegetation, into high-density urban areas plays a vital role in mitigating heat stress, as emphasized by [57]. Trees, through their canopy structure and foliage density, influence local microclimatic conditions by altering radiative fluxes and enhancing evapotranspiration. Several empirical studies support this claim by providing detailed data on the physical parameters of urban vegetation. For instance, [58] used terrestrial laser scanning and digital hemispherical photography to assess mature broadleaf trees (~15 m tall), reporting leaf area index (LAI) values near 7.5 and leaf area density (LAD) around $5.7 \text{ m}^2/\text{m}^3$ —similar to plane trees in semi-arid cities. [59], through satellite and ground measurements in semi-arid Lebanon, observed comparable LAI values (~7.5) in irrigated broadleaf canopies. Similarly, [45] documented LAI and LAD values of 7.5 and $5.7 \text{ m}^2/\text{m}^3$, respectively, for dense deciduous species in urban Cairo, reaffirming their thermal regulation role. For conifers, [60] reported LAI values between 4 and 5 and LAD values around $3.97 \text{ m}^2/\text{m}^3$ in Mediterranean pines

(~10 m tall), consistent with semi-arid climatic conditions. Drawing on these findings, our model applied LAI values from 4.73 to 7.53 and LAD values between 3.97 and 5.68 for trees 10–15 m in height. These parameters reflect validated empirical ranges, supporting the robustness of our assumptions and the reliability of our simulations in assessing the influence of vegetation on the urban microclimate of Mashhad.

However, the orientation of urban elements is equally important. [61] demonstrate that aligning street networks with prevailing wind directions can enhance natural ventilation and contribute to more favorable microclimatic conditions.

Our findings support this: simulations conducted using ENVI-met for District 9 in Mashhad reveal that streets perpendicular to the dominant wind direction can reduce local air temperatures by up to 1.5 °C. These results demonstrate that street orientation, when combined with strategic vegetation placement, can significantly improve outdoor thermal conditions [44].

Despite a wide body of research on urban geometry and microclimate, previous studies have often produced inconsistent outcomes. These variations are largely due to differing climates, measurement methods, and the specific thermal indicators used—such as air temperature, wind speed, mean radiant temperature, and composite indices like PET and UTCI [61]. Many of these studies apply thermal metrics inconsistently or in isolation, limiting their generalizability. Our study addresses this by employing a more comprehensive approach, integrating morphological analysis with environmental simulation and field validation. The strong correlation ($R^2 = 0.98$) between simulated and measured data, as reported by [4], supports the reliability of this method.

In addition to evaluating built form and street orientation, this study explores the relationship between vegetation density, spatial openness, and airflow. While vegetation is often assumed to provide universal cooling benefits [62,63], our results suggest a more complex dynamic. In compact urban settings, overly dense tree canopies may restrict ventilation and trap humidity, ultimately leading to localized heat buildup. These findings challenge the common assumption that increased greenery always leads to improved microclimatic conditions. Instead, they underscore the need to design green spaces that balance shading with sufficient air circulation, a strategy referred to in this study as green-ventilation.

Furthermore, the assumption that low-density urban forms inherently offer better thermal conditions is not always accurate. Our study shows that unless these areas are designed to facilitate effective wind flow, they may not provide meaningful cooling benefits. While the previous literature often links compact urban forms with elevated heat stress [61], our findings indicate that permeability and spatial integration are more important than density alone. Well-designed compact areas that support ventilation can outperform low-density areas in terms of microclimate.

A key contribution of this research is its interdisciplinary approach, combining urban morphology, climatology, and landscape design to better understand microclimatic behavior. The study also brings forward a more nuanced understanding of vegetation's role in urban environments. Although vegetation can cool through evapotranspiration and shading, its effectiveness depends on context. In narrow, enclosed spaces, dense greenery can obstruct airflow and increase humidity, reducing its cooling efficiency.

The analysis of building density, street patterns, and vegetation distribution demonstrates strong connections between physical urban features and local thermal performance. These findings point to the need for climate-responsive design strategies that integrate permeable spatial layouts and strategically placed greenery.

Finally, the study includes a comparative assessment of three urban fabric types in Mashhad's District 9—a region characterized by a cold semi-arid climate that is often

overlooked in microclimatic research. This analysis shows that urban areas designed with open layouts, aligned with prevailing winds and complemented by thoughtfully distributed vegetation, are more resilient to thermal stress. This is particularly relevant in light of ongoing urban expansion and climate change.

7. Conclusions

This study demonstrates that key morphological factors—such as street orientation, green space placement, and shading strategies—play a central role in regulating urban microclimates and mitigating the urban heat island (UHI) effect. Through a comparative analysis of three urban fabric typologies in District 9 of Mashhad, it becomes clear that urban form strongly influences microclimate.

Among the studied configurations, open and permeable layouts with moderate vegetation showed the most favorable thermal performance, promoting both effective airflow and heat dissipation. In contrast, layouts with dense vegetation but limited ventilation created humid microclimates with reduced comfort. The most compact form, lacking both vegetation and ventilation, produced the most adverse thermal conditions, intensifying the UHI effect.

These results highlight the importance of a balanced approach that combines greenery with sufficient ventilation. While dispersed urban layouts support airflow, they may require additional shading. Dense vegetation in poorly ventilated areas, however, can trap humidity and restrict air movement, worsening thermal discomfort.

Although rooted in Mashhad's cold semi-arid climate, the findings offer broader insights for cities in similar environments. The study introduces a context-specific planning framework that integrates vegetation with ventilation strategies, moving beyond traditional models that often ignore the unique thermal dynamics of arid regions. By aligning green infrastructure with airflow, the proposed approach enhances not only the aesthetic and ecological quality of urban spaces but also their thermal performance. It supports climate-responsive design strategies that promote sustainable, livable, and thermally comfortable urban environments under the increasing pressures of climate change and urbanization.

The implications of these findings are particularly important for urban planners and policymakers in cold semi-arid regions. By moving beyond conventional design models and adopting a climate-responsive planning framework, future urban developments can achieve significant improvements in microclimatic regulation and more effectively mitigate extreme heat-related challenges. This approach highlights the critical role of integrating urban morphology, vegetation planning, and shading strategies to create environments that are better aligned with local climatic conditions. Such integration enhances both the sustainability and livability of urban spaces.

It is important to note that urban materials absorb heat during the day and gradually release it at night, which can contribute to elevated nighttime temperatures and delayed cooling. Although this study primarily focused on the daytime period, future research should incorporate full 24-h simulations to better understand the heat retention and release patterns of different urban forms. This will help provide a more comprehensive view of thermal dynamics, especially in compact or poorly ventilated areas where nocturnal heat retention can significantly affect urban comfort.

This study provides a strong foundation for future research on the complex relationship between urban form and microclimatic conditions. Further studies should expand on these findings by examining the long-term impacts of urban design interventions across various climatic contexts. Such research will contribute to the development of best practices for designing sustainable and microclimatically resilient urban environments.

Further research should expand the scope by examining a wider range of thermal comfort indices, such as the Universal Thermal Climate Index (UTCI) and Physiologically Equivalent Temperature (PET), across various climatic zones. Additionally, there is a need to explore the role of urban greenery and blue infrastructure in regions that are prone to extreme heat events.

The use of smart urban design technologies and advanced climate simulation tools is strongly recommended. These technologies can enhance the accuracy of microclimatic modeling and provide valuable insights to improve urban planning strategies, particularly in mitigating the urban heat island effect.

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