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Comparing Microclimate Dynamics in Urban Areas with Distinct Morphological Changes Using AI-Based Predictions and Climate Scenarios

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ABSTRACT

Rapid urbanization and climate change are reshaping urban microclimates, yet existing assessments of future outdoor thermal comfort predominantly rely on annual or seasonal climate averages, overlooking extreme summer heat conditions — the periods of greatest risk to public health and outdoor livability. Moreover, studies projecting future thermal comfort typically hold urban morphology fixed, applying future climate scenarios to present-day city form, without accounting for how distinct growth mechanisms reshape building volume, height, and density over time. This study addresses both gaps by examining peak summer heat extremes in Tabriz through 2050, comparing two districts undergoing distinct growth mechanisms: Khavaran, developing through both new infill construction and building height increases, and Baghshomal, growing solely through vertical renovation of existing buildings. District-specific future morphology is simulated using AI-based prediction models calibrated to each district's observed growth pattern, and future climate scenarios are generated using the CCWorld WeatherGen tool; both are jointly input into ENVI-met to assess microclimatic conditions and outdoor thermal comfort under extreme summer heat. Results show that Baghshomal, despite its slower growth, is more vulnerable to extreme heat than Khavaran. Compared with 2025, maximum air temperature increased by 3.52°C in Baghshomal and 4.66°C in Khavaran, while maximum relative humidity decreased by 8.73% and 14.22%, respectively. This is driven by street-level morphology rather than growth rate: Khavaran's higher street height-to-width ratio and denser vegetation cover provide greater shading and lower solar exposure during peak heat hours, while Baghshomal's wider, lower-density streets remain more exposed. These findings indicate that the mechanism and morphological configuration of urban growth, not only its rate, shape future thermal resilience, offering a growth-mechanism-sensitive framework for evaluating extreme-heat vulnerability in Tabriz's rapidly transforming districts, with potential relevance to similar semi-arid cities after local calibration.

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1. Introduction

1.1 Background and Context

Given that thermal stress affects everyday activities including walking, resting, and social interaction its management has evolved into a matter of urban health and governance, rather than remaining a purely climatological concern (Glodeanu et al. 2026). Urban heat risk is escalating, yet fixed monitoring networks remain too sparse and coarse-grained to capture the pedestrian-scale variability particularly in radiative loads that critically governs outdoor thermal stress. This limitation has motivated the production of georeferenced datasets that elucidate how morphology and materials shape thermal conditions at specific locations and times. Such datasets can significantly enhance our understanding of the situation and support more informed urban planning decisions (Lau et al. 2026).Metropolitan areas are distinguished by high population densities and substantial energy consumption, both of which contribute to urban environmental pollution. The quality of urban spaces particularly in terms of public comfort is of critical importance, as it directly influences both public well-being and the utilization of these spaces (Shimazaki, Yuan, and Tajima 2025) (Adams 2013).

Over the past few decades, urban environments have expanded at a remarkable rate. This vast and largely unplanned urban growth has diminished environmental quality and increased the energy consumption of buildings. The construction and operation of built environments are major determinants of quality of life within urban areas. Studies indicate that global mean surface temperatures in cities are likely to rise by 1.4–4.8°C before the year 2100 (Aghamolaei et al. 2023).

Rapid urbanization and climate change represent two of the most pressing challenges confronting cities in the 21st century. As urban populations continue to grow with projections indicating that over 68% of the global population will reside in urban areas by 2050 cities face unprecedented pressures to accommodate expansion while mitigating environmental degradation (Du et al. 2026). Urban areas currently account for approximately 75% of global energy consumption and more than 70% of greenhouse gas emissions, positioning them as both significant contributors to and primary victims of climate change (Du et al. 2026). The spatial organization of cities, encompassing building density, height distributions, and transportation networks, fundamentally determines urban sustainability outcomes, influencing energy consumption patterns, mobility, and quality of life (Li et al. 2026).

The transformation of natural landscapes into built environments fundamentally alters local climatic conditions, giving rise to the Urban Heat Island (UHI) effect, characterized by elevated temperatures in urban areas compared to their rural surroundings (Lefevre et al. 2025). This phenomenon, combined with intensifying global climate change, poses significant risks to outdoor thermal comfort, public health, and urban resilience. Research has demonstrated strong thematic intersections among land surface temperature, vegetation cover, population growth, land use and land cover change, and their collective influence on urban microclimates (De 2025). However, despite advances in understanding these relationships, the operationalization of climate change mitigation frameworks within urban planning remains underdeveloped, particularly in rapidly urbanizing regions.

Urban districts exhibit varying degrees of vulnerability to climate change, influenced by the combined effects of climate variability and urban morphological evolution (Shen et al. 2025). This vulnerability is especially pronounced in newly developed areas experiencing rapid transformations, where the absence of historical planning controls often leads to suboptimal outcomes. Recent advances in artificial intelligence have opened new possibilities for addressing these challenges. Generative AI-driven frameworks now enable planners to forecast urban layout evolution by comprehensively modelling the complex interactions among building density, height distribution, transportation networks, and historical development patterns (Wu et al. 2026). These tools achieve substantial improvements in prediction accuracy and spatial coherence, offering technical support for evidence-based sustainable development scenario analysis.

Urban morphology affects local microclimates by altering radiation exchange, airflow, and shading patterns. Although its impact on outdoor thermal comfort is well documented, the extent to which pedestrian-level heat stress responds to geometric urban form relative to the dominant atmospheric forces during extreme hot and humid conditions has not been sufficiently quantified (Nazeri et al. 2026). In hot–humid regions, urban areas are facing growing exposure to extreme thermal stress, driven by the concurrent impacts of rapid urbanisation and climate change (Santamouris 2015). And also High temperatures coupled with elevated humidity impair the body's evaporative cooling capacity, rendering outdoor environments physiologically taxing and socially limiting (Zheng, Chen, and Yang 2023) (Karimi et al. 2023) (Aghamolaei et al. 2023) (Zhan et al. 2024). And also Neglecting climate-related priorities in urban planning studies will have adverse consequences for outdoor thermal comfort and, consequently, for public health (Buchin et al. 2016). Thoughtful urban design and planning principles can foster comfortable and healthy microclimatic conditions while simultaneously reducing the energy demand of adjacent buildings. Therefore, numerous studies have sought to evaluate the outdoor thermal comfort performance of urban settings and to propose mitigation strategies aimed at counteracting the adverse effects of thermal discomfort and heat stress (Parker 2021) (Jia and Wang 2021) (Aghamolaei, Fallahpour, and Mirzaei 2021).

Parallel to advances in urban morphology modelling, significant progress has been made in microclimate simulation and future climate projection. ENVI-met has emerged as a leading microclimate modelling system capable of simulating surface-plant-atmosphere interactions at high spatial and temporal resolution, with integrated thermal comfort indices including Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) (Gregorčič et al. 2026). The Physiologically Equivalent Temperature (PET) was introduced by Höppe (1999) as an equivalent air temperature at which the human energy balance is maintained under minimal thermal stress. In contrast, the Universal Thermal Climate Index (UTCI) provides an equivalent temperature derived from the most advanced multi-node thermoregulation model, incorporating standardized clothing insulation and adaptive clothing adjustments (Heidari, Davtalab, and Sargazi 2024) (Jendritzky, de Dear, and Havenith 2012) (Mayer and Höppe 1987).

For future climate data generation, tools such as CCWorldWeatherGen enable the morphing of existing weather files to reflect projected climate conditions under various emission scenarios. Recent validation studies have demonstrated the tool's suitability for generating future weather files, with annual relative root mean square errors for dry-bulb temperature at 17.04% (good) and relative humidity at 17.95% (good), though caution is warranted for variables like solar radiation and wind speed (Nunes et al. 2024).

Urban morphological transformation affects outdoor thermal comfort through changes in urban form, thereby influencing thermal resilience and the effectiveness of climate adaptation strategies. Evaluating climate change alongside urban morphological evolution provides a more comprehensive basis for climate-adaptive urban planning. Existing studies on urban microclimate and outdoor thermal comfort predominantly focus on current conditions, and even those incorporating future climate scenarios typically assume static urban morphology, using present-day urban structures as their baseline. Taken together, this body of literature reveals a shared limitation: morphological change is either disregarded altogether or treated as spatially uniform across a city, with little attention paid to the fact that different districts follow fundamentally different trajectories of physical transformation. In reality, urban form evolves dynamically over time, and different urban districts experience divergent rates and modes of morphological change depending on their historical context, regulatory constraints, and development pressures. For instance, historic city centers with strict preservation laws undergo minimal structural transformation, while newly developed peri-urban districts may experience rapid and substantial morphological shifts over just a few decades.

This divergence is clearly observable in Tabriz, where the district of Baghshomal and the peripheral district of Khavaran represent two structurally contrasting trajectories of morphological change. In Baghshomal, redevelopment cannot occur through spatial expansion or large-scale renewal; the stock of buildings physically and legally eligible for reconstruction is limited, and change where it does occur is rare and confined almost exclusively to vertical infill, as aging villa-type houses are gradually replaced by newly built apartment blocks. It is precisely this limited yet non-negligible redevelopment potential that qualifies Baghshomal as a district of prospective, rather than negligible, future morphological change. Khavaran, by contrast, is characterized by an intensive, grid-like (chessboard) pattern of new construction and one of the highest development rates in the city; notably, however, building heights across new construction remain largely uniform, as nearly all new structures are built to the maximum permissible density. These two districts therefore embody fundamentally different modes of morphological transformation one driven by sparse, height-limited infill within a older constrained fabric, and the other by dense, laterally expansive, density-maximizing new construction

offering an ideal empirical basis for isolating the microclimatic consequences of differential urban transformation trajectories.
It is also worth clarifying why this study prioritizes extreme summer heat as its critical climatic scenario. Tabriz has historically been characterized by a temperate-to-cold climate, in which severe winter cold has long stood as the dominant climatic force shaping the city's urban form; compact building footprints, narrow streets, and dense fabric have evolved over decades primarily as adaptive responses to cold exposure, an influence well documented in the local urban planning literature. Summer heat, by contrast, has historically been a secondary concern. In recent years, however, this balance has shifted: Tabriz has begun experiencing increasingly severe and prolonged summer heat events that depart markedly from its traditional temperate summer pattern, yet no policy, planning regulation, or urban design strategy currently exists to address this emerging thermal risk. While the city's morphology has had decades to adapt to cold, it has had no comparable opportunity, nor any regulatory impetus, to adapt to heat. This asymmetry motivates the present study's focus on projected extreme heat scenarios: if urban form in Tabriz has long been shaped by winter cold, it is now equally urgent to understand how the same form performs, and how it should evolve, under the summer heat conditions the city has only recently begun to face.
This study addresses the critical oversight that, under identical climate change scenarios, districts with higher rates of morphological change will experience significantly greater microclimatic deterioration than relatively stable urban fabrics. By comparing the rapidly evolving Khavaran district with the stabilized Baghshomal district in Tabriz over a 30-year period, this research demonstrates that future microclimate vulnerability is not solely a function of climate exposure but is profoundly shaped by differential urban transformation trajectories.
Accordingly, this study formally poses the following research question: how do the projected morphological transformations mostly physical growth patterns associated with urban growth in Tabriz manifested in two districts with old and new morphological characteristics that stand in direct contrast to one another affect outdoor thermal comfort and microclimatic resilience under the most severe future climate scenarios?
According to (Nazeri et al. 2026), most existing studies evaluate morphological effects either under moderate climatic conditions or through mixed observational datasets, where atmospheric and geometric drivers are inherently intertwined (Bedra et al. 2023) (Meng et al. 2024) (Fan et al. 2024). Furthermore, previous studies generally apply future climate scenarios to static representations of urban morphology, overlooking district-specific morphological evolution over time. To address this gap, the present study proposes an integrated framework that combines district-specific urban morphological evolution with future climate scenarios prior to ENVI-met simulations. This approach enables the simultaneous assessment of two interacting processes, urban growth and climate change under extreme summer heat conditions, providing a more realistic representation of future urban microclimates.

2. Materials and Methods

2.1 General Framework

This study aims to investigate the combined effects of climate change and differing rates of urban morphological changes on the microclimate of neighbourhoods in Tabriz, Iran. To evaluate the simultaneous effect of physical and climatic changes on urban microclimate, two neighbourhoods with contrasting rates of growth and development in Tabriz city (Baghshomal and Khavaran) were selected as case studies. The independent variables in this research are structural changes and climate change over three decades. The dependent variables are temperature, relative humidity, and UTCI. Other variables including building materials and vegetation cover are assumed constant in this study.
To investigate the impact of these variables, it was necessary to project the future structure of the two selected case studies over a 30-year horizon. For this purpose, the structure of Baghshomal was studied from 2000 to the present, and the required data were extracted from GIS, municipal documents, and Google Earth imagery. Changes within this area have been markedly limited over the

study period, with the built environment showing relatively few alterations. This structural stability was, in fact, the primary rationale for selecting this neighborhood as the case study: its low rate of physical change made it possible to isolate and model renovation dynamics with minimal confounding from new construction. Buildings in the area are therefore expected to undergo relatively few changes over the next 30 years as well, with only a limited number of newly constructed buildings anticipated within the projection horizon.

The historical renovation rate is calculated based on this dataset and then applied to the buildings that remained stable throughout the period. A Cox survival model is used to estimate the renovation probability for each stable building. A Random Forest regressor is then trained on the historically renovated buildings to learn the relationship between initial height, renovation year, and post-renovation height, and this model predicts the new heights for the selected buildings.

For Khavoran, the future development plan was predicted on the basis of construction progress monitored using aerial photographs and five-year statistics, validated by field surveys. The relevant maps and the extent of construction are clearly documented, and planned data on the number of floors and heights are also available for this area. Since the buildings in Khavoran are newly constructed or currently under construction, most of these buildings share a uniform height, giving the urban fabric a relatively regular and consistent structure. In both study areas, physical change is most pronounced with respect to building height. This pattern reflects Iran's prevailing urban development model, in which renovated buildings are predominantly converted into apartment blocks, while the overall spatial composition and land-use mix remain largely unchanged. Consequently, vertical (height-related) transformation constitutes the most significant dimension of physical change and its associated environmental impact, with infill development also present within Khavoran.In the next step, RCP 8.5 scenario is used to predict climate change for 2050 on the basis of 2025 weather data using World Weather Gen software. Simulations were conducted for the hottest day of the year 2025 (AUG 3, 2025) and its corresponding date in 2050. Meteorological data were extracted from official weather stations in Tabriz. Microclimatic simulations of the two urban fabrics (Baghshomal and Khavaran) were conducted using ENVI-met 5.6 software. The obtained results were first compared in the Leonardo module of ENVI-met using the "Compare 2D" function, which visualized the changes through numerical data and graphical contours. Analysis is conducted in two stages: (1) comparing each fabric's 2025 and 2050 outputs using raster maps and frequency charts to assess combined climate and structural effects, and (2) directly comparing temperature, humidity, and UTCI (max/min/mean) between the two fabrics to isolate the impact of different growth rates and structural modifications (Figure 1.)

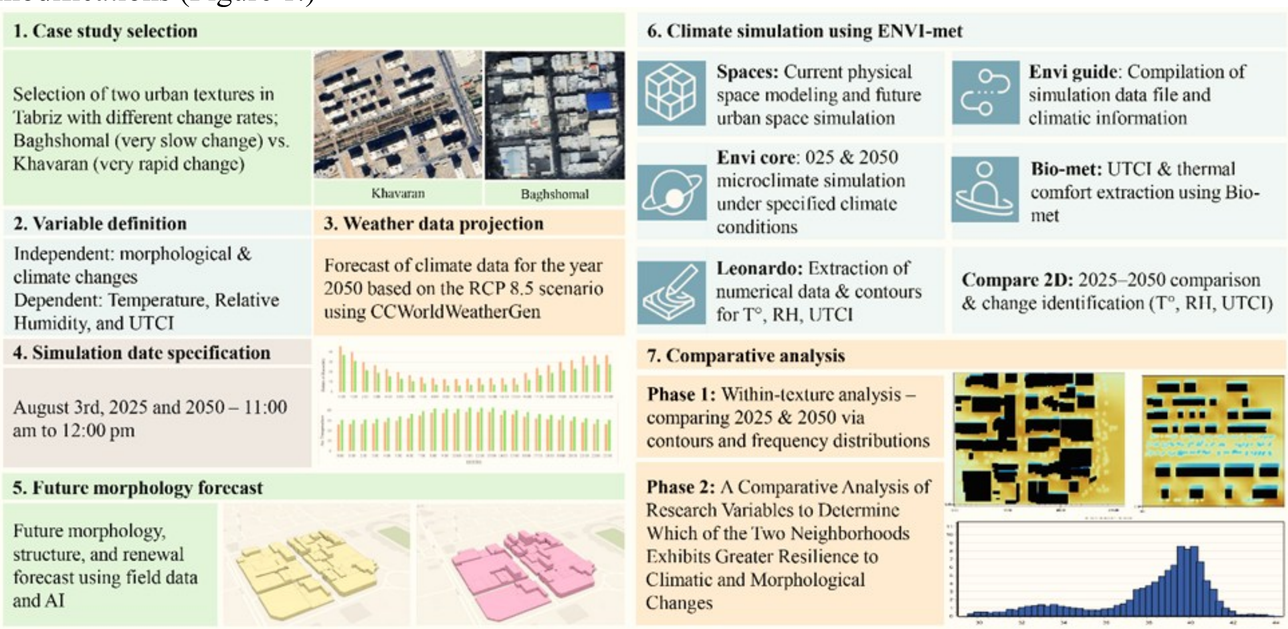

Figure 1. Structure of the Study (Developed by the Authors).

2.2 Case Study Area and Morphological Predictions

Tabriz is a major metropolitan centre in northwestern Iran with a semi-arid climate. In Tabriz, different parts of the city are experiencing different rates of structural change (Mahmoudzadeh and Masoudi 2019). Core central districts of Tabriz are shifting from single-family houses to high-rise apartments, while newly annexed areas are transitioning from pristine land into urbanized spaces. Building heights are lower in the historic central fabric compared to the eastern districts, where the tallest buildings are located. District 8 (with Baghshomal neighbourhood on the edge of District 3) contains deteriorated urban fabric concentrated in District 4, while informal settlements are found in District 10. Together, these areas shape the central and northwestern fabric of Tabriz, featuring an organic pattern with irregular building heights.

Khavaran, a newly developed town located in the centre of District 9, is the newest annexed fabric to the city. It exhibits a regular, grid-like pattern with uniform building heights, relatively fragmented spatial arrangement, and significantly higher structural density compared to the central urban fabric. In contrast, the neighbourhood presents a fine-grained urban fabric where large blocks are less common. Buildings are generally less than 10 years old or still under construction, with regular heights that increase from northwest to southeast, as each block tends to have greater height and more stories than the preceding one. Building orientation follows a northwest-to-southwest direction. The rate of change is very high, with significant transformations occurring every few months, involving both vertical (height) and spatial dimensions simultaneously (Figure 2.).

The Baghshomal neighbourhood exhibits a fabric characterized by buildings of varying ages and diverse heights, ranging from 1–2 stories to 7 stories. The orientation is predominantly north–south, with a mix of fine-grained and coarse-grained urban fabric observed. The rate of change in this fabric is very low, with alterations occurring only every few years. These changes are primarily vertical (height-related) rather than spatial or pertaining to the layout of urban parcels (Figure 2.).

This duality between the two urban fabrics and their distinct characteristics forms the rationale for selecting these two neighbourhoods. The aim is to assess climatic variations within both patterns and derive a specific model. The study area in Baghshomal covers an area of 65205m² and comprises 59 blocks, while the Khavaran study area covers approximately 122184m² and comprises 74 blocks (Table 1).

To predict the height of 59 buildings in Baghshomal in 2050 based on five time points (2000, 2007, 2014, 2021, 2026), a hybrid method combining Survival Analysis (Cox model) and Random Forest regression is proposed. The key assumption is that buildings already renovated by 2026 will not change further by 2050, while only stable buildings may undergo future renovation. First, the historical renovation rate is calculated: 9 out of 59 buildings experienced at least one height change between 2000 and 2026, yielding a renovation rate of 15.25%. Applying this same rate to the 50 stable buildings predicts that 8 buildings will be renovated by 2050. To select which 8 buildings, the Cox model is used. This model estimates the probability of renovation for each stable building by 2050 using features such as initial height, current height (2026), and year of last change. The 8 buildings with the highest probabilities are selected for renovation. To predict the new height of these 8 buildings, a Random Forest regressor with 100 decision trees is trained on the 9 historically renovated buildings. Input features include initial height and year of renovation, while the output is the post-renovation height. For all other buildings, the 2050 height equals their 2026 height. The main advantage of this method is that it uses actual historical renovation rates and learns change patterns from real data, while avoiding the unbounded height growth seen in linear regression. The main limitations are the small dataset size and the assumption of a constant renovation rate into the future.

For Khavoran, which is a new and developing neighbourhood officially established in 2010, construction activity has been monitored using aerial photographs and construction statistics over five-year intervals. Within this neighbourhood, which consists of 101 land plots, it was observed that 10% of the plots were built by 2016 and 30% were built by 2021. Field surveys indicate that currently, 73% of the land plots in this neighbourhood have been constructed. By 2026, a total of 74 blocks had been built in the neighbourhood, and according to the future development plan, the remaining 27 units are scheduled to be added by 2050.

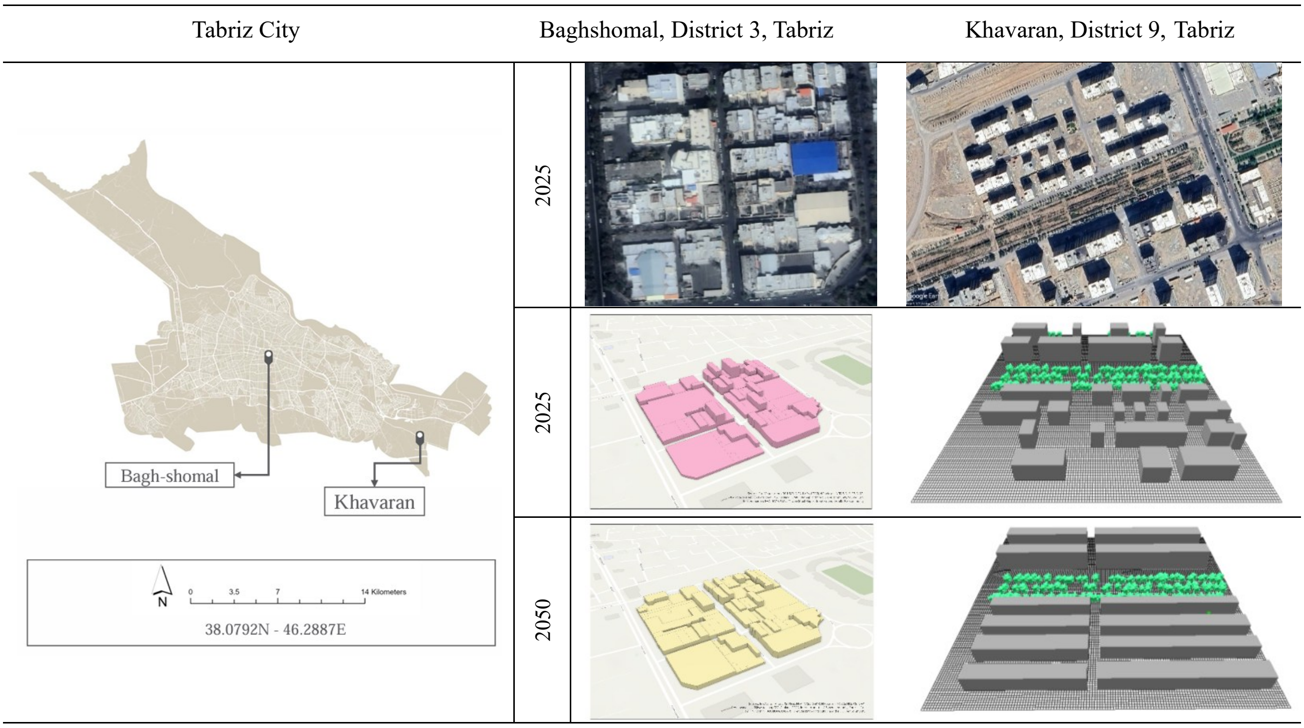

Figure 2. Study areas: Baghshomal and Khavaran neighbourhoods in Tabriz.

Table 1: Comparative Urban Attributes in Baghshomal and Khavaran neighbourhoods.

	District	Grain size	Age	Fabric	Change rate	Density	Area m²	Num of blocks 2026	Num of blocks 2050	Avg height 2026 m	Avg height 2050 m
Zone A Baghshomal	3	Fine & coarse grained	1920	Organic	Low	Horizontal	65205	59	59	12	12
Zone B Khavaran	9	Fine-grained	2010	Grid-like	High	Vertical	122184	74	101	26.5	26.5

2.3 Climate Change and Weather Data Prediction

Tabriz is a mountainous city characterized by a specific climatic condition with warm summers and cold winters (Tahooni et al. 2025). Recent research has documented significant environmental pressures in the Tabriz metropolitan area, including a 0.23 million m^3 increase in surface runoff and a 0.06 °C rise in average urban temperature over a seven-year period, indicating reduced resilience and increased vulnerability to climate-related hazards (Nabikandi et al. 2025). The increasing trend of hot weather in Tabriz began around the year 2000, occurring simultaneously with the onset of the drying of Lake Urmia.

Tabriz weather data were obtained from Tabriz meteorological stations and were used as a basis for future weather data. To predict climatic conditions for the year 2050, the CCWorldWeatherGen tool was employed, utilizing the Representative Concentration Pathway 8.5 (RCP8.5) scenario for future climate forecasting. RCP8.5 is the highest greenhouse gas emission scenario defined by the IPCC, projecting a radiative forcing of 8.5 W/m² by 2100 due to continued fossil fuel dependency and limited climate policies (Riahi et al., 2011). This scenario is commonly applied in urban climate studies to evaluate worst-case warming conditions and assess urban resilience under extreme heat stress.

After identifying the maximum temperature of all summer days, the hottest day was selected. Within that day, the hottest hour was chosen as the representative sample for simulation. Consequently, the simulation was conducted based on data from 11:00 AM to 12:00 PM on AUG 3, 2025. Temperature, relative humidity, wind direction, and wind speed data were extracted from this period and used as inputs for the model. This simulation period was selected to represent peak summer heat conditions, enabling the assessment of urban thermal performance during periods of maximum heat stress rather than annual or seasonal climatic behavior. Constant boundary conditions were adopted to isolate the effects of future urban morphological change on the simulated microclimate.

Analysis of hourly data for August 3, 2025, and August 3, 2050, under the RCP 8.5 scenario (the worst-case global warming pathway) shows that temperatures rise uniformly by approximately 4.3°C across all hours. The hottest hour (11:00 AM) increases from 38.6°C in 2025 to 42.9°C in 2050, while the coldest hour (midnight) rises from 26.3°C to 30.6°C, meaning nighttime offers significantly less cooling relief. Simultaneously, relative humidity drops sharply: peak humidity (midnight) falls from 46% in 2025 to 37.2% in 2050, and minimum humidity (9:00–10:00 AM) plummets from 13% to just 6.7%. These changes indicate a shift toward more severe heat extremes, with warmer nights and drier days exacerbating thermal discomfort and health risks by 2050 (Figure 3, 4.)

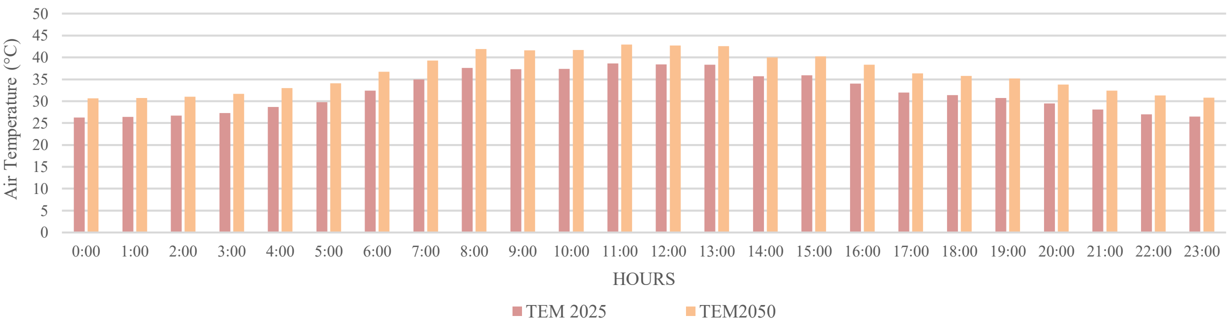

Figure 3. Daily air temperature, August 3, 2025, and August 3, 2050, according to RCP 8.5.

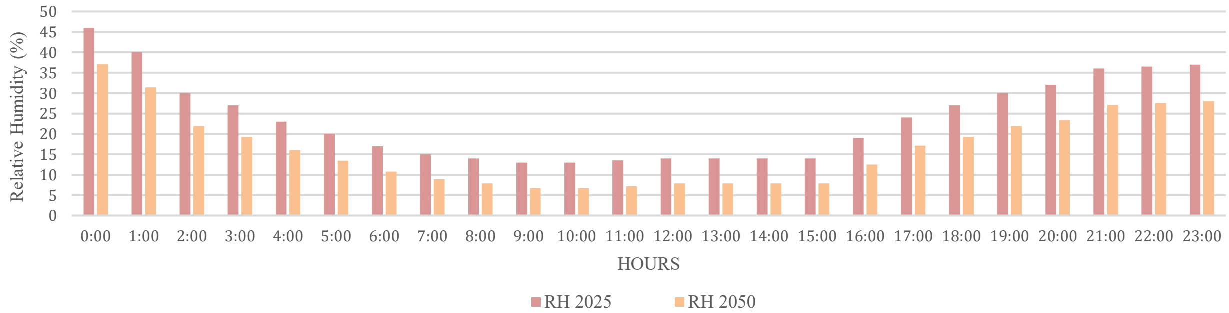

Figure 4. Relative humidity, August 3, 2025, and August 3, 2050, according to RCP 8.5.

2.4 Simulation Settings

In this research, climate simulations were conducted at 11:00 AM on August 3 for the years 2025 and 2050. On August 3, 2025, the maximum recorded temperature was 38.6°C, which rose to 42.9°C by 2050. Relative humidity changed as well from 13.5% in 2025 to 7.18% in 2050. Despite these shifts in temperature and humidity, wind speed and direction remained constant across both simulations, at 4 m/s and 280 degrees, respectively.

In this study, UTCI was evaluated using the BIO MET module. This analysis is instrumental in assessing the climatic quality of different simulated areas. UTCI is expressed as an equivalent temperature in degrees Celsius and is classified into thermal stress levels ranging from "extreme cold stress" to "extreme heat stress." Both humidity and shading can increase the index value. Developed in recent years, UTCI is among the newest and most comprehensive thermal comfort assessment indices available (Velea, Chițu, and Bojariu 2024).

The Khavaran simulation area measures 363.05 m in length and 336.55 m in width, with a pixel resolution of 2.65 m. The Baghshomal area measures 289.8 m by 225 m, with a pixel resolution of

1.8 m. Vegetation was positioned based on satellite imagery and matches field conditions in terms of type and cover. The same building materials were assumed for both areas (Table 2).

In the next step, the primary climate data for ENVI-met 5 were defined. Weather data for the years 2025 and 2050 including air temperature, specific humidity, wind speed, and wind direction were determined based on the data collected from the previous step. To assess thermal comfort, the UTCI was evaluated using the BIO-met application within the ENVI-met software. A comparative raster map (at the height of 1.5m) was created for both areas, illustrating the 2025 and 2050 conditions alongside their differences in temperature, humidity, and UTCI. Table 2 details the environmental grid characteristics (e.g., model cell size and simulation timing) as well as the input parameters used in the BIO-met module.

Finally, nine graphical contours were extracted from each simulation area, resulting in a total of 18 contours from four simulations across two time periods. These contours were then subjected to network analysis (Table 2).

Table 2: ENVI-met simulation settings and input parameters.

	Parameter	input
Weather data	Temperature (°C)	38.6 (2025), 42.9 (2050)
	Humidity (%)	13.5 (2025), 7.18 (2050)
	Wind speed (m/s)	4 (2025), 4 (2050)
Simulation parameters	Location	Tabriz, Khavran, Baghshomal
	Simulation Date	2025/3/AUG
	Simulation Period	11:00 am- 12:00 am
	Dimensions	Khavaran: x-grid: 137, y-grid 127, z-grid 48 Baghshomal: x-grid: 161, y-grid 125, z-grid 36
	Resolution (X, Y, Z)	Khavaran: dx 2.65m, dy 2.65m, dz 1m Baghshomal: dx 1.8m, dy 1.8 m, dz 1m
	Nesting Grid	5
	Model rotation out of north grid	Baghshomal: 4, Khavaran: 21
Physiological parameters	Age	35
	Weight	75 kg
	Height	1.75 m
	Gender	Male
	Clothing	90 Clo
	Metabolic work	1.48 Met

3. Results

The numerical results obtained from the simulations were analysed and evaluated in two stages:

Stage One: In order to investigate the extent of microclimatic changes under the influence of two factors, climate change and structural changes, within each urban fabric, the numerical outputs for each case are compared between the years 2025 and 2050. This comparison makes it possible to examine the effects applied over three decades within each area (i.e., each case is compared with itself). To perform this analysis, first, graphical contours in the form of raster maps for temperature, humidity, and UTCI variables are examined to determine in which parts of the study area the changes in each variable are most significant. Additionally, examining these contours helps identify whether noticeable microclimatic changes have occurred around buildings and structurally modified areas. Next, distribution charts (bar charts) for temperature, humidity, and UTCI are compared. These charts show the frequency of points with specific temperature, humidity, and UTCI values. Comparing these charts allows observing the combined effects of climate change and structural changes on microclimatic changes within each urban fabric.

Stage Two: To determine the extent to which microclimatic changes vary between two urban fabrics with distinct growth rates and structural modification levels, a direct, side-by-side comparison of their numerical outputs is required. Accordingly, the maximum, minimum, and mean values of temperature, relative humidity, and UTCI are compared between the two fabrics for the years 2025 and 2050. The differences in these values were then analysed to identify which fabric exhibited more substantial microclimatic changes.

3.1 Baghshomal Simulation Outputs

The results of raster data analysis of temperature maps in the Baghshomal neighbourhood (Figure 5.) indicate that heat intensification was influential in the central core of the area. The eastern strip, which was among the cooler zones in 2025, became significantly warmer by 2050 especially around and behind Al-Zahra Hospital, where this heat core exhibited substantial growth, despite minimal or very limited morphological changes in these areas. Regarding humidity, numerical values have decreased due to climatic changes, although the spatial pattern shows no significant variation. However, in locations with morphological changes, such as the northeastern corner of the fabric, humidity has shown an increasing trend. In line with this trend, a zone of climatic comfort based on UTCI emerged in areas with low-rise villa-type buildings; but by 2050, with the construction of high-rise buildings on these sites, such zones have become more apparent, also influencing reductions in temperature and increase in humidity.

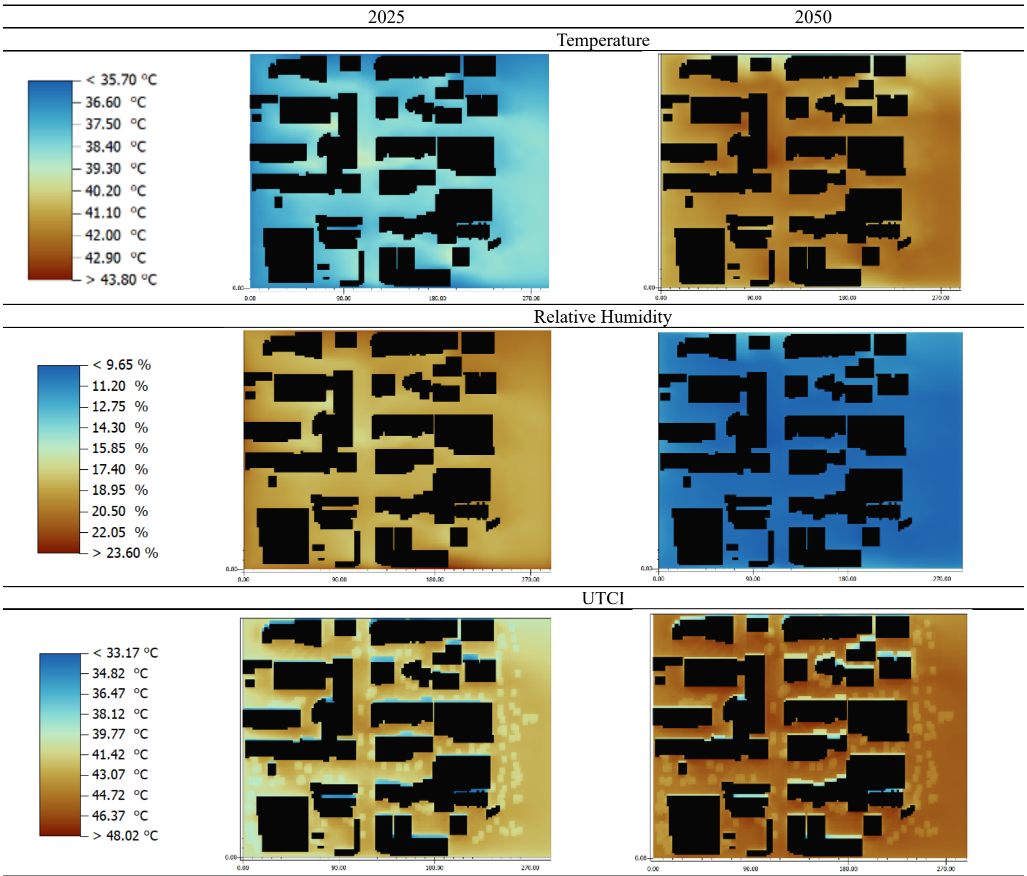

Figure 5. Temperature, humidity and UTCI raster maps for the Baghshomal neighbourhood in 2025 and 2050.

To compare the numerical outputs of temperature, humidity, and UTCI variables, we used frequency distribution plots of these values within the study area for the years 2025 and 2050. In 2025, temperature variations ranged from 37.5 to 38.6 °C, humidity from 18.5% to 19.2%, and UTCI from 41.5 to 43, indicating data dispersion. By 2050, temperature is projected to range from 41.6 to 42.2 °C, humidity from 10% to 10.6%, and UTCI from 44.5 to 46, reflecting a shift in numerical data distribution. The average temperature increased by approximately 3.9 °C (about 10.3%), while average humidity decreased by 8.55 percentage points (approximately 45.4%). The average UTCI rose by about 3.0 units (approximately 7.1%), indicating a substantial decline in outdoor thermal comfort conditions over the study period. It is noteworthy that the spatial pattern and visual distribution of the data in 2025 and 2050 exhibited a similar form, with a visible clustered configuration; however, the numerical values had changed (Figure 6.)

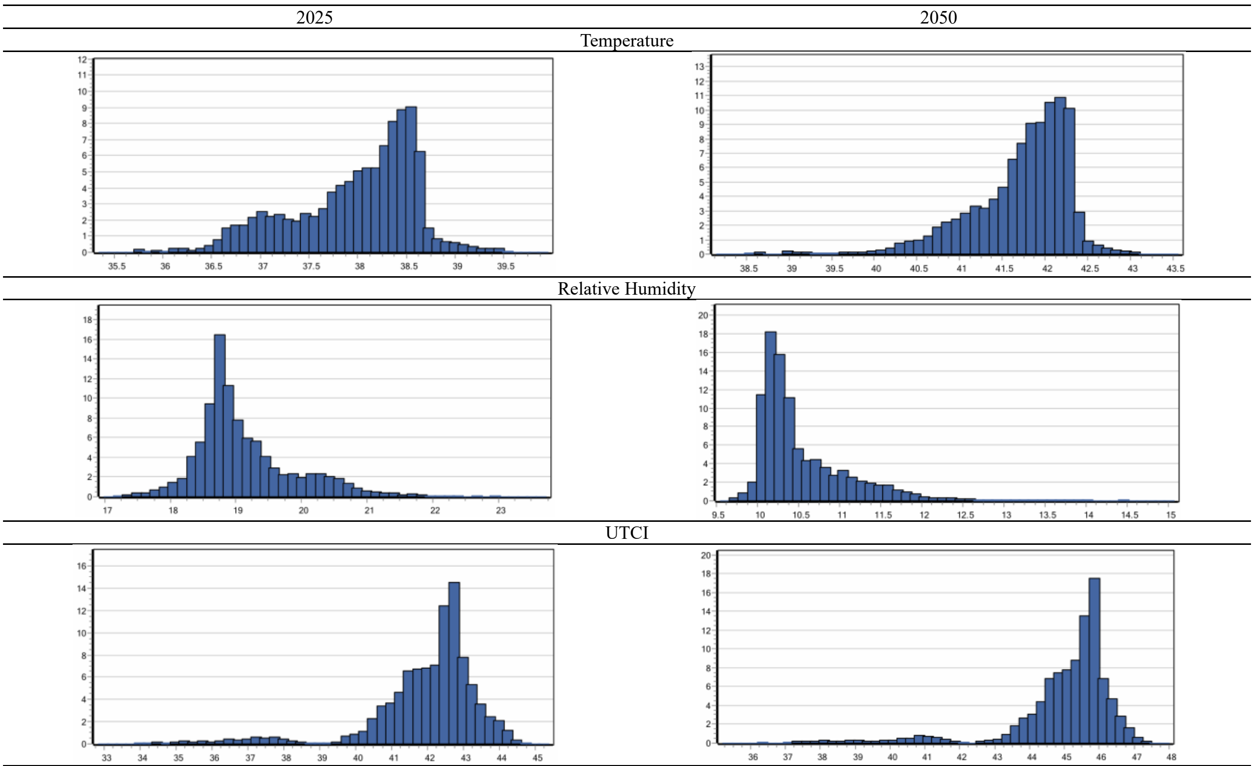

Figure 6. Temperature, humidity and UTCI distribution charts for the Baghshomal neighbourhood in 2025 and 2050

3.2 Khavaran Simulation Outputs

In the temperature and humidity results for the Khavaran neighbourhood for the years 2025 and 2050, a clear pattern emerges: temperature and humidity exhibit an inverse relationship. Wherever temperatures are high on the map, humidity levels are correspondingly low, a relationship that is clearly visible in the graphical contours. This phenomenon persists in 2050 as well. Despite significant morphological changes occurring within this growing urban fabric, the inverse relationship between temperature and humidity has remained intact. The presence of asphalt materials has generated hotspots, particularly on the southern fronts of the blocks, while the existence of a local park has contributed to moderating and controlling climatic conditions.

Temperature and humidity display a dispersed pattern. As the urban morphology of this neighbourhood has been completed, this scattered and irregular pattern of climatic contours has given way to a more organized configuration. The southern areas are very hot and exhibit low humidity.

Regarding the UTCI, hot spots with low thermal comfort were observed between buildings. Following the completion of development projects, these locations have experienced an improvement in climatic comfort. Furthermore, light and shade patterns on the northern sides of the blocks have created a zone of thermal comfort for the courtyards of north-facing buildings, an advantage in itself. The local park offers highly favourable climatic comfort (Figure 7.)

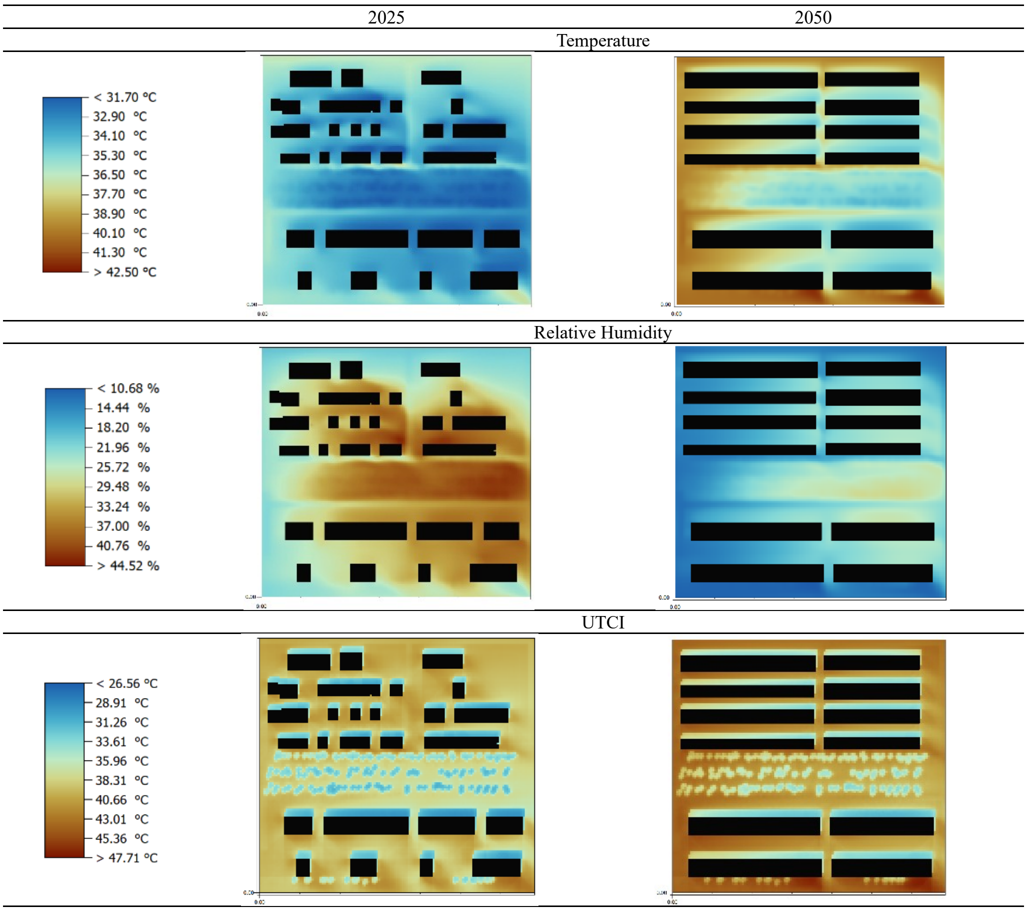

Figure 7. Temperature, humidity and UTCI raster maps for the Khavaran neighbourhood in 2025 – 2050.

The numerical data distribution pattern for temperature and humidity in 2025 and 2050 shows a similar form. However, for UTCI, this form has shifted from a clustered pattern toward a more linear configuration. The data for temperature and humidity exhibit a more linear trend, with less evidence of a clustered pattern.

In 2025, temperature variations ranged from 32 to 36 °C, humidity from 20.5% to 40%, and UTCI from 37.5 to 41, indicating data dispersion. By 2050, temperature is projected to range from 35 to 36.5 °C, humidity from 11.5% to 15% and 21.5 to 25, and UTCI from 39.5 to 44.5, reflecting a shift in numerical data distribution. Specifically, from 2025 to 2050, the mean temperature increased by 1.75 °C (approximately 5.1%), mean humidity decreased by approximately 17 percentage points (56.2%) for the lower range and 7 percentage points (23.1%) for the upper range, and the mean UTCI increased by 2.75 units (approximately 7.0%), indicating a notable decline in thermal comfort conditions in the Khavaran neighbourhood (Figure 8.)

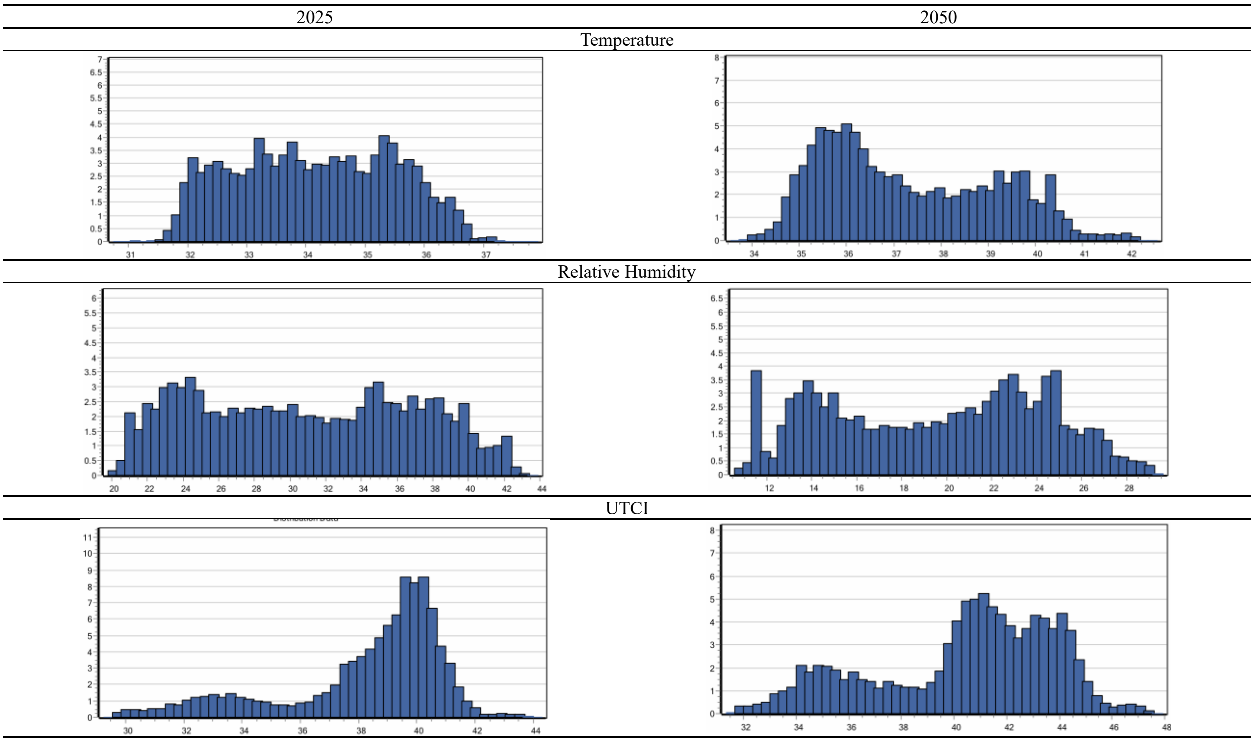

Figure 8. temperature, humidity and UTCI distribution charts for the Khavaran neighbourhood 2025-2050

3.3. Comparative Analysis of Temperature, Humidity, and UTCI

The comparative numerical simulation for Baghshomal and Khavaran reveals distinct climatic trajectories and divergent adaptive capacities under future forcing (2050), with Khavaran's rapid urban expansion and Baghshomal's very slow growth gradient imposing fundamentally different resilience potentials. In the baseline period (2025), Baghshomal exhibits higher thermal extremes. Its maximum temperature reaches 39.56 °C, compared to Khavaran's 37.48 °C.

By 2050, both zones warm, but the magnitude of change differs. Baghshomal's minimum temperature rises from 35.7 °C to 38.56 °C (+2.86 °C), whereas Khavaran's minimum increases from 31.07 °C to 33.89 °C (+2.82 °C). This indicates a similar base warming in both areas.

Crucially, Baghshomal's maximum temperature in 2050 (43.08 °C) is only slightly higher than Khavaran's (42.14 °C). Despite this similarity in peak values, the frequency temperature (most probable condition) reveals a notable divergence. In 2025, Baghshomal's frequency temperature (37.97) is higher than Khavaran's (34.15). By 2050, Baghshomal's frequency temperature rises to 41.71, while Khavaran's reaches 37.31 a smaller absolute shift.

Thus, although both fabrics experience warming, Baghshomal's modal temperature remains consistently higher and increases more substantially than Khavaran's (Figure 9.)

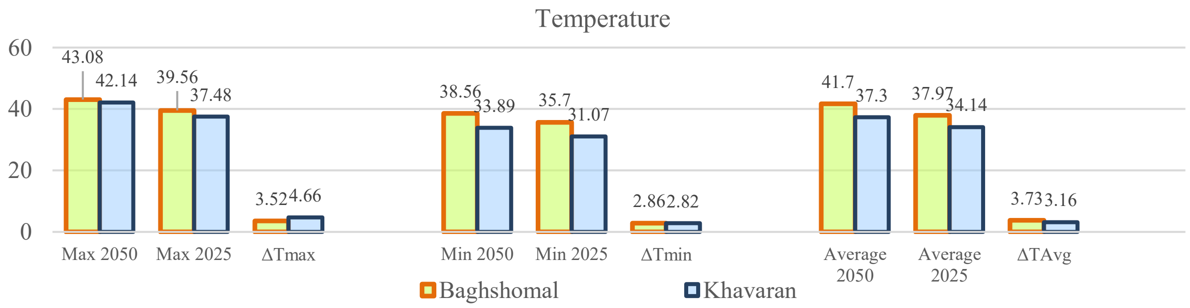

Figure 9. Comparative Temperature Across Fabrics (2025–2050)

In the baseline period (2025), Khavaran exhibits a markedly higher humidity profile than Baghshomal. Maximum relative humidity reaches 43.50% in Khavaran compared to only 23.51% in Baghshomal. Similarly, minimum humidity (20.02% vs. 17.16%) and average humidity (30.87% vs. 19.14%) are substantially higher in Khavaran. This indicates that Khavaran already experiences a more humid environment under current conditions.

By 2050, both zones undergo significant drying, but the magnitude of decline differs considerably. Khavaran's maximum humidity drops drastically from 43.50% to 29.28% (ΔRHmax = -14.22%), whereas Baghshomal's maximum declines from 23.51% to 14.78% (ΔRHmax = -8.73%). Similarly, Khavaran's minimum humidity falls from 20.02% to 10.68% (ΔRHmin = -9.34%), while Baghshomal's minimum decreases from 17.16% to 9.65% (ΔRHmin = -7.51%).

The average humidity values reinforce this pattern. Khavaran's average humidity drops by -11.33% (from 30.87% to 19.54%), compared to Baghshomal's decline of -8.58% (from 19.14% to 10.56%).

Although Khavaran starts with a much more humid environment in 2025, it experiences a substantially greater drying trend across all metrics (max, min, and average) compared to Baghshomal. The absolute reduction in Khavaran's humidity is nearly double that of Baghshomal for maximum values (-14.22% vs. -8.73%) (Figure 10.)

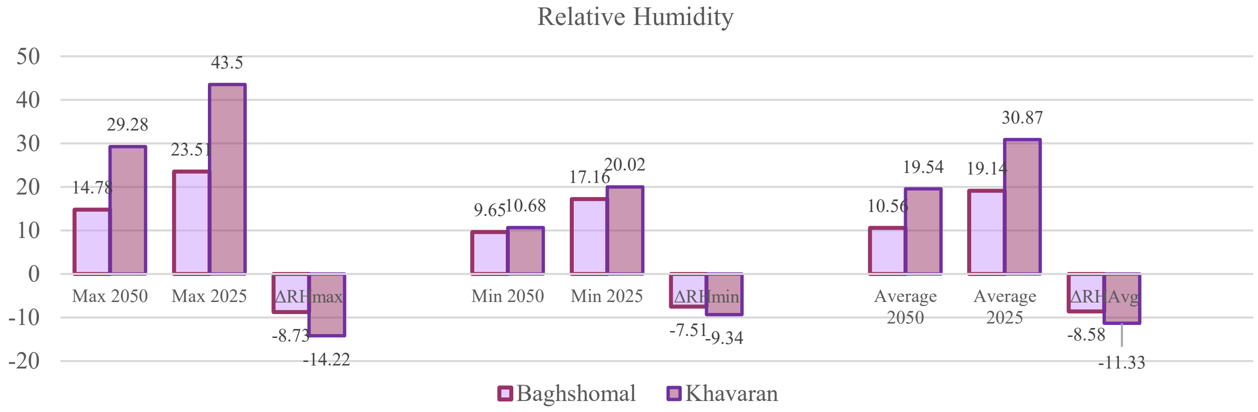

Figure 10. Comparative Relative Humidity Across Fabrics (2025–2050)

In the baseline period (2025), Baghshomal exhibits higher heat stress levels than Khavaran. Maximum UTCI reaches 44.90 in Baghshomal compared to 43.87 in Khavaran. Similarly, minimum UTCI (33.17 vs. 29.56) and average UTCI (41.91 vs. 38.24) are substantially higher in Baghshomal. This indicates that Baghshomal already experiences a more severe heat stress burden under current conditions.

By 2050, both zones experience increased heat stress, but the magnitude of change differs considerably. Baghshomal's maximum UTCI rises from 44.90 to 47.47, whereas Khavaran's increases from 43.87 to 47.40. Although Khavaran starts with a lower baseline, it experiences a larger absolute increase in peak heat stress. However, Baghshomal's final maximum UTCI (47.47) remains marginally higher than Khavaran's (47.40).

Baghshomal's minimum UTCI rises from 33.17 to 35.57 (+2.40), while Khavaran's increases from 29.56 to 31.69 (+2.13). The increase in minimum UTCI is slightly larger in Baghshomal, indicating that nighttime heat stress recovery may be more compromised in Baghshomal due to its dense central urban form and urban heat island effect.

The average UTCI values reinforce this pattern. Baghshomal's average UTCI rises from 41.91 to 44.92 (+3.01), whereas Khavaran's increases from 38.24 to 40.39 (+2.15). The increase in average heat stress is notably larger in Baghshomal, suggesting that the most probable heat stress condition in Baghshomal becomes considerably more severe by 2050.

Although Khavaran shows a larger increase in maximum UTCI (+3.53 vs. +2.57), Baghshomal maintains consistently higher absolute UTCI values across all metrics in both 2025 and 2050. Moreover, the gap in average UTCI between the two fabrics widens from 3.67°C in 2025 to 4.53°C in 2050, indicating that Baghshomal's modal heat stress condition becomes increasingly more severe relative to Khavaran (Figure 11.)

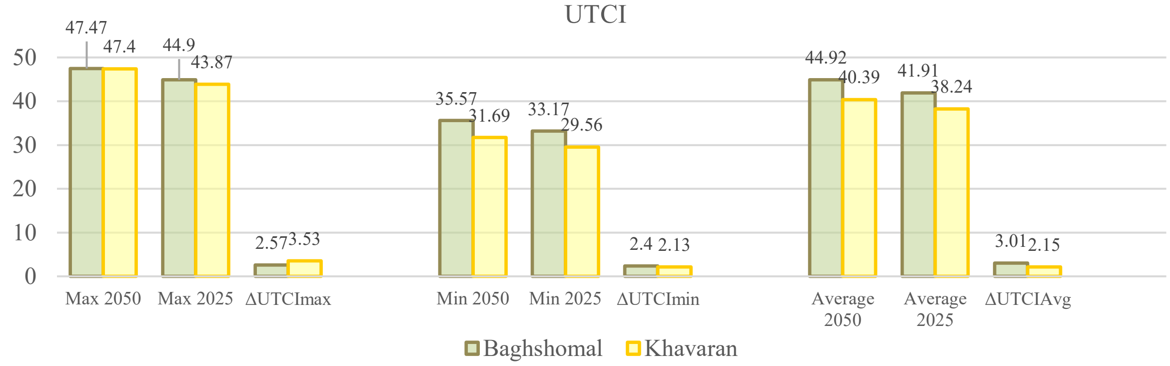

Figure 11. Comparative UTCI Across Fabrics (2025–2050)

4. Discussion

A substantial body of research has shown that parameters such as building morphology including height-to-width (H/W) ratio, street orientation, and building configuration, significantly influence pedestrian-level thermal comfort. For instance, greater canyon depth can lower mean radiant temperature (MRT) by providing more shading, while suitable street orientation can improve ventilation or reduce solar exposure (Abd Elraouf et al. 2022) (Abdollahzadeh and Biloria 2021). This very mechanism explains the observed climatic conditions in the Khavaran and Baghshomal districts. The more favourable thermal environment projected for Khavoran in the coming years can be attributed to the higher building heights and deeper urban canyons, which result in reduced solar radiation at pedestrian level. Conversely, the lower building heights in Baghshomal offer less shade, contributing to comparatively greater thermal stress.

More importantly, these findings indicate that the future thermal response of urban environments is governed not merely by the magnitude of urban growth but by the way urban form evolves. Street geometry, canyon depth, and building configuration collectively regulate solar access and long-wave radiation exchange, thereby influencing pedestrian-level thermal resilience under future climate conditions.As stated by (Shimazaki et al. 2025) and (Oke 1982), as a city expands, the natural landscape is largely replaced by built environments, resulting in diminished vegetation cover and greater absorption of solar radiation by buildings and paved surfaces. Consequently, urban areas tend to experience higher temperatures than their rural surroundings a phenomenon commonly referred to as the urban heat island effect. In the present case, however, the built environment presents a somewhat different scenario. Here, the man-made structures have, to some extent, moderated this effect by providing shading, thereby helping to regulate microclimatic conditions and enhance outdoor thermal comfort. Although uncontrolled urban sprawl generally carries adverse consequences, under certain circumstances, such positive outcomes can also emerge.

This observation is consistent with Urban Heat Island theory, which suggests that urban form can either intensify or mitigate heat accumulation depending on its influence on radiation exchange, airflow, and the surface energy balance. Therefore, the climatic consequences of urbanization depend not only on the extent of development but also on the spatial configuration of the built environment.

The comparison between Baghshomal and Khavaran reveals that resilience to future climate change is not simply a function of baseline temperature or morphological type, but is critically shaped by the rate of urban transformation. Baghshomal, as a compact, slow-growing central fabric, exhibits higher absolute temperatures and UTCI values in both 2025 and 2050, which is consistent with classical urban heat island effects in dense, self-shaded morphologies. However, its very low development velocity (only 15.25% of buildings renovated over three decades) preserves passive microclimatic regulation through narrow alleys, aged porous surfaces, and limited ventilation. Consequently, Baghshomal experiences a lower rate of increase in maximum temperature (+3.52°C) and, more importantly, a significantly milder decline in relative humidity (ΔRHmax = -8.73%).

In contrast, Khavaran a dispersed, rapidly developing peripheral fabric, begins with lower absolute temperatures and higher humidity in 2025, yet undergoes a much more dramatic transformation by 2050. Its maximum temperature rises by +4.66°C, and its relative humidity collapses by -14.22%. Under identical climate forcing (RCP8.5), identical material properties, and the absence of vegetation, this divergence must be explained by morphological and aerodynamic differences. Khavaran's regular grid pattern, wide sunlit streets, extensive impervious surfaces (asphalt, concrete), and strong ventilation all accelerate surface heating and evaporative moisture loss. Furthermore, its newly built, uniform fabric lacks the natural moisture-buffering capacity that comes from the aged, weathered surfaces and self-shading geometry of Baghshomal's compact organic layout.

Thus, Khavaran appears more vulnerable to future climate change, despite its lower absolute temperatures, because its rapid urban transformation substantially amplifies warming and drying trends. This finding demonstrates that the mechanism of urban transformation exerts a stronger influence on future thermal resilience than the absolute magnitude of physical change alone. Therefore, urban growth intensity should not be interpreted independently of urban form and spatial configuration when evaluating future climate vulnerability.

These findings are also consistent with previous thermal comfort studies showing that pedestrian heat stress is governed not only by air temperature but also by radiation exchange, shading conditions, and urban geometry, all of which are reflected in the UTCI index.

Nevertheless, these findings should be interpreted within the methodological scope of this study. The simulations were performed under identical material properties, constant vegetation conditions, and a single extreme summer climate scenario to isolate the effects of urban morphological change on outdoor thermal conditions. Future studies should extend this framework by incorporating seasonal variability, multiple climate scenarios, dynamic vegetation evolution, and uncertainty analyses.

The AI-based models were intended to generate plausible future urban morphology scenarios rather than precise long-term forecasts. Therefore, the assumption of continued historical renovation trends to 2050 should be interpreted as a scenario-based simplification for comparative microclimate assessment.

5. Conclusion

Beyond its findings for Tabriz, this study offers a transferable methodological framework for future urban climate assessments. The proposed workflow demonstrates how AI-based urban growth prediction, future weather generation, and ENVI-met simulation can be integrated into a single modelling framework capable of evaluating the coupled impacts of climate change and urban transformation. This framework can be adapted for other rapidly urbanizing cities experiencing heterogeneous growth mechanisms.

This study compared a compact, slow-growing central fabric (Baghshomal) with a dispersed, rapidly developing peripheral district (Khavaran) in Tabriz under identical climate forcing (RCP8.5), material properties, and no vegetation. The results demonstrate that development velocity is a more critical determinant of future urban heat resilience than morphological type or baseline temperature alone.

Baghshomal, despite having higher absolute temperatures and UTCI values in both 2025 and 2050, exhibits a lower rate of maximum temperature increase (+3.52°C vs. +4.66°C) and a substantially milder humidity decline (-8.73% vs. -14.22%). Its slow structural change (only 15.25% renovation over three decades) preserves passive microclimatic regulation through compact, self-shading geometry, aged porous surfaces, and limited ventilation. In contrast, Khavaran's rapid expansion characterized by wide sunlit streets, impervious surfaces, strong ventilation, and a uniform new fabric accelerates warming and induces a sharp humidity collapse, making it the more vulnerable fabric under 2050 conditions.

Therefore, the following conclusions are drawn:

1. Development velocity matters more than morphological type alone. A slowly evolving compact fabric can be more resilient than a rapidly transformed dispersed fabric, even when the latter has lower absolute temperatures.
2. Humidity collapse is a critical but often overlooked indicator of vulnerability. Khavaran's severe drying, despite its lower UTCI, poses serious risks for evaporative cooling and human thermoregulation during extreme heat events.
3. Compact, slow-growing central fabrics offer inherent adaptive advantages that are systematically eroded by fast, unregulated urban expansion.

For urban planning, these findings imply that controlling development velocity in peripheral growth zones, preserving the microclimatic benefits of compact organic forms, and avoiding uniform grid patterns with wide sunlit streets are essential strategies for climate-adaptive design. Future research should incorporate dynamic material scenarios, seasonal simulations, and vegetation to further validate these conclusions. Ultimately, how cities grow may be as important as how much they grow in determining their capacity to withstand the accelerating climate crisis. The findings should be interpreted within the assumptions of the adopted scenario-based framework, including simplified morphological representation, and a single climate scenario.

Although the proposed framework is methodologically transferable, its application to other cities requires local calibration of AI prediction models, future climate scenarios, and urban morphological characteristics.

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Conflicts of Interest

"The author(s) report no conflicts of interest."

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Institutional Review Board Statement

This study did not involve human participants or animal subjects in any capacity, whether in the form of experimentation, observation, or data collection. As such, no ethical approval from an institutional review board or equivalent ethics committee was sought or required. The authors affirm that all applicable institutional and national regulations concerning research conduct were nevertheless duly observed.

CRediT author statement:

Paria Saadatjoo: Writing – original draft, Software, Methodology, Conceptualization. Kiomars Fathimajd: Writing – original draft, Visualization, Software, Methodology. Hourakhsh Ahmad Nia: Review & editing, Supervision, Resources, Methodology, Conceptualization. "All authors have read and approved the final manuscript."

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